UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Civil, Maritime, Environmental Engineering & Science

The Thermal Performance of Foundation Piles used as Heat Exchangers in Ground Energy Systems

by

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ABSTRACT

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THE THERMAL PERFORMANCE OF FOUNDATION PILES USED AS HEAT EXCHANGERS IN GROUND ENERGY SYSTEMS

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Pile heat exchangers are expected to make a significant contribution to meeting UK and EU renewable energy and carbon dioxide reduction targets. However, design for the thermal capacity of pile heat exchangers has to date been largely based on methods developed for borehole heat exchangers. Piles have a much smaller aspect (length to diameter) ratio than boreholes and consequently their thermal behaviour is different in a number of important ways. This thesis explores these differences and makes recommendations for improved assessment of pile heat exchanger thermal capacity.

Traditionally vertical heat exchanger design assumes separation of the thermal effects in the ground and in the pile. A transient temperature response function is used to assess temperature changes in the ground and a steady state resistance is applied to the pile concrete. In this thesis existing approaches to temperature response functions are critically assessed for use with thermal piles. It is important to take into account the larger pile diameter, which causes increased temperature changes in the short term. In the long term, the shorter pile length will result in reduced temperature changes as steady state is reached more quickly.

Simple 2D numerical modelling has been carried out and the results used to derive a new method for determining pile thermal resistance. However, for large diameter piles, the time taken for the pile to reach steady state suggests that the use of a constant thermal resistance in design is not always appropriate. In these cases it is recommended that a transient temperature response function is used to assess the response of the ground and the concrete together.

The applicability of short duration thermal response testing for pile heat exchangers has been examined. Modelling and case study data has shown that the technique is only reliable for piles of 300mm diameter or less. For the special case of large diameter piles with centrally placed heat transfer pipes then it is possible to use the test to determine the thermal conductivity of the pile concrete, but not pile thermal resistance.

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Author's Declaration

I, Fleur Loveridge, declare that the thesis entitled *The Thermal Performance of Foundation Piles used as Heat Exchangers in Ground Energy Systems* and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research.

I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published, or are currently under review to be published, as journal papers, oral presentations and technical documentation as listed in Appendix C.

Signed:

Date:

Acknowledgements

The journey which has led to the completion of this thesis would not have been possible without the support of Tony O'Brien and colleagues at Mott MacDonald. I would also like to thank the other partners in my industrial steering group: WJ Groundwater, Cementation Skanska and Golder Associates for their input and advice. I am particularly grateful for the time given to me in the early stages of this work by Professor Dietmar Adam and Roman Markiewicz at Vienna University of Technology. I learnt a lot there in a fascinating week.

I would like to thank Professor William Powrie for his support and thought provoking reviews of my work. This often led me to return to and place greater emphasis on understanding underlying scientific principles.

In the latter stages of this work I have been involved with the sub-committee of the Ground Source Heat Pump Association which has been tasked with producing a standard for the design and installation of thermal piles. This has proved a fruitful forum for the discussion of ideas and concepts and has helped to shape my thinking in a number of respects.

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Finally I would like to thank Peter Talling for his patience and loyal support.

Abbreviations

AR	Aspect ratio
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BHE	Borehole heat exchanger
BSI	British Standards Institution
CFA	contiguous flight auger (pile)
CIBSE	Chartered Institute of Building Services Engineers
COP	Coefficient of performance
DECC	Department for Energy and Climate Change
DST	duct storage model
EPSRC	Engineering and Physical Sciences Research Council
FCS	finite cylindrical source
FLS	finite line source
GSHP	ground source heat pump
GSHPA	Ground Source Heat Pump Association
HDPE	high density polyethelene
HMSO	Her Majesty's Stationary Office
ICE	Institution of Civil Engineers
ICS	infinite cylindrical source
ID	internal diameter
IEEE	Institute Electrical and Electronics Engineers
ILS	infinite line source
NHBC	National House Building Council
OD	outer diameter

RHI	Renewable Heat Incentive
SIA	Swiss Society for Engineers and Architects
SPF	Seasonal performance factor
TRT	thermal response test
VDI	Verein Deutscher Ingenieure (Association of German Engineers)

Notation

Main symbols

A	area (m^2)
c	concrete cover to pipework (m)
d	diameter (m)
F	dimensionless temperature response function
f	friction factor
G	temperature response function for an infinite cylindrical heat source
H	pile or borehole length (m)
h	heat transfer coefficient (W/m^2K)
L	thickness of material, characteristic length (m)
m	mass flow rate (kg/s)
Nu	$\frac{hL}{\lambda_{fluid}}$ Nusselt number (ratio of convective to conductive heat transfer)
n	number of pipes, porosity
Pr	$\frac{\upsilon}{\alpha}$ Prandl number (ratio of viscous diffusion rate to thermal diffusion rate)
Q	rate of heat transfer (W)
q	heat flux (W/m)
R	thermal resistance (K/W in conjunction with Q or mK/W in conjunction with q)
R_b	thermal resistance of borehole or pile (mK/W)
R_c	thermal resistance of concrete (mK/W)
Re	$\frac{uL}{\upsilon}$ Reynolds number (ratio of inertial to viscous forces for fluid flow)
r	radial coordinate, radius (m)

S_b	Remund's shape factor for borehole heat exchangers
S_c	specific heat capacity (J/kgK), shape factor for concrete in pile heat exchangers
S_c'	effective specific heat capacity used in diffusion-advection equation (J/kgK)
S_{cv}	ρS_c volumetric heat capacity
S_f	shape factor
s	shank spacing (m)
T	temperature (^{o}C or K)
t	time (s)
u	pipe flow velocity (m/s)
v	darcy velocity (m/s)
x	distance, length along pipe circuit (m)
α	thermal diffusivity (m^2/s)
χ	volumetric phase proportion
Δ	change in value (usually temperature)
γ	Euler's constant
λ	thermal conductivity (W/mK)
λ'	effective thermal conductivity used in diffusion-advection equation (W/mK)
Φ	normalised temperature
μ	viscosity (kg/ms)
ρ	density (kg/m^3)
ρ'	effective density used in diffusion-advection equation (kg/m^3)
υ	kinematic viscosity (m^2/s)

Subscripts

b	borehole or pile
c	concrete
cond	conductive
conv	convective
f	fluid
g	ground
i	inner dimension of pipe
in	inlet
o	outer dimension of pipe
out	outlet
p	pipe
s	solid component
steady	steady state heat flow
trans	transient heat flow
w	water

List of Physical Constants

γ	Euler's constant	0.5772
σ	Stefan-Boltzmann constant	$5.669 \times 10^{-8}\ Wm^{-2}K^{-4}$

Chapter 1. Introduction

1.1. Research Objectives

This thesis is formed around three papers on the use of structural pile foundations as heat exchangers in a ground energy system (Table 1-1). Dual use of piles in this way, often referred to as energy piles or thermal piles, has seen increased take up in recent years as government targets for greener energy and carbon dioxide emissions reductions have led to changes in legislation to encourage adoption of renewable heat energy technologies. The recently introduced Renewable Heat Incentive (RHI) now offers subsidy to energy piles and other ground energy systems on a pay per kilo-watt-hour basis (DECC, 2011a).

Research into the behaviour of energy piles has not kept pace with the recent increase in their use. There remain uncertainties regarding many aspects of energy pile behaviour and few thoroughly documented case studies exist to validate design approaches. This work aims to investigate a number of these uncertainties by addressing the following objectives:

1. To assess the reliability of current analytical and numerical models used to determine the thermal capacity of pile heat exchangers;

2. To investigate the internal thermal behaviour of energy piles to provide better recommendations for design parameters;

3. To assess the applicability of the thermal response test when applied to energy piles, including the use of existing interpretation techniques;

4. To make recommendations for design and investigation approaches relevant to energy piles.

1.2. Thesis Outline

The first three chapters of this thesis set out relevant background information regarding ground energy systems with a particular focus on energy piles. The remainder of this chapter introduces ground energy systems generally, while Chapter 2 provides a summary of the relevant physical concepts required for understanding their thermal behaviour. An overview of the use of closed loop ground energy systems is then presented in Chapter 3. This includes details of the system components, how piled foundations can be used as heat exchangers, details on construction methods, design approaches and an introduction to the research themes.

Table 1-1 Papers Forming the Thesis

Chapter	***Reference***
Chapter 4	Pile heat exchangers: thermal behaviour and interactions, *Proceedings of the Institution of Civil Engineers Geotechnical Engineering,* accepted for publication.
Chapter 5	On the thermal resistance of pile heat exchangers*, Geothermics,* in review.
Chapter 6	Thermal response testing for pile heat exchangers, *Journal of Geotechnical and Geoenvironmental Engineering,* in review.

The research papers follow in Chapters 4, 5 and 6 (Table 1-1). Chapter 4 provides an in-depth review of existing analytical and numerical approaches for the design of pile heat exchangers. It looks separately at the internal response of the pile to heating and the thermal response of the ground surrounding the pile. Design methods developed for borehole heat exchangers are critically assessed and their limitations for use with piles are set out. All ground heat exchangers rely on circulation of a heat transfer fluid and the influence of the thermal regime within this fluid is also examined.

Chapter 5 looks in more detail at the internal behaviour of energy piles. Very little guidance is available for the selection of design parameters for energy pile internal behaviour. Numerical models are presented and the results of the modelling are used to provide a guide to the likely range of input parameters. The modelling results also illustrate the limitations of a number of simplifications normally made in the design process, namely a constant heat exchanger surface temperature and steady state heat flow.

Chapter 6 considers thermal response testing for heat exchanger piles. This simple in situ test is commonly used with borehole heat exchangers to determine the thermal conductivity of the ground. The test method and interpretation techniques are reviewed, focussing on the potential limitations for use with different types of piles, which will have much larger diameters than typical boreholes. Numerical models are used to produce synthetic thermal response test data which can then be used to back calculate the thermal conductivity in a situation where this is already known, hence allowing evaluation of the technique. The results from thermal response tests carried out on three different types of pile heat exchangers are then presented and compared with the results of the modelling. Recommendations for carrying out and interpreting tests are made.

Discussion of the findings and the overall conclusions of this work are presented in Chapter 7 with Chapter 8 setting out detailed recommendations for practice. Chapter 9 contains suggestions for further research, including how the results presented in this thesis link to other work currently underway.

1.3. Types and Uses of Ground Energy Systems

Heating accounts for 47 per cent of total UK final energy consumption and more than three-quarters (77 per cent) of energy use across all non-transport sectors (DECC, 2011a). The provision of renewable energy and especially renewable heat energy to buildings is therefore of prime importance if UK and EU targets for reducing carbon dioxide emissions and increasing the usage of renewable energy (Council Directive, 2009) are to be met.

A potentially important means of delivering renewable heat energy to buildings is the use of ground energy systems. The concept is based on utilising the low enthalpy heat stored at shallow depths (<200m) within the earth's crust. The temperature in the ground at such depths is relatively constant throughout the year, although the near surface (<15m deep) temperatures fluctuate seasonally due to the patterns of incoming solar radiation. In winter the ground temperature is higher than the air temperature, while in summer it is lower. This means that the ground may be used as a heat source during winter and a heat sink during summer.

1.3.1. Types of System

Two main types of ground energy system are used, open loop and closed loop, based principally on convection and conduction respectively. In an open loop system groundwater is extracted from an aquifer and passed through a heat exchanger to heat a secondary fluid that is used in the heating and/or air conditioning system. In closed loop systems pipes installed in the ground allow circulation of a heat transfer fluid to transfer heat energy between the heating / cooling system and the ground through conduction. Both systems usually operate with a heat pump, which allows a greater temperature difference to be achieved between the fluid circuit in the ground and the heating / cooling system in the building.

Closed loop systems are often installed in boreholes, with single or double "U" pipes being grouted into the open hole. However, where foundation elements are being constructed economic, spatial and carbon benefits can be achieved by installing the fluid pipes within the foundation elements. Bored piles are the most common type of energy foundation but any structure in contact with the ground can be used (Adam & Markiewicz, 2009).

1.3.2. Global Context

Ground energy systems are used across much of northern Europe and North America. There are now estimated to be around 1.1 million installations worldwide, see Table 1-2 (Lund et al, 2004). Although USA and Canada have the greatest number of installed heat pumps, the Scandinavian nations have the greatest number of installations per head of population (Midttomme et al, 2008).

Table 1-2 Installed Ground Energy Systems in Leading Countries (after Lund et al, 2004)

Country	GWhr per year	Number Installed
Austria	370	23,000
Switzerland	780	30,000
Canada	600	36,000
Germany	930	46,400
Sweden	9200	230,000
USA	6,300	600,000

In the UK, however, the use of ground energy systems has been much more limited. This is due principally to the historic relative prices of gas (traditionally used for heating) and electricity (required for the heat and circulation pumps). Research in ground energy systems was pioneered in Sweden and North America in the 1980's (eg, Bose et al, 1985, Eskilson, 1987). However, there are still several significant gaps in the state of knowledge, especially in the context of long term usage and in the application of the technology to foundation elements. The following chapter will focus on understanding the physical concepts relevant to ground energy systems so that these uncertainties can be addressed in the subsequent chapters.

Chapter 2. Physical Concepts

Energy is often understood as the ability to do work. Work is typically defined in terms of mechanics, as the product of a force applied to a body and the displacement of that body caused by the application of that force. Work and energy are both scalar quantities and have the same units, being kgm^2/s^2 or Joules (J). Energy is subject to conservation law and cannot be created or destroyed, only transferred between forms. These forms include kinetic, potential, thermal, gravitational, sound, light, elastic, and electromagnetic energy.

Thermal energy, which is transferred by ground energy systems, is the internal energy of a body associated with the random movement (ie potential and kinetic energies) of atomic particles as well as the energy attributable to the phase (ie solid, liquid, gas) of the body. The fundamental thermal property is temperature. If components of an isolated system are at different temperatures then transfer of thermal energy will occur until the temperatures are equal and there is thermal equilibrium. This transfer of thermal energy is termed heat. The parameter of most interest for ground energy systems is the rate of heat transfer (or power), usually given the symbol Q, with units of Joules per second or Watts (W). For vertical heat exchangers the heating power is often expressed per metre length of the heat exchanger and given the symbol q (W/m).

Neglecting heat associated with phase change, heat transfer may occur via three principal mechanisms: conduction, convection and radiation. These concepts are briefly outlined below.

2.1. Heat Transfer Mechanisms

2.1.1. Conduction

When there is a temperature gradient in a body, heat transfer will occur from the higher temperature region to the lower temperature region. This transfer occurs because the vibration amplitudes of the atomic particles are greater at higher temperatures, and the energy of these particles is transferred as collisions occur. Experience has shown that when heat transfer occurs at a steady state, then the rate of heat transfer is proportional to the temperature gradient and this is expressed as Fourier's law:

$$\frac{Q}{A} = -\lambda \frac{dT}{dx}$$ **Equation 2-1**

where dT/dx is the thermal gradient in the direction of the heat flow, A is the cross sectional area subject to the heat transfer and λ is the proportionality constant called the thermal conductivity. The units of thermal conductivity are W/mK. As with electrical conductance, a resistance to heat flow can also be defined. This can be a very useful concept as it combines both the thermal properties (conductivity) and the geometric properties (length, L and area, A) into a single parameter:

$$R = \frac{\Delta T}{Q} = \frac{L}{A\lambda}$$ **Equation 2-2**

For complex geometries it can be useful to express the resistance in terms of the thermal conductivity and a shape factor, S_f:

$$R = \frac{1}{S_f \lambda}$$ **Equation 2-3**

Both thermal resistance and shape factor are constant when the heat transfer is steady. When conductive heat flow is unsteady and the temperature gradient varies with time, a more general approach must be adopted. This is known as the heat diffusion equation:

$$\frac{d^2T}{dx^2} = \frac{\rho S_c}{\lambda}\frac{dT}{dt} = \frac{1}{\alpha}\frac{dT}{dt}$$ **Equation 2-4**

where α, the thermal diffusivity in m^2/s, is a measure of how quickly a material responds to changes in temperature. The thermal diffusivity may also be expressed as $\alpha = \lambda / \rho S_C$ where ρ is the density and S_c is the specific heat capacity (the amount of heat released per unit mass for a one degree change in temperature).

2.1.2. Convection

Free convection of fluids occurs when they are exposed to a surface of a different temperature. As the fluid changes temperature at the contact zone it also changes in density and this drives flow of the fluid. Convection can also be forced, when a flowing fluid passes over a surface of a different temperature. This type of convection, sometimes termed advection, is most relevant for ground energy systems and occurs due to the temperature difference between the circulated heat exchange fluid and the closed loop pipe walls. Forced convection can also occur due to the movement of flowing groundwater.

Newton's law of cooling describes convection as follows:

$$\frac{Q}{A} = h\left(T - T_f\right) \qquad \textbf{Equation 2-5}$$

where T_f and T are the respective temperatures of the fluid and the surface over which it is flowing and h is the heat transfer coefficient in W/m^{2}K. The value of h depends not only on the properties of the fluid such as its density, viscosity, specific heat capacity and flow rate, but also on the properties of the surface including its roughness and the geometry of the interface.

2.1.3. Radiation

All bodies radiate energy in the form of electromagnetic radiation. Radiation does not require a medium to transfer energy and can occur in a vacuum. The Stefan-Boltzmann law relates the amount of thermal energy radiated from a "black body" (an ideal thermal radiator) to its absolute temperature:

$$\frac{Q}{A} = \sigma T^4 \qquad \textbf{Equation 2-6}$$

where A is the surface area of the body, T is its absolute temperature in Kelvin and σ is the Stefan-Boltzmann constant. However, in reality, most bodies are not purely black and they do not exist in isolation. Consequently the rate of heat transfer is reduced compared to the idealised Stefan-Boltzmann law.

2.2. Heat Transfer in Soils

The three mechanisms of heat transfer described above all operate within soils and rocks, but conduction is usually the dominant process unless significant groundwater flows are present (Rees et al, 2000). Figure 2—1 illustrates the situations where convection and radiation may become important, mainly at large grain sizes where the pore spaces are sufficiently large to allow these processes to become significant. Movement of moisture may also be important in fine grained unsaturated soils. The influence of these different mechanisms is discussed below.

Figure 2—1 Predominant Heat Transfer Mechanisms by Grain Size and Saturation (redrawn from Farouki, 1986)

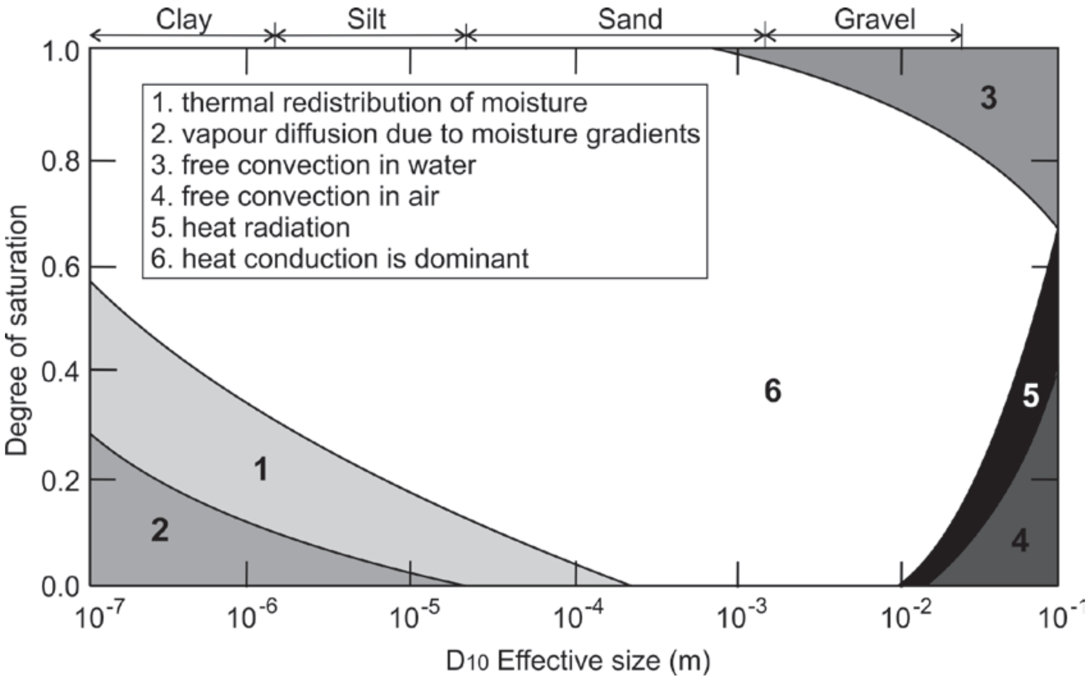


Table 2-1 Typical Thermal Properties for Soil Constituents

Material	***Thermal Conductivity W/mK***
Air	0.024
Water	0.6
Feldspar	1.4 – 2.5
Plagioclase	1.5 – 2.0
Mica	1.6 – 3.5
Amphibole	2.8 – 4.8
Garnet	3.1 – 5.5
Olivine	3.2 – 5.0
Pyroxene	3.5 – 5.7
Calcite	3.6
Chlorite	5.2
Quartz	7.7

Data from Cote & Conrad (2005) and Banks (2008)

2.2.1. Conduction in Soils

Typical thermal conductivity values for various soil constituents are given in Table 2-1. Conduction will occur through all parts of the soil with the solid components having the highest thermal conductivity and hence theoretically being the preferred path for heat transfer. However, heat flow through the soil solids will be limited by the particle contacts, and hence water and/or air in the pore spaces also plays an important role in the overall thermal conductivity of the soil.

It can be seen from Table 2-1 that the most conductive mineral is quartz. Of the other soil constituents, water is an order of magnitude more conductive than air and consequently the highest thermal conductivity soils or rocks are those which are saturated and have a high quartz content. However, generally the thermal conductivity of soils and rocks does not vary significantly, from around 0.25 W/mK to 5 W/mK in extreme cases. Generally soils and rocks have a modest thermal conductivity compared to other materials. However, with a specific heat capacity for soil solids around 800J/kgK, soils have a high heat storage capacity (Banks, 2008). Therefore, ignoring the influence of flowing groundwater, soil and rocks do not transmit heat very far or fast due to their low thermal diffusivity, but do hold a potentially large amount of heat that can be exploited, as long as it is done sustainably.

Table 2-2 Thermal Conductivity Values for Selected UK Lithologies (based Downing & Gray, 1986)

Formation	*Number of Tests*	*Thermal Conductivity W/mK*
London Clay – sandy mudstone	5	2.45 ±0.07
Lambeth Group – sandy mudstone	4	2.33 ± 0.04
Lambeth Group – mudstone	10	1.63 ± 0.11
Chalk	41	1.79 ± 0.54
Upper Greensand - sandstone	18	2.66 ± 0.19
Gault – sandy mudstone	32	2.32 ± 0.04
Gault – mudstone	4	1.67 ± 0.11
Kimmeridge Clay	58	1.51 ± 0.09
Oxford Clay	27	1.56 ± 0.09
Mercia Mudstone	225	1.88 ± 0.03
Sherwood Sandstone	64	3.41 ± 0.09
Westphalian Coal Measures – sandstone	37	3.31 ± 0.62
Westphalian Coal Measures – siltstone	12	2.22 ± 0.29
Westphalian Coal Measures – mudstone	25	1.49 ± 0.41
Westphalian Coal Measures – coal	8	0.31 ± 0.08
Millstone Grit	7	3.75 ± 0.16
Carboniferous limestone	14	3.14 ± 0.13
Old Red Sandstone	27	3.26 ± 0.11
Hercynian Ganites	895	3.30 ± 0.18
Basalt	17	1.80 ± 0.11

Table 2-2 presents thermal conductivity data for soils and rocks in the UK based on the summary by Downing & Gray (1986). The data has been derived principally from two sorts of test. For solid rock core samples, the divided bar method, a laboratory based steady state apparatus was used, while for unconsolidated sediments drill cuttings were usually tested in situ using a transient needle probe. No data about density or moisture content of the samples is provided, but given that most of the source boreholes were deep exploration holes for petroleum or geothermal resources it would be expected that the samples would be of lower porosity and higher saturation than would be representative of the range of conditions relevant to shallower ground energy systems.

In common with other non metallic solids, conduction occurs through the movement of excited atomic particles and, consequently the thermal conductivity of soils is also temperature dependent. Laboratory studies by Hiraiwa, et al (2000) suggests that soil thermal conductivity may increase by around 0.4W/mK at 50degC, with exact values depending on moisture content.

2.2.2. Convection in Soils

Free convection in soil can only occur where the pore spaces are large enough for convection cells to develop. This is typically of the order of several millimetres in size (Farouki, 1986). In such coarse soils, Martynov (1959) reports that free convection can become important at temperatures above 30^{o}C or at high temperature gradients ($dT / dx \geq 1^{o}/cm$). Above this critical temperature gradient an increase in the effective thermal conductivity of the soil can be observed due to the additional contribution to heat transfer from convection. Hellstrom (1991) reports that performance of ground energy storage systems can be affected by free convection if the hydraulic conductivity is greater than around 10^{-5}m/s in both vertical and horizontal directions. However, in most cases soil and rock stratification reduces the vertical permeability or introduces less permeable horizons which would be a significant barrier to this process.

In soils forced convection is typically more significant than free convection and occurs if groundwater is flowing though a porous soil or rock formation. Where flow is minor then this is often accounted for by an increased effective thermal conductivity. However, at greater flow rates convection can dominate and this is no longer appropriate.

Convection is really the combination of two processes operating simultaneously: diffusion through the soil constituents and advection due to the movement of the pore fluid. Together these processes are described by the diffusion-advection equation:

$$\frac{\rho' c'}{\lambda'}\frac{dT}{dt} = \frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} - \frac{\rho_w c_w}{\lambda'} v \frac{dT}{dx}$$ **Equation 2-7**

In this expression the effective thermal properties of the soil are used:

$$\rho' S_c' = n\rho_w S_{cw} + (1-n)\rho_s S_{cs}$$ **Equation 2-8**

$$\lambda' = n\lambda_w + (1-n)\lambda_w$$ **Equation 2-9**

where n is the porosity and the subscripts w and s refer to the pore water and the solid components of the soil respectively. The relative importance of convection and diffusion is given by the Peclet number. For heat transport in groundwater the Peclet number is expressed as (Domenico & Schwartz, 1990):

$$Pe = \frac{Lv\rho_w S_{cw}}{\lambda'}$$ **Equation 2-10**

where, L is the characteristic length, ν is the Darcy velocity, and λ' is the effective thermal conductivity.

Analytical and numerical studies of ground energy systems affected by flowing groundwater (eg, Claesson & Hellstrom, 2000, Chiasson et al 2000) suggest that the impact of groundwater flow becomes significant above flow velocities of around 1m/day. On the other hand, the Swiss Society for Engineers and Architects recommend that groundwater effects can be neglected if the flow is less than a few metres per year (refer to Figure 3—8, after Anstett et al, 2005). This flow rate is two orders of magnitude less than the results of other studies and the source of the discrepancy is not clear. Practically, impact would need to be assessed on a site by site basis, especially since the effect of the groundwater will be different depending on the operation of the ground energy system. Where the system is designed for principally one way heat transfer (ie only heating or only cooling) then flow of groundwater will greatly enhance the available thermal energy. However, the presence of groundwater flow will prevent thermal energy storage which can also be an important aspect of ground energy systems.

2.2.3. Radiation in Soils

Except in coarse materials, radiation in soils is negligible at normal atmospheric temperatures and is therefore usually neglected (Rees et al, 2000). However, Fillion et al (2011) have shown theoretically and experimentally that radiation increases the effective thermal conductivity of dry porous materials in accordance with the particle size. They demonstrated radiation to become significant for d_{10} > 10mm, and for the heat transfer to increase to at least double for d_{10} >200mm. As their experiments were all carried out at room temperature it would be expected that the significance of radiation would be greater at elevated temperatures.

2.2.4. Heat Transfer and Moisture Migration

In many situations heat and moisture transfer are inseparable and also have an impact on thermal properties as the phase proportions of a soil change. Consequently, moisture migration due to evaporation and condensation can be an important process in unsaturated soils (Farouki, 1986). Heating can cause pore water to evaporate. As it does so the water absorbs the energy associated with the latent heat of evaporation. As a vapour the water will then be susceptible to vapour pressure gradients and will migrate through the soil to an area of lower vapour pressure. Here the temperature may also be lower and the vapour would then condense releasing the latent heat in a new location. As well as making a contribution to the heat transfer process, moisture migration also changes the thermal properties of the soil by affecting the degree of saturation. With high temperature gradients resulting from heat injection, drying of the soil will reduce the thermal conductivity and hence the efficiency of the heat transfer. Hellstrom (1991) suggests that this phenomenon becomes significant in high porosity soils of low saturation when temperatures increase above 25 ^{o}C. Consequently some researchers are now starting to include this effect in their modelling (eg Laloui et al, 2006).

2.2.5. Freeze-Thaw Processes

Heat transfer in soils can also be associated with zones of freezing and thawing. The process of freezing in soil is a highly coupled process with heat and moisture transfer being accompanied by mechanical effects, usually resulting in frost heave and cracking. For these reasons it is essential to avoid soil freezing resulting from operation of ground energy systems

2.3. Heat Transfer and Pipe Flow

Heat exchange from the heat transfer fluid to the pipe wall is an important aspect of any ground energy system. To determine the heat transfer coefficient which controls the convective heat flow from the fluid to the pipe it is necessary to know the details of the flow regime within the pipe. The following sections provide the background to the hydrodynamic and thermal aspects of pipe flow relevant to heat transfer in ground energy systems.

2.3.1. Flow Conditions

2.3.1.1 Hydrodynamic Considerations

The rate of heat transfer from a fluid flowing through a pipe to the pipe wall depends strongly on the flow conditions. Internal pipe flow is classified as either laminar or turbulent. In laminar flow, the streamlines of fluid movement are smooth, largely linear and highly ordered. By contrast, the streamlines of turbulent flow are chaotic and the velocity is subject to significant fluctuations. The intense mixing of fluids in turbulent flow causes them to exhibit enhanced heat transfer characteristics compared with laminar flow. For this reason most ground energy systems aim to achieve turbulent flow within the heat exchange pipes.

The onset of turbulent flow occurs when the Reynolds number (the relative balance of inertial and viscous forces) reaches about Re=2,300. Below this value the flow is laminar. Above Re=2,300 the flow transitions to turbulence, with full turbulence reached at about Re=4,000. For flow in a circular pipe, the Reynolds number is given by:

$$\mathrm{Re} = \frac{\rho u_m d}{\mu} = \frac{u_m d}{\upsilon}$$ **Equation 2-11**

Where ρ is the fluid density, u_m is the mean velocity, d is the hydraulic diameter (in this case equal to the pipe diameter), μ is the fluid viscosity (kgm/s) and υ is the kinematic viscosity (m^2/s).

Due to friction at the pipe wall, both the velocity profile and the temperature profile of the fluid will vary across the pipe cross section. At the start of a pipe circuit, known as the entry region, the shape of the velocity and temperature profile will initially vary along the length of the pipe until at a certain point the shape becomes constant and the flow is known as fully developed. For laminar flow, the hydrodynamic entry length, which defines the distance at which the velocity profile becomes fully developed is:

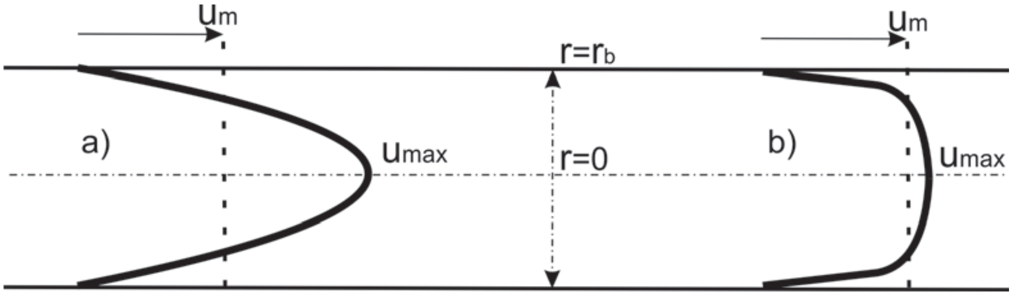
$$x_{lam} = 0.05 d \,\mathrm{Re}$$ **Equation 2-12**

For turbulent flow there is no exact solution for the hydrodynamic entry length, although it is often approximated to (Incropera et al, 2007):

$$10d \leq x_{turb} \leq 60d$$ **Equation 2-13**

For laminar flow conditions the velocity profile is a parabola, while for turbulent flow the profile shape is much flatter (Figure 2–2).

Figure 2—2 Fully Developed Velocity Profiles a) Laminar Flow; b) Turbulent Flow (redrawn from Cengal & Cimbala, 2010)



2.3.1.2 Thermal Considerations

As with the flow regime, the temperature profile of the fluid also evolves over the start of the pipe circuit. However, the thermal regime does not become fully developed unless one of the following boundary conditions exists:

1. A constant temperature pipe wall; or
2. A constant heat flux pipe wall.

If one of these conditions is met, then the thermal entry length for laminar flow to become thermally fully developed is:

$$x_{lam} = 0.05d \,\mathrm{Re}\,\mathrm{Pr}$$ **Equation 2-14**

where Pr is the Prandtl number given by $\mathrm{Pr} = \upsilon/\alpha = \mu S_c/\lambda$. The Prandtl number is a measure of the relative importance of viscous diffusion to thermal diffusion. For water and most other heat transfer fluids the Prandtl number is greater than one at temperatures relevant to ground energy systems. Hence the thermal entry length for laminar flow is typically longer than the hydrodynamic entry length (Equation 2–12).

For turbulent flow there is no exact solution for the thermal entry length, although it is shorter than for laminar flow and often approximated to (Incropera et al, 2007):

$$x_{turb} = 10d$$ **Equation 2-15**

Therefore the thermal entry length is typically less than the hydrodynamic entry length (Equation 2–13) for fully developed turbulent conditions.

For typical ground energy system heat transfer pipes with turbulent flow, the distances into the pipe circuit before hydrodynamically and thermally fully developed conditions and hence stable heat transfer have been reached are typically up to about 2m. For laminar flow the distances could be much longer, potentially up to 30 m to 50 m.

The thermally fully developed temperature profile depends not only on whether there is laminar or turbulent flow, but also on which of the two pipe wall boundary conditions listed above is present. For laminar flow the temperature profile is highly non uniform and close to parabolic when the heat transfer rate is constant (Figure 2–3a). For a constant temperature boundary condition the temperature profile contains an inflexion (Figure 2–3b). For turbulent flow the situation is more complex and difficult to calculate and the temperature profile is dependent on the Reynolds number and the Prandtl number. Figure 2–4 shows an example for the case of constant pipe wall temperature and suggests that for typical heat transfer fluids (eg Table 3-1), which will have a Prandtl number greater than one, then a flatter temperature profile is likely.

Figure 2—3 Fully Developed Temperature Profiles for Laminar flow a) Constant Heat Flux at Pipe Wall; b) Constant Temperature at Pipe Wall (redrawn after Incropera et al, 2007)

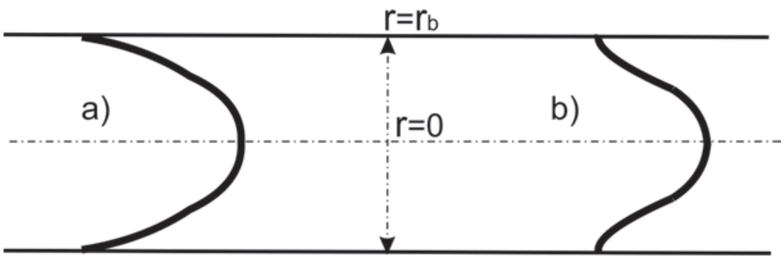
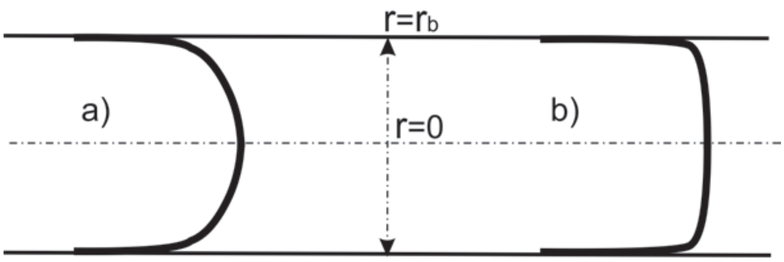


Figure 2—4 Fully Developed Temperature Profiles for Turbulent Flow with Constant Temperature at Pipe Wall; a) Re=10,000 Pr=1; b) Re=10,000 Pr=10 (redrawn after Kakac & Yemer, 1995 and Martinelli, 1947)



2.3.2. Longitudinal Temperature Profiles

For fully developed hydrodynamic and thermal conditions, the variations of temperature along a pipe circuit can be determined based on an energy balance calculation. In its simplest form:

$$Q = mS_c(T_{out} - T_{in})$$ **Equation 2-16**

where m is the mass flow rate of the fluid in (kg/s) and T_{in} and T_{out} are the inlet and outlet temperatures respectively. For the case of a constant pipe wall heat flux it can be shown that:

$$T(x) = T_{in} + \frac{q}{mS_c}x$$ **Equation 2-17**

where q is the heat transfer rate per metre length of the pipe (in W/m), and x is the distance around the pipe circuit. Given the variation in temperature profile across the pipe cross section it is important that the mean temperature is used. From Equation 2–17 it can be seen that the rate of change of temperature around the pipe circuit in this case is constant (as shown in Figure 2–5a).

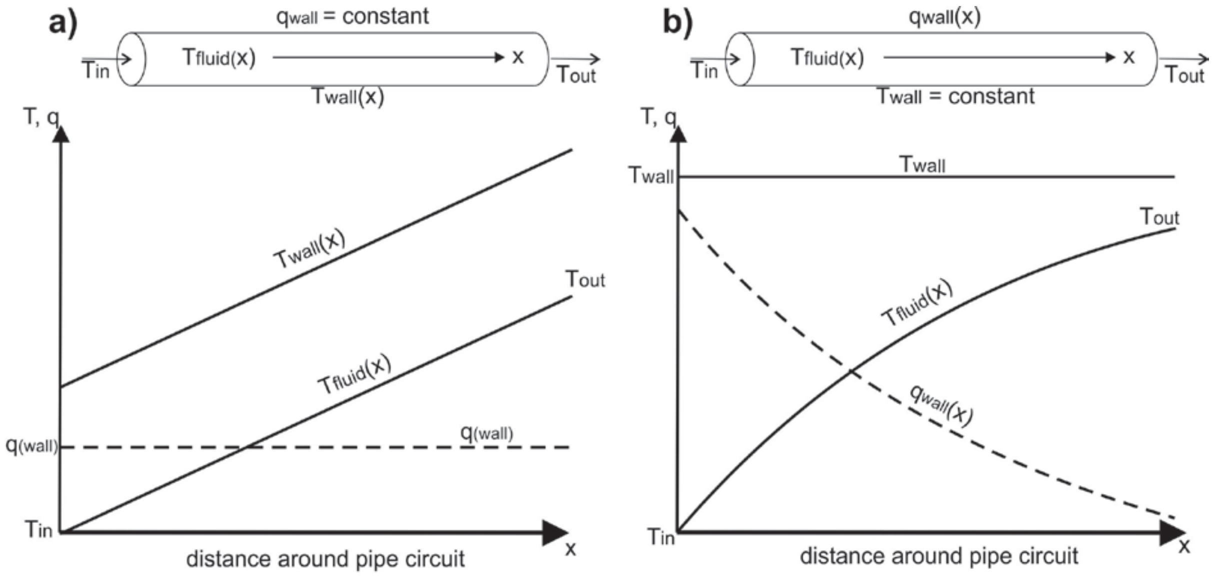
For the case where the pipe wall is maintained at constant temperature it can be shown that:

$$\frac{T(x) - T_{wall}}{T_{in} - T_{wall}} = \exp\left(-\frac{\pi dx}{mS_c}h\right)$$ **Equation 2-18**

where h is the convective heat transfer coefficient and T_p is the constant temperature at the pipe wall. In this case the variation of the fluid temperature is exponential in form (Figure 2—5b). As the temperature difference between the fluid and the pipe wall decays so does the heat transfer rate. The rate of this decay is dependent on the nature of the flow conditions.

For ground energy systems it is important to understand, which, if any, of these two boundary conditions are appropriate. For the case of a constant heat flux, the constant rate of change of the fluid temperature means that it is straightforward to calculate the mean fluid temperature within any heat exchanger: it is simply the mean of the fluid inlet and outlet temperatures. Due to its simplicity, this assumption is often taken as correct during ground heat exchanger design. However, in reality the constant temperature boundary condition may be more appropriate. The consequences of this are discussed subsequently in Chapter 4.

Figure 2—5 Heat Transfer in Pipes; a) Constant Heat Flux at Pipe Wall; b) Constant Pipe Wall Temperature



2.3.3. Heat Transfer Coefficients

The first stage in calculating the heat transfer between the heat exchange fluid and the ground in any ground energy system is to determine the heat transfer coefficient, h, for the convective heat flow between the fluid and the pipe wall. Using Newton's law of cooling, the heat transfer coefficient is then used to determine the temperature difference between the average fluid temperature and the pipe wall. Assuming constant fluid properties, it can be shown that for thermally fully developed conditions the heat transfer coefficient is constant over the pipe length.

For laminar flow, the heat transfer coefficient can be related directly to the Nusselt number, the ratio of convective to conductive heat transfer across a boundary. For the case of a constant heat flux pipe wall boundary condition the relationship is as follows:

$$Nu = \frac{hd}{\lambda} = 4.36$$ **Equation 2-19**

For a constant pipe wall temperature boundary condition the relationship is:

$$Nu = \frac{hd}{\lambda} = 3.66$$ **Equation 2-20**

For turbulent flow with fully developed thermal conditions the Nusselt number is not a constant, but depends on the Reynolds number and the Prandtl number. The most commonly used expression in this case is the so called Dittus-Boelter equation (actually introduced by McAdams, 1942):

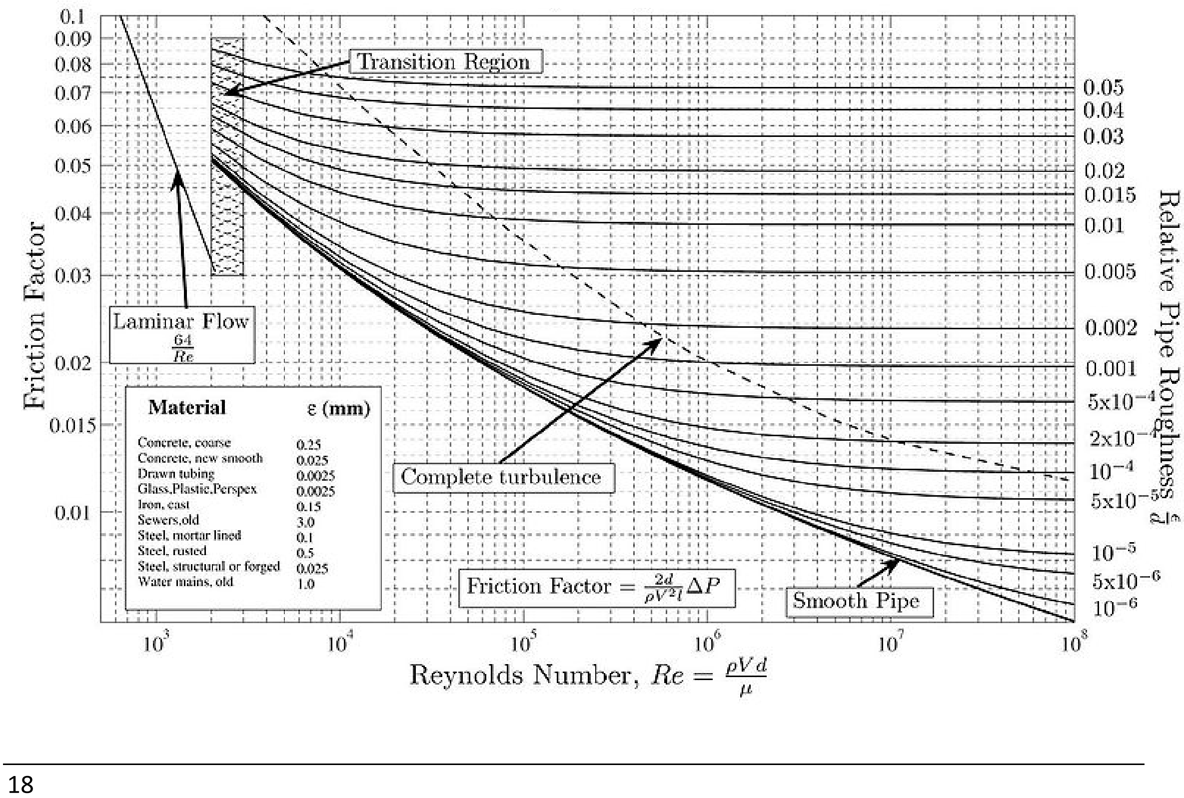
$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}$$ **Equation 2-21**

where n is a constant, taken as 0.4 for heating and 0.3 for cooling. However, this expression is only valid for Re>10,000 and may overestimate the Nusselt number and hence the heat transfer coefficient at smaller Reynolds numbers. The Dittus-Boelter equation also assumes a relatively small temperature difference and hence can result in errors when used with fluids which have highly temperature dependent properties, especially viscosity. Consequently, Incropera et al (2007) suggest that up to 25% errors can result in some cases. These can be reduced to around 10% by use of the more complex Gnielinksi correlation (Gnielinksi, 1976):

$$Nu = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{0.5}\left(\mathrm{Pr}^{2/3}-1\right)}$$ **Equation 2-22**

where f is the Moody friction factor, a dimensionless parameter used in the estimation of pressure loss in pipes, and usually determined from the Moody diagram (Moody, 1944) as shown in Figure 2–6.

Figure 2—6 Moody Diagram (Beck & Collins, 1998)



Alternatively, for turbulent flow in smooth pipes empirical correlations have been developed to determine the Moody friction factor; for example, this expression from Petukhov (1970), which is valid over a wide range of Reynolds number values:

$$f = \left(0.79\ln(\mathrm{Re}) - 1.64\right)^{-2}$$ **Equation 2-23**

2.4. Application to Ground Energy Systems

This chapter has developed the general concepts which are used in the design and assessment of ground energy systems. The following chapter provides an introduction to use of piles as heat exchangers. Design concepts for energy piles are typically based on the following heat transfer mechanisms:

- Transient conduction through soils,
- Steady conduction through the pile concrete and heat transfer pipes,
- Convection at the pipe-fluid boundary.

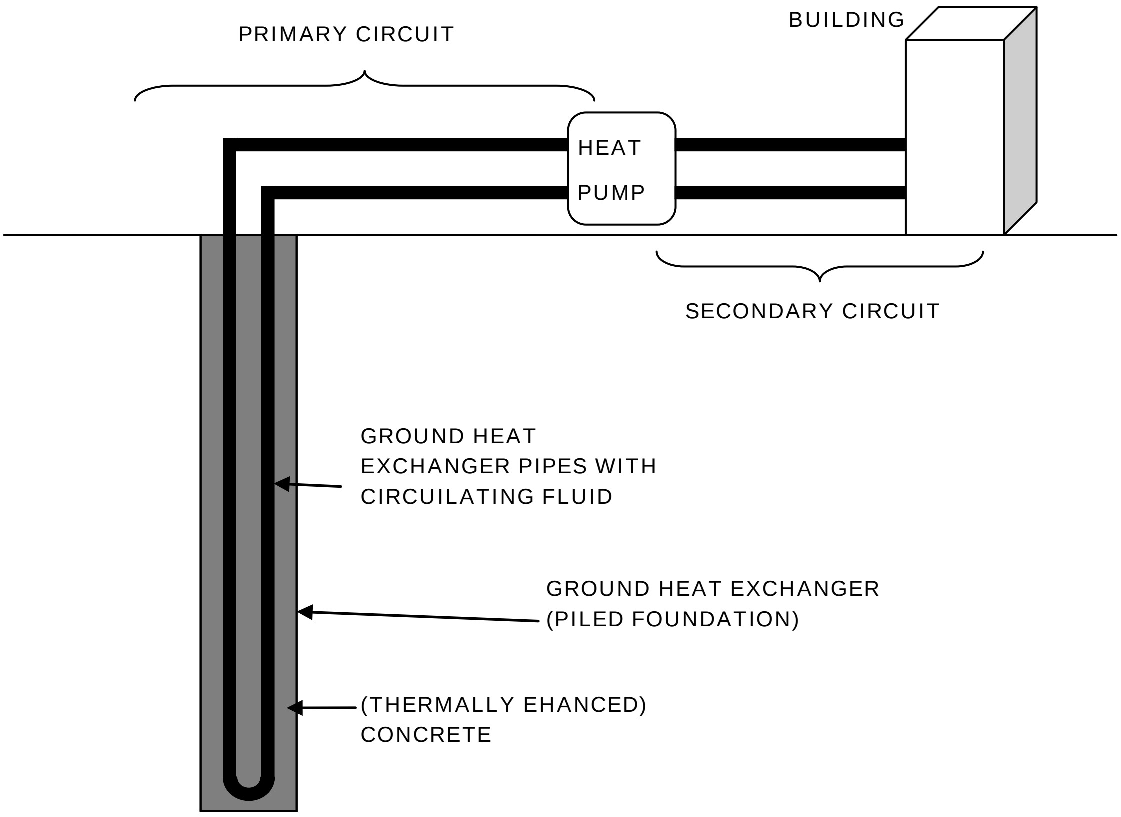
Chapter 4, 5 & 6 will consider the application of these three physical concepts in more detail.

Chapter 3. Closed Loop Ground Energy Systems

3.1. Introduction to Closed Loop Ground Energy Systems

Closed loops ground energy systems comprise a number of components which can be sub-divided into the primary circuit, the heat pump and the secondary circuit (Figure 3– 1). The primary circuit comprises the elements of the system which interacts with the heat source (the ground and groundwater) and includes not just the ground heat exchanger, but also the header pipes which connect the ground heat exchanger to the heat pump. The secondary circuit comprises the heating and cooling delivery system, which includes any distribution pipes and the heating/air conditioning system itself. Details of the system components are included in the following sections.

Figure 3—1 Typical Arrangement of Closed Loop Ground Energy System installed in a Pile

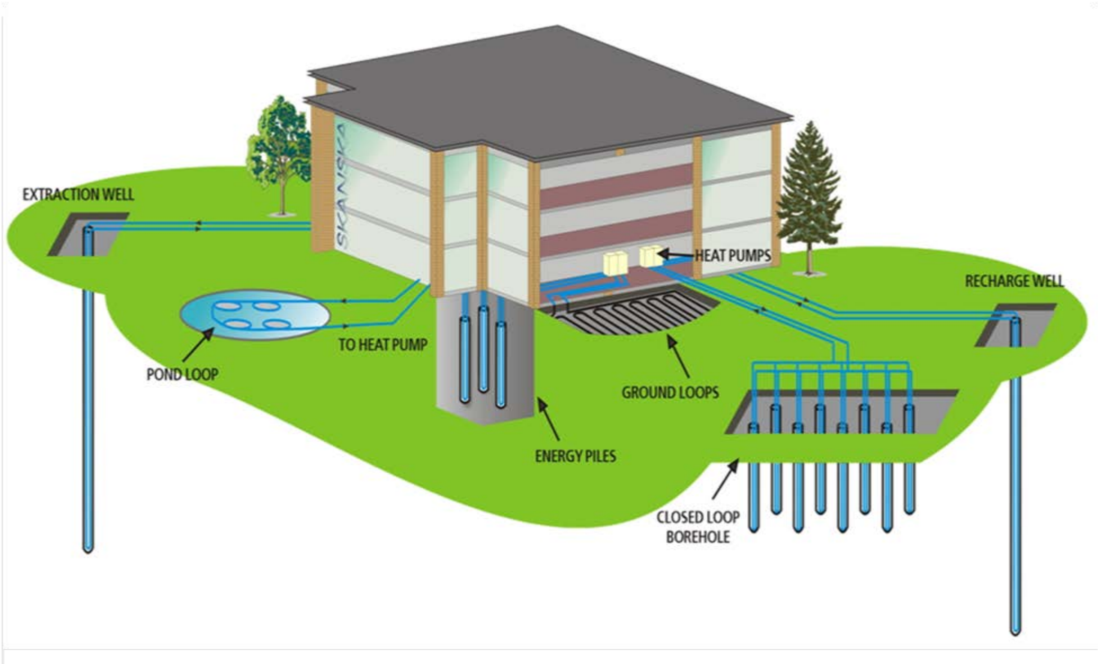


3.1.1. Ground Heat Exchangers

Closed loop ground heat exchangers comprise plastic pipes cast into the ground so that heat exchange fluid circulated through those pipes can be used to transfer heat to/from the ground. The most common types of ground heat exchanger are closed loop vertical boreholes or horizontal style ground loops (Figure 3–2). However, ponds, lakes and other water bodies, such as those in disused mines, can also be used. Increasingly, foundation piles are being used as heat exchangers as this can be cheaper and involve the use of fewer materials compared with constructing additional special purpose borehole heat exchangers. However, this complicates the foundation construction process (see Section 3.2.1) and therefore must be allowed for in the construction programme.

The fluid flowing through the heat exchange pipes is driven by a circulation pump. It is important that this is sized correctly to minimise additional energy expenditure. It is normal to try and achieve turbulent flow to provide improved heat transfer between the fluid and the pipes. However, this can lead to additional electricity usage for the circulation pump and in some cases, especially smaller domestic systems, laminar flow can be more cost effective overall.

Figure 3—2 Types of Ground Heat Exchanger



courtesy of Cementation Skanska

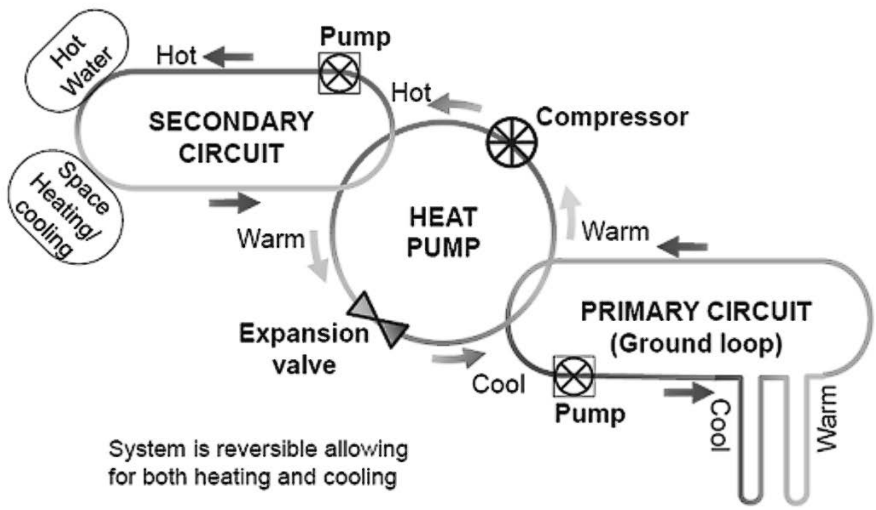
3.1.2. Header Works

To connect the ground heat exchangers to the heat pump and the building heating/cooling system header pipes are used. The flow from a number of ground heat exchangers may be grouped together into larger pipes and then run in trenches to the building plant room. It is important that the flows between these larger pipe circuits are balanced. In some cases where piles are used as heat exchangers the header pipes may be cast into the floor slab of the building. Two approaches may be taken to the header pipes thermal design. The aim can be to ensure that heat loss is minimised during this stage of the fluid circulation. Or alternatively the potential for additional ground heat exchange opportunities can be can be exploited along the length of the pipe circuit.

3.1.3. Heat Pumps

Ground energy systems make use of both (water) circulation pumps and heat pumps. In the same way that a water pump moves water from a location of low potential (or head) to a location of higher potential, a heat pump can be used to increase the temperature of a fluid. In both cases the input of a small amount of (usually electrical) energy is required. For the water pump this enables the mechanical work of raising the potential of the water; for the heat pump, the electrical energy enables the transfer of heat.

Figure 3—3 Heat Pump Interactions with the Primary and Secondary Circuits (after Perry et al, 2011)



The heat transfer in the heat pump occurs through the use of a compression-expansion circuit (Figure 3–3). The fluid circulating in the primary circuit exchangers heats with a refrigerant in the heat pump. The refrigerant is designed to boil at low temperature, so that after receiving heat from the ground via the primary circuit, it reaches the compressor in its gaseous phase. Electricity powers the compressor and, due to Boyle's Law, as the gas pressure is increased at constant volume, so the temperature of the refrigerant is increased. The refrigerant is now at a useful temperature and ready to exchange heat with the secondary circuit for use in the building. The refrigerant then passes back through an expansion valve which lowers its temperature and the condensed vapour is now ready to receive heat from the primary circuit once more. Heat pumps can either be unidirectional, only allowing heat transfer in the direction described, or for most commercial building operations, they are bi-directional, also facilitating injection of heat into the ground with a reverse cycle.

3.1.4. Heating and Cooling Delivery

The ground energy system secondary circuit is the heating and cooling delivery system in the building. In order to make best use of the heat obtained from the ground, the temperature increase facilitated by the heat pump should be minimised (see also Section 3.1.6 below). For this reason any ground energy system will delivery greatest efficiency when used with low temperature delivery systems such as underfloor heating. Underfloor heating typically requires heating delivery at 30^{o}C to 45^{o}C, compared with 45^{o}C to 55^{o}C for modern low temperature boilers used with high surface area radiators (Banks, 2008). Even better is the use of a warm air heating system which can be operated with temperatures lower than 30^{o}C.

Hot water requires higher temperatures, with water at greater than 55^{o}C being essential to provide conditions in which the bacterium *Legionella* cannot survive. Consequently using a ground energy system retrofitted to an old conventional heating and hot water system operating at 60^{o}C will be highly inefficient. However, there are ways to provide hot water from heat pump systems. These mainly involve a two stage approach whereby the ground energy system heats the water to the temperature required for the heating system and an additional process is used to raise the temperature further. This could be a separate heat pump or an alternative heating system, but because the volume of water used for hot water is usually much less than that used for heating, this two stage approach increases the efficiency.

In the same way in which it is better to use a ground energy system in conjunction with a low temperature heating delivery system, suitable cooling systems also need to minimise the temperature difference between the air conditioning function and the ground. The balance between the amount of heating and the amount of cooling required by a building will also influence the performance of the ground energy system as a whole and this is considered in Section 3.1.6 below.

3.1.5. Energy Demand

Ground energy systems are designed to provide either all or part of the heating and cooling needs of a building. Therefore an important part of the design and assessment process is to gain an understanding of the likely thermal demands of the building. In most cases these will be driven by the outside air temperatures, but also influenced by the building characteristics, the end use of the occupied space and by the behaviour of the building occupants. Traditional boilers are normally sized according to the volume or surface area of a building and the typical outside air temperature profile for its location. However, ground energy systems are much more complicated and design requires a thermal load profile for a typical year of operation. This can vary considerably depending on the type of building. For example a domestic property will only require heating in the winter. The amount of heating power required will relate directly to the outside air temperature and may include distinct peaks for specific cold periods. On the other hand, large and complex commercial developments may require heating during the winter and cooling in the summer. In fact it is quite common for cooling to be the dominant requirement due to the presence of computer and other electrical equipment, and year round cooling is not uncommon. Peak cooling power requirements can also be considerably higher than peak heating power requirements.

Depending on the thermal load requirements, it may be uneconomic to provide a ground energy system sized to cover all the peaks in the power demand. It may be more sensible to provide a system which is capable of providing heating or cooling to only a fraction of the maximum power requirements. However, this can still represent the majority of the energy requirements. For example Rosen et al (2001) have demonstrated that in Sweden, if a heat pump is sized to provide for 60% of the peak thermal power demand for a domestic property that it will deliver over 90% of the thermal energy required. Supplementary systems can then be provided to cover the remaining 10%.

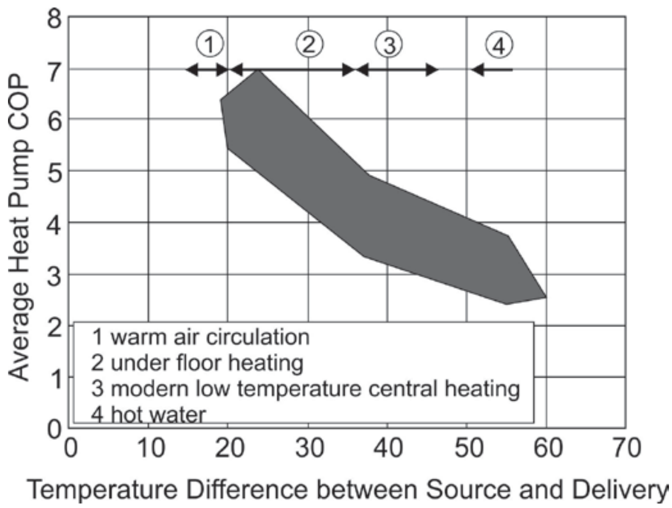
3.1.6. System Efficiency

As discussed above, a number of factors will affect the efficiency of a ground energy system. These include the heat pump itself, the building heating/cooling delivery system, the balance of the thermal load requirements and also the mechanical design of the header and ground heat exchanger pipe circuits and their circulation pumps. The efficiency of the system can be quantified by considering the coefficient of performance and the system seasonal performance factor.

3.1.6.1 Heat Pump Coefficient of Performance

Heat pumps work because the amount of energy required by the compressor is less than the amount of heat released by the heat pump. The efficiency of the heat pump depends on the amount of electrical energy required for their operation. This is usually quantified in terms of the Coefficient of Performance or COP. COP is defined as the amount of useful heat energy obtained from the heat pumped compared to the amount of (electrical) energy input to make it run. Theoretically heat pumps can have a coefficient of performance of 5 or even more. However this is rarely achieved as the COP will depend on the difference between the heat source temperature (ie the ground) and the delivery temperature (ie the radiator or underfloor heating temperature). Generally a reduction in COP of between 0.6 and 1.0 is observed for an increase in temperature difference between the source and the delivery system of around 10^{o}C (Figure 3–4). A COP of greater than 2.5 is required in order for the system to have lower energy consumption when compared with a condensing boiler (Stafell et al 2010).

Figure 3—4 Average Heat Pump COP in Heating Mode



source: Stafell et al, 2010, based on range of manufacturers data and field trials

The COP is also dependent on the direction of heat flow. When heat is being extracted from the ground the electrical energy input is also converted to useful heat, whereas when surplus heat is being returned to the ground the electrical energy converts to additional waste heat which must also be rejected via the ground heat exchanger. For this reason the COP for a heat pump will always be higher when it is used to heat a building compared to when it is used with an air conditioning system.

3.1.6.2 System Seasonal Performance Factor

The system seasonal performance factor (SSPF) of a ground energy system is analogous to the heat pump COP except that it covers the entire system. Thus it is the ratio of the useable heating energy for the system compared with all of the required energy inputs. This includes the circulation pumps for the ground heat exchangers and header pipes. The SSPF is calculated over an entire season, rather than just instantaneously and therefore provides a much better indication of the actual performance of the system. Typical SSPF values are in the range three to four depending on the mode of operation (van Gelder, 2010) and the precise system boundary used when calculating the energy input.

3.1.6.3 Modes of Operation

How ground energy systems are operated can have a large impact on their design and overall efficiency. Generally it is recommended to use the ground as a thermal store where possible, rather than just a resource, as recharge of heat from solar radiation is relatively slow. Four typical modes of operation are described below.

1. Heating only systems, which are operational for only part of the year. These are most commonly adopted for domestic properties and hence are less commonly used with energy piles. Heating only systems need careful design so that the temperature in the ground does not reduce to the extent that ground freezing may occur. This is usually achieved by ensuring there is sufficient recovery when the system is not in use and/or using a low heat extraction rate per unit length of the heat exchangers so that the temperature change over the lifetime of the structure is minimised. SSPF values are typically in the range of 3.0 to 3.5 (van Gelder, 2010).

2. Balanced systems, which use summer cooling demands to recharge the ground following winter heat extraction. These systems work most effectively with larger building developments which have both a heating and a cooling demand. Balancing these demands makes the system much more energy efficient and maximises the amount of energy that can be extracted per unit length of the heat exchanger. SSPF values are typically in the range of 3.5 to 4.0 (van Gelder, 2010).

3. Additional solar recharge. Where it is not possible to thermally recharge the ground through summer cooling demand of the building then it is possible to build in an

artificial solar recharge system instead. SSPF values are typically in the range of 3.5 to 4.0 depending on the area of the solar collector system (Kjellsson et al, 2005).

4. Free cooling. In some circumstances, it is possible to return the warm heat transfer fluid from the air conditioning system directly to the ground heat exchanger without the use of a heat pump. This so called "free cooling" is the most efficient means of heat transfer. However, this can only be achieved if the temperature difference between the fluid returned to the ground and the ground itself is low enough. In combination with mode 2 or 3 this leads to the most efficient mode of operation. SSPF values are typically in the range of 3.5 to 4.0 (van Gelder, 2010), possibly higher.

3.1.7. Benefits of using Ground Energy Systems

Aside from the energy saving potential, ground energy systems offer a number of benefits over traditional heating and cooling systems. Heat pumps are relatively small, especially compared to larger chiller units and therefore provide valuable space savings as well as energy savings. Systems are also quiet to run, which combined with the small size of heat pumps makes ground energy systems very unobtrusive, an important asset when there are increasing objections to wind turbines on aesthetic grounds.

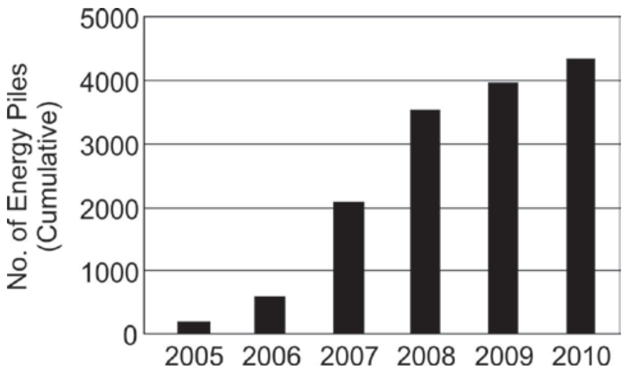
While heat pumps have a high capital cost (eg £3000 for a 6kW unit, Banks, 2008), their benefit comes from reduced operating costs and reduced maintenance costs. Operational costs depend on the price of electricity. In the past, electricity in the UK has been up to seven times more expensive than gas (traditionally used for space heating systems). This meant that the payback time for ground energy systems were too long to be economic. The ratio is now between three and four (Stafell et al, 2010), bringing payback times down to three to seven years on average. The longevity of heat pumps should also be considered when assessing their affordability; they tend to be designed for a lifespan of at least 25 years, commonly more than twice that of the average gas boiler. The ground heat exchanger itself may have a design life of 50 years or more.

Ground energy systems also offer the potential for real carbon benefits by using only 25% of the energy required for an equivalent conventional heating and cooling scheme. The precise carbon savings will depend on the source of the electricity, as coal fired power stations produce carbon dioxide emissions at two to three times the rate per kW compared to gas fired power stations (Fritsche, 2006). The greatest potential for carbon savings clearly comes from using renewable generated electricity to run the heat pump and circulations pumps. Based on the current energy sources for electricity in the UK, ground energy systems do out-perform gas heating systems in terms of carbon emissions, but this is dependent on having a SSPF approaching 3. However, if projections for reduced carbon intensity electricity in the UK are realised, then the carbon advantages of ground energy systems can be expected to greatly increase in the future (Fawcett, 2011).

3.2. Foundation Piles used as Heat Exchangers

Brandl (2006) records energy pile installations in Austria since 1984. In the subsequent decades energy piles have been installed in many countries including the Netherlands (eg Koene et al, 2000), Switzerland (eg Laloui et al, 1999, Pahud & Hubbuch, 2007a), Belgium (eg Desmedt & Hoes, 2007), China (eg Gao et al, 2008a) and Japan (eg Sekine et al, 2006, Hamada et al, 2007). In the UK, the first energy piles were installed at Keble College in Oxford in 2001 (Suckling & Smith, 2002). Since then installation of energy foundations has been increasing rapidly. Just 150 energy piles were installed per year in the UK in 2004; by 2008 this has risen to nearly 1600 energy piles per year (Amis, 2009). Recently the rate of increase has reduced in line with the economic situation (Figure 3–5), but there still remains significant interest in this relatively new technology.

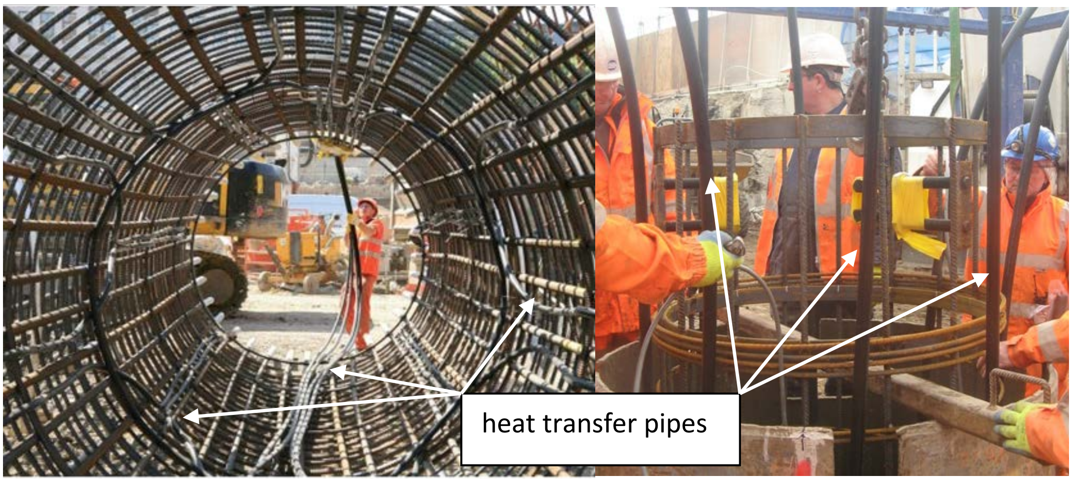
Figure 3—5 Construction of Energy Piles in the UK (redrawn from Laloui & Di Donna, 2011)



3.2.1. Construction Methods

Construction techniques for energy piles depend largely on the type of pile being constructed. For rotary bored piles where the holes are constructed by an auger and supported by casing over at least part of the bore depth, the heat exchange pipes are typically installed with the reinforcement cage. Where it is possible to install the cage in one piece, the heat exchange pipes may be fixed to the cage in advance of construction, either at the offsite cage fabrication location or at a separate location on site prior to placing the cage. If the cage must be installed in sections and coupled, then the heat transfer pipes would need to be attached during installation of the cage (Figure 3–6).

Figure 3—6 Bored Energy Piles; (left) Pipes Prefixed to Steel Cage; (right) Pipes Fixed to Cage during Installation



left image courtesy of Cementation Skanska

Figure 3—7 Contiguous Flight Auger (CFA) Energy Pile with Central Pipework

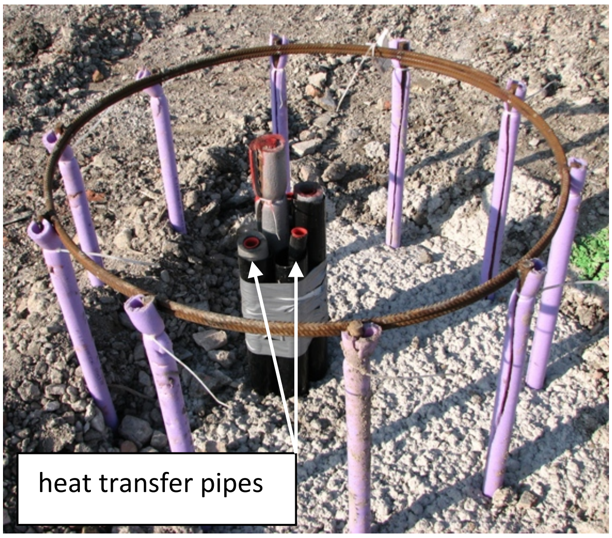


image courtesy of Balfour Beatty Ground Engineering

For contiguous flight auger (CFA) piles, or in other installations where the cage does not extend the full depth of the pile bore, in the UK it is now more common for the heat exchanger pipes to be installed in the centre of the pile, independently from the pile cage. In such cases the heat exchanger pipes, usually fixed to a steel bar for support and weight, are plunged into the concrete after installation of the pile cage. This results in the pipes being installed centrally within the pile (Figure 3–7) rather than around the circumference as they would for a bored pile. Consequently there is far less control over the precise positioning of the heat exchanger pipes in a CFA pile.

3.2.1.1 Materials

There are three main materials through which heat transfer occurs in an energy pile: the heat transfer fluid, the pipes and the reinforced concrete which forms the pile. Water is the most efficient heat transfer fluid due to its advantageous heat transfer characteristics and low viscosity. However, due to the temperature gradient across the energy pile it is possible to operate with the heat transfer fluid close to or just below 0°C and still ensure that the ground does not freeze. It is therefore common for anti-freeze, such as propylene glycol or ethylene glycol to be added to the heat transfer fluid in order to reduce its freezing point. This usually causes an increase in viscosity (Table 3-1), which increases the energy required for pumping. Although ethylene glycol has better thermo-physical properties than propylene glycol, the latter is sometimes mandated by regulations owing to its lower toxicity.

The heat transfer pipes are usually formed from HDPE to ensure longevity as once systems are embedded within the concrete it is not possible to return to the pipe network to carry out maintenance. The concrete used is often of a standard specification used for foundation construction (eg ICE, 2007). However, as cement is less conductive than most aggregate, thermally enhanced characteristics can be achieved by specifying a high aggregate content. More details on the thermal properties of concrete are given in Chapter 5 and Appendix D.

Table 3-1 Properties of Heat Transfer Fluids

Material	***Freezing Point***	***Properties at 20°C***					
		Density kg/m3	***S_c J/kgK***	***λ W/mK***	***μ 10^{-3} Pa s***	***υ 10^{-6} m^2/s***	***Prandtl Number***
Water[1]	O °C	998	4182	0.60	1	1	7
Ethylene Gylcol solution (20% by volume) [2]	-7.8 °C	1038	3756	0.46	3.9	3.8	32
Propylene Gylcol solution (20% by volume) [2]	-7.1 °C	1029	3919	0.46	5.4	5.2	46

1. Kakic & Yener (1995)
2. ASHRAE (2005)

3.2.2. Design Principles

The ultimate aim of the design process is to determine what energy can be extracted or stored within the ground (or how many energy piles are required to achieve a certain energy demand) while achieving good operating efficiency and restricting the temperature changes in the ground and the pile to sensible levels. The efficiency of the system is usually quantified by means of the coefficient of performance or the system seasonal performance factor (refer to Section 3.1.6). Consequently efficient system design involves correct sizing of the heat pump and appropriate mechanical design to ensure a minimum quantity of energy is used for the fluid circulation system, while simultaneously maintaining turbulent flow. Greatest efficiency is also achieved when the end use of the heat is a low temperature operation. For a well designed, constructed and operated system, a SSPF between 3 and 4 should be achievable.

In terms of the heat exchangers, the energy attainable from the piles will depend on the ground conditions and thermal properties, the nature of the energy pile including its size and the arrangement of pipes, and the duration and rate at which the thermal load (Q) is applied. Simple design methods incorporate some of these factors into rules of thumb, while analytical and numerical methods can allow more robust predictions of energy pile performance.

3.2.2.1 Rules of Thumb for Heat Exchanger Thermal Capacity

For the simplest ground energy systems rules of thumb are sometimes applied. Although widely cited, these can be very misleading for large complex ground energy systems (Bose et al, 1985). Nevertheless they can still be useful as a starting point prior to more sophisticated analysis and design. The Verein Deutscher Ingenieure publish some simple rules of thumb (VDI, 1998) which are often quoted, including in BS14450 "*Heating systems in buildings — Design of heat pump heating systems"*, and are reproduced here in Table 3-2.

Table 3-2 is primarily aimed at small diameter borehole heat exchangers and assumes an internal arrangement of double U-tube pipes and a combined system capacity less than 30kW. More comprehensive and flexible look up tables have recently been published by MCS (2011) for typical UK rather than northern European conditions, as represented by the VDI guidance. These give a wide range of values, between 14 W/m and 83 W/m for boreholes, depending on the geology, mean undisturbed ground temperature and the hours of system operation.

For energy piles, the larger diameter of the heat exchanger and, in many cases the greater system capacity, must be taken into account. Brandl (2006) suggests heat output values according to pile diameter (Table 3-3). The values for smaller diameter piles are comparable to the VDI figures, but lack the subdivisions according to ground conditions or thermal loading period. Higher heat extraction rates per metre depth for larger diameter piles are also suggested. Boennec (2009) has also reported typical heat extraction rates for energy piles

(Table 3-3). Although the range is somewhat wider, a larger diameter pile would be expected to have a greater output per metre depth.

A more sophisticated decision tree for thermal pile capacity comes from the Swiss Society for Engineers and Architects and is reproduced in Figure 3–8. Importantly, this considers the mode of operation of the ground energy system as well as the ground conditions in which the heat exchangers are installed. The capacities recommended in Figure 3–8 are notably low compared to some of those given in Table 3-2 and Table 3-3, although the guidance does give scope for increasing these values by around 50% in cases of groundwater flow or where large piles (>1m diameter) are used at large spacing.

Table 3-2 Rules of Thumb for Vertical Heat Exchanger Output (after BSI, 2007)

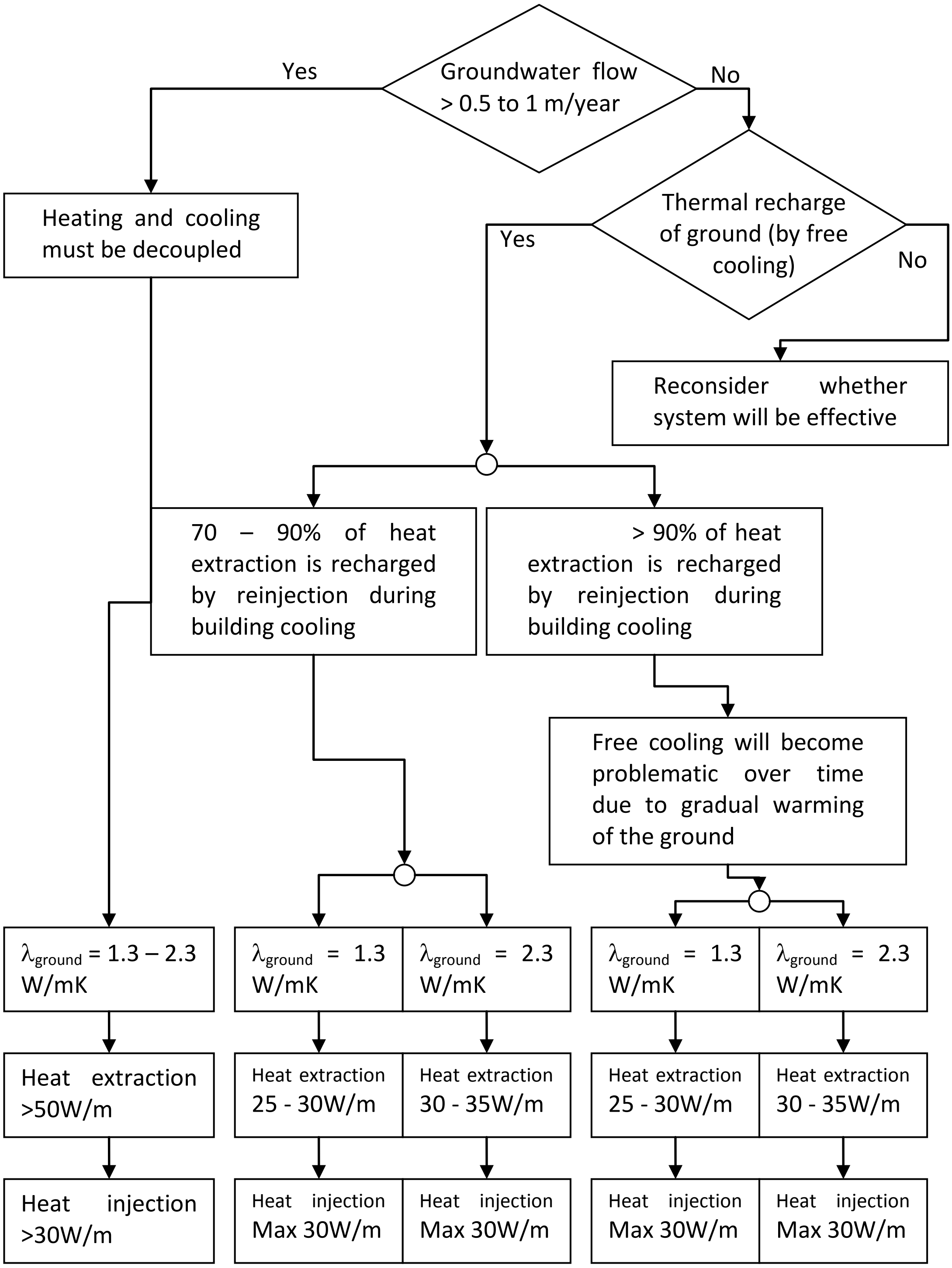
Ground Type	***Specific Heat Extraction Rate (W/m)***	
	Operation period: 75 days	Operation period: 150 days
Dry gravel or sand	<25	<20
Gravel or sand saturated with water	65 – 80	55 – 65
Gravel or sand; strong groundwater flow	80 – 100	80 – 100
Moist clay	35 – 50	30 – 40
Massive limestone	55 – 70	45 – 60
Sandstone	65 – 80	55 – 65
Siliceous igneous rocks (eg granite)	65 – 84	55 – 70
Basic igneous rocks (eg basalt)	40 – 65	35 - 55

Table 3-3 Rules of Thumb for Energy Pile Heat Output

Scenario	***Specific Heat Extraction Rate***	***Source***
Pile foundations, 0.4 to 0.5m in diameter	40 – 60 W/m	Brandl, 2006
Pile foundations, ≥ 0.6m in diameter	35 W/m^2	
Pile foundations	20 – 100 W/m	Boennec, 2009

There are few case studies with thorough monitoring following installation in order to verify the recommendations given in Table 3-3 and Figure 3–8. The only published study is for Zurich Airport, where over 300 pile heat exchangers, between 1m and 1.5m in diameter, were installed for a new terminal (Pahud & Hubbuch, 2007b). These delivered around 45W/m in heating, but only 16W/m in cooling during the first year of operation. This is fairly comparable with the recommendations of Figure 3–8, but is lower than some of the values given in Table 3-3. Consequently it is clear that there remain uncertainties with respect to thermal behaviour and significant risks associated with using an empirical rules of thumb approach to design.

Figure 3—8 Flow Chart for Energy Output for Pile Heat Exchangers (after Anstett et al, 2005)



Note: for piles greater than 0.4m diameter, the spacing is usually larger and the above performance can be improved upon, possibly by up to 50% for large (>1m) diameters.

3.2.2.2 Analytical Assessment of Heat Exchanger Thermal Capacity

For anything other than the very simplest applications a full design for the heat exchanger capacity should be carried out. The objective is to relate the applied thermal load to the temperature change in the heat exchange fluid. This temperature depends on both the temperature change in the ground and the temperature change across the energy pile. In the case where multiple heat exchangers are installed in close proximity to each other then the analysis methods also need to account for whether the individual heat exchangers will be within each other's zone of thermal influence, thus reducing the overall efficiency.

It is important to apply limits to the temperature changes that develop within the system to ensure its long term sustainability. At the lower end of the temperature range it is important that the quantity of heat extracted is not so great that the temperature of the ground drops to freezing as this can cause ground heave and deterioration in the mechanical properties of the soil. There are no hard rules regarding maximum upper temperature in the ground. However, temperatures are usually restricted to a maximum of 30°C to 40°C to avoid substantive changes to the soil thermal and mechanical properties. In addition, restricting the upper temperature in this was maintains good efficiency at the heat pump.

The temperature change within the energy pile is usually assessed separately from the external ground response. The temperature changes in the ground and the pile are then summed to provide the design temperature change of the heat exchange fluid. Typically, pile heat exchangers are assumed to be at steady state. This means that temperature changes within the pile can be assessed based on the thermal resistance of the concrete. This gives a simpler design procedure compared to the ground response, which must be treated as transient.

For conditions of little or no groundwater flow, the thermal response of the ground to heating is obtained by solving the heat diffusion equation (Equation 2–4). Various analytical and semi-analytical solutions have been developed for use in the design of borehole heat exchangers, a number of which are in common usage within commercially available software tools. These tools also allow superposition of the analytical solutions, usually for preset regular arrangement of multiple heat exchangers, in order to account for potential interactions between individual elements.

Analytical solutions developed for borehole heat exchangers are often applied to energy piles, despite the fact that they principally assume radial one dimensional heat flow, based on the concept of a long narrow heat exchanger. In addition superposition of the solutions for arrays of heat exchangers tends to be limited to regular arrays which may not be appropriate to more irregular arrangements of piles installed for modern building developments. Consequently it is important to understand the applicability of these methods and their limitations when applied to energy piles. Chapter 4 provides a critical assessment of the main solutions in this respect.

Where flowing groundwater is present it is most common to use numerical methods for design. This is because closed form solutions to the diffusion-advection equation (Equation 2–7) quickly become very complex and realistically are limited to two dimensions. A number of solutions to Equation 2–7 for the case of boreholes affected by groundwater flow have been presented in the literature (eg, Diao et al, 2004a, Sutton et al, 2003). However, they are not straightforward to apply and are not in common usage. Commercial software normally neglects groundwater flow.

For almost all of the analytical methods developed for use with borehole heat exchangers their adoption for use with energy piles has not been thoroughly tested. In particular, there is an urgent need for complete and detailed monitoring datasets to allow validation of the solutions with real operational data. Only the Zurich Airport case study (Pahud & Hubbuch, 2007b) stands as an exception to this situation, but unfortunately not all of the relevant data is published in the public domain.

3.2.2.3 Design Parameters

Besides the geometry and spacing of the heat exchangers, there are four key thermal properties which influence the thermal capacity of an energy pile system:

1. Pile thermal resistance. This is used to calculate the temperature difference between the heat exchange fluid in the pipes and the ground surrounding the pile. Traditional design methods assume that the pile is at steady state and hence the resistance is constant. There is very little guidance published regarding selecting values of thermal resistance for piles and indeed minimal examination of whether this is even the correct design approach for the internal behaviour of the pile. Chapter 5 examines thermal resistance of piles in more detail and uses numerical modelling to provide guidance on parameter selection and the appropriateness of using a constant resistance.

2. Ground thermal conductivity. Published information for the thermal conductivity of UK geology is given in Table 2-2. Selection of thermal conductivity values from the literature in this way has shortcomings in that it neglects local factors and variation in

properties according to the stratigraphic position within any lithology. Consequently it is common to carry out borehole thermal response testing at the sites of large ground energy systems in order to determine the soil thermal properties in situ. An introduction to thermal response testing is given in Section 3.2.2.4 below, while Chapter 6 focuses on assessing whether the test can be applied reliably to energy piles. Thermal response testing can also potentially be used to determine the pile thermal resistance in situ.

3. Ground volumetric heat capacity. In order to determine the thermal diffusivity of the ground both the thermal conductivity and the volumetric heat capacity are required. However, typically the latter is just assumed in analysis and there is not a reliable database of values. This remains an area which would warrant further research, but falls outside of the scope of this project.

4. Mean undisturbed ground temperature. Undisturbed ground temperature is usually close to the average mean air temperature for a region and varies significantly across the country. In addition, urban heat island effects, such as in London, can lead to elevated ground temperature (eg Bourne-Webb et al, 2009). Undisturbed ground temperature can also be determined in situ from a thermal response test.

3.2.2.4 Thermal Response Testing

A thermal response test works by injecting heat into a ground heat exchanger at a constant rate for a period of a few days. Recording the temperature evolution of the heat transfer fluid with time permits determination of the overall ground thermal conductivity and the pile thermal resistance. Interpretation is usually carried out using a simple analytical technique which assumes a line heat source to be in operation causing purely radial one dimensional heat flow. This is a good assumption for long thin heat exchangers such as boreholes, but is less applicable to energy piles which tend to be significantly shorter and of larger diameter. There is currently a lack of understanding of the accuracy of applying these tests to pile heat exchangers and little guidance about best practice interpretation. Chapter 6 aims to address these knowledge gaps by systematic assessment of the test method for different types of piles.

3.2.3. Knowledge Gaps

Based on the foregoing discussion, this thesis will address three key knowledge gaps regarding the thermal performance of energy piles. These are:

1. How the temperature in the ground responds to the extraction or injection of heat by an energy pile. While there are existing numerical and analytical solutions to the diffusion equation which have been developed to predict the ground temperature response around borehole heat exchangers, these have not been properly evaluated for use with energy piles. Chapter 4 of this thesis will address this knowledge gap via numerical simulation of pile heat exchanger performance.

2. Determination of pile thermal resistance. There is minimal guidance relating to selection of this key design parameter. Chapter 5 uses numerical models to determine values of pile thermal resistance for a wide range of conditions leading to a new empirical equation for its derivation.

3. The applicability of thermal response tests. Thermal response tests are being carried out on energy piles without consideration as to whether this technique, developed for borehole heat exchangers, is appropriate for larger diameter and shorter length piles. Chapter 6 will evaluate the testing method for pile heat exchangers, using numerical methods to predict likely temperature changes during testing.

3.3. Research Methods

To address the knowledge gaps identified above a research programme was designed and implemented. The research outputs are presented in the following three Chapters (4, 5 & 6) with the sections below providing more details of the methods employed.

3.3.1. Literature Review

A wide range of existing publications have been reviewed during the compilation of this thesis. Publications fall into three main topics:

1. General information regarding ground energy systems and the use of foundation piles as heat exchangers. This was augmented by discussions with designers and contractors regarding actual construction techniques and processes as well as methods adopted during design. The information from these sources is primarily contained within the earlier parts of this Chapter.

2. Existing analytical and numerical design approaches for vertical heat exchangers. As there are few existing methods developed specifically for pile heat exchangers, extensive use was made of existing research into the thermal performance of borehole heat exchangers. This approach is justified as many design approaches currently adopted for pile heat exchangers are based on those developed for borehole heat exchangers. Existing design approaches are reviewed in Chapter 4.

3. The thermal resistance of vertical heat exchangers. There is little published material regarding the thermal resistance of pile heat exchangers and therefore literature relating to methods for calculating borehole thermal resistance was reviewed. The results of this study are contained primarily in Chapter 5.

4. The requirements for, limitations and accuracy of thermal response testing. Before attempting to extend standard thermal response testing techniques to pile heat exchangers it is vital to understand the existing state of the art. Chapter 6 contains a summary of information regarding thermal testing.

3.3.2. Analytical Modelling Techniques

Both analytical and numerical modelling techniques have been used to assess the thermal performance of pile heat exchangers. Analytical techniques are usually simpler and quicker to implement than numerical techniques, but are commonly based on underlying assumptions and simplifications which limit their applicability. Therefore analytical techniques have typically been used to validate numerical methods and to provide solutions to simpler problems only. Uses of analytical methods in this thesis include:

1. The line source equation for heat flow from an infinitely thin infinitely long heat source. This simple equation is very easy to implement, but has many limitations. These are discussed with respect to heat exchanger thermal design in Chapter 4 and with respect to thermal response testing in Chapter 6.

2. Analytical equations for thermal resistance. Simple analytical equations for thermal resistance of the pipes and the pipe fluid have been applied in Chapter 5. It is also possible to use more complex line source and multipole equations to calculate borehole and pile thermal resistance. However, except in the simplest of scenarios these equations are likely to provide too complex for routine use. This is discussed further in Chapter 5.

3.3.3. Numerical Modelling Techniques

This thesis makes extensive use of numerical calculation methods in order to determine the thermal performance of pile heat exchangers. Two different off-the-shelf software packages have been used in this respect and are described below.

3.3.3.1 ABAQUS

ABAQUS is a suite of engineering simulation programmes based on the finite element method. For the work presented in this thesis ABAQUS/CAE was used as the user interface in order to develop simulations which were run in ABAQUS/Standard. ABQAQUS/CAE allows definition of the problem geometry, material properties, boundary conditions and meshing, while ABAQUS/Standard solves the governing equations to produce a solution which can then be visually inspected and interrogated in ABAQUS/CAE.

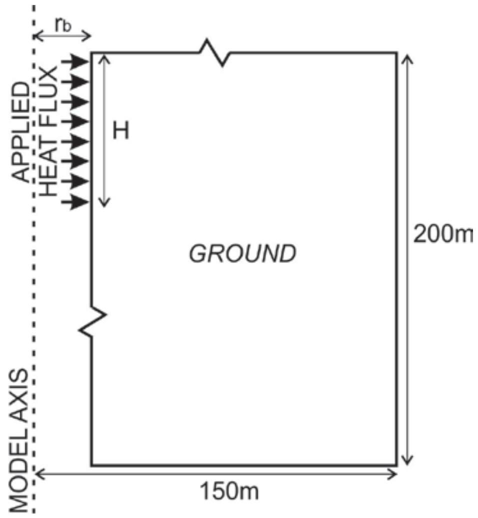
(i) Model Definition

ABAQUS was used to create axis-symmetric models of the ground surrounding a pile heat exchanger (Figure 3—9) to allow the difference in performance to be assessed according to the external geometry (pile length, H and pile radius, r_b) of the pile. The heat conduction mode of the software was used in the analysis. To assess the performance in the context of existing design approaches (refer to Chapter 4), the following analysis was carried out:

1. An infinite line heat source (ILS) was evaluated analytically.
2. An infinite line heat source (ILS) was evaluated numerically.
3. An infinite cylindrical heat source (ICS) evaluated numerically.
4. A finite line heat source (FLS) was evaluated numerically.
5. A finite cylindrical heat source (FCS) was evaluated numerically.

The internal pile details are not included in the numerical models, which are effectively hollow cylinders, as the aim this part of the study is purely to consider the response of the ground and to assess the relative performance of different analytical and numerical models. While this type of analysis has been carried out for assessment of borehole heat exchangers (eg Philippe et al, 2009), the application to energy piles requires consideration for a different range of geometries.

Figure 3—9 Schematic of ABAQUS Axis-symmetric Ground Model



For line source models, the simulation has used a heat source applied at very small radius (r=0.001m) as it is not possible to apply the heat source at the axis of the model. For cylindrical source models the heat source has been applied at the radius of the pile or borehole. Heating in an infinite medium was modelled using a short (10m) model with insulated upper and lower boundary conditions so that the temperature evolution is not constrained due to the inclusion of those boundaries.

For heating in a finite medium, the actual length of the energy pile was modelled, with an upper boundary set to zero and constant temperature to represent the ground surface. This is assumed to have an average temperature equal to the initial temperature in the ground, an approach consistent with existing design approaches. Zero temperature was used as both the initial conditions and the boundary conditions so that the model outputs simply provided direct information about the change in temperature resulting from the heating.

The lower boundary was set also set to zero and constant temperature, but at a sufficient offset so as not to interfere with the simulation (Figure 3—9). This was also the case for the radial far field boundary condition for all simulation scenarios. Heat penetrates a distance proportional to the square root of time and the thermal diffusivity and Eskilson & Claesson (1988) recommend a minimum model dimension equal to $3\sqrt{\alpha t}$, which equates to approximately 200m for a 100 year time period. However, sensitivity studies have suggested that a 150m buffer around the ground energy system would provide equivalent results.

Mesh refinement is important for numerical analysis and sensitivity studies also showed that a small element size was required close to the heat source. Element sizes of 12mm were used at the position of the heat exchanger radius. To ensure the model was of a manageable size overall, the element sizes where expanded away from the heat source using biased seeding. The maximum element size at the furthest extent of the mesh was approximately 6m depending on the particular geometry. Final element configurations were determined by comparing the numerical outputs for a line heat source with the equivalent analytical model. At all times a balance between accuracy and run time was maintained.

The thermal properties of the medium were the same in all cases and are summarised in Table 3–4. A constant heat source of 50W per metre depth was applied to all models for the duration of the analysis. Due to the varying radii of the models this means that to provide the same heat input, different heat fluxes (power per unit surface area) were applied according to the model under consideration. As the results of the analysis are considered in non-dimensional terms in Chapter 4 it was not necessary to carry out sensitivity to different soil properties or heat flux values. Geometry, however, is important in heat transfer problems and a range of typical energy pile and borehole geometries were used in the analysis, as summarised in Table 3–5.

Table 3-4 ABAQUS Model Input Parameters

Heating Power	50 W/m
Thermal Conductivity	3 W/mK
Thermal Diffusivity	1.875×10^{-6} m^2/s

Table 3-5 ABAQUS Model Ground Heat Exchanger Geometries

Type	Length (m)	Diameter (m)	Aspect (length to diameter) Ratio
Borehole	200	0.1	2000
	200	0.2	1000
	100	0.1	1000
	50	0.1	500
Pile	50	1	50
	30	0.6	50
	50	1.5	33.3
	40	1.2	33.3
	25	0.75	33.3
	25	1	25
	15	0.6	25
	10	0.4	25
	11.25	0.75	15
	9	0.6	15

(ii) Model Output

Examples of the model output are contained in the following Figures. Figure 3–10 shows the temperature contours around a 9m long, 0.6m diameter pile heat exchanger after 100 years. As the pile is short and of relatively large diameter the temperature contours are quite curved due to the influence of the ground surface. By contrast, at short times the ground surface does not affect the temperature changes. Figure 3–11 illustrates typical short time output, plotting the temperature change at the borehole or pile radius with time. It can be seen that the nature of the heat source is important at these short times. In the longer term, the curved contours result in the development of a steady state. Figure 3–12 illustrates this for a number of different heat exchanger geometries.

Full discussion of these results is provided in Chapter 4.

Figure 3—10 Example of Temperature Contours around a 9m long, 6m diameter Pile (after 100 years of constant heating at 50W/m)

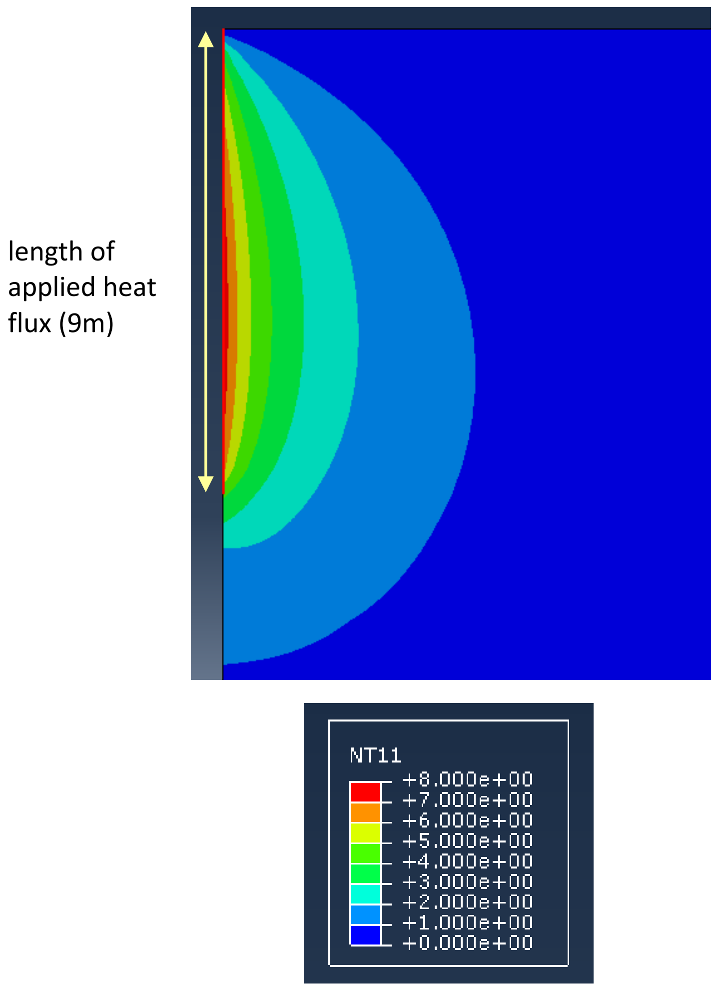


Figure 3—11 Example Temperature Response of the Ground at Short Times (evaluated at $r=r_b$)

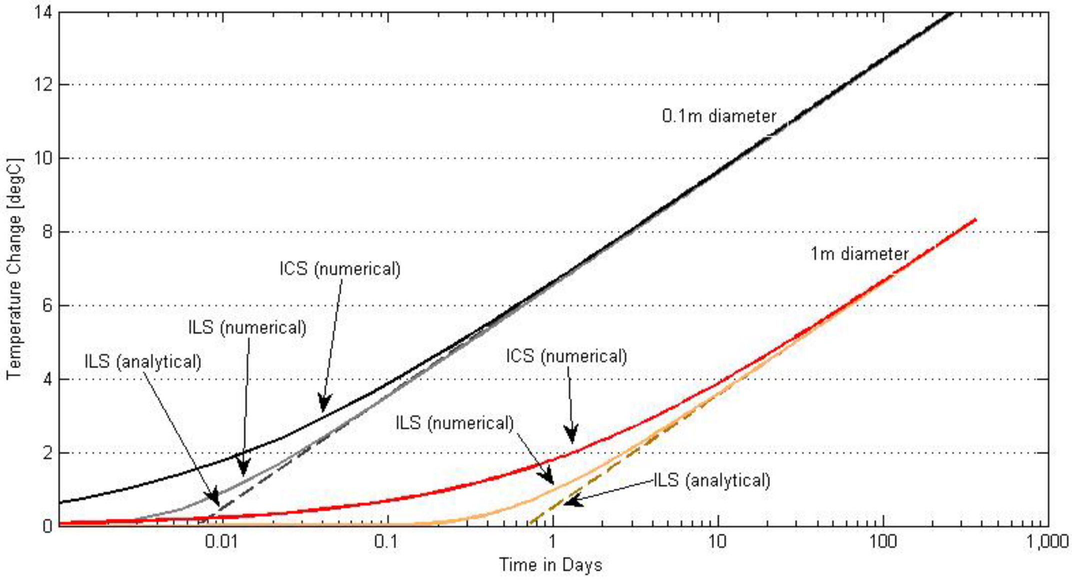
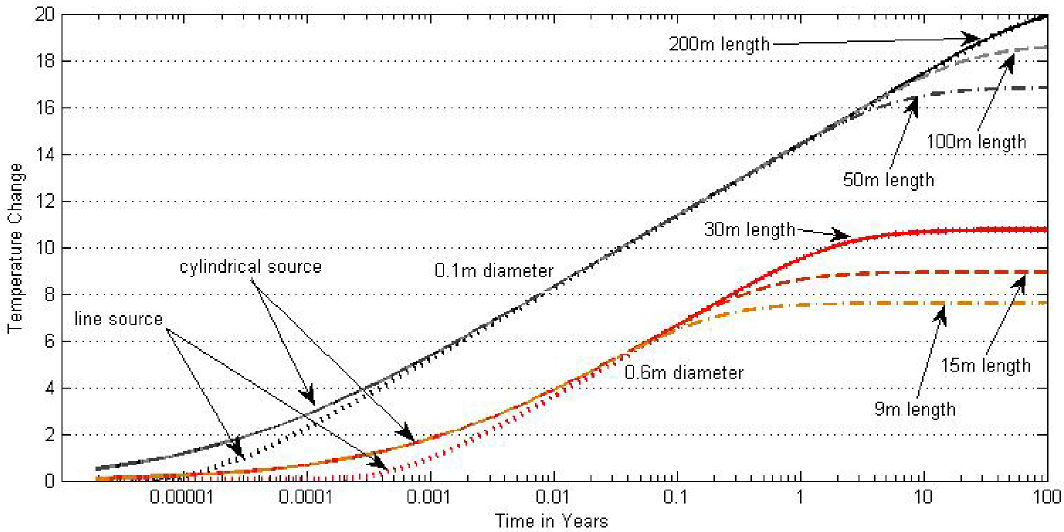


Figure 3—12 Examples Temperature Response of the Ground to Finite Heat Sources for different Pile Lengths and Diameters (evaluated at $r=r_b$ and z=H/2)



3.3.3.2 COMSOL

COMSOL is a "mulit-physics" software which uses the finite element technique to solve various equations for physical problems. In this case the diffusion equation (Equation 2–4) is solved for the geometry, boundary conditions and applied thermal loads defined by the user. The software is operated through a graphical user interface (GUI) through which the problem definition, solution, and post-processing are carried out. COMSOL is a more user-friendly package than ABAQUS, with greater post-processing power built into the GUI. However, it rapidly generates large file sizes which require large amounts of computer memory to produce solutions in reasonable timescales. Therefore COMSOL has only been adopted for smaller, shorter timescale modelling of the internal pile behaviour.

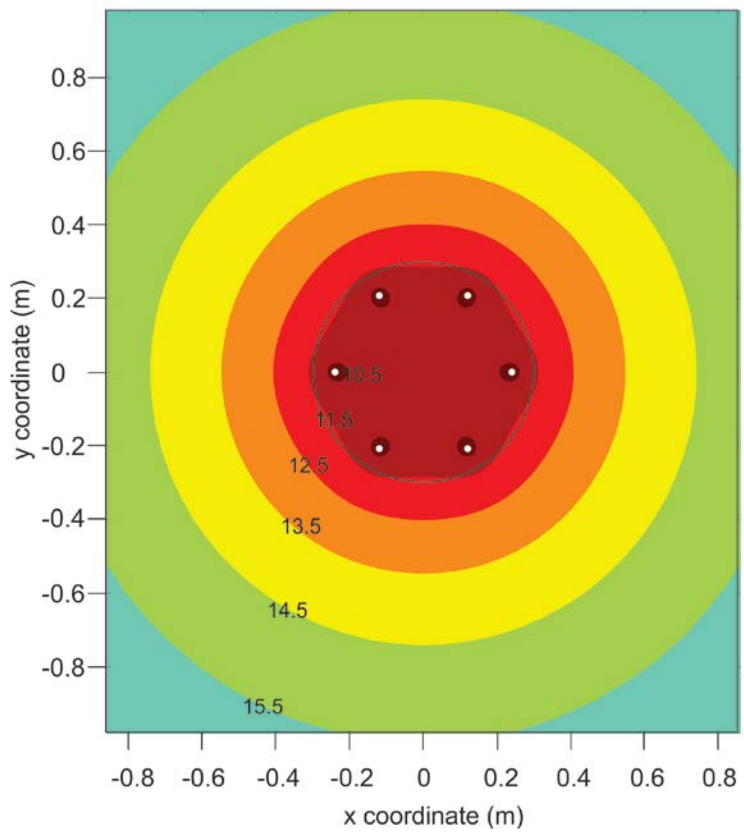
COMSOL has been used to develop two dimensional horizontal slice models through pile heat exchangers. Based on the results of the ABAQUS modelling this approach is considered appropriate for short timescales problems relevant to transient heat transfer within the pile concrete. These 2D analyses underpin the research presented in Chapters 5 & 6. Two types of geometry were used, models which just included the pile, and models which included the pile and the surrounding ground. As with the ABAQUS modelling, sufficient ground was included so that the farfield boundary did not influence the outcome of the analysis. By carrying out sensitivity analysis, this was found to be around 25m for the timescales of the analyses undertaken (up to approximately two months). The pipes and the fluid, which are a much smaller component of the heat transfer compared to the concrete, were not included in the models. Schematics of the model geometry are given in Figure 5–1 and Figure 6–1.

Boundary conditions for the models depend on the particular analyses being undertaken and these are set out in detail in Chapters 5 & 6. However, generally either a constant temperature of a constant heat flux was applied to the pipe boundaries with a constant temperature boundary at either the pile edge or the far field boundary. The models were validated against an analytical equation for the thermal resistance of an eccentric cylinder and this method allowed refinement of the mesh sizes in order to produce the desired accuracy (refer to Section 5.4).

In Chapter 5 the models are used to explore the temperature distributions within the pile and the temperature differences between the pipes and the edge of the concrete. Figure 3–13 shows example temperature contours from a model which comprises a 600mm diameter pile with six 20mm outer diameter pipes installed 50mm from the edge of the pile. The ground is included to a radial distance of 25m. The temperature contours are presented for a period of analysis totalling 45 days, during which constant temperatures were applied to the pipes and far field boundary. This allowed development of a thermal steady state within the pile as shown in Figure 3–13. A large number of pile sizes, pipe numbers, sizes and arrangements and also thermal property combinations were assessed in this way, full details of which are contained in Chapter 5.

In Chapter 6 the COMSOL models are used with a constant heat flux at the pipe boundary to determine the temperature response at both the pile edge and at the pipes themselves. This is to facilitate evaluation of the applicability of the thermal response test to pile heat exchangers, full details of which are contained in Chapter 6.

Figure 3—13 Example 2D COMSOL Model Output showing Temperature Contours in ^{o}C (for a 600mm diameter Pile with 6 no. 20mm diameter pipes and constant temperature pipe boundary conditions)



3.4. Introduction to Research Papers

Ground energy systems installed in piled foundations are expected to make a significant contribution to meeting UK and EU energy and carbon dioxide targets in the coming decade. However, it is clear that some uncertainties remain regarding certain aspects of their design and assessment. In particular three key knowledge gaps have been identified which will be addressed in this thesis. These relate to the thermal response of the ground surrounding the pile heat exchanger, the thermal resistance of the heat exchanger itself, and the applicability of the standard thermal response testing techniques to pile heat exchangers.

Gaining a greater understanding of pile heat exchanger behaviour by addressing these knowledge gaps will be key to providing opportunities for more efficient systems and hence reducing costs and improving the carbon benefits from system installation.

The following Chapters will now consider these knowledge gaps in more detail and in particular:

- Chapter 4 provides a critical review of the thermal behaviour of pile heat exchangers and the surrounding ground, focusing on the limitations of existing approaches to accurately determine the temperature change around the heat exchanger. Numerical simulation is used to compare different approaches for determining the ground temperature response for a range of energy pile geometries. This highlights important differences between the behaviour of boreholes and pile heat exchangers.
- Chapter 5 presents results of numerical modelling designed to investigate the internal thermal behaviour of pile heat exchangers. Recommendations for choosing thermal resistance values are made, including development of a new empirical equation for calculating the pile resistance based on the pile size and pipe arrangements. Situations where adoption of a constant pile resistance may not be appropriate are also identified.
- Chapter 6 discusses thermal response testing for pile heat exchangers. Numerical models are used to examine idealised behaviour, which is then compared with real test datasets from different pile heat exchangers. Recommendations are then made for the application of thermal response testing to piles.

Discussion, conclusions and recommendations for practice arising from the research results follow in the succeeding Chapters (7 and 8).

Chapter 4. Pile Heat Exchangers: Thermal Behaviour and Interactions

A version of this chapter has been accepted for publication in the Proceedings of the Institution of Civil Engineers Geotechnical Engineering.

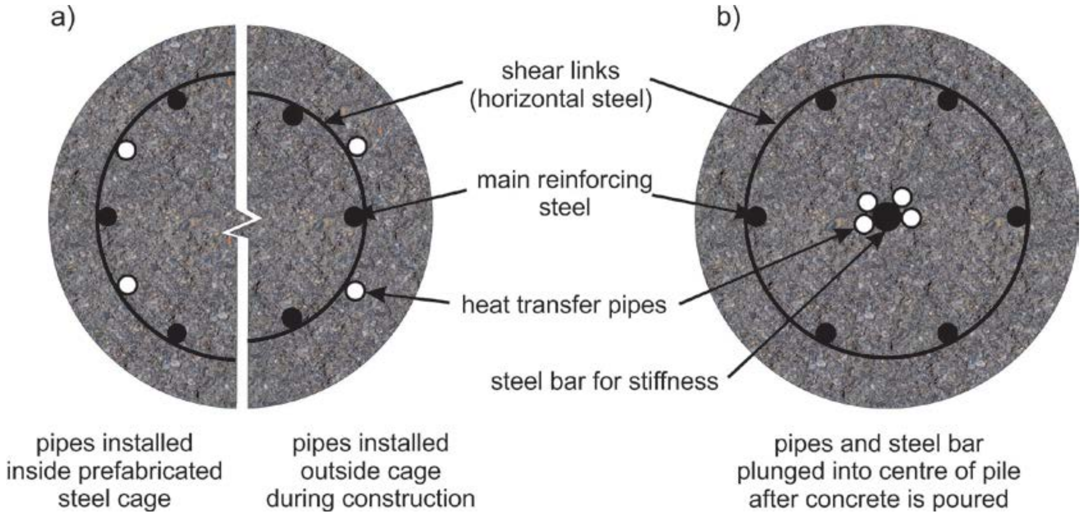
4.1. Abstract

Thermal piles - that is structural foundation piles also used as heat exchangers as part of a ground energy system - are increasingly being adopted for their contribution to more sustainable energy strategies for new buildings. Despite over a quarter of a century having passed since the installation of the first thermal piles in northern Europe, uncertainties regarding their behaviour remain. This paper identifies the key factors which influence the heat transfer and thermal-mechanical interactions of such piles. In terms of heat output, pile aspect ratio is identified as an important parameter controlling the overall thermal performance. The internal geometry is also important, and the influence of the arrangement and lengths of the heat exchanger pipe circuits needs to be better understood. Temperature changes in the concrete and surrounding ground during thermal pile operation will lead to additional stresses within the pile/soil system. Consequently design of a ground energy system must ensure that temperatures remain within acceptable limits, while the pile geotechnical analysis needs to demonstrate that any adverse thermal effects are within design safety factors.

4.2. Introduction

Rising energy prices and government policy drivers are leading to an increase in the use of ground energy systems to contribute to the heating and cooling requirements of new buildings (Preene & Powrie, 2009). Thermal piles are a specialist type of closed loop ground energy system in which small diameter pipes are cast into the piled foundations of a building to allow circulation of a heat transfer fluid. For rotary bored piles with a full depth cage, the pipes are usually fixed to the pile cage either during prefabrication, or on site if the cage comes in sections (Figure 4–1a). For CFA piles, or piles where the cage is less than full depth, it is common to plunge the pipe loops into the centre of the concrete, often attached to a steel bar for stiffness (Figure 4–1b).

Figure 4—1 Typical thermal pile construction details
a) pipework fixed to a rotary bored pile cage; b) pipework installed in the centre of a pile



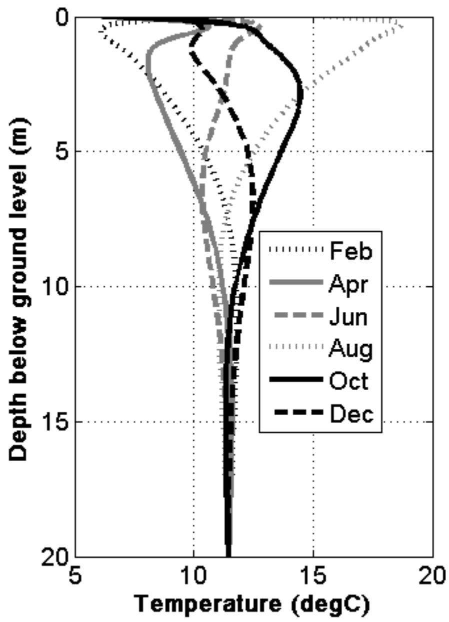
Below the upper few metres, the ground is essentially of constant temperature throughout the year (Figure 4–2). Hence in winter, circulation of cooler fluid within thermal piles allows heat extraction from the surrounding ground and in summer, circulation of warmer fluid allows injection of excess heat into the ground. A heat pump enables the temperature of the heated fluid to be increased to a more useful level by the input of a small amount of electrical energy. Similarly in cooling mode, a heat pump allows a reduction in fluid temperature to below that used in the air conditioning system, increasing the effectiveness of heat transfer on reinjection into the ground. Operation philosophies may differ, as follows:

- For small or domestic properties there is usually only a heating demand, which is met in conjunction with a heat pump. Heat transfer is unidirectional and systems must be designed to prevent excessive temperatures developing in the ground.

- For larger structures, which have both heating and cooling needs, it is advantageous to balance these and make use of inter-seasonal ground energy storage. This allows greater thermal efficiency between the same ground temperature limits. In this case the heat pump must be reversible.

- In some circumstances it is possible to adopt so called “free cooling” whereby warm fluid is returned to the ground heat exchangers without passing through a heat pump. If temperatures allow, this mode of operation is highly efficient.

Figure 4—2 Typical near surface seasonal temperature variation (calculated numerically assuming dry bulb air temperature profile for London, UK (CIBSE, 2005) and α=1.875x10^{-6}m^2/s)



Ground energy systems have been in use for decades, with significant take up (particularly in Northern Europe and North America) commencing in the 1970's due to increasing oil prices. Many ground energy systems use drilled boreholes as heat exchangers and research into these systems was pioneered in the 1980's in Scandinavia (eg Eskilson, 1987) and North America (eg Bose et al, 1985). The first thermal piles were installed in the 1980's (Brandl, 2006), but while design methods for borehole heat exchangers have matured, research into the behaviour of thermal piles has been more limited. In addition, coupling the structural and heat exchange functions of a pile means that the impact of thermal changes in the pile on its load bearing capacity must be addressed. Standard design methods for either the thermal or the geotechnical aspects are not yet available and few sources of guidance are published (Anstett et al, 2005, NHBC, 2010).

This paper sets out the underlying thermodynamic concepts relevant to thermal pile performance. It then outlines the key thermal design aspects for borehole heat exchangers (BHEs). This is important as these approaches are often used as a basis for assessing the heat output of thermal piles. Lessons learnt from the study of BHEs are then used to help understand the key factors controlling pile thermal behaviour. The paper then examines the interactions between thermal behaviour and mechanical performance of thermal piles, before introducing some more practical issues that must be considered. Finally knowledge gaps and areas where further research is required are identified.

4.3. Heat Transfer Concepts

Thermal piles, like other ground energy systems, function through the transfer of heat via conduction and convection. Conduction, due to the movement of atomic particles, is the primary heat transfer mechanism in solids. It is also referred to as diffusion. Convection is actually two heat transfer mechanisms: diffusion and the bulk movement of a fluid, termed advection. Convection is referred to as forced when the fluid flow is driven by external forces such as pumps. The flow may be internal (eg within a pipe) or external (eg around a fixed body).

Figure 4—3 Thermal pile Heat Transfer Concepts
a) plan of thermal pile components; b) temperature differences and component resistances

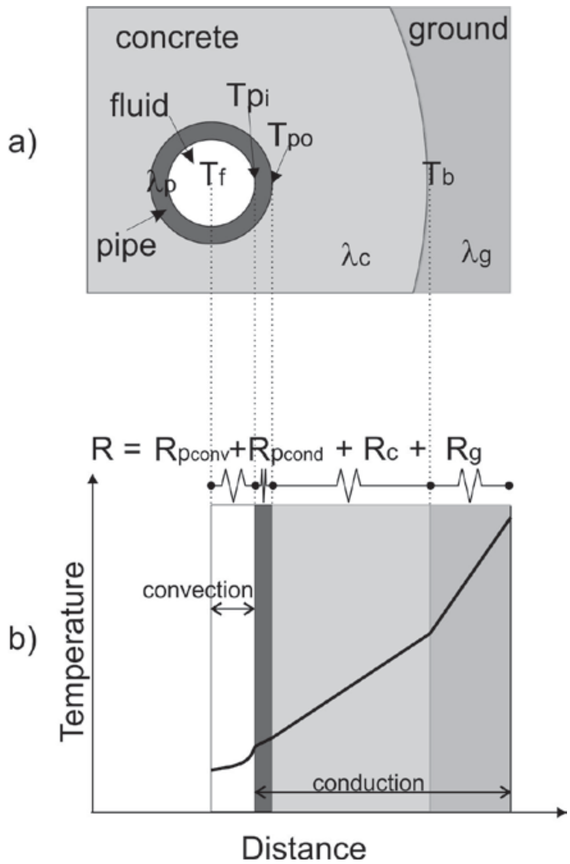


Figure 4–3 illustrates a simplified heat transfer pathway for a thermal pile from the heat transfer fluid through to the ground. Forced convection occurs via the internal flow in the pipes; conduction occurs across the pipe walls and through the concrete to the ground. In the ground, conduction is usually the dominant process (Rees et al, 2000), but if groundwater is flowing then advection can also be important (Chiasson et al, 2000).

All convection is described by Newton's law of cooling which relates the rate of heat transfer (Q in Watts) per unit area (A in m^2) to the temperature difference (in K) across the convection surface and a heat transfer coefficient, h (in W/m^2K). Thus for heat transfer between the heat exchange fluid in the pipes and the pipe wall:

$$\frac{Q}{A} = h\left(T_{pi} - T_f\right)$$

Equation 4-1

The value of h will depend on the properties of the heat transfer fluid, the nature of the flow conditions and the size of the pipe (eg Coulson & Richardson, 1990; Hellstrom, 1991). For water with turbulent flow the value of h is typically between 1,000 and 3,000 depending on the Reynolds Number. For laminar flow the heat transfer coefficient is an order of magnitude less.

For steady heat conduction in one dimension, Fourier's Law describes the relationship between the heat transfer rate and the temperature profile. Fourier's Law is analogous to Darcy's Law (Table 4-1) for groundwater flow, and for a temperature difference ΔT over a length L:

$$\frac{Q}{A} = -\lambda \frac{\Delta T}{L}$$

Equation 4-2

The constant of proportionality λ is the thermal conductivity (in W/mK) and is a measure of how well a substance conducts heat. It is analogous to the Darcy permeability and to electrical conductance. Hence a resistance to heat transfer, R (in K/W), can also be defined:

$$R = \frac{\Delta T}{Q} = \frac{L}{A\lambda}$$

Equation 4-3

Thermal resistance is a useful concept, as like electrical resistance, the component resistances of a system in series may be added to give an overall resistance (Figure 4–3b). The concept of resistance can also be used for convection, in which case:

$$R = \frac{\Delta T}{Q} = \frac{1}{hA}$$

Equation 4-4

Table 4-1 Comparison between heat flow and groundwater flow

	Heat Flow		**Groundwater Flow**			
	Temperature, T		**Excess (total) head, h**		**Excess pore water pressure, U_e**	
Steady State Flow	$\frac{Q}{A} = -\lambda \frac{\Delta T}{L}$	Fourier's Law	$\frac{Q}{A} = -k \frac{\Delta h}{L}$	Darcy's Law	$v = -\frac{k}{\gamma_w}\frac{dUe}{dz}$	Darcy's Law (in terms of excess pressure)
	Q	Rate of heat energy transfer (W)	Q	Rate of groundwater flow (m^3/s)	v	Darcy (superficial) flow velocity (m/s)
	λ	Thermal conductivity (W/mK)	k	Darcy permeability (m/s)	$\frac{k}{\gamma_w}$	
Transient Flow	$\frac{dT}{dt} = \alpha \frac{d^2T}{dx^2}$	Thermal Diffusivity Equation	$\frac{dh}{dt} = \frac{T}{S}\frac{d^2h}{dx^2}$	Groundwater Diffusivity Equation	$\frac{dUe}{dt} = Cv\frac{d^2Ue}{dx^2}$	1-D consolidation equation
	$\alpha = \frac{\lambda}{\rho Sc}$	Thermal diffusivity (m^2/s)	$\frac{T}{S} = \frac{kb}{S_s b} = \frac{k}{S_s} = D$	Hydraulic Diffusivity (m^2/s)	$Cv = \frac{k}{m_v \gamma_w}$	Coefficient of consolidation (m^2/s)
	ρS_c	Volumetric Heat Capacity (J/m^3K)	$S_s = m_v \gamma_w = k/C_v$	Specific Storage (m^3/m^3m)	m_v	Coefficient of volume compressibility (m^2/kN)
Radial Transient Flow	$\Delta T = \frac{q}{4\pi\lambda}\int_{r^2/4\alpha t}^{\infty}\frac{e^{-u}}{u}du$	Infinite Line Source	$\Delta h = \frac{Q}{4\pi T}\int_{r^2S/4Tt}^{\infty}\frac{e^{-a}}{a}da$	Theis Equation	Note: q is rate of heat transfer per length of heat exchanger	
	$\Delta T = \frac{q}{\lambda}.\frac{1}{4\pi}\left[\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right]$	Infinite Line Source (simplified)	$\Delta h = \frac{Q}{T}.\frac{1}{4\pi}\left[\ln\left(\frac{4Tt}{r^2 S}\right) - \gamma\right]$	Cooper-Jacob approximation		

Note: T=transmissivity; S=storativity; b=aquifer thickness

While heat transfer within a heat exchanger is often assumed to be at steady state and therefore considered in terms of its resistance, the response in the ground is usually transient. In transient conditions, heat transfer depends not only on the combination of thermal conductivity and geometry (ie resistance) but also on the speed at which temperatures change. This in turn is governed by the specific heat capacity of the ground, S_C (the amount of heat released per unit mass for a one degree change in temperature). Transient conduction is described by the diffusion equation, which is analogous to the groundwater diffusion equation (Table 4-1) and relates the change in temperature with time to the temperature gradient:

$$\frac{dT}{dt} = \alpha \frac{d^2T}{dx^2}$$

Equation 4-5

α is the thermal diffusivity in m^2s^{-1} and is a measure of how quickly a material responds to a change in the temperature regime. α can also be expressed as $\alpha = \lambda / \rho S_C$ where ρ is the density. Extending the groundwater flow analogy, the thermal diffusivity is effectively equivalent to the hydraulic diffusivity in aquifer terminology or the coefficient of consolidation in consolidation theory (Table 4-1). Thermal conductivity and thermal diffusivity (or specific heat capacity) are the key ground parameters required on the design ground energy systems, and are discussed by Busby et al (2009), VDI (2009), Banks (2008) and Kavanaugh & Rafferty (1997).

In reality, the heat transfer occurring within a thermal pile is more complex than is shown in Figure 4–3. The heat transfer pathway is not simply linear and it is possible for the different pipes to exchange heat with each other as well as with the ground via the concrete. In addition, everywhere that there is a change of material type, and the interface between those materials is imperfect, additional resistance to heat flow is provided by a so called 'contact resistance'. Some of these complexities are discussed further in the following sections.

4.4. Thermal Performance of Borehole Heat Exchangers

BHEs have a number of similarities to thermal piles, but also some important differences. Consequently lessons can be learnt from the extensive research and experience on borehole design methods, as long as these are tempered with an understanding of the key differences in behaviour. This section sets out some important concepts relevant to BHE behaviour. These concepts will then be extended for thermal piles in Section 4.5.

In the assessment of BHEs, the external response of the ground and the internal response of the heat exchanger are usually considered separately. Assuming steady state conditions in the borehole, the temperature change across the borehole and the temperature change in the ground can be summed as follows:

$$T_f - T_0 = \Delta T_{borehole} + \Delta T_{ground} = qR_b + \frac{q}{\lambda}F$$

Equation 4-6

where T_f is the temperature of the circulating fluid and T_0 is the initial temperature in the ground. q is the heat flux or rate of heat transfer per unit length and R_b is the borehole thermal resistance (in mK/W). F is a transient temperature response function, which describes the transient change in temperature in the ground in response to the applied thermal load q. F is a function of time, distance and thermal diffusivity, but is of the same mathematical form for a given geometry. Thus the shape of the temperature response curve is independent of the actual temperatures and heat fluxes. This type of behaviour is common to many heat transfer problems and lends itself to dimensionless analysis.

4.4.1. External Response

The simplest method of calculating the ground thermal response is to consider the borehole to be an infinitely long line heat source (ILS) within an infinite medium. This is analogous to the radial flow of groundwater to a well (Table 4-1). As in the Theis Equation, assuming a constant flux q, the temperature response function due to the heat source can be simplified to a log-linear relationship (Figure 4–4). The response function then becomes (Carslaw & Jaeger, 1959):

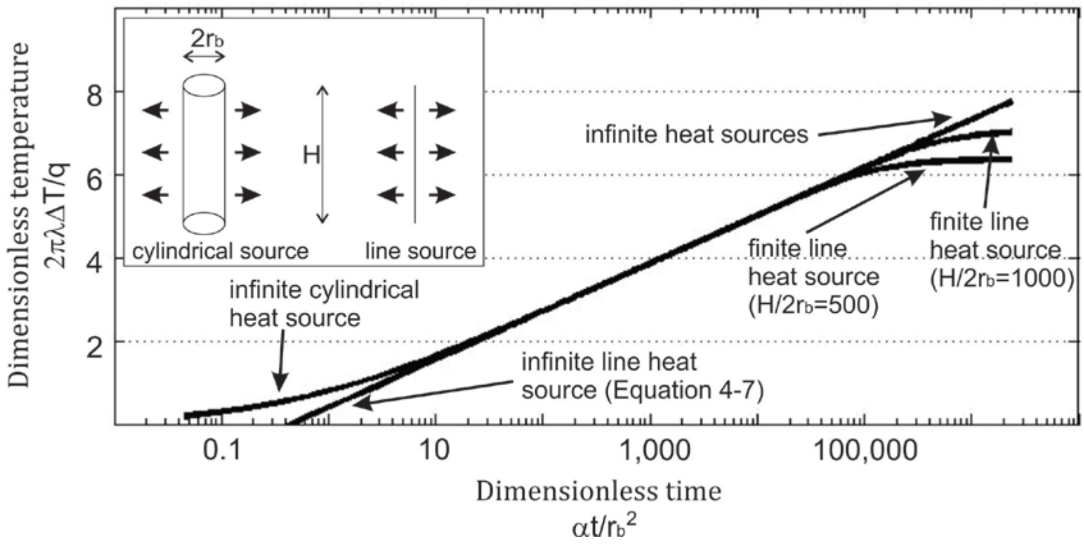
$$\Delta T = \frac{q}{\lambda}.\frac{1}{4\pi}\left[\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right]$$

Equation 4-7

However, at small times the ILS approach will underestimate the temperature response. This is because it assumes that the heat source is at the centre of the borehole rather than the circumference. This shortcoming can be addressed by modelling the borehole as an infinite cylindrical heat source (ICS). The analytical solution for the temperature response function for the ICS is more complex (Ingersoll et al, 1954), but a simpler curve fitted version can be used (Bernier, 2001). Figure 4–4 compares the ILS (Equation 4–7) and ICS (calculated numerically) temperature response functions. For typical BHE diameters (100mm to 200mm) the ILS will underestimate the temperature response by over 10% for approximately the first half day of heating. For the first six hours these errors will be in excess of 25%.

For an infinite heat source the temperature change in the ground continues indefinitely. In reality, a steady state will be reached as heat extraction (or input) is matched by solar recharge (or losses) at the ground surface. Using a constant surface temperature boundary condition, Eskilson (1987) developed a finite line source (FLS) model using a combination of analytical and numerical approaches to derive a series of temperature response functions (termed g-functions) to take account of this effect. Figure 4–4 gives example FLS g-functions compared with the ICS and ILS temperature response functions. These show the ILS to overestimate temperature changes at large times; however, for typical boreholes which are longer than 100m, it will take over 30 years for these errors to reach 10% (Philippe et al, 2009).

Figure 4—4 Dimensionless Temperature Response Functions for Heat Exchanger Design



Eskilson (1987) also made an important step forward in borehole heat exchanger design by superimposing numerical solutions to account for interactions between different borehole installations. These multiple borehole g-functions, which now underpin a number of commercial software packages, allow designers to take account of the reduction in available thermal capacity when multiple heat exchangers are within each others' zones of influence.

All the preceding discussions assume a constant and continuous applied power q. In reality the applied power will be time stepped according to the actual energy use in the building. Consequently the response will step from one temperature response curve to another depending on the actual value of q at any one time.

4.4.2. Internal Response

The heat exchanger is usually considered to be at a steady state (Remund, 1999; Shonder & Beck; 1999; Bernier, 2001; Xu & Spitler, 2006) and the estimated resistance is used to calculate the temperature change between the fluid and the borehole edge. The standard approach is to sum the resistances of the different components (Figure 4–3b), but this is a simplification as it can neglect contact resistances and pipe to pipe interactions. The former are usually assumed to be negligible, although there is a lack of research to confirm this. This simple approach also neglects the heat capacity of the borehole, although this is of minor significance for BHEs which would reach a steady state within a few hours.

Standard approaches for determining the resistance associated with the fluid (R_{pconv}) and the pipe (R_{pcond}) are well known (Bernier, 2001; Marcotte & Pasquier, 2008) and are equally applicable to thermal piles. The effective resistance of the grout within a borehole heat exchanger is more complex and depends on the geometric positioning of the pipes with respect to the hole. Consequently common empirical approaches (eg Remund, 1999) cannot be applied to thermal piles and new methods are required.

4.4.3. Fluid temperature profiles

Simple design methods assume that the rate of heat transfer between the fluid and the borehole is constant around the length of the pipe circuit and hence with depth down the heat exchanger. For this to be the case, the fluid must lose heat (and change temperature) at a constant rate around the pipe circuit (Figure 2–5a). Then, for a single U-tube installed in a borehole, the mean of the up and down fluid temperatures is constant with depth. However, numerical modelling (Lee & Lam, 2008, Marcotte & Pasquier, 2008) and field measurements (Acuna et al, 2009) show that a constant temperature boundary condition (Figure 2–5b) is more representative of reality and this results in an exponential variation in the fluid temperature with distance x around the pipe circuit (Incropera et al, 2007):

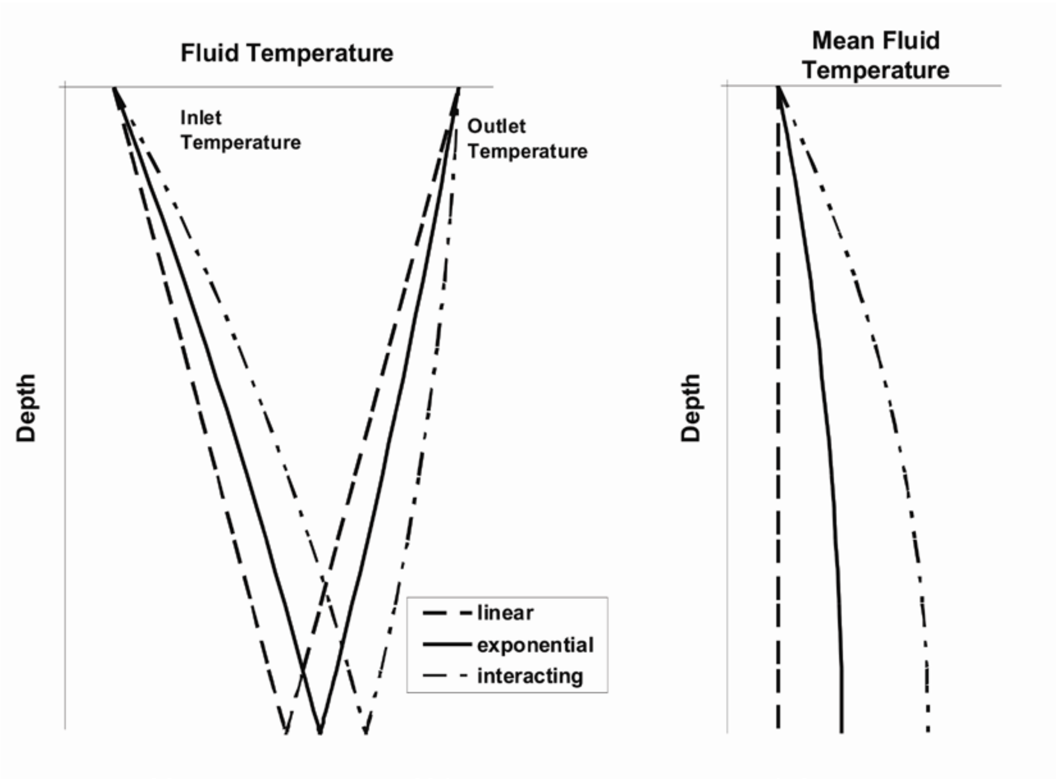
$$\frac{T_f - T_b}{T_{fin} - T_b} = \exp\left(\frac{-x}{2R_b m S_c}\right)$$

Equation 4-8

where T_{fin} is the inlet fluid temperature and m is the fluid mass flow rate. As a consequence the average fluid temperature for a single U-tube, and by extension the heat transfer rate, is not constant with depth (Figure 4–5).

Depending on the spacing of the two shanks of a U-tube, the two pipes may also exchange heat with each other (eg Diao et al, 2004b), thus reducing the efficiency of the system and increasing the variation of mean fluid temperature with depth (Figure 4–5). This is reflected in an increased borehole thermal resistance. Analytical solutions do exist for the calculation of the exact fluid temperature profile for a single U-tube (Hellstrom, 1991, Diao et al, 2004b); however, to implement these solutions allowing for interference between pipes is complex and requires knowledge of the precise internal geometry of the pipes within the borehole. Alternatively, an empirical solution for the fluid profile is available (Marcotte & Pasquier, 2008) and may be appropriate for cases where interference between the pipes is not excessive (Lamarche et al, 2010).

Figure 4—5 Fluid Temperature Profiles for a Single U-tube in a Vertical Ground Heat Exchanger (calculated based on Equation 4–8 and the approach of Diao et al, 2004b for interacting pipes)



4.5. Thermal Performance of Pile Heat Exchangers

4.5.1. External Thermal Response

There are very few data sets available for verification of the thermal design methods for piles used as heat exchangers. Published case studies often focus on the heat pump and overall system performance and do not consider the ground thermal response. This is unfortunate as the analytical approaches used for borehole heat exchanger design all have shortcomings when applied to thermal piles. Methods that assume a line source may be valid for small diameter holes but for piled foundations, with the heat exchange pipes fixed near to the circumference steel, there will be errors for analysis periods of less than a few days or even months. Figure 4–4 shows these differences non-dimensionally; for a 600mm diameter pile they translate to an underestimation of the temperature change by more than 10% for times up to 5 days, and by at least 25% for up to 2 days. For a 1.2m diameter pile these times increase to 21 days and 8 days respectively. This underestimation of temperature changes is not conservative in terms of both the thermal capacity of the system and assessing the potential for adverse thermo-mechanical interactions (see Section 4.6).

For piles with heat exchanger pipes installed in the centre of the concrete, although the heat source may more closely approximate a line, there will be two regions (concrete and ground) with different thermal properties that need to be accounted for in the thermal design.

For short piles, a steady state may develop within a few years rather than decades as for longer boreholes. For example, while for a 50m long pile it may take 15 to 20 years for the error in the ILS solution to reach 10%. The corresponding figure for a 20m long pile is only 2 or 3 years. For domestic housing piles, typically only 10m deep, the time can be less than a year. This leads to a significant overestimation of the temperature response if an infinite source is assumed. While this is conservative in terms of assessing thermo-mechanical interactions and thermal capacity, it does reduce the opportunities for maximising the capacity of the system. Therefore it is important to have a fully three dimensional model as a basis for determining performance.

The importance of the geometry of thermal piles is best indicated by the aspect (length to diameter) ratio (AR). Figure 4–6 shows aspect ratios for constructed thermal piles, which are generally in the range of 10 to 50 - in contrast to values of 500 to 1000 typical for BHEs. Figure 4–7a shows how the aspect ratio of a thermal pile governs its temperature response function. Figure 4–7b highlights the differences between the ILS and a finite cylindrical heat source (FCS) for four different aspect ratios. This shows the small time periods for which the ILS approach gives an acceptable error range when applied to thermal piles rather than BHEs.

Some of the differences between the models discussed above may be less important for a truly thermally balanced system, where heat extraction continues for six months only and is then balanced by re-injection of surplus heat from air conditioning systems. However, it is rare for systems to be perfectly balanced and hence it is likely that there will be a net accumulation of heat (or cold) in the ground over time.

As a result of the potential for errors in predicting the ground thermal response at small and large periods of times, considerable caution should be exercised when using any design software based on techniques developed for the assessment of BHEs. This has been highlighted by Wood et al (2010a) who compared actual fluid inlet and outlet temperatures for a thermal pile test plot with values determined from commercial software using a FLS approach over a one year period. While the overall trend calculated was reasonable, errors of about 2°C were apparent in the lower ranges of temperatures, with the design software under-predicting the fluid temperature. While this might not appear much, systems tend to operate with small temperature differences and over small temperature ranges. For example, 2°C is 40% of the total temperature variation range presented by Wood et al (2010a). In this context, and given the restrictions which need to be placed on systems to avoid ground freezing, an additional 2°C margin will reduce the efficiency of the system significantly.

Figure 4—6 Aspect Ratios (AR) of Constructed Thermal piles

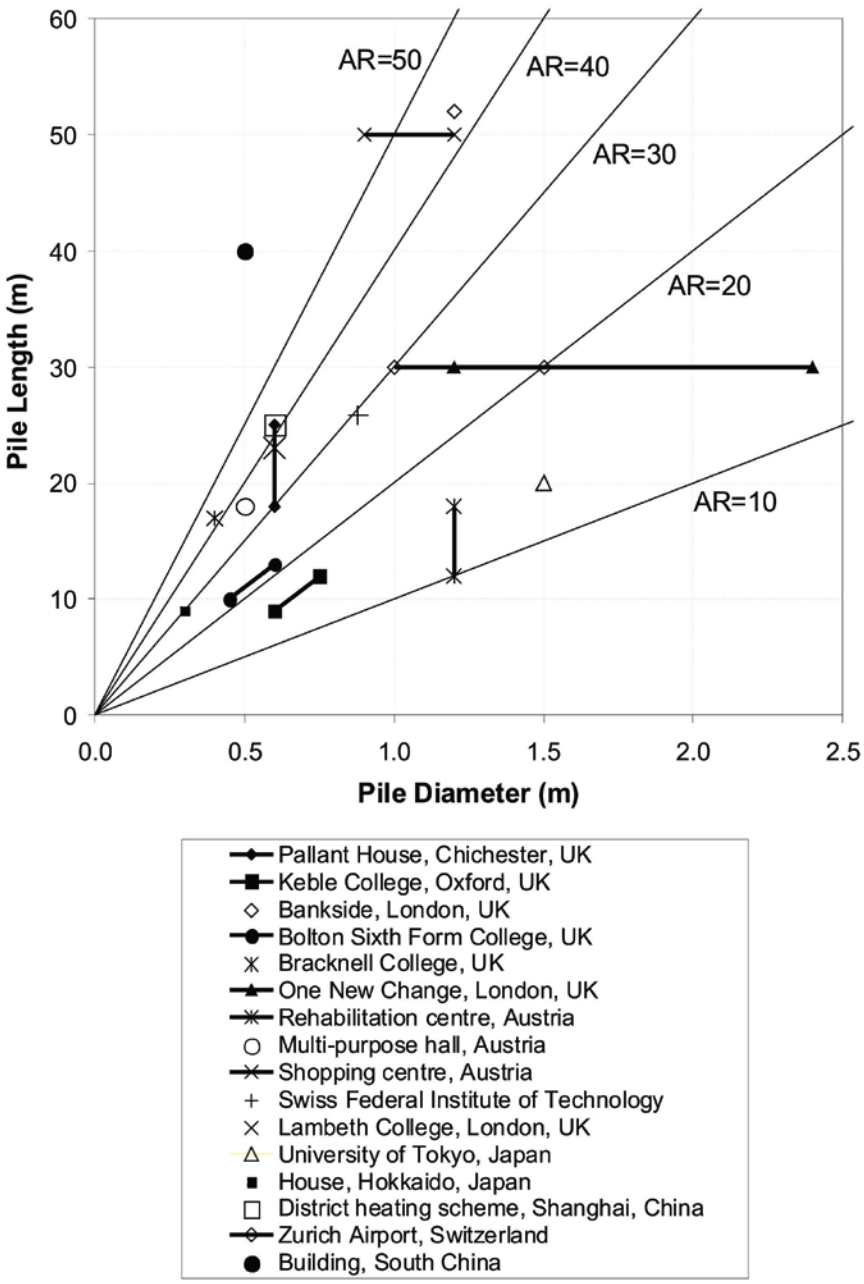
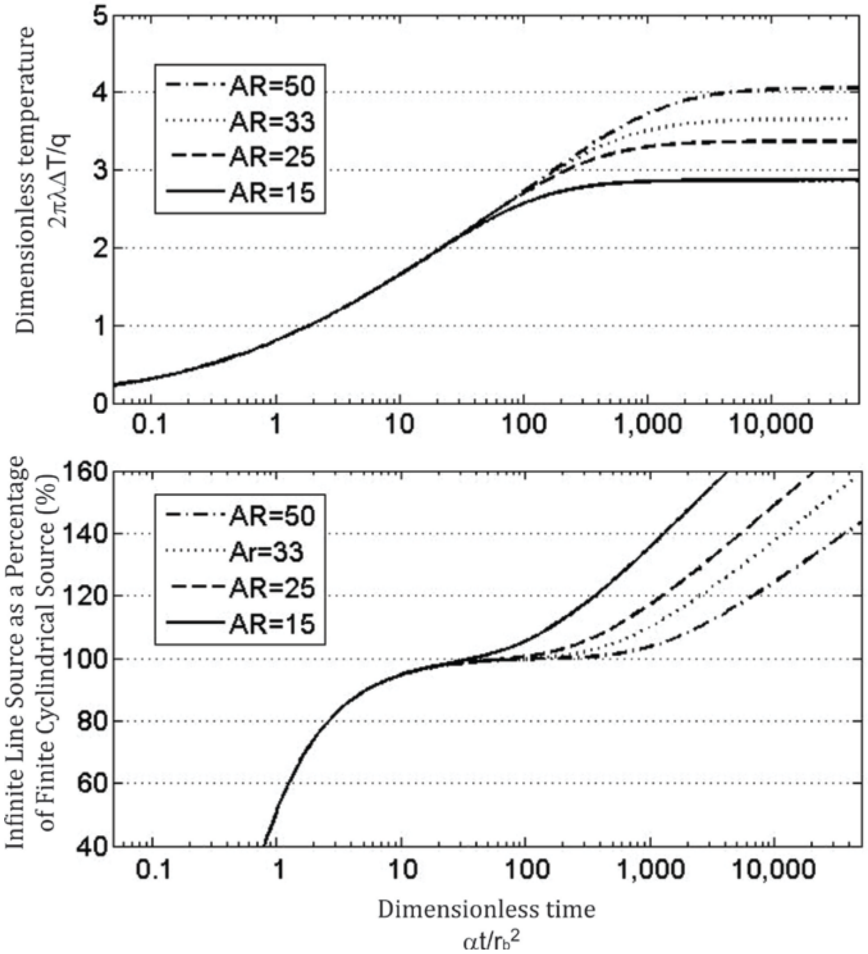


Figure 4—7 Effect of Aspect Ratio on Ground Temperature Response Function for Thermal piles a) finite cylindrical source (FCS); b) analytical methods as a percentage of FCS



A design approach which has been validated for use with thermal piles is the so called Duct Storage Model or DST (Claesson & Hellstrom, 1981, Hellstrom, 1989). This assumes that a large number of vertical heat exchangers, or ducts, are installed close together to act as an underground thermal store. The model separates analysis of the local heat transfer around each duct from global heat transfer into and out of the thermal store. For local heat transfer an ILS is applied for short duration heat pulses. Globally and at larger periods of times (defined as when the individual ducts are thermally interacting) a steady state is assumed within the store and subsequent heat input leads to linear changes in temperatures throughout the store. The local and global solutions are then combined to assess the overall performance of the heat store. The DST was initially validated against field data for small diameter (<50mm) borehole thermal stores in Sweden (Hellstrom, 1983). Subsequently, the DST approach has been implemented specifically for use with thermal piles in the software PILESIM (Pahud, 2007). PILESIM has been validated against thermal pile field data from Switzerland (Pahud & Hubbuch, 2007b), focusing on the overall heat exchange capacity of the system. Independent analysis using time-stepping finite element models (Markiewicz, R., 2010. Pers.

Comm.) implies that for regular arrays of piles the results provided by PILESIM are appropriate. However, the DST assumes a large number of identical piles installed in a regular array within a circular plan area and it is not clear what errors result from smaller or less regular pile group arrangements that are more representative of typical foundation layouts.

The methods discussed above were all originally developed from the design of BHEs and assume a constant ground surface temperature equal to the initial average temperature in the ground. This neglects the seasonal variation of the ground surface temperature, which will affect the ground temperatures to about 10m depth (Figure 4–2). For short uncovered heat exchangers this can have a major influence on temperatures (Wood et al, 2009). For thermal piles covered by buildings, there will be no incoming solar radiation to recharge the ground temperature, but studies by Thomas & Rees (1999) show that buildings provide a small net heat flux to the ground and this may be a more appropriate long term boundary condition. No methods of analysis take this into account and the topic requires further research to determine its importance.

4.5.2. Thermal Resistance for Pile Heat Exchangers

Theoretical values of R_b for thermal piles are given by the Swiss Society for Architects and Engineers (Table 4-2). These are typically smaller, by up to a factor of two, than published values derived from either in situ thermal testing or back analysis of system operations (Table 4-3). This is likely to be due to the high values of thermal conductivity for concrete assumed in the Swiss analysis (λ_c=1.8 W/mK). In reality, for a heat exchange pile λ_c is likely to be in the range 1 to 1.5 W/mK, owing to the high cement content required for strength and the presence of admixtures which can reduce thermal conductivity (Neville, 1995, Tatro, 2006, Kim et al, 2003).

The total thermal resistance of a pile would be expected to be larger than for a borehole (typically in the range 0.05mK/W to 0.2mK/W, Sanner et al 2005) based on the geometric arrangement of the pipes. As pile reinforcement must be protected from corrosion due to groundwater there tends to be a greater concrete cover to the pipes than for BHEs. This can lead to a larger resistance, especially if the pipes are actually in the centre of the pile. On the other hand, a greater number of pipes within the cross section would lower the resistance.

R_b is usually calculated by the separate assessment of R_c, R_{pconv} and R_{pcond} (see Figure 4–3). Assuming turbulent flow, R_{pconv} and R_{pcond} tend to be small, in total around 0.01mK/W for four pipes in parallel, and easy to calculate (for example, Bernier, 2001, Marcotte & Pasquier, 2008). R_{pconv} depends on the flow conditions, captured in the heat transfer coefficient h (Equation 4–1). The largest component of the thermal resistance of a pile is in the concrete or grout. This is more difficult to determine and depends on the arrangement of pipes and the concrete thermal conductivity. Currently, the most practical method for determining R_c is by numerical modelling.

Table 4-2 Pile thermal resistance values (after Anstett et al, 2005)

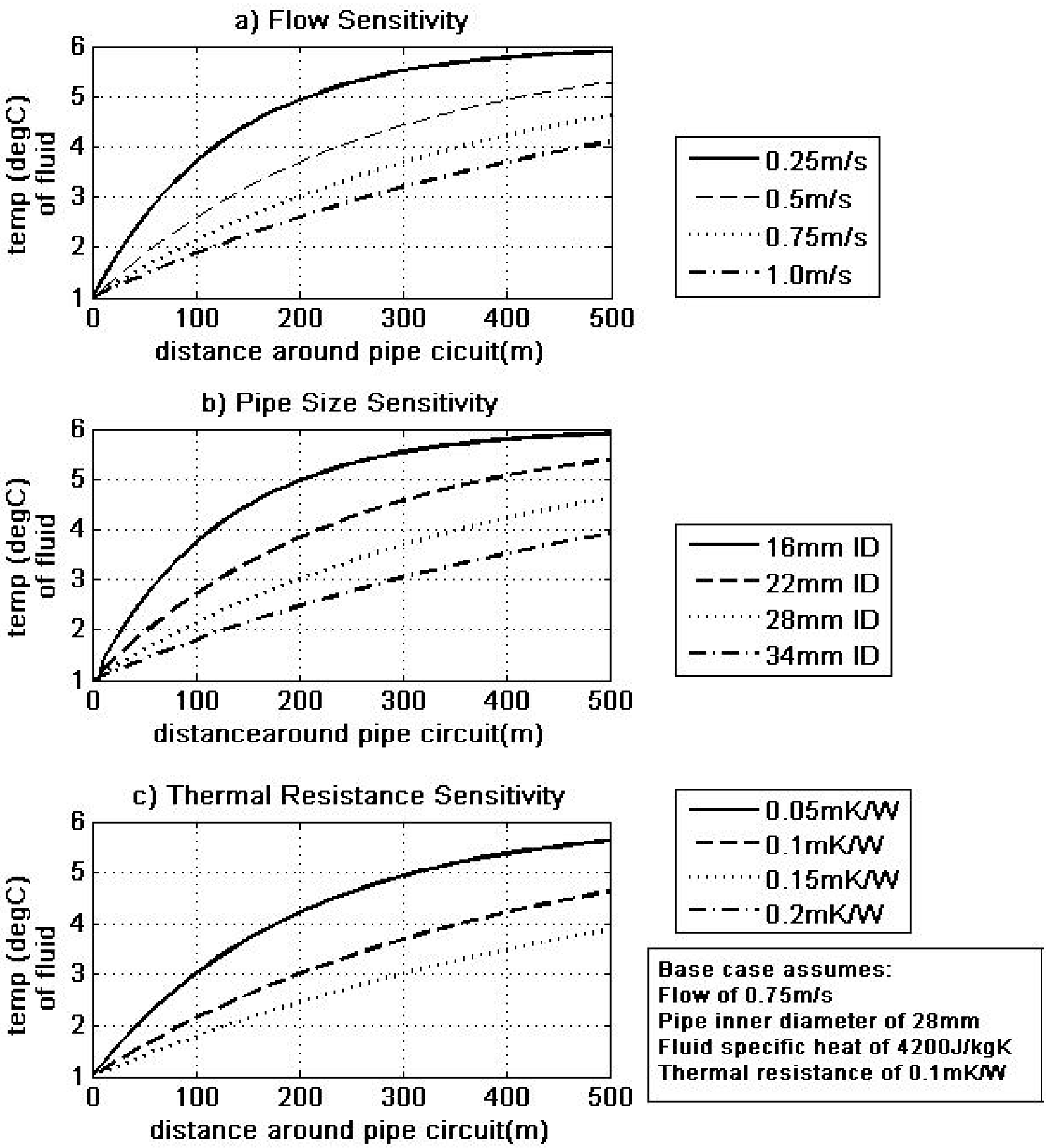
Pile Type	Pile Diameters	Total Thermal Resistance
Driven tube with double U-tube	0.3m to 0.5m	0.15 mK/W
Precast or cast in situ, with double U-tube attached to reinforcement	0.3m to 1.5m	0.1 – 0.11 mK/W
Precast or cast in situ, with triple U-tube attached to reinforcement	0.3m to 1.5m	0.07 – 0.08 mK/W
Precast or cast in situ, with quadruple U-tube attached to reinforcement	0.3m to 1.5m	0.06 mK/W

Table 4-3 Thermal resistance values from in situ measurement or back analysis

Pile Diameter/Type	Pipe Arrangement	Total Thermal Resistance	Source	Comments
0.3m Continuous flight auger	Single U-tube	0.22 mK/W	Wood et al (2010a)	Derived from combination of analytical methods and back analysis. Laminar flow conditions.
0.6m Cast in situ	Single U-tube	0.25 mK/W	Gao et al (2008b)	Bespoke thermal testing. Range of values represents different flow rates and connections between different U tubes.
	Double U-tube in series	0.15 – 0.2 mK/W		
	Triple U-tube in series	0.125 – 0.15 mK/W		
0.27m square driven	Single U-tube	0.17	Lennon et al (2009)	Short duration (<30hrs) thermal response tests
0.244m drive steel tube	Single U-tube	0.11		

Minimising the thermal resistance is important for improving thermal performance and reducing the temperature gradient across the pile. This has been the subject of some attention for borehole design and appropriate measures include ensuring that fluid flow is turbulent, using high thermal conductivity materials (Sanner er al, 2005) and installing more pipes within the hole (Zeng et al, 2003, Gao et al, 2008b). For thermal piles, maximising the number of pipes and minimising the cover to those pipes are likely to be important factors. However, for large diameter and CFA type piles with central pipes, the contribution of the pile to heat storage and not just transfer to the ground must be recognised. In such cases, a steady state resistance may no longer be valid and a two zone transient analysis of the concrete and ground response may be required. This area has seen little attention and requires further research.

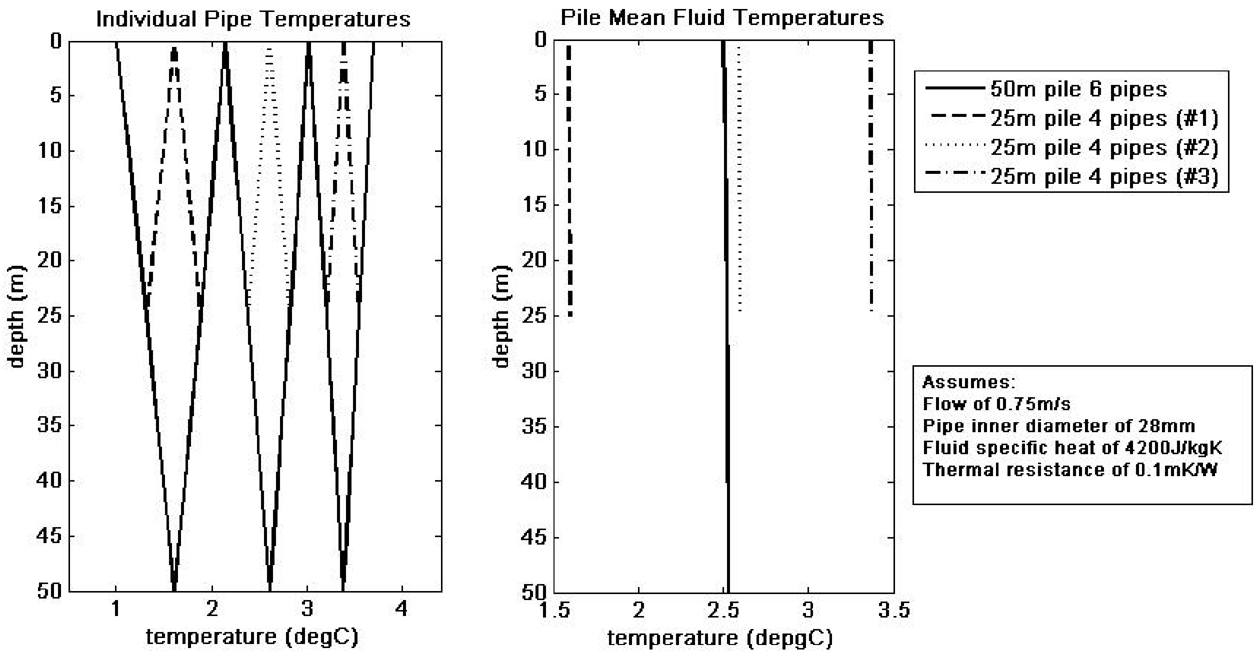
Figure 4—8 Exponential Fluid Temperature Variation in Pipe Circuits based on Equation 4–8 (assumes inlet temperature of 1°C and pile surface temperature of 6°C)
a) sensitivity to flow rate; b) sensitivity to pipe size; c) sensitivity to pile thermal resistance



4.5.3. Fluid Temperature Profiles

Heat transfer from the fluid to the edge of the pile depends on two factors; the resistance as discussed in Section 4.5.2 and the temperature difference. The latter depends on the flow conditions as described in Equation 4–8. Profiles of fluid temperature against distance along the pipe circuit, based on Equation 4–8 with a pile surface temperature T_b = 6°C and a fluid inlet temperature of 1°C, are given in Figure 4–8. The effectiveness of heat transfer will reduce substantially as the temperature difference between the fluid and the outside boundary, $T_b - T_f$, reduces round the pipe circuit. For this reason it is best to keep the circuit length to a maximum of 300m to 400m depending on the flow conditions. Maintaining a high flow rate (and high Reynolds Number) will also maximise heat transfer regardless of circuit length. However, it should be noted that in reality, the pile circumference is unlikely to remain at a uniform temperature (as assumed in Equation 4–8), especially for low flow velocities where there is a large temperature difference between the inlet and the outlet.

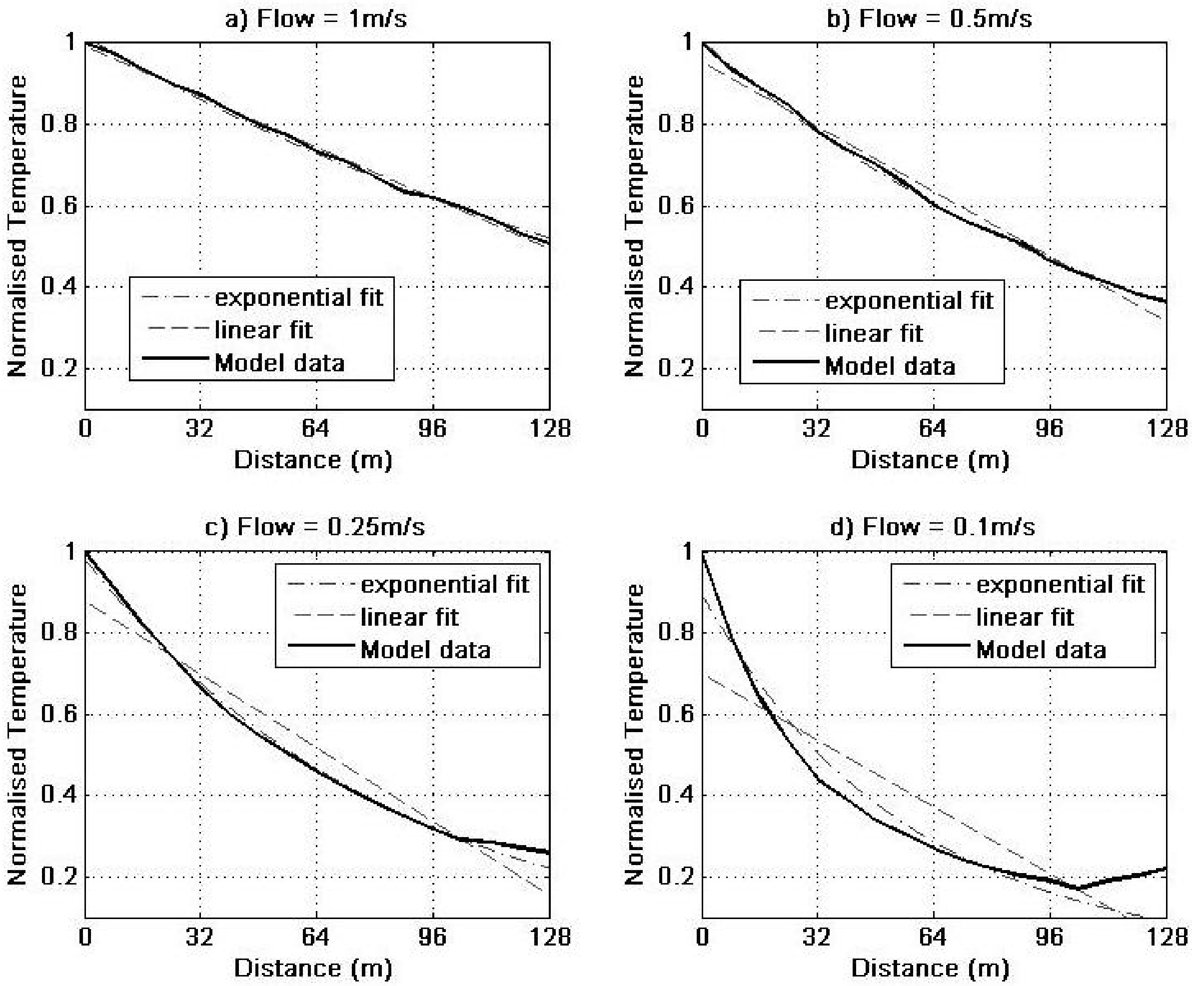
Figure 4—9 Example Mean Fluid Temperatures for Thermal piles Connected in Series (calculated using Equation 4–8 with inlet temperature of 1°C and pile surface temperature of 6°C)



As thermal piles are much shorter than boreholes, multiple piles are sometimes connected together into a single pipe circuit. Specific arrangements will depend on the number of pipes in a given cross section. For example, while an installation of larger diameter 50m deep piles may contain 6 pipes as one circuit, an installation of shorter 25m deep piles of smaller diameter with only 4 pipes may have 3 piles connected in series. In the latter case, the mean temperature of the fluid in each pile may vary significantly (Figure 4–9, right hand side). Hence the temperature difference relative to the ground and also the heat transfer rate may be different for each pile. This has been observed by Wood et al (2010b) where in a circuit comprising four 10 m deep piles connected in series the temperature difference between each successive pile was approximately 0.5 °C. For longer circuits and deeper piles these differences may be more substantial; unsurprisingly, the magnitude of the temperature difference decreases at higher fluid flow rate.

Thermal interactions between individual pipes will also affect the fluid temperature profile and hence the heat transfer achieved. As the pipes in thermal piles tend to be fixed between the main steel of the pile cage, their separation is likely to be about 250 mm to 300 mm (Smith, P., 2010. Pers. Comm.) compared with less than 100 mm for typical boreholes. Consequently, less interaction between the pipes would be expected in piles than in boreholes. This is beneficial as it both maximises the heat transfer and reduces the thermal resistance. No field measurements of the fluid temperatures within the pipe circuits of thermal piles have been carried out to date; only the inlet and outlet temperatures have been verified in situ.

Figure 4—10 Normalised Fluid Temperature Profiles from Thermal Pile Modelling by Markiewicz, 2004
(Inlet temperature is 2°C, borehole wall temperature taken as 1°C higher than outlet temperature based on results of original model. For curve fit data refer to Table 4-4.)



Simulation of the fluid (water) temperature profile for a 16 m long, 1.2 m diameter pile with 8 pipes installed in series has been carried out by Markiewicz (2004). The profiles are replotted here (Figure 4–10) in terms of non-dimensional temperature in keeping with Equation 4–8. An average borehole wall temperature had to be estimated from the published model results. Curve fitting for the profiles was then carried out as summarised in Table 4-4.

Table 4-4 Curve fitting parameters for fluid profiles from Markiewicz (2004)
(to be read in conjunction with Figure 4—10)

Flow (m/s)	Curve Type	Coefficients		Coefficient of Determination	Root Mean Square Error	Rb (mK/W)[1]	Comments
		a	b				
1	$ax+b$	-0.0039	0.9938	0.9968	0.0096		Linear and exponential curves provide good and comparable fit.
	$a\exp(bx)$	1.019	-0.005227	0.9965	0.0092	0.051	
0.5	$ax+b$	-0.0050	0.9551	0.9848	0.0258		Exponential curve provides better fit as temperature difference between inlet and outlet increases.
	$a\exp(bx)$	1.008	-0.007956	0.9988	0.0073	0.066	
0.25	$ax+b$	-0.0056	0.8801	0.9938	0.0627		Increased errors compared to higher velocities.
	$a\exp(bx)$	0.945	-0.01165	0.9957	0.0160	0.091	Some loss of fit at end of circuit due to minor interference
0.1	$ax+b$	-0.0051	0.7012	0.7490	0.1240		Significantly greater errors for linear fit.
	$a\exp(bx)$	0.898	-0.01783	0.9383	0.0615	0.148	Increased errors due to interference causing poor fit

[1] assuming $b = \frac{-1}{2R_b m S_c}$ and fluid and pipe properties as per Markiewicz (2004).

This assessment shows that for high flow rates (> 1m/s) the fluid profile is sufficiently close to a straight line to allow this simplified approach to be adopted (Figure 4–10a). An exponential curve of a form matching Equation 4–8 is appropriate for intermediate to high velocities, between about 0.25 m/s and 1 m/s (Figure 4–10b). However at low flow velocities (< 0.25 m/s), significant interference is observed with fluid near the end of the circuit relinquishing heat energy to that at the start of the circuit (Figure 4—100c and d). In such cases an exponential type curve is not appropriate. The interference also has a detrimental effect on the thermal resistance (Table 4-4), significantly reducing efficiencies of the pile as a heat exchanger. This illustrates the importance of maximising fluid flow rates while retaining pipe separation and limiting pipe circuit lengths in order to reduce interactions and hence facilitate maximum heat transfer.

4.5.4. Groundwater Flow

Where groundwater is flowing, the temperature change in the ground adjacent to the heat exchanger will be reduced by additional advective heat transfer. While this is potentially a huge benefit in terms of the capacity of an individual ground energy system, the resulting thermal plume will travel a greater distance downstream giving the potential for interactions over a much wider area. This is evident from open loop ground energy systems within aquifers beneath conurbations, where widespread adoption and extended use has led to significant changes in the aquifer temperatures (Gustafsson, 1993; Ferguson & Woodbury 2006).

Design approaches for systems affected by groundwater are not well defined. Analytical solutions for the ground temperature response functions (Claesson & Hellstrom, 2000; Sutton et al, 2003; Diao et al, 2004a) are based on the principle of an infinite line heat source moving through the medium being heated and thus disregard the development of a diffusive steady state. They also do not consider characteristics of real groundwater flow, including the effects of inhomogeneity and possible fracture flow. Consequently, numerical methods are often used to assess heat transfer in the presence of moving groundwater (eg Gehlin & Hellstrom, 2003, Anstett et al, 2005). While it is important to question whether a sustained and consistent groundwater flow in an urban area can be relied upon over the design life of a system, any potential for adverse effects resulting from groundwater flow must also be assessed. In particular, the capacity for inter-seasonal energy storage will be reduced by flowing groundwater, which must be accounted for in any assessment of thermal potential.

4.6. Thermo-Mechanical Interactions and Pile Behaviour

The potential for adverse thermal interactions between heat exchanger piles and the ground has led to concerns that inappropriate operation may lead to ground freezing, excessive ground deformations or additional pile stresses that cannot be safely carried by the structure. Despite these fears, no mechanical issues with thermal piles have been reported to date, possibly as a result of conservative design and geotechnical factors of safety providing capacity within which additional thermal loads can be accommodated. However, such factors of safety are used to account for other uncertainties (eg ground heterogeneity) and therefore this is not a satisfactory design approach.

Consequently, it is important that the potential for additional thermal stresses is assessed and temperature limits placed on ground energy systems to prevent structures from experiencing excessive temperature ranges. The following sections discuss the theoretical framework for thermal-mechanical interactions, what can be learnt from recent case studies and uncertainties that still remain, especially with respect to long term cyclic loading. As temperature changes resulting from ground energy systems only occur after the building is complete and operational the discussion will exclude early age thermal effects in concrete. This is in keeping with recent research which argues that for piles in saturated ground creep and shrinkage effects are insignificant compared with other loads (Bicocchi, 2011).

4.6.1. Behavioural Framework

In principle, when a thermal pile is heated it will tend to expand and when it is cooled it will tend to contract. Free expansion or contraction will not occur because the pile is restrained, both by the surrounding soil and by any overlying structure. Consequently a proportion of the theoretical free strain will be expressed instead as a change in longitudinal stress within the pile and transferred to the ground by skin friction or end bearing. A pile that expands relative to the surrounding soil will tend to experience an increase in the axial stress (termed hereafter the “pile axial load”), and a pile that contracts a reduction; however, the exact effect will vary, and could even be locally reversed along the length of the pile depending on the degree and nature (resilience) of the end restraints. A similar observation applies to the mobilised skin friction. Potential concerns include overstressing the cross-section, an excessive increase in base bearing pressure, or the development of negative (downward) skin friction resulting potentially in the loss of external load carrying capacity. A useful conceptual framework for assessing this complex behaviour has been presented by Bourne-Webb et al (*in press*) and illustrates in particular the importance of the end restraints in controlling the thermo-mechanical response. This framework can be used to assess potential thermal effects in terms of additional forces that must be accommodated in design. However, case studies are important for validation of the approach.

4.6.2. Lessons from Case Studies

Early observations of strain and temperature within a thermal pile were reported by Brandl (1998). While the study did not give sufficient detail to enable a full assessment of the thermo-mechanical behaviour, it does illustrate the consequences of excessive heat extraction. As fluid temperatures reached -5 °C ice lenses formed within the ground causing 150 mm of heave at the surface. Relative movement between the pile and the ground would also have been expected to have altered the shaft skin friction.

This case study illustrates the importance of ensuring that the pile and ground do not freeze. The simplest way of achieving this is to specify that the fluid outlet temperature from the piles must not fall below 0°C, allowing for an appropriate margin of safety, usually 2°C (eg NHBC, 2010, SIA, 2005). However, this is a conservative approach and will result in a failure to utilise the ground to its full thermal potential. Therefore a more sophisticated approach may be adopted whereby assessment of the pile thermal resistance and fluid temperature profiles can be made to demonstrate that lower fluid outlet temperatures will not lead to development of freezing conditions at the soil pile interface. As well as this assessment, it is important that a suitable building control system is in place to prevent excessively low temperatures from occurring in the case of a higher than expected heating demand.

Two systematic attempts to assess the thermo-mechanical response of thermal piles have recently been made. A working pile for a new building at the Swiss Federal Institute of Technology was used for thermo-mechanical testing, reported by Laloui et al (1999, 2006) and summarised in Table 5. Before construction of the building a simple thermal test was carried out and the resulting temperature changes and strain data used to calculate the mobilised skin friction. For a 22°C temperature increase the pile expanded by 4 mm at the head, with a small amount of compression at the toe reflecting the high end restraint due to the embedment of the pile in hard sandstone. Near uniform heating caused between 30 kPa and 80 kPa of skin friction to develop in the different soil layers. Further heating of the pile was carried out under different pile head loads (Table 4-5). The pile was constrained, both at the toe (by bedrock) and at its head (by the structure). Pile axial loads of up to 2 MN were induced over the full length, the largest of which were over the lower portion of the pile. This additional thermal load was greater than the mechanical pile axial load of 1.3 MN at the pile head (Table 4-5).

Table 4-5 In situ Measurements of Pile Thermo-Mechanical Reponses

Reference	Borne-Webb et al (2009)		Laloui et al (1999)	Laloui et al (2006)
Test	Test pile - cooled	Test pile - heated	Operational pile – 1 storey constructed	Operational pile – 7 stories constructed
Pile Length	23m		25.8m	
Pile Diameter	0.6m		0.88m	
Ground Conditions	made ground and river terrace deposits to 5m overlying London Clay		alluvium to 12, glacial till to 25m, toed into sandstone	
Restraint	not significant		large 7 storey building and piled toed into rock	
Temperature Change	-15 to -20 degC	+5 to +10 degC	+22 degC	+13 degC
Head Load	1200kN	1200kN	300kN	1300kN
Mechanical Load	+1200kN near head zero at toe	+1200kN near head zero at toe	+300kN at head	+1300kN at head zero at toe
Thermal Load	zero at head -300kN near base	+800kN at 4m +200kN at base	+1000kN at head	+1200kN at head +2000kN at toe

A thermo-mechanical load test was carried out on a sacrificial test pile at Lambeth College in London (Bourne-Webb et al, 2009). The pile was subjected to separate heating and cooling cycles while the carrying an external mechanical load of 1200 kN at the head (Table 4-5), equivalent to the anticipated working load. The heating caused an increase in pile axial load of up to 800 kN in the upper part of the pile, while the cooling cycle led to a reduction in load of about 500 kN, mainly near the base of the pile. This smaller (up to about 70% of the original external load) and less even distribution of additional pile axial load compared with the Swiss test is a reflection of the lower degree of restraint of the Lambeth College pile. The consequent changes in shaft friction were estimated to be up to about 50 kPa, with a maximum total of 75k Pa developing during the thermal tests compared with a value in excess of 90 kPa developed at the ultimate limit state in subsequent destructive load testing.

Both tests indicated the thermo-mechanical response of the thermal pile to be largely reversible, and the pile-soil system to be acting thermo-elastically, at least over small numbers of cycles. This elastic behaviour was confirmed when a new approach for calculating the effects of thermal loading on piles using an elastic load transfer method was tested on the above case studies (Knellwolf et al, 2011). In addition to providing a good match to the experiment data the method of Knellwolf et al went on to assess a number of possible working scenarios. It was shown that for a pile where the head load induces skin friction close to the ultimate capacity, additional heating may cause the ultimate skin friction capacity to be reached. Conversely, cooling of the pile can cause a reversal of shear stresses and the development of negative skin friction.

The observed reversible nature of the thermal-mechanical behaviour is encouraging as the range of temperatures used in the testing is realistic compared to likely operational ranges, thereby suggesting that permanent deformation is unlikely to result from operation of ground energy systems. However, short term testing cannot identify smaller cyclic effects that could become significant over longer timescales and larger numbers of cycles. Thus longer term in situ trials and/or laboratory testing will be required to confirm the soil-structure behaviour over the lifetime of a system.

4.6.3. Soil Thermal Behaviour and Cyclic Loading Effects

The above discussion has focused solely on the potential for volume change and induced stresses within the concrete pile. However, the temperature changes will also result in volume change in the soil and potentially in changes to the soil properties. Volume changes may occur due to both thermal expansion and temperature induced mechanical changes to the soil structure. For normally or lightly over-consolidated clay soils heating usually results in contraction, while for highly over-consolidated clays elastic expansion is typical (Cekerevac & Laloui, 2004). However, most investigations of thermally driven volume change in soils have focused on heating clays to high temperatures to simulate conditions relevant to nuclear waste disposal. The effect of smaller magnitude cycles of heating and cooling over a number of years has yet to be investigated.

Most studies of cyclic loading of piles relate to offshore structures. Poulos (1988) provides a useful discussion in this respect and highlights that two-way cyclic loading, as would probably be the case for thermal piles, is more damaging. Beyond a threshold cyclic load, typically close to the static load required to cause pile/soil slip, degradation of the shaft skin friction can occur (Poulos, 1989). Reduction in skin friction by up to 20% has been recorded (Jardine, 1991) but any individual case will depend on the soil properties, the nature of the pile, the static and cyclic loads and the loading rate. Full assessment of behaviour can be made if appropriate laboratory tests have been carried out, but caution must be exercised as thermal piles will be subject to a more uniform (with length) loading than offshore piles where the axial load is concentrated at the head.

Laloui & Cekerevac (2008) suggest that the number of mechanical load cycles required to fail a test specimen increases with temperature. Soil strength tests at elevated temperatures show varying results, but any deterioration of peak or critical state friction angle over the range of temperatures relevant to ground energy systems is likely to be small (Laloui, 2001); hence a significant reduction in the ultimate shaft capacity due to a general change in temperature is unlikely. Again, however, the effect of longer term cyclic changes should be investigated further.

4.7. Practical Constraints

The foregoing discussions relate to largely theoretical aspects of thermal pile behaviour. However, there are many design and construction interfaces which will affect any thermal pile scheme. While for traditional ground energy systems the layout of the heat exchangers is optimised to maximise thermal output, for thermal piles, the structural and geotechnical design will take priority. This means that the aim is to determine the thermal capacity from a given pile layout and also to check the thermo-mechanical effects on the geotechnical design. It is unlikely to be economic to install additional piles or increase their lengths purely to provide additional energy capacity. The ground conditions and any natural variability in their properties are also a given parameter that must be accounted for. Currently it is usual for average thermal properties to be used in design regardless of the soil complexity. This is despite the fact that is known from studies of BHEs that stratified soil conditions can cause differences in behaviour between heating and cooling (Signorelli et al, 2007).

To some extent the layout of fluid pipes can be optimised once the pile layout has been determined. The number of pipes installed and their positions will be determined by the thermal design, as long as this is compatible with the construction process. For example with a full depth cage the number of pipes and their locations and pipe circuit lengths can easily be adjusted to maximise thermal output. However, if the pile is to be constructed by CFA techniques or has a cage over only part of its length, then it is likely that this will force installation of the pipes within the centre of the pile. It is also essential to ensure that any pipes fixed to cages during the construction process are fixed using a safe system of working and this has encouraged the placement of pipes on the outside of cages (Figure 4–1a).

If possible it will be advantageous to use concrete with a high thermal conductivity. This would mean maximising the aggregate content and using higher conductivity aggregates like sandstone. However, practically the mix design is driven by the structural strength and slump requirements and it will always be more economic and more sustainable to use local sources of aggregate than to import special materials from greater distances.

Whereas construction of piles for building developments usually only interfaces with the groundworks contractor, thermal piles and the pipes which come from them have far more design and construction interfaces. It is important to protect pipes from damage at all stages of construction, from breaking out the piles, to extending the pipes beneath the building slab and ultimately to the plant room. It is essential to have redundancy in the system in case of damage during construction, but this should be coordinated by all the parties which interface with the ground energy system in order to prevent over-conservatism. Pressure testing of the pipes to confirm integrity at key construction stages is essential for managing this process.

4.8. Conclusions

The ground is well suited to act as a thermal store and using structural piled foundations as heat exchangers is an increasingly common approach to improving the energy efficiency and reducing the carbon emissions from new buildings. The design of thermal piles has two distinct components: assessment of available heating and cooling capacity and additional checks as part of the geotechnical design to ensure that the cycles of temperature change do not have an adverse effect.

Assessment of heating and cooling capacities has often followed similar approaches to those used for the design of borehole heat exchanger arrays. However, care must be taken as the smaller aspect ratio of piles compared with boreholes means that thermal piles will reach a steady state more quickly. Consequently, analytical methods which assume an infinite heat source will overestimate the temperature change in the ground. While conservative, in terms of assessing both the available heat output and the potential for adverse thermo-mechanical interactions, this approach will result in the thermal potential of the ground not being maximised. Hence, it could potentially lead to systems being assessed as uneconomic. One of the few validated design approaches for estimating the thermal response of the ground to thermal piles is based on the Duct Storage Model. However, this method assumes that all the piles are installed on a regular grid and it is not clear what uncertainties are introduced from more realistic pile layouts.

Thermal piles will also be significantly influenced by their internal thermal behaviour – in particular, the amount of concrete cover and the relative positions of the pipework within the pile which can cause internal heat transfer. These factors are usually accounted for by the pile thermal resistance. However, there are no standard methods available for calculating the thermal resistance of piles, leading to uncertainty regarding parameter selection. The few published values of pile resistance have been derived principally from in situ tests. However, the discrepancy between these values and theoretical values suggests that more research is required in this area.

Thermal resistance is also influenced by the temperature profile of the heat exchanger fluid, which may vary non-linearly around the heat exchanger circuit. There are two typical scenarios for thermal piles, one with pipes placed around the circumference of the pile (attached to the steel cage) and one with the pipes placed centrally within the pile. The former is beneficial and will have a lower resistance as the pipes are closer to the ground. However, in the latter case there will be a large resistance, the pipes are more likely to interact adversely and questions remain as to whether a steady state approach to the pile behaviour is appropriate. These topics all warrant further research in order to assist more efficient heat exchanger design.

When multiple piles are connected in series, the change in heat transfer rate along the length of the pipe circuits can lead to each pile in the series having a different heat transfer rate to the ground. This is not accounted for in standard thermal design methods and the importance of this effect is still not known. All these uncertainties in the assessment of thermal capacity are exacerbated by the lack of high quality monitoring data from case studies with which to validate potential new approaches.

Chapter 5. On the Thermal Resistance of Pile Heat Exchangers

This chapter has been submitted as a stand alone paper to Geothermics and is currently under review for publication.

5.1. Abstract

Structural foundation piles are being used increasingly as heat exchangers to provide renewable heat for new buildings. To design such energy systems a steady state is assumed within the pile, which is conventionally characterised by constant thermal resistance. However, there has been little research regarding pile resistance and there are few published case studies. Numerical modelling results are presented here to provide typical values of pile resistance, depending on the details of the heat exchange pipes. Analysis suggests large diameter piles may take several days to reach steady state; in these cases a transient design approach may be more appropriate.

5.2. Introduction

Closed loop ground energy systems, with heat exchange pipes embedded in the ground, have long been recognised as a potentially sustainable means of providing heating and cooling to buildings. Systems typically comprise vertical drilled heat exchangers or horizontal "slinky" type pipe installations depending on the land available and the building thermal loads. Recently there has been an increase in the use of structural foundation piles as closed loop vertical heat exchangers (Amis, 2009). In this case the heat exchanger pipes are typically fixed to the structural pile steel reinforcement cage prior to placing the cage in the pile bore and concreting (Figure 4–1a). Alternatively for contiguous flight auger (CFA) type piles, the pipes may be plunged into the centre of the pile bore after placing the concrete (Figure 4–1b). Despite the increased use of pile heat exchangers, often termed thermal piles, research into their behaviour has been limited compared with other types of ground heat exchanger (refer to Chapter 4). Consequently uncertainties remain about design methods and parameter selection.

Conventional design of closed loop pile heat exchangers typically separates the internal (ie within the heat exchanger) and the external (ie within the ground) thermal response of the system. The pile element is usually assumed to be at an instantaneous steady state as far as internal heat transfer between the thermal fluid and the exterior surface of the concrete is concerned. While the temperature of the pile may vary with time, it is usually assumed that the pile surface temperature is constant around the circumference and along the length of the pile at any point in time. However, this simplification, while making analysis more straightforward, does not represent real behaviour.

This paper investigates, by means of numerical analyses, heat transfer within a pile and at the concrete surface, and how this varies depending on the number of heat exchange pipes and the depth of concrete cover. The results of the analyses are then used to define the limits of validity of the conventional design assumptions listed above, and to propose an empirical equation to allow calculation of the temperature difference between the fluid and the ground.

5.3. Background

Design approaches for closed loop vertical ground energy systems typically assume that the heat exchanger is at steady state. The temperature change across the heat exchanger can then be calculated on the basis of the resistance of the heat exchanger, R_b.

$$R_b = \frac{\Delta T}{q}$$

Equation 5-1

where q is the heat transfer rate per unit length of the heat exchanger and R_b is the resistance. Thermal resistance depends on both the material property (thermal conductivity) and the heat flow path lengths, which in turn depends on the object geometry and the distribution of the temperature at the boundaries. ΔT in Equation 5–1 is the temperature difference between the source and sink, ie between the fluid and the edge of the concrete heat exchanger. It is common to assume that the temperature at these boundaries is, at a given time, uniform but in some cases (eg constant applied heat flux to a solid object) this is not so. In such cases it is appropriate to use a mean value of the temperature, but a different value of R_b will result (Incropera et al, 2007), owing to changes in the heat flow path geometry.

For drilled borehole heat exchangers there has been significant research regarding methods for determining R_b (eg Hellstrom, 1991; Lamarche et al 2010; Remund, 1999), in addition to well documented case studies and published typical values based on in situ testing (eg Table 5-1). However, the corresponding database of both experience and research has yet to be fully developed for pile heat exchangers and there is an absence of reliable guidance for designers in selecting values of thermal resistance for use in design.

The following sections of this paper review existing approaches for determining heat exchanger thermal resistance, and the key parameters influencing the result. Sections 5.4 and 5.5 present numerical modelling data which explore the importance of the different parameters and challenge some of the assumptions behind the simpler analytical design approaches which are commonly adopted.

Table 5-1 Typical Values of Borehole Thermal Resistance based on in situ Testing (after Sanner et al , 2005)

Boreholes	Grout	Thermal Resistance (mK/W)
100 to 200 mm diameter	Standard	0.10 – 0.20
	Thermally Enhanced	0.06 – 0.10

5.3.1. Analytical Approaches

Thermal resistance for vertical ground heat exchangers is usually expressed as the sum of its component parts:

$$R_b = R_{pconv} + R_{pcond} + R_c$$ **Equation 5-2**

where the subscripts *p* and *c* refer to the pipe and concrete (or grout). R_{pconv} and P_{pcond}, the resistances associated with the flowing fluid and the pipe material respectively, usually represent the effects of a number of individual pipes operating in parallel.

Assuming a spatially uniform pipe wall temperature, R_{pconv} is usually calculated using the following expression:

$$R_{p_{conv}} = \frac{1}{2n\pi r_i h_i}$$ **Equation 5-3**

where n is the number of pipes within the heat exchanger cross section, r_i is the pipe internal radius and h_i is the heat transfer coefficient. The Nusselt number can be used to calculate h_i; for turbulent flow the most common expression for this is the Dittus-Boelter equation, which gives:

$$h_i = \frac{Nu\lambda_{fluid}}{2r_i} = \frac{0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.35}\,\lambda_{fluid}}{2r_i}$$ **Equation 5-4**

The pipe conductive resistance can be assessed using the equation for the resistance of a hollow cylinder with constant temperature boundaries on the inner and outer surfaces. For n pipes in parallel:

$$R_{p_{cond}} = \frac{\ln(r_o/r_i)}{2n\pi\lambda_{pipe}}$$ **Equation 5-5**

where r_o is the outer radius of the pipe.

The concrete or grout resistance is more difficult to assess and a number of methods have been adopted for borehole heat exchangers. The first (eg Shonder & Beck, 2000) considers the material as an equivalent hollow cylinder with the outer radius taken to be the heat exchanger radius r_b and an inner effective radius, r_{eff}, determined as follows:

$$r_{eff} = r_o\sqrt{n}$$

The concrete resistance then becomes:

$$R_c = \frac{\ln(r_b/r_{eff})}{2\pi\lambda_c}$$ **Equation 5-6**

To apply the analytical solution for the thermal resistance of a cylinder it is assumed that at a given point along the length of the heat exchanger the outside of the cylinder is at a uniform temperature. Although that temperature may vary with time and with depth, around the circumference it must be constant. In reality, this is not necessarily the case for vertical heat exchangers, and the significance of a variable circumferential temperature will be explored later in section 5.5 of this paper. Also the equivalent cylinder approach takes no account of the actual positioning of the pipes, specifically their offset from the edge of the heat exchanger and their distance from each other. Consequently, unless the pipes are in contact with each other at the centre of the hole, Equation 5–6 will overestimate the thermal resistance (Sharqawy et al, 2009).

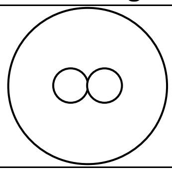
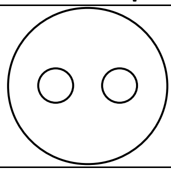
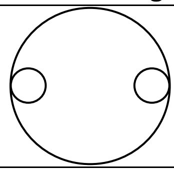
The second method, developed by Remund (1999), uses an empirically derived shape factor, S_b, to determine R_c. Values of R_c were determined experimentally from field tests of borehole heat exchangers with three configurations of two pipes (Table 5-2). Shape factors were then back calculated from the measured values of R_c (Equation 5–7) and an empirical equation for S_b was derived (Equation 5–8). S_b depends on the ratio of the borehole and pipe radii and two empirical constants β_0 and β_1. The values of the constants for the different pipe configurations are given in Table 5-2.

$$R_c = \frac{1}{S_b \lambda_{grout}}$$ **Equation 5-7**

$$S_b = \beta_0 \left(\frac{r_b}{r_o} \right)^{\beta_1}$$ **Equation 5-8**

The disadvantage of Remund's approach is that it can be difficult to know accurately the positions of the installed pipes. It is also not applicable to most pile heat exchangers, which are installed with more than one pair of pipes.

Table 5-2 Borehole heat exchanger configurations (after, Remund, 1999)

	Configuration A Shanks central and touching	**Configuration B Intermediate position of equal shank spacing**	**Configuration C Shanks touching borehole edge**
			
β_0	20.10	17.44	21.91
β_1	-0.9447	-0.6052	-0.3796

The most rigorous method of determining R_c is to assume that each pipe is a line heat source or a multipole (a complex number derivative of a line source) and then use superposition to determine exactly the heat flux related to each pipe and hence the overall resistance. The multipole method (Bennet et al, 1987) is very powerful and a review by Lamarche et al (2010) showed that it provided the best match to numerical simulations of heat transfer within borehole heat exchangers. However, precise internal geometry information is required to make such calculations and the mathematical approach is complex. Relatively simple expressions can be derived for two pipe systems (Hellstrom, 1991). These are included in Appendix A, but they will not be suitable for most pile heat exchangers which contain more than one pair of pipes.

5.3.2. Factors Affecting Thermal Resistance of the Concrete

If the temperature around the pile circumference is constant, it is apparent from Equations 5–6 to 5–8 that the two factors controlling R_c are the concrete thermal conductivity, λ_c and the concrete geometry, ie the size and arrangement of the pipes relative to the pile cross section. The constituents of concrete have widely differing thermal conductivities (Table 5-3), and overall thermal conductivity depends mainly on the aggregate lithology, aggregate volume ratio and water content (Tatro, 2006). Concrete piles installed in clay soils or in any geological conditions below the water table are likely to be saturated. Neville (1995) reports typical values of saturated concrete thermal conductivity between 1.4 W/mK and 3.6 W/mK. However, the more conductive concrete mixes will be those with a high volume ratio of aggregates. Since foundation concrete is of high strength it will have a smaller proportion of aggregates and hence be at the lower end of this thermal conductivity range. Piles installed in dry sands may have a lower thermal conductivity owing to the reduced water content. The use of cement replacement products can also lead to a reduction in thermal conductivity by up to 20% (Kim et al, 2003).

Table 5-3 Typical Thermal Conductivities of Materials

Material	Typical Thermal Conductivity (W/mK)
Neat cement paste	1.2
Saturated concrete	1.4 – 3.6
Air	0.024
Water	0.6
Sandstone	3 – 3.5
Limestone	2.5
Clay	1.0 – 1.5

If, however, the temperature of the concrete at the edge of the heat exchanger varies around the circumference, as is the case in most real scenarios, the thermal resistance will also be affected by the thermal conductivity of the surrounding ground (as reflected in Equations A1 and A2). This is because the heat flow paths are altered by the non-uniform temperature around the circumference. The thermal conductivities of soils and rocks fall within a similar range to concrete with typical values between 1 W/mK for dry clay soils up to about 3.5 W/mK for saturated quartz rich formations such as sandstones (Banks, 2008; Cote & Konrad, 2005). As with concrete, replacement of air within the pore-spaces by water will increase the thermal conductivity.

The geometric arrangement of the heat exchanger pipes is usually well known, if they are fixed to the pile steel reinforcement cage and controlled within standard construction tolerances. As pile reinforcement must be protected from corrosion there tends to be a greater concrete cover to the pipes than with borehole heat exchangers. This can lead to a greater resistance. On the other hand, the likely increased number of pipes within the cross section would tend to reduce the resistance. However, if the pipes are too closely spaced thermal interactions can occur, reducing the efficiency of heat transfer and hence increasing the thermal resistance (Chapter 4). This tends to be exacerbated at low fluid flow rates.

5.4. Pile Only Model

To investigate the effects of the number and arrangement of pipes on the thermal resistance of pile heat exchangers, two-dimensional heat transfer models have been set up using the finite element software COMSOL (version 4.1, COMSOL, 2010). The programme solves the diffusion equation for a given pile geometry and boundary conditions. Figure 5–1a shows a schematic layout for the steady state model with pipes installed with a concrete cover, c, from the edge of the pile. The pipes are equally spaced around the pile circumference, and the distance between pipe centres measured across the pile is the shank spacing, s. Constant temperatures T_b and T_p are applied at the pile edge and the pipe surface boundaries respectively.

The model domain is restricted to the pile concrete (assumed to be homogeneous); the pipe material and fluid are not modelled. This means that the model can only determine the concrete resistance R_c and that the pipe resistances R_{pcond} and R_{pconv} are neglected. These are both straightforward to calculate and providing flow is turbulent are typically lower in value than R_c and hence less significant. The concrete domain was meshed using triangular elements of a maximum size of 2mm at the pipe boundary and 10mm at the pile edge. Steady state analyses were carried out using a stationary PARDISO solver assuming constant temperatures at pipe and pile circumference.

When the pile alone is included within the model domain and the boundary temperatures are constant, the thermal resistance will depend only on the geometry and the thermal conductivity. It will not be influenced by the temperatures imposed or the magnitude of the heat fluxes resulting from the temperature differences. To separate the geometry and thermal conductivity components of the resistance, the results of the model analyses are presented in terms of a shape factor, S_c, where:

$$R = \frac{1}{\lambda_c S_c}$$

Equation 5-9

The shape factor was determined as:

$$S_c = \frac{\sum_{i=1}^{i=n} q_{p(i)}}{\lambda_c \left(T_b - T_p\right)}$$

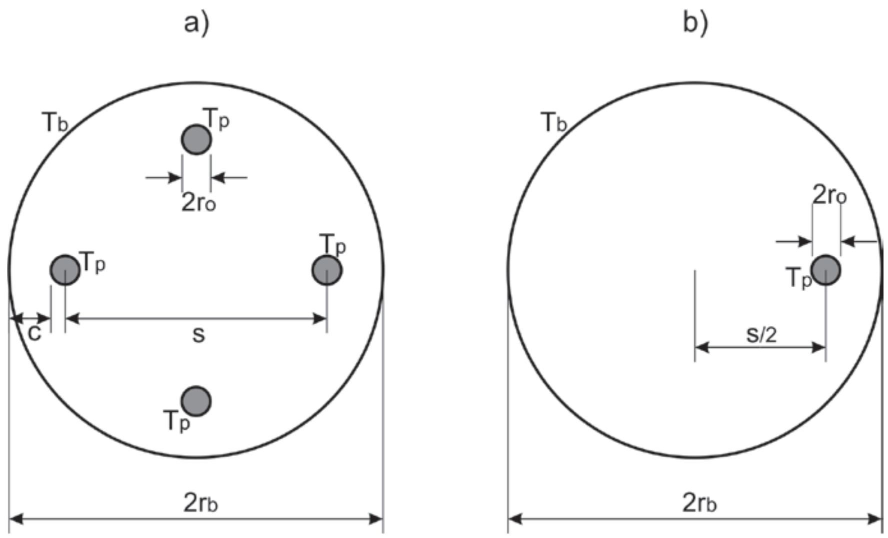
Equation 5-10

where $q_{p(i)}$ is the calculated heat flux along a single pipe circumference and there are n pipes in the model. The model and mesh resolution were validated by considering a 600mm diameter pile heat exchanger with only one pipe installed (Figure 5–1b). The results for this case were checked against Equation 5–11, the analytical solution for an eccentric cylinder (Incropera et al, 2007). The mesh was refined until the difference between Equations 10 and Equation 11 was less than 0.2%.

$$S_c = \frac{2\pi}{\cosh^{-1}\left(\frac{4r_b^{\ 2} + 4r_{ro}^{\ 2} - s^2}{8 r_b r_{ro}}\right)}$$

Equation 5-11

Figure 5—1 Schematic of 2D heat transfer model
a) generalised pile geometry; b) eccentric cylinder validation geometry



During each analysis the heat flux across the pile circumference (q_b) was also checked against the heat flux for the pipe surfaces:

$$q_b = \sum_{i=1}^{i=n} q_{p(i)}$$

Equation 5-12

The error was consistently less than 0.3% in all analyses.

Some additional error is introduced into the analysis by the simplified boundary conditions used within the model. The movement of the heat transfer fluid through the pipes will result in a spatially non uniform heat flux around the pipe wall circumference. However, sensitivity analyses suggest that this variation in the heat flux leads to only a small spatial variation in the pipe wall temperature. Moreover the difference in the values of shape factor and thermal resistance resulting from these temperature variations is of the same order of magnitude as the errors resulting from the numerical discretisation. Consequently this simplification is considered of negligible significance compared with the overall result. The consequence of assuming a constant temperature around the pile circumference is of greater impact and this is investigated in Section 5.5.

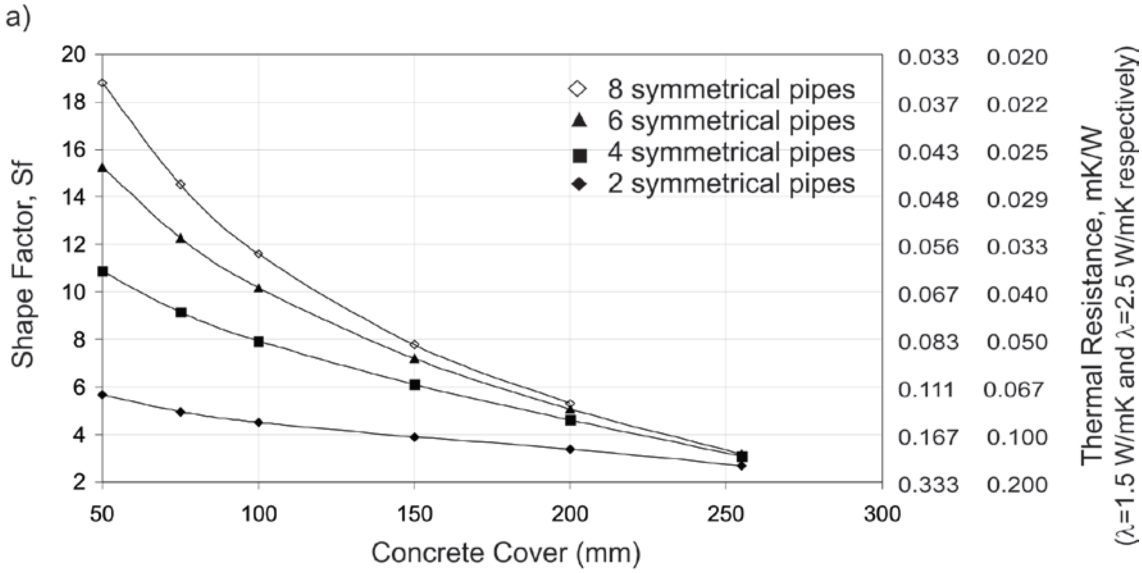
5.4.1. Results

The model was used to calculate the shape factors for a number of different pile and pipe geometries. The full range of results is tabulated in Appendix B and selected results are shown in Figure 5–2 to illustrate important trends. The range of theoretical shape factor values is wide; from 2 to 20. This gives equivalent resistance values from ~0.02 mK/W to ~0.3 mK/W, depending on the thermal conductivity of the concrete. The results of the analyses are discussed in more detail below. Except where specifically indicated in the text, the pipes were always arranged symmetrically, corresponding to their having been fixed to the pile steel reinforcement in a controlled manner.

5.4.1.1 Effect of Number of Pipes and Concrete Cover

Figure 5–2a shows the shape factors and thermal resistances calculated for a typical 600mm diameter heat exchanger pile with 25mm diameter pipes installed. It can be seen that the number of pipes installed and their concrete cover, c, have a large influence. The shape factor increases (and the resistance reduces) with the number of pipes and as the cover is reduced. The range of values of shape factor is greatest when the cover is small. This range is significantly reduced where the cover is greatest.

Figure 5—2 Results of steady state model for 600mm diameter pile with 25mm OD pipes a) effect of number of pipes and concrete cover; b) effect of pipe positioning for CFA piles (c=255mm)



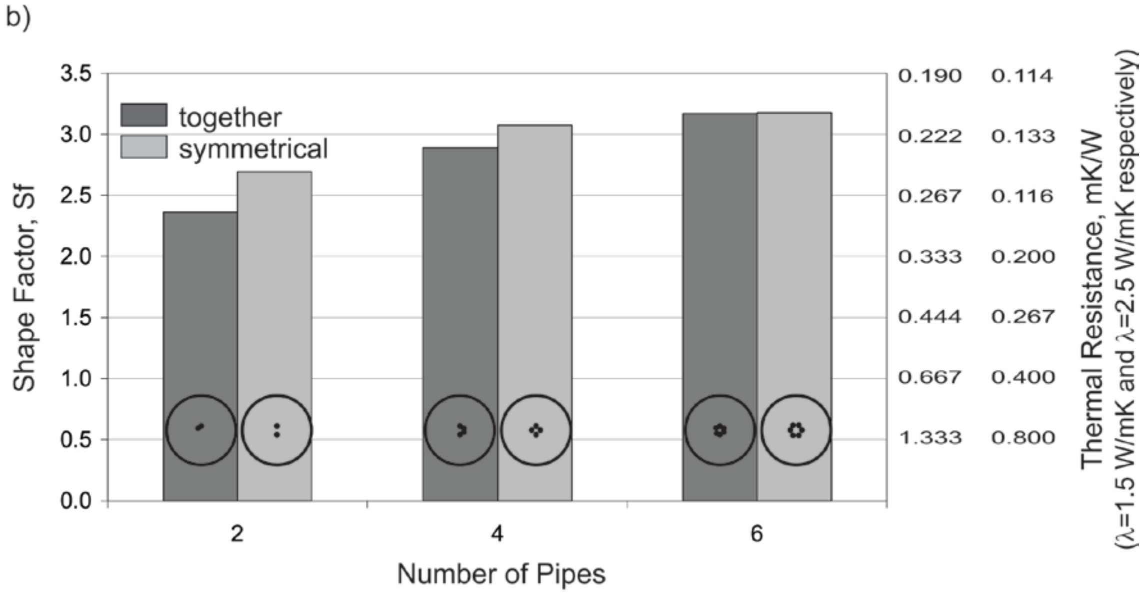


Figure 5–2b shows the shape factors for a 600mm CFA pile where the pipes are attached to a 40mm steel bar for installation, giving a concrete cover of 255mm. As it is difficult to control whether the pipes are evenly spaced in a CFA pile, the effect of all the pipes being bunched together was investigated. The results show a small reduction in the shape factor when the pipes are not symmetrical, but this is minor compared with the other factors discussed above. Thus the importance of the number and arrangement of pipes is less for CFA or other piles with substantial concrete cover to the pipes.

5.4.1.2 Effect of Pipe and Pile Size

A parametric study was carried out for three pile diameters ($2r_b$=300 mm, 600 mm and 1200 mm) and three pipe sizes ($2r_o$=20 mm, 25 mm and 30 mm) for a range of concrete cover depths c. The results are tabulated non-dimensionally in Appendix B in terms of the ratios r_b/c and r_b/r_o. Larger values of r_b/c and smaller values of r_b/r_o give the largest shape factors and hence the smallest resistances. Thus smaller pile diameters typically give larger shape factors. However, larger piles can also be associated with large values of shape factor when the ratio r_b/c is high. Again for a larger cover (small r_b/c) the outcome is less sensitive to both the pipe size and the number of pipes installed.

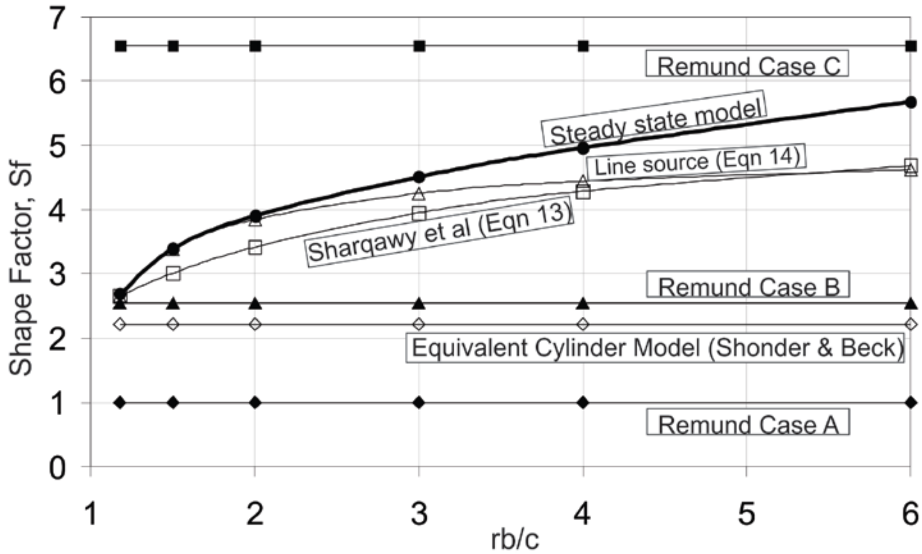
5.4.1.3 Comparison with Analytical and Empirical Solutions

For the special case of only two pipes installed the calculated shape factor values may be compared with analytical and empirical methods developed for borehole heat exchangers. Figure 5–3 compares the results for a 600mm diameter pile with $2r_o$=25mm to the three methods described in Section 5.3 and also the empirical Equation 5–13 derived by Sharqawy et al (2009) based on numerical modelling of borehole heat exchangers. Sharqawy et al (2009)'s 2D steady state model is similar to that presented in this paper, but for different geometries.

$$R_c = \frac{1}{2\pi\lambda_c}\left[-1.49\left(\frac{s}{2r_b}\right) + 0.656\ln\left(\frac{r_b}{r_o}\right) + 0.436\right]$$

Equation 5-13

Figure 5—3 Comparison of 2 pipe steady state model with analytical solutions (for the case of a 600mm diameter pile with 25mm diameter pipes)



It can be seen from Figure 5–3 that the simple equivalent cylinder approach (Equation 5–6) always underestimates the shape factor (overestimates the resistance), with the difference being greatest when the cover is smaller. Of the three scenarios proposed by Remund (1999), Case B gives a similar result to that for a pile with a large concrete cover. The empirical equation of Sharqawy et al (2009) provides a better approximation to the shape factor as it takes into account changes in cover through the shank spacing term, s, in Equation 5–13. The closest match is provided by the line source equation (Equation 5–14, Hellstrom, 1991). For the special case where the ground and concrete have the same thermal conductivity then the line source and first order multipole equations reduce to the same simple expression:

$$R_c = \frac{1}{4\pi\lambda_c}\left[\ln\left(\frac{r_b}{r_o}\right) + \ln\left(\frac{r_b}{s}\right)\right]$$

Equation 5-14

The key difference between Equation 5–13 and Equation 5–14 is that the shank spacing to pile radius ratio appears non-linearly in Equation 5–14. Equation 5–14 provides a much better fit to the modelled pile heat exchanger data, especially for large values of concrete cover ($r_b/c \leq 3$). However, there are still discrepancies of up to 18% at smaller values of concrete cover. This is because the numerical model imposes a uniform temperature around the pile circumference, whereas the line source equation does not include this restriction (Hellstrom, 1991). For $r_b/c < 2$ the nature of the circumferential temperature distribution appears not to be significant, but errors in the steady state model increase as the pipes get closer to the edge of the pile. To improve accuracy in this respect, transient analysis including the ground surrounding the pile is required; this is discussed in Section 5.5.

5.5. Extended Pile and Ground Model

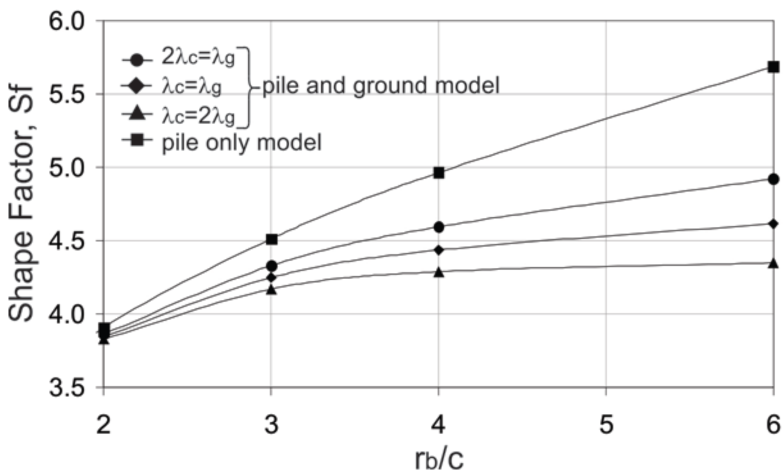
In most cases the temperature around the circumference of the pile will vary spatially as opposed to being constant as assumed in the pile only model described in Section 5.4 (Figure 5–1). To investigate the importance of this, a two dimensional transient heat transfer model was created. The model domain is now extended to include the ground surrounding the pile out to a radial distance of 25m. This is sufficient for the influence of the boundary on the heat transfer around and within the pile to be negligible. Constant temperatures were imposed at the pipe boundaries as before and also at the new outer far field boundary. The mesh was generated on the same basis as the pile only model, except that the element size expands from the pile edge towards the farfield boundary. The analyses were carried out using a time dependent backward differentiation formula (BDF) solver.

The temperature at the pile circumference, for use in calculating R_c and the shape factor, was determined from the results of transient analysis. An integral mean value of temperature was used to allow for the fact that the temperature is now no longer uniform around the pile circumference. As both the heat flux from the pipes and the pile circumferential temperature also change with time, the shape factor was calculated dynamically as a function of time using Equation 5–10 and the analysis continued until an asymptotic value of the steady state shape factor was approached. For the purpose of the analysis, the asymptotic value was chosen as the calculated shape factor when this value did not change by more than 10^{-4} over a time period of one day.

5.5.1. Results

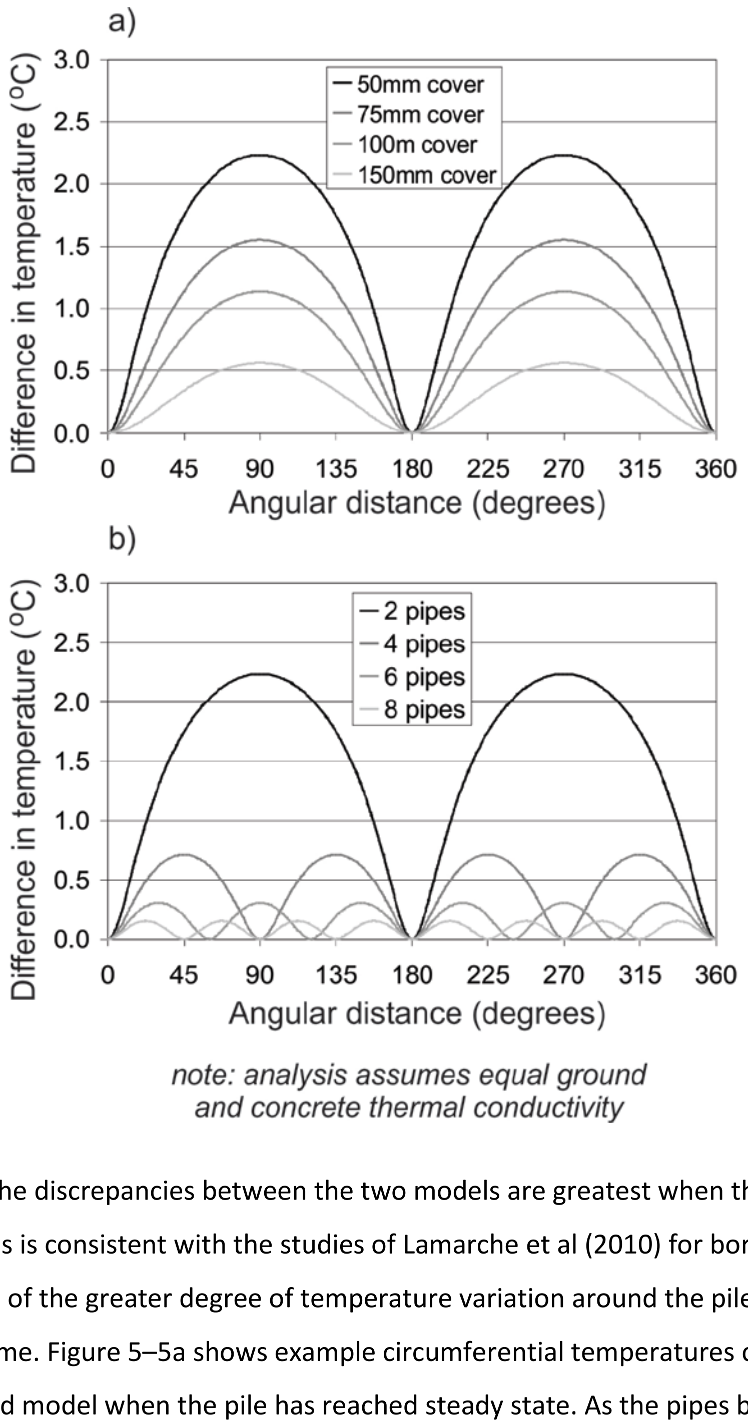
Full results from the analysis are presented as dimensionless look up tables in Appendix B. For a 600mm diameter pile with two pipes of diameter $2r_o$=25mm, Figure 5–4 compares the pile only shape factor derived in Section 5.4.1 with the results for the extended pile and ground model. In this case the simpler model overestimates the shape factor by as much as 10% to 25% when the concrete cover is small. The error reduces as the cover increases and as suggested in Section 5.4.1.3; the effect becomes insignificant for $r_b/c \leq 2$.

Figure 5—4 Results of transient model for 600mm diameter pile with two 25mm OD pipes



The shape factor results depend on the ratio of the ground and concrete thermal conductivities as well as the concrete cover depth (Figure 5–4). As an asymptotic steady state shape factor is being calculated, the thermal diffusivity does not effect the outcome, only the time taken for the model to reach a steady state (see also Section 5.5.4). Variations in thermal conductivity by up to a factor of two have been investigated; this can change the shape factor by ± ~5% compared with the case where the thermal conductivities of the ground and concrete are equal. Shape factors are larger and hence resistances smaller where the ground conductivity is greater than that of the concrete.

Figure 5—5 Temperature changes around the pile circumference for a 600mm diameter pile with 25mm OD pipes
a) with two pipes showing the effect of concrete cover; b) with 50mm concrete cover showing the effect of the number of pipes

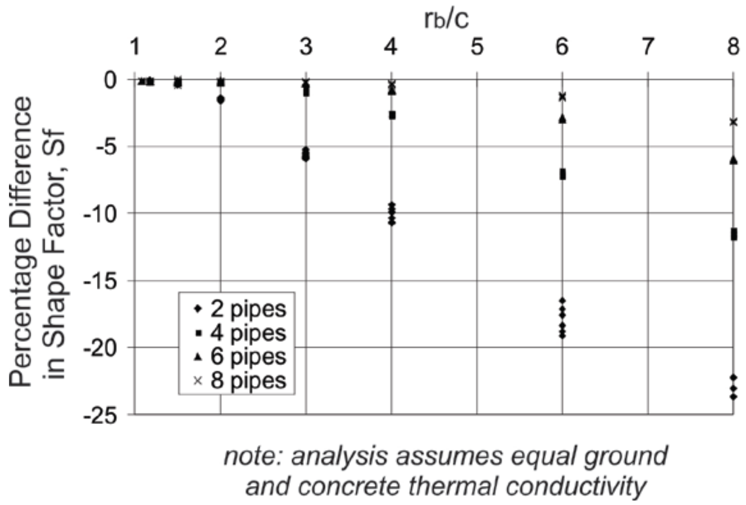


As indicated, the discrepancies between the two models are greatest when the concrete cover is smallest. This is consistent with the studies of Lamarche et al (2010) for boreholes, and arises because of the greater degree of temperature variation around the pile circumference at any given time. Figure 5–5a shows example circumferential temperatures changes from the pile and ground model when the pile has reached steady state. As the pipes become closer to the centre of the pile, the temperature of the circumference approaches a constant value.

Similarly, as shown in Figure 5–5b, if more pipes are installed there will be less variation in the temperature at the circumference.

Both points are also illustrated in Figure 5–6, which shows the percentage difference in shape factor calculated using the two models for the case where the concrete and ground have the same thermal conductivity. The difference between the ground only and the pile and ground model appears to be controlled mainly by the number of pipes and the pile radius to cover ratio r_b/c. Any influence of the pile to pipe radius ratio r_b/r_o appears much less significant. This is in contrast to borehole heat exchangers, for which r_b/r_o appears to be a more important parameter (Lamarche et al, 2010). This is likely to be because of the different ranges of this parameter; $r_b/r_o \geq 10$ for piles, but is as low as 3 for boreholes.

Figure 5—6 Difference in shape factor values between the steady state and transient models



5.5.2. A New Expression for Thermal Resistance of Pile Heat Exchangers

The results given in Appendix B may be represented by an equation of the form:

$$S_{c(steady)} = \frac{A}{B\ln\left(\frac{r_b}{r_o}\right) + C\ln\left(\frac{r_b}{c}\right) + \left(\frac{r_b}{r_o}\right)^D + \left(\frac{r_b}{c}\right)^E + F}$$ **Equation 5-15**

where A, B, C, D, E and F are constants whose values depend on the number of pipes and the conductivity ratio, as shown in Table 5-4. The coefficient of determination was >0.99 in all cases, but the residuals were found to vary, with the largest values being associated with the case of 8 pipes installed in the pile cross section. Figure 5–7 quantifies the resulting error in concrete resistance calculated using Equation 5–9 and Equation 5–15 compared with the numerical model. A range of realistic values of thermal resistance based on the results of this study are used to bound the output. It can be seen that the errors are typically of the order of a few percent, but are larger when the resistance is greater and where there are more pipes installed. However, in reality, a situation with 8 pipes in the cross section and a resistance >0.2 mK/W is unlikely to occur. Therefore, the errors in determining R_c using Equation 5–15 are likely to be less than 5% compared with the numerical model. Limitations to this approach which may result in other sources of error are discussed in Section 5.5.5.

Figure 5—7 Errors in determining R_c when using the shape factor equation (Equation 5–15) compared with the numerical simulation
a) 2 pipes; b) 4 pipes; c) 6 pipes; d) 8 pipes.

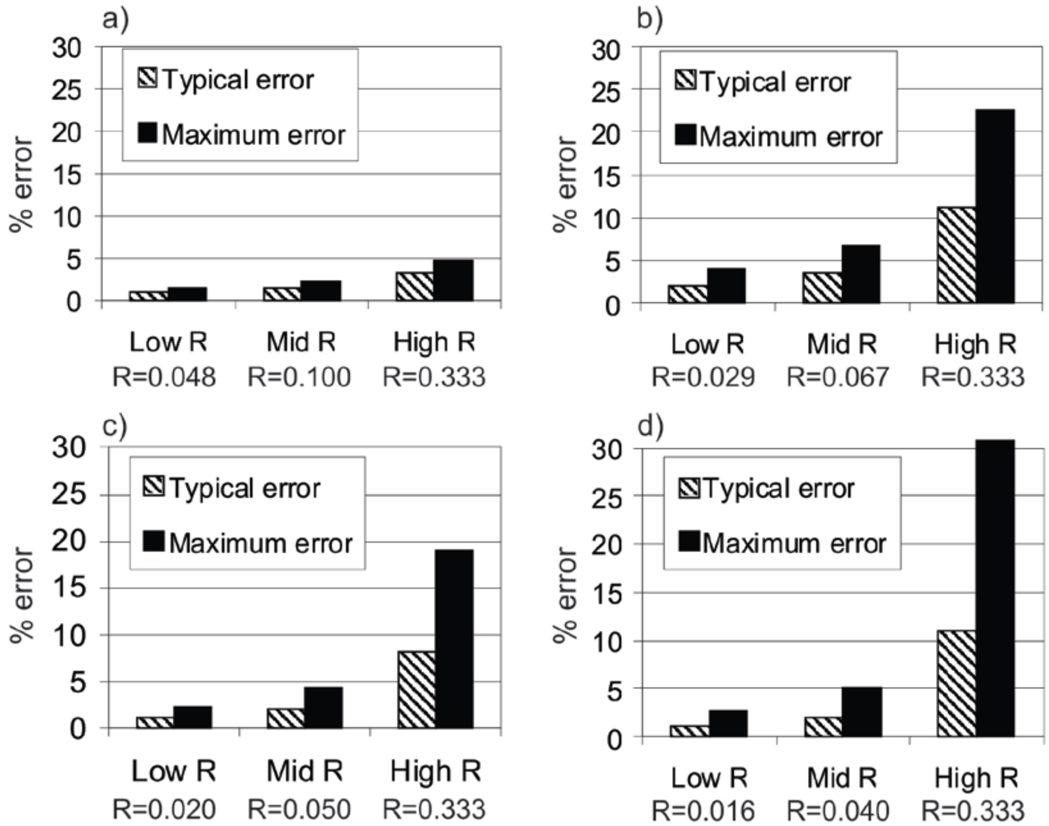


Table 5-4 Curve fitting results for the pile and ground model (Equation 5–15)

	2 pipes			4 pipes			6 pipes			8 pipes		
	$\lambda_c=\lambda_g$	$\lambda_c=2\lambda_g$	$2\lambda_c=\lambda_g$	$\lambda_c=\lambda_g$	$\lambda_c=2\lambda_g$	$2\lambda_c=\lambda_g$	$\lambda_c=\lambda_g$	$\lambda_c=2\lambda_g$	$2\lambda_c=\lambda_g$	$\lambda_c=\lambda_g$	$\lambda_c=2\lambda_g$	$2\lambda_c=\lambda_g$
A	4.919	4.34	4.853	3.33	3.284	3.369	3.171	3.162	3.18	3.203	3.201	3.208
B	0.3549	0.317	0.345	0.1073	0.1051	0.1091	0.08526	0.08669	0.08386	0.0609	0.06157	0.05989
C	-0.07127	-0.001228	-0.1676	-0.07727	-0.05823	-0.09659	-0.07458	-0.06736	-0.08085	-0.06795	-0.06399	-0.06839
D	-11.41	-10.18	-16.76	-10.9	-11.98	-11.79	-1.28	-1.256	-1.304	-1.391	-1.378	-1.394
E	-2.88	-2.953	-3.611	-2.9	-2.782	-3.032	-2.743	-2.686	-2.791	-2.503	-2.466	-2.499
F	0.06819	-0.002101	0.1938	0.1278	0.1027	0.1535	0.05347	0.03534	0.06954	0.07836	0.06846	0.08188
R^2	0.9985	0.9975	0.9987	0.9976	0.9971	0.9975	0.9991	0.9990	0.9992	0.9993	0.9993	0.9992
RMSE	0.033	0.044	0.035	0.120	0.130	0.126	0.117	0.123	0.113	0.132	0.137	
Typical value of residuals	<0.04	<0.06	<0.04	<0.15	<0.2	<0.2	<0.15	<0.15	<0.15	<0.15	<0.2	<0.2
Maximum value of residuals	0.06	0.09	0.08	0.22	0.27	0.37	0.31	0.32	0.30	0.42	0.43	0.48

5.5.3. Comparison with line source and multipole equations

For the special case of two pipes, the results in Figure 5–4 have been compared with the line source and multipole equations given in Appendix A. The transient model shows less than 0.5% variation from the line source equation, which itself results in values within 0.1% of the first order multipole equation. Consequently, for energy piles with two pipes it is recommended that the line source equation is used to determine R_c. The additional accuracy gained from the more complex multipole equation does not appear to be justified.

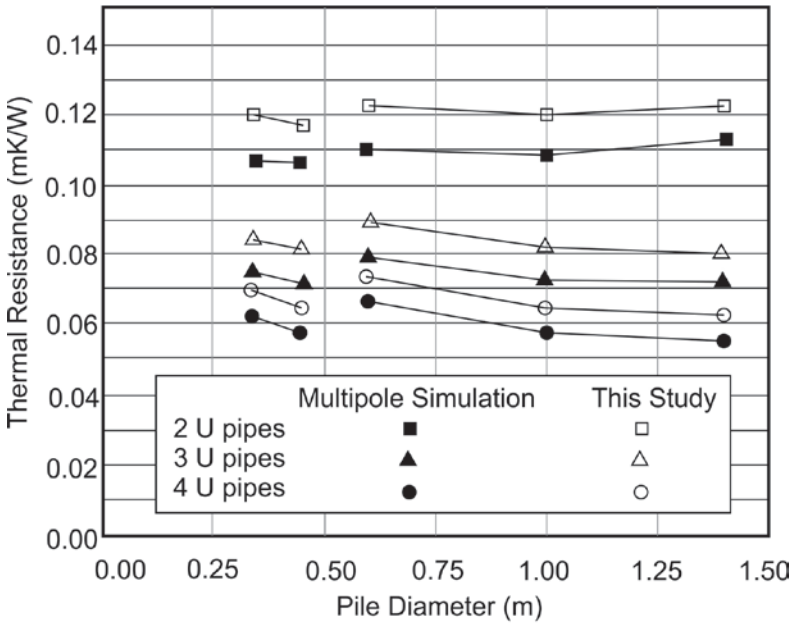
For piles with more than one pair of pipes installed, Equation 5–15 has been compared with values of the total pile thermal resistance calculated using the multipole method and published by the Swiss Society of Engineers and Architects (Anstett et al, 2005). To make the results directly comparable R_{pconv} and R_{pcond} were added to the value of R_c determined using Equation 5–15. As the Swiss simulations assumed laminar flow a constant value of 3.66 was assumed for the Nusselt number (Hellstrom, 1991) used for calculating the heat transfer coefficient between the fluid and the pipe. Pipe conductivity was taken as 0.4 W/mK in keeping with Anstett et al (2005) and the fluid conductivity was assumed to be 0.6 W/mK.

Figure 5–8 shows the results of the multipole simulations assuming a concrete thermal conductivity of 1.8W/mK. Superimposed on this are total resistance values calculated using Equations 5–2, 5–3, 5–4, 5–5 and 5–15, with the input parameters described above. This results in slightly larger values of resistance than calculated by the multipole method, by up to about 0.01mK/W or 10%. There are two potential sources for this discrepancy. Some errors may result from the curve fitting used to derive Equation 5–15. In addition it has been necessary to make an assumption regarding the thermal conductivity of the fluid which was not specified in Anstett et al (2005). Nonetheless the trends are well matched and the use of Equation 5–15 is considered a useful and simpler alternative to a full multipole simulation.

5.5.4. Time to Achieve Steady State

As design methods for pile heat exchangers (eg Pahud, 2007) usually assume that the pile is at steady state, the time to achieve this has been determined from the analysis. For practical purposes the definition of steady state could be less rigorous than the criterion adopted for the asymptotic value of the shape factor presented in Section 5.5.1 and Appendix B. Therefore the time to achieve steady state has been assessed as when 98% of the asymptotic value of R_c has been reached.

Figure 5—8 Comparison of Transient Model Results for Pile Thermal Resistance with Multipole Simulations (Anstett et al, 2005)



Case assessed: concrete thermal conductivity 1.8 W/mK and laminar flow in fluid. For piles less than 0.5m diameter ri=8mm, ro=10mm and c=50mm. For piles greater than 0.5m diameter ri=13mm, ro=16mm and c=100mm (Anstett et al, 2005).

Figure 5–9 shows the range of times taken for the piles to reach steady state assuming a thermal diffusivity of the ground and concrete of $1.25x10^{-6}$ m^2/s. This is at the high end of the range of concrete diffusivity values quoted by Neville (1995) and Tatro (2006) and therefore longer timescales than those indicated below would be required with concrete of a lower thermal diffusivity (see also Figure 5–10). Generally the most important factor is the size of the pile, with 1200mm diameter piles taking up to 4 days to reach a steady state compared with 300mm piles which take less than half a day (Figure 5–9). The larger diameter piles also have a greater range of times, with piles with smaller concrete cover taking less time to reach steady state compared with piles with centrally placed pipes.

Figure 5–10 shows the effect of thermal diffusivity on the time taken to reach steady state for a 1200mm diameter pile with 8 pipes installed with 75mm concrete cover. This shows that both the ground and concrete diffusivity affect the results with the effect of the concrete being the more significant. When the thermal diffusivity of both these materials is reduced from $1.25x10^{-6}$ m^2/s to $0.625x10^{-6}$ m^2/s, the time to achieve steady state increases from just under three days to approximately 5 days.

Figure 5—9 Range of Times for Pile Heat Exchangers to Reach Steady State (α=1.25x10^{-6} m^2/s)

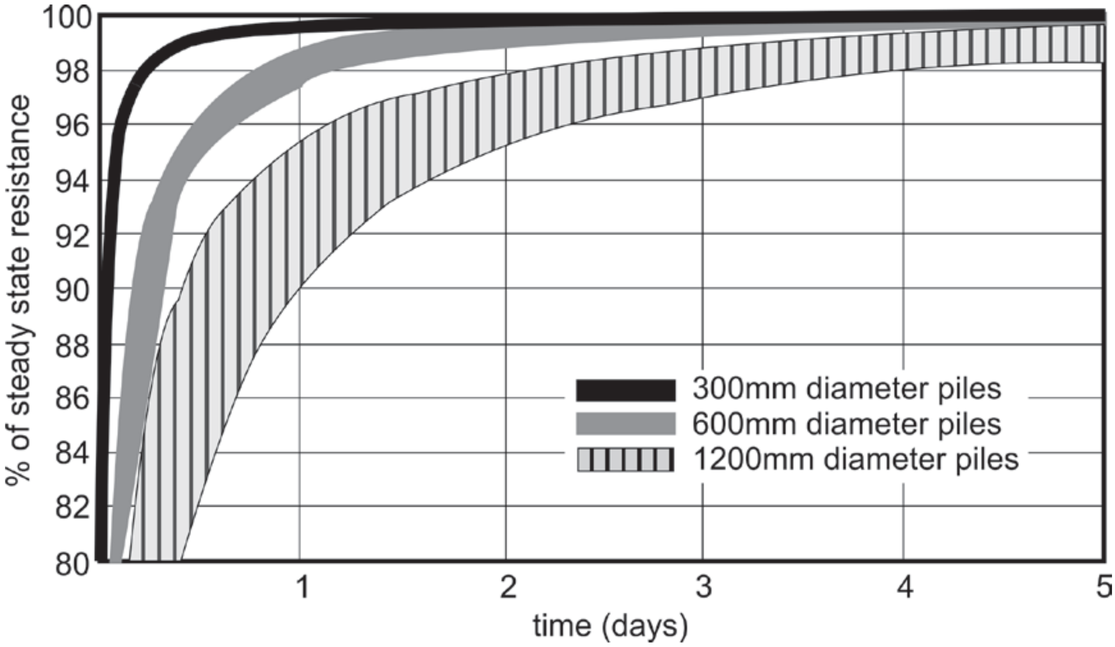
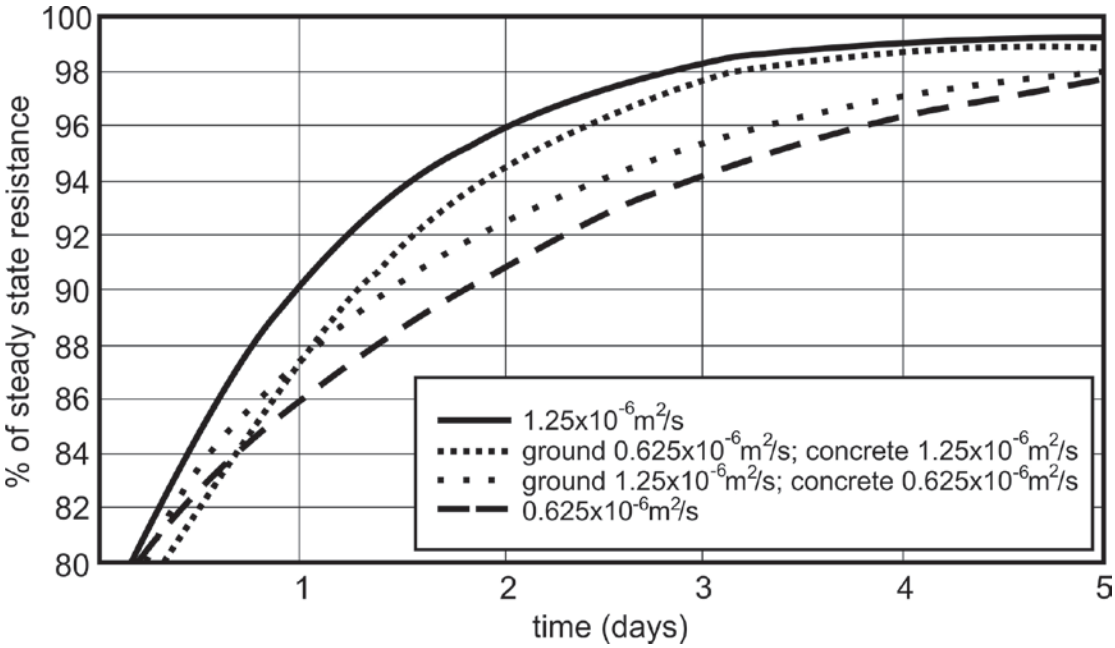


Figure 5—10 Effect of thermal diffusivity on time taken to achieve steady state (1200mm diameter pile, 8 pipes, 75mm concrete cover)



These results are significant as most design software uses hourly heating and cooling load timesteps. Significant changes to the heating and cooling load profiles can occur over a single day as the energy demand can differ markedly between day and night. Use of a steady state pile resistance in these cases, rather than a combined transient model of the pile and the ground, could lead to the overestimation of the temperature changes of the heat exchange fluid, especially for larger diameter piles with a highly variable thermal load. The results also suggest that the piles themselves are playing an important role in storing energy rather than just transferring it to the ground.

5.5.5. Model Limitations

The pile and ground model overcomes important shortcomings associated with the simpler pile only model, but still cannot take into account a number of other factors that affect real heat exchangers. Most importantly, the two dimensional model cannot take into account three dimensional effects. These include the ability of the pipes to exchange heat with each other, rather than just transfer it to the ground. This will affect the heat flow path and as a consequence the thermal resistance. The magnitude of the effect depends not only on the flow conditions within the pipes (Chapter 4) but also the spacing between them. In most cases pile heat exchangers will be less susceptible to interference between the pipes than borehole heat exchangers owing to the greater separation between the pipes (typically 250 mm to 300 mm). However, there is an increasing trend for pipes to be installed together in the centre of piles and this would lead to the potential for increased interactions between the pipes. In such cases the method of calculating thermal resistance presented in this paper should be treated with caution on two counts. First any interactions will reduce the accuracy of the method and secondly, centrally placed pipes are usually associated with larger resistance for which the errors associated with Equation 5–15 will also be greater.

Two dimensional models also assume that the pile cross section extends to infinity into and out of the plane of the model. In reality, the pile will be affected by the surface boundary condition at the top of the pile, and by the underlying ground at the base of the pile. This has a significant impact on the thermal behaviour of the ground in the long term, but it is not known how important the effect is within the pile in the shorter term. To capture these behaviours, a truly three dimensional model would be needed.

5.6. Comparison with Case Study Data

The results from three published case studies where the thermal resistances of pile heat exchangers were determined in situ from thermal response testing and/or system back analysis are sumarrised in Table 5-5. As thermal response testing determines only the total resistance, R_b, it has been necessary to calculate the pipe resistance R_p (according to Equations 5–2 to 5–5) and subtract this from the total resistance in order to facilitate comparison.

The range of concrete resistance values estimated from the simulatioms described in this paper is wide, with values from 0.02 mK/W 0.3 mK/W being feasible depending on the thermal conductivity of the concrete. This is a a significantly greater range than the *in situ* derived data for concrete resistance given in Table 5-5. In addition, the *in situ* results are skewed to the higher end of the theoretical resistance range, typically being greater than 0.1, even for small diameter piles. There are three possible explanations for this. First, as has already been suggested, concrete used in piling is typically at the lower end of the thermal conductivity range. Secondly, these two dimensional models do not take into account the 3D effects related to flow within the pipes and potential thermal interactions between the pipes. Finally, the available *in situ* testing dataset is very small. Thus the comparison illustrates that a much greater range of case studies is required in order to build a reliable empirical knowledge base. Also, the level of detail associated with such case studies needs to be increased to allow proper evaluation of design approaches.

5.7. Conclusions

Numerical models presented in this study have demonstrated a wide range of possible values for the thermal resistance of reinforced concrete pile heat exchangers, with the key controlling factors being the thermal conductivity of the concrete, the number of heat exchange pipes and the amount of concrete cover to those pipes. Whether the pipes are arranged symmetrically or not can also affect the resistance, but to a lesser degree. Generally, the pile resistance will be less in cases where there are more pipes installed with less concrete cover. Larger piles tend to have a larger thermal resistance unless they have a large number of pipes installed. Where the concrete cover is particularly large, for example with CFA piles, the number and arrangement of pipes has less influence on the resistance.

Table 5-5 In situ measurements of pile thermal resistance

Pile Type	Pile Diameter	No Pipes	Pipe Diameter	In Situ Total Thermal Resistance (Rb)[1]	In Situ Concrete Resistance (Rc)[2]	Source
continuous flight auger (CFA)	0.3 m	Single U-tube	r_o=32mm	0.22 mK/W[2]	0.11	Wood et al (2010a)[3]
bored cast in situ	0.6 m	Single U-tube	r_i=20mm	0.25 mK/W	0.19	Gao et al (2008b)
		Double U-tube in series		0.175 mK/W	0.15	
		Triple U-tube in series		0.15 mK/W	0.13	
square concrete driven	0.27 m	Single U-tube	r_o=32mm	0.17 mK/W	In sufficient data to calculate	Lennon et al (2009)
steel tubular driven; grouted inside	0.244 m	Single U-tube	r_o=32mm	0.11 mK/W	In sufficient data to calculate	

1. Total thermal resistance as published by the source document.
2. Concerete resistance calculated subtracting the pipe resistance (Equations 2 to 5) from the value in the previous column. Pipe numbers and sizes as per source document; turbulent flow assumed in all cases except Wood et al (2010) where flow was known to be laminar (Wood, C., 2011, Pers Comm.).
3. In situ testing was supplemented by back analysis of system behaviour.

Many simple methods for estimating thermal resistance assume that while the surface temperature of a vertical heat exchanger may vary with time, the circumferential temperature is uniform at any given time. Numerical modelling of pile heat exchangers has shown that in most cases this is unlikely to be the case, especially when the heat exchange pipes are close to the edge of the pile and relatively widely spaced.

For the special case of pile heat exchangers with only one pair of pipes installed, the validity of existing analytical approaches for determining resistance of borehole heat exchangers has been tested. It was found that the line source equation provides an appropriate solution with a high degree of accuracy. This is because the approach accounts fully for the arrangement of the pipes as well as allowing for a spatially variable circumferential temperature. The results of the numerical models have been used to derive an empirical equation for the shape factor which allows the thermal resistance to be determined where more than two pipes are installed.

Modelling demonstrates that it may take several days for larger diameter (1.2m) pile heat exchangers to reach steady state. This means that existing design approaches which assume a steady state resistance are neglecting important thermal storage within the pile concrete. This will result in an overestimation of the temperature changes in the system. While this is conservative in terms of design, it misses opportunities to improve the efficiency of pile heat exchanger systems. Transient design methods which take account of the heat stored within the concrete would be more appropriate in these cases. Development of such tools should be regarded as key aims for the research community. However, until this goal has been reached the approach described in this paper may serve as an improved method for determining the thermal resistance of piles.

The large range of thermal resistance values obtained from this study also highlights the urgent need for detailed and thorough case studies of pile heat exchanger behaviour. This will help to validate fully the models presented and also build an empirical knowledge base to provide confidence in design methods and parameter selection.

Chapter 6. Thermal Response Testing for Pile Heat Exchangers

This chapter has been submitted as a stand alone paper to the Journal of Geotechnical and Geoenvironmental Engineering and is currently under review for publication.

6.1. Abstract

Developers seeking to minimise the energy use of new buildings are increasingly adopting piled foundations as heat exchangers as part of ground energy systems. To ensure the energy available from the ground is maximised, it is common to carry out thermal response testing of these heat exchangers. However, the application of this testing technique to pile heat exchangers, which have much larger diameters than more traditional borehole heat exchangers is uncertain. This paper uses numerical modelling and case study data to assess the short term thermal behaviour of pile heat exchangers to evaluate the applicability of the standard thermal response test to piles. Different testing strategies are found to be appropriate for different types and sizes of piles. Recommendations for practice are made on this basis.

6.2. Introduction

Planning requirements for site developments increasingly mandate the consideration of renewable energy technologies. In parallel, governments are passing legislation to encourage the use of renewable heat (eg DECC, 2011a) in order to meet renewable energy and carbon dioxide emissions targets (eg Council Directive, 2009). Consequently there is an increase in the number of new buildings using ground energy systems, with Lund et al (2010) reporting an order of magnitude increase in the total energy obtained from heat pump systems since the turn of the century. Projections by the IEA and the IPCC suggest energy use from heat pump schemes will double again within the next decade (IEA, 2011).

Ground energy systems operate by exchange of heat with the ground to provide renewable heating and cooling energy for all or part of a development's thermal energy needs. Deep boreholes, with plastic pipes installed for the circulation of a heat transfer fluid, are the most common heat exchanger in large developments, with horizontal slinky type pipe installations being common for domestic dwellings. However, increasingly foundation piles are being used as heat exchangers and this brings new challenges (Brandl, 2006); both with respect to the dual use of the structural element and with respect to determination of energy output.

For larger ground energy systems using borehole heat exchangers it is common to carry out an *in situ* thermal response test to determine both the thermal conductivity of the ground and the thermal resistance of the borehole. These two parameters are key for the design of the heat exchanger system and will allow appropriate sizing of the borehole field to meet the energy demands of the building development.

With the growth in adoption of pile heat exchangers it is important to consider the application of thermal response testing techniques to this new technology. The thermal behaviour of piles is different from that of borehole heat exchangers in a number of important ways (Chapter 4). These differences relate principally to the geometry of the heat exchanger, with piles typically being shorter and larger in cross sectional area than boreholes. The latter facilitates inclusion of a greater number of heat transfer pipes within an individual heat exchanger cross section.

This paper assesses how the different geometry of piles (compared with conventional boreholes) affects the response of the heat exchanger when it is subject to a short duration thermal response test, with the aim of providing practical guidelines for test methods. The assessment is made on the basis of 2D numerical models of pile heat exchangers which have been used to generate synthetic thermal response test datasets. Interpretation of these datasets, when the actual solution is known, allows assessment of the accuracy and appropriateness of the test for pile heat exchangers. These results are then compared with data from real tests on three different types of piles. The paper then makes recommendations for approaches to thermal response testing in piles and identifies the range of pile sizes and types for which the standard test method is appropriate.

6.3. Procedure for thermal response testing

A heated fluid is circulated through the pipes of the heat exchanger system and the temperature of the fluid as it enters and leaves the ground is measured. The returning temperature is cooler than the fluid injection temperature due to heat transfer to the ground. By analysis of the rate of change of temperature with time and, with knowledge of the power input required to heat the fluid, an assessment of the ground thermal conductivity can be made. Interpretation is usually carried out assuming that the heat exchanger behaves as an infinite line heat source. Assuming a constant heat injection rate per unit depth, q (W/m), the temperature change in the ground, ΔT (°C), with time, t (s), can be characterised by the following analytical expression (Carslaw & Jaeger, 1959):

$$\Delta T_g = \frac{q}{4\pi\lambda}\int_{r^2/4\alpha t}^{\infty}\frac{e^{-u}}{u}du \cong \frac{q}{4\pi\lambda}\left(\ln\left(\frac{4\alpha t}{r^2}\right)-\gamma\right) \quad \textbf{Equation 6-1}$$

where λ and α are the ground thermal conductivity (W/mk) and diffusivity (m^2/s) respectively, r is the radial coordinate and γ is Euler's Constant. As the heat injection is not applied directly to the ground, but via the heat transfer fluid within the borehole, the heat transfer between the fluid and the ground at the edge of the borehole ($r=r_b$) must also be accounted for. This is usually done by assuming a constant thermal resistance for the borehole, so that the temperature change of the fluid is given by:

$$\Delta T_f = qR_b + \Delta T_g$$

$$\Delta T_f = qR_b + \frac{q}{4\pi\lambda}\left(\ln\left(\frac{4\alpha t}{r_b^2}\right)-\gamma\right) \quad \textbf{Equation 6-2}$$

The thermal resistance term, R_b, is a lumped term, which includes the effects of the fluid, the pipes and the concrete or grout within the borehole. In accordance with Equation 6–2 , the gradient of a graph describing the evolution of the fluid temperature change against the natural logarithm of time can be used to determine the thermal conductivity λ. It is also possible to determine the borehole thermal resistance R_b from the straight line intercept, providing an assumption is made regarding the value of volumetric heat capacity (S_{cv} in J/m^3K) used to derive the thermal diffusivity:

$$\alpha = \frac{\lambda}{S_{cv}} \quad \textbf{Equation 6-3}$$

Use of a constant resistance in Equation 6–2 means that the borehole is assumed to be at an instantaneous steady state. As this is not really the case, and it takes some hours for a steady state to be reached, then the first few hours of the test data are normally neglected. Therefore interpretation typically commences after a minimum time, t_{min}:

$$t_{\min} = 5r_b^2/\alpha \quad \textbf{Equation 6-4}$$

However, it is good practice to consider the sensitivity of the result to different start times for the analysis.

There are now three available international guidelines for the thermal reponse test, one published by ASHRAE (2002); one arising from a working group of the Implementing Agreement on Energy Conservation through Energy Storage of the International Energy Agency (IEA) (Sanner et al, 2005); and one published as part of a wider standard by the Ground Source Heat Pump Association in the UK (GHSPA, 2011). These guidelines provide advice on the test duration, fluid flow rate and temperature differences to be achieved, power levels and acceptable power fluctuations, and insulation requirements for the surface equipment. These operational factors are of critical importance in obtaining reliable test results.

6.3.1. Limitations and Accuracy

Thermal response tests provide reliable results for the ground conductivity and borehole thermal resistance when the underlying assumptions related to the interpretation method are consistent with the test conditions. This means that the length to diameter ratio of the borehole should be high so that its geometry approaches a line, the rate of heat transfer should be constant and the system should be isolated from external thermal influences.

A comprehensive parametric study using numerical modelling of simulated borehole thermal response tests was carried out by Signorelli et al (2007) to investigate some of these factors. Output from the model was used to manually back calculate values of ground thermal conductivity using Equation 6–2 and compare these with the actual thermal conductivity used in the model. Using different start times for the test interpretation makes the influence of the borehole obvious. For test interpretation commencing shortly after t_{min}, then the test had to run for at least 30 hours for the effects of the borehole to be reduced such that the predicted thermal conductivity was within ten percent of the actual value. By commencing the test interpretation later, closer results were obtained. Consequently, it appears that longer duration tests provide greater accuracy. However, small scale power variations were shown to have the greatest relative impact later in the test when the rate of change of temperature with time diminishes. This effect has also been observed in real datasets (Witte et al, 2002, Pahud, 2000) and suggests diminishing returns with respect to accuracy from extending tests beyond around 60 hours unless the power supply is very stable.

When Signorelli et al (2007) included variations in the undisturbed ground temperature due to the geothermal gradient in their numerical model, the length of the borehole was also shown to influence the result. This is because the imposed temperature field due to heating is now superimposed on an existing geothermal gradient. Consequently heat flow is no longer purely radial as it would be for a line heat source. Stratification of the ground also becomes important in these circumstances as the heat flux is no longer constant with depth. Although the thermal response test only calculates a single lumped value of thermal conductivity, it does not always provide a simple average of the different values for the various strata encountered by the heat exchanger.

Generally individual sources of error identified in the Signorelli et al (2007) study did not exceed 10%, which is the degree of accuracy recommended by the Swiss Federal Office of Energy (Eugster, 2002). However, it is possible that the effect of a number of compounded errors could exceed this value. In addition there are limitations to the accuracy of real test data sets associated with the instrumentation used. Pahud (2000) and Spitler et al (2000) examined the uncertainties relating to measurement and power input and suggest that these may sum to between 5% and 10%.

For these reasons increasing use is being made of numerical techniques to determine thermal conductivity from thermal response tests. This usually takes one of two forms, either a parameter estimation technique based on multiple analysis of numerical solutions with different input parameters (eg Shonder & Beck, 2000b, Wagner & Clauser, 2005) or the use of finite element or finite difference numerical models (eg Yavuzturk et al, 1999, Zanchini & Terlizzese, 2008). These numerical techniques can provide a much more accurate match to the test temperatures than the analytical line source model approach.

6.3.2. Applications to pile heat exchangers

Limited numbers of thermal response tests have been carried out on pile heat exchangers. A number of small diameter piles have been tested (Lennon et al, 2009, Wood et al, 2010a) and some initial data suggests successful tests on piles up to 450mm diameter (Brettman et al, 2010). However, there remain uncertainties regarding the applicability of thermal response testing to pile heat exchangers more widely due to both their shorter length and larger cross section. The latter means that it will take much longer to reach steady state (Chapter 5) and the theoretical t_{min} values will increase dramatically. Table 6-1 gives examples of t_{min} values for two representative values of soil thermal diffusivity. Given that standard thermal response tests rarely exceed 60 hours, this initial assessment suggests that only the smallest diameter piles would be suitable for testing without significantly extending the test period. The following sections of this paper describe the use of numerical models to consider in more detail the applicability of thermal response testing to various sizes and types of pile heat exchangers. These results are then compared to real pile thermal response test datasets.

Table 6-1 Theoretical Minimum Time to be excluded from Thermal Response Test Datasets

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

6.4. 2D Numerical Model

To investigate the potential application of thermal response testing for pile heat exchangers a 2D numerical model has been established for a number of different pile heat exchanger geometries (Table 6-2). The models have been created in the software COMSOL and comprise a slice through a pile. For the timescale of thermal response tests the short nature of the piles will only affect the outcome if there is significant variation of the undisturbed ground temperatures over the depth of the pile. For this reason a simpler 2D rather than 3D model has been used. The model includes the concrete pile and the surrounding ground to a radial distance of 25m, chosen to ensure that the constant temperature model boundary does not influence the heat transfer within and close to the pile. All models are based on heat transfer pipes with a diameter of 25mm and symmetrical placement of the pipes within the pile (Figure 6–1). Realistic soil and concrete thermal properties are used in the models, with different combinations used to reflect a range of conductivity ratios (Table 6-3). Full details of the model set up and validation are given in Chapter 5.

Table 6-2 Pile Heat Exchanger Geometries used in the 2D Model

Pile Diameter	Pipe External Diameter	Number of Pipes	Pipe Positions (see note)
300mm	25mm	2	Edge - 50mm cover
			Central – 105mm cover
600mm		4	Edge - 75mm cover
			Central – 255mm cover
1200mm		8	Edge - 75mm cover
		4	Central – 555mm cover

Note: cover is the amount of concrete between pipes and the ground; centrally placed pipes are assumed to be symmetrically placed around a 40mm diameter steel bar.

Figure 6—1 Model Schematic

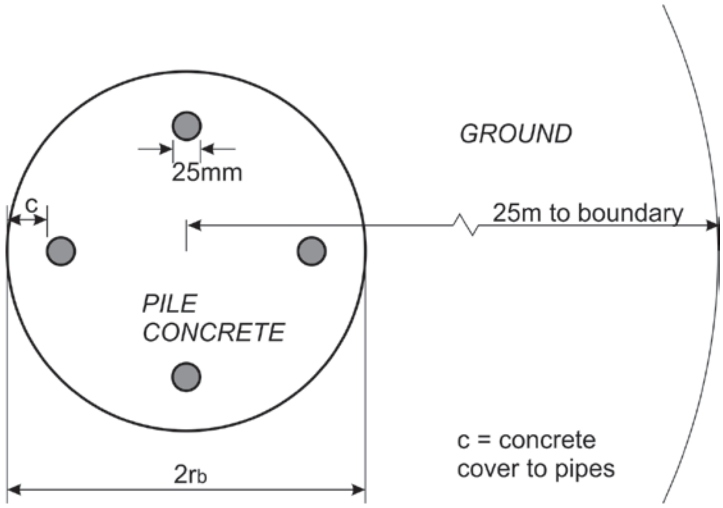


Table 6-3 Thermal Properties used in the 2D Model

Property	Value(s)
Pile concrete thermal conductivity	1 W/mK
	2 W/mK
Pile concrete volumetric heat capacity	1.6MJ/m^{3}K
Ground concrete thermal conductivity	1 W/mK
	2 W/mK
Pile concrete volumetric heat capacity	1.6MJ/m^{3}K

The model does not actually include the plastic pipes or the heat transfer fluid. This is because the temperature difference between the fluid and the outside of the pipes is small and hence the thermal inertia of the concrete is the most significant part of the pile response to heating. To simulate the thermal response test, a constant heat flux is applied to the position of the outside of each of the heat transfer pipes. This is a simplification of the real boundary conditions, as in reality there is a small variation in the heat flux according to the position on the pipe circumference. Typically the outside of the pipes, closest to the ground, will have slightly elevated heat flux compared to the inside. However, this difference is small and has a minor influence on the overall behaviour of the heat exchanger.

The model is used to calculate the temperature at the heat transfer pipes and at the ground-concrete interface with time. The temperature at the pipes is taken to be equivalent to the fluid temperature and used as synthetic thermal response test data to back calculate the thermal conductivity of the ground and the thermal resistance of the pile. The actual thermal resistance of the pile is calculated by taking the difference between the temperature at the pipes and at the concrete edge and dividing by the applied heat flux. Full details of the method are given within Chapter 5.

6.4.1. Temperature Response Functions

Figures 6–2, 6–3 and 6–4 show the calculated temperature response functions for the ground (temperature change with time at the edge of the pile concrete) for all the cases modelled. The figures are plotted dimensionlessly, with a normalised temperature $\Phi = 2\pi\lambda T / q$ on the vertical axis and the Fourier number (or normalised time), $Fo = \alpha t / r_b^2$ on the horizontal axis. Each figure gives the temperature response for a different ratio of the ground to concrete thermal conductivity. Also plotted on the figures are three analytical solutions to the diffusion equation which can be used to design heat exchangers: the line heat source model (Equation 6–1), the cylindrical heat source model and the solid cylinder model. All models assume the heat source to be infinite and are hence compatible with the numerical model. The cylindrical source model (Equation 6–5, Bernier 2001) assumes the heat source to be a hollow cylinder from which all heat flows in an outwards direction, while the solid cylinder model (Equation 6–6, Man et al, 2010) assumes that a solid cylinder is heated at its outer edge so that heat flows in both inwards and also outwards into the ground.

$$\Delta T_g = \frac{q}{\lambda} 10^{\left[-0.89129 + 0.36081 \log Fo - 0.05508 \log^2 Fo + 0.00359617 \log^3 Fo\right]}$$

Equation 6-5

$$\ln\left(\frac{\lambda \Delta T_g}{q}\right) = -2.321016 + 0.499615 \ln\left(\frac{\alpha t}{r_b^2}\right) - 0.027243 \left[\ln\left(\frac{\alpha t}{r_b^2}\right)\right]^2 - 0.00525 \left[\ln\left(\frac{\alpha t}{r_b^2}\right)\right]^3 + 0.000264311 \left[\ln\left(\frac{\alpha t}{r_b^2}\right)\right]^4 + 0.00006873912 \left[\ln\left(\frac{\alpha t}{r_b^2}\right)\right]^5$$

Equation 6-6

Figure 6–2 shows the case where the ground and concrete thermal conductivities are equal. The temperature response functions for the piles all fall between the line source and solid cylinder analytical solutions, typically being closer to the latter. There is a spread of responses, depending on the arrangement of the pipes within the pile cross section. Those with pipes closer to the edge of the concrete tend to be closer to the solid cylinder model, while those with pipes near the centre of the pile tend to have a response approximately half way between the solid cylinder model and the line source model.

Figure 6—2 Ground Temperature Response Functions assuming $\lambda_g = \lambda_c$

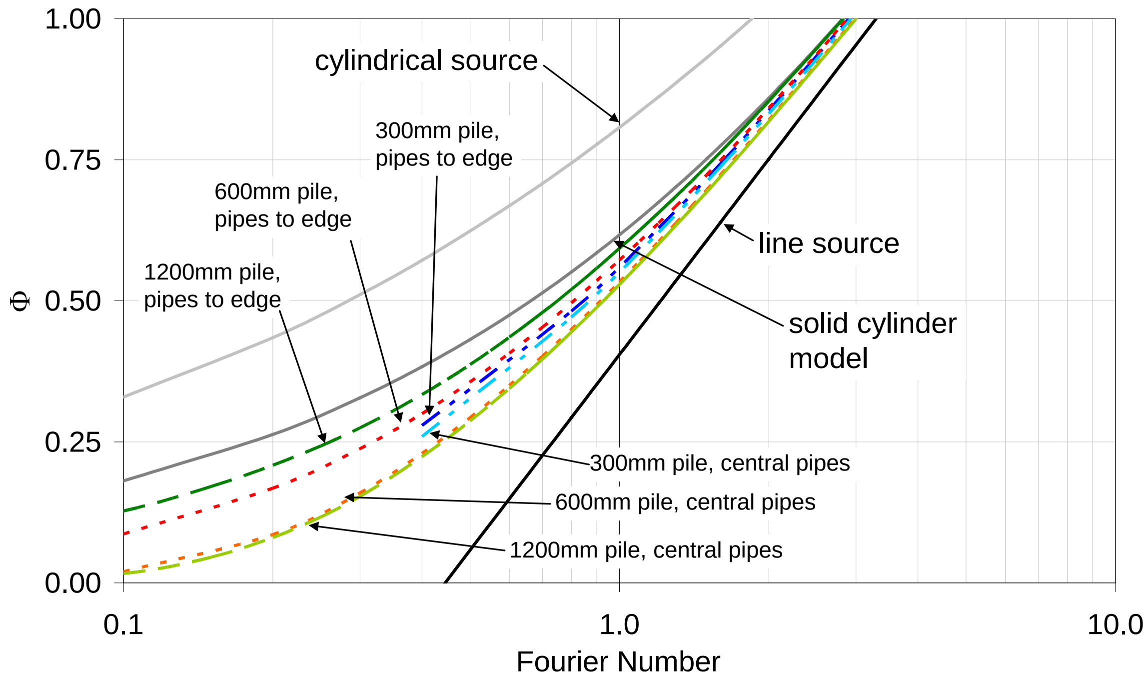


Figure 6—3 Ground Temperature Response Functions assuming $\lambda_g = 2\lambda_c$

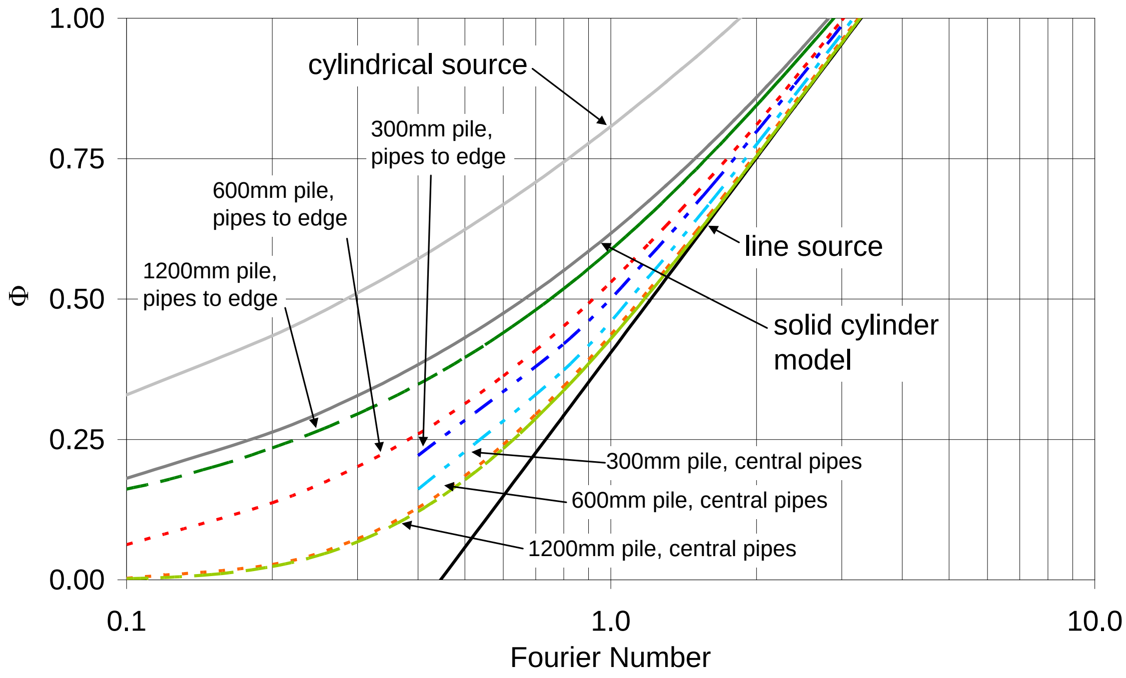


Figure 6—4 Ground Temperature Response Functions assuming $2\lambda_g = \lambda_c$

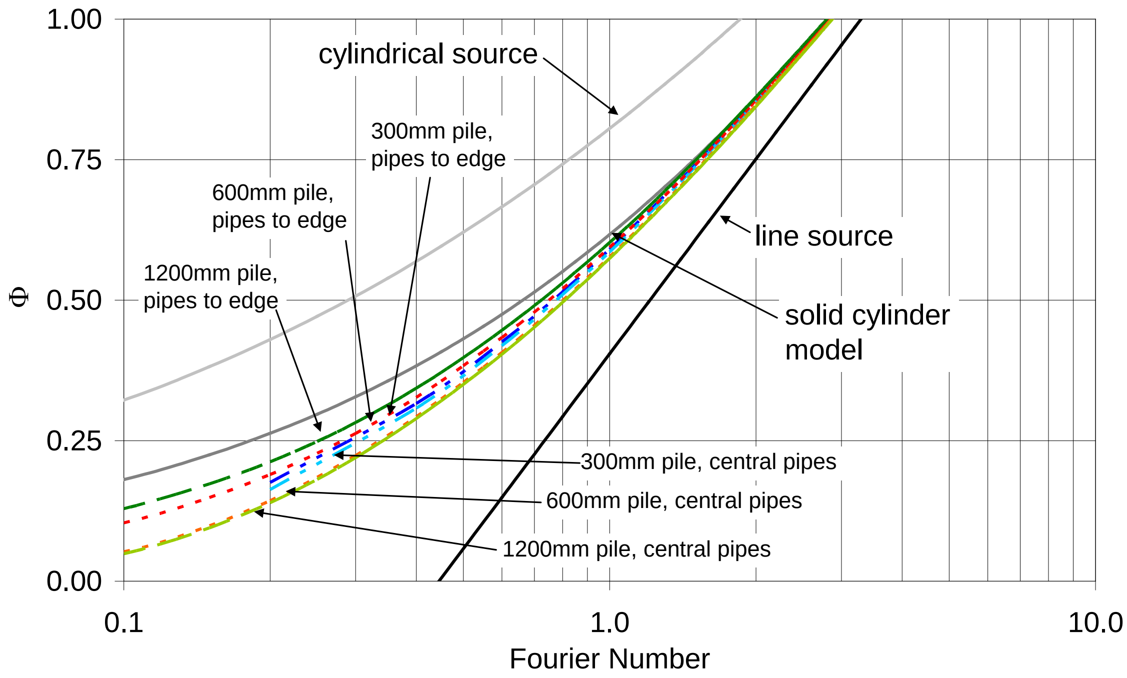


Figure 6–3 shows the case when the concrete is less conductive than the ground. Due to the increased time it takes the heat to travel from the fluid to the edge of the concrete, all the temperature response functions move towards the line source model as the early temperature response is retarded. Conversely, when the ground is less conductive than the concrete all the temperature response functions move towards the solid cylinder model (Figure 6–4), showing greater response at short times. In this case, all the piles exhibit behaviour somewhere between the line and solid cylinder models, with their position depending on the arrangement of the pipes and the relative conductivities of the ground and the concrete.

6.4.2. Derived Thermal Conductivity

Using the temperature change at the pipes predicted by the model, Equation 6–2 was applied to back calculate the thermal conductivity and thermal resistance assuming a line heat source was in operation. Table 6-4 provides a summary of the results where the start time for the calculation of the thermal properties was 10 hours into the test and the end time was 60 hours, as for a standard thermal response test. The shaded boxes in Table 6-4 highlight where the derived values are within 10% of the actual values used in the model. As expected, when the pile diameter is small, a better estimate of the thermal conductivity is obtained regardless of the ratio of the ground and concrete thermal conductivities. Close agreement can also be achieved when the pipes are placed centrally, but only if the ground and the concrete have the same thermal conductivity. The influence of the thermal conductivity ratio is explored further in the following sections.

Table 6-4 Derived Thermal Conductivity and Thermal Resistance as a percentage of Actual Model Values

		λ_g at 60 hours (assessment start time = 10 hours)			R_b at 60 hours (assessment start time = 10 hours)		
Pile Diameter	Pipe Location	$\lambda_g = \lambda_c$	$\lambda_g = 2\lambda_c$	$2\lambda_g = \lambda_c$	$\lambda_g = \lambda_c$	$\lambda_g = 2\lambda_c$	$2\lambda_g = \lambda_c$
300mm	Edge	105	96	115	106	97	132
	Central	102	92	112	102	96	120
600mm	Edge	121	***103***	159	128	***96***	191
	Central	102	67 / 134*	138 / 69*	101	88	122
1200mm	Edge	216	207	328	191	137	274
	Central	104	53 / 107*	189 / 95*	101	89	115

Notes:
* Second value is percentage of concrete thermal conductivity assumed in the model
Shaded cells have derived thermal conductivity values within 10% of the model value.
Bold italic text highlights unexpected test accuracy, as discussed in the main text.

6.4.2.1 Results for $\lambda_g = \lambda_c$

The derived thermal conductivity values for the case where the ground and concrete have the same thermal conductivity are plotted in Figure 6–5 and Figure 6–6 for different analysis start times. Figure 6–5 shows the case where the pipes are placed near the edge of the pile. For a 300mm diameter pile the derived values of thermal conductivity are always within 7.5% of those used in the model, even near the start of the test. After a 60 hour period the derived values are within 5% of those modelled. However, for larger diameters the errors rapidly increase. For a 600mm pile the test would need to run for at least 60 to 100 hours for the derived values of thermal conductivity to be within 10% of the actual values. For a 1200mm diameter pile this increases to in excess of 1000 hours. This would clearly be impractical and uneconomic in most cases.

For the case with pipes installed in the centre of the pile (Figure 6–6) the derived thermal conductivity values are typically less than 6% of the actual values used in the model. Perhaps counter-intuitively, this is because of the larger thermal resistance in these cases and the fact that the pile can take a number of days to reach steady state. Figure 6–7, which plots dimensionlessly the temperature change of the fluid in the 600mm diameter pile models with time helps to explain this. Also included on the figure are the solid cylinder and line source analytical models, assuming a constant thermal resistance. The latter is equivalent to Equation 6–2 which is being used to interpret the data. Where the pipes are near the edge of the pile, the thermal resistance is low (0.056 mK/W) and hence the concrete reaches steady state more quickly. Thus the temperature response function for the fluid is close to that for the solid cylinder model and in a similar relative position to that shown in Figure 6–2.

Figure 6—5 Derived Ground Thermal Conductivity for Piles with Pipes near the Edge and $\lambda_g = \lambda_c$=2W/mK

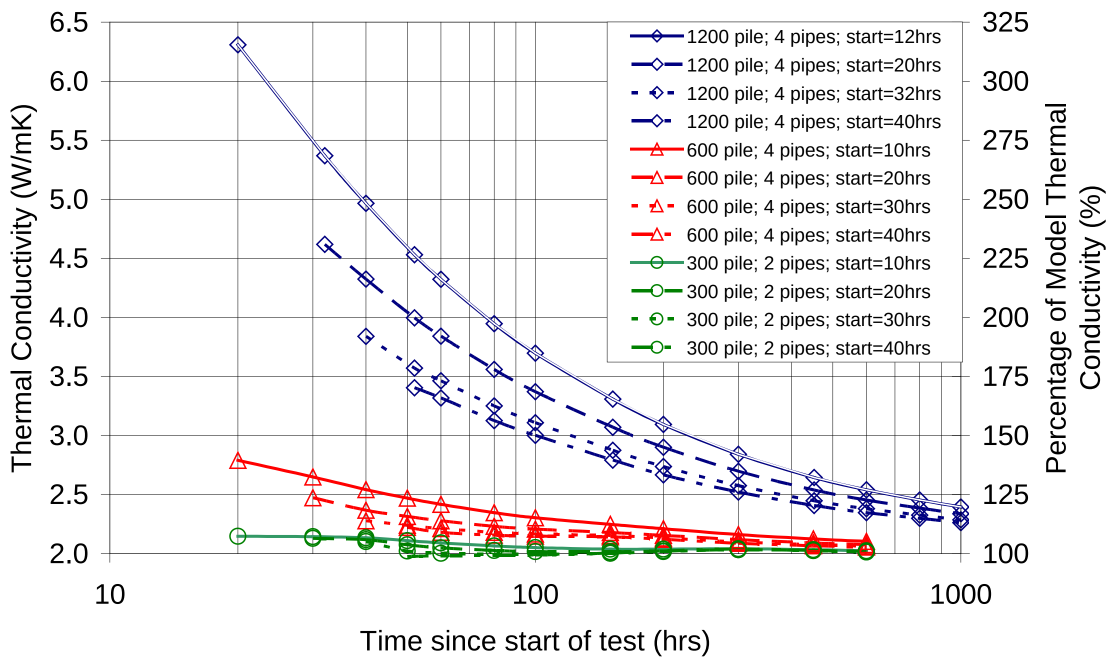
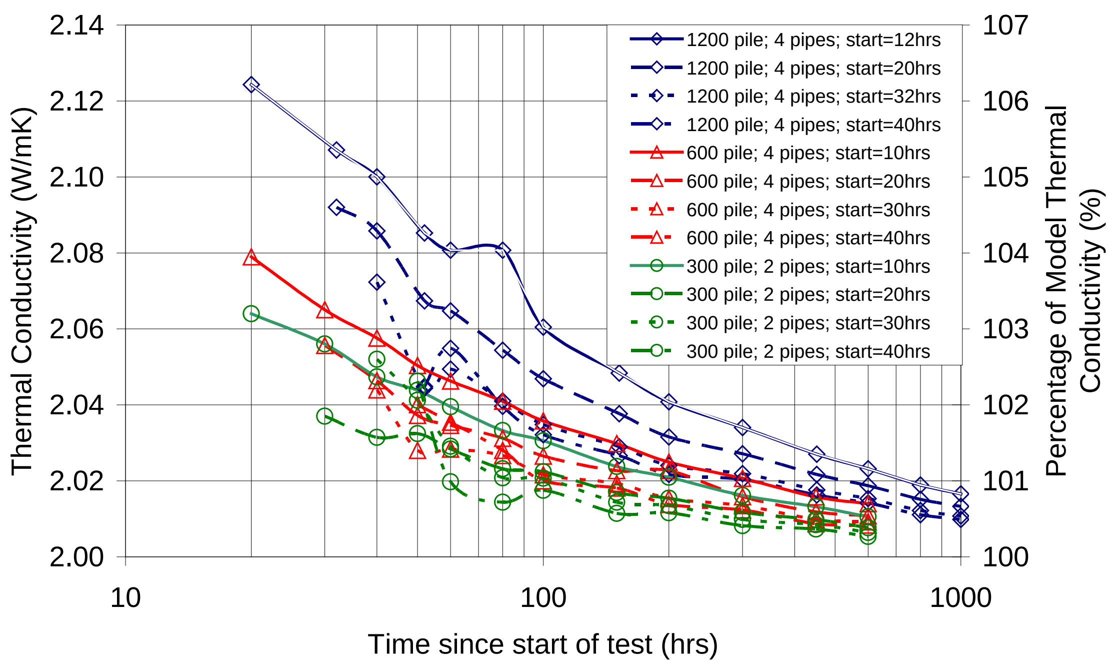


Figure 6—6 Derived Ground Thermal Conductivity for Piles with Centrally Placed Pipes and $\lambda_g = \lambda_c$=2W/mK



However, when the pipes are installed close to the centre of the pile and the resistance is large (0.176 mK/W), then the concrete takes longer to reach steady state and hence the temperature response function for the fluid moves closer to the line source model as shown in Figure 6–7. This means that although the results appear compatible with the line source model it is actually the combination of a more curved ground temperature response plus non steady temperature change in the concrete which are providing the overall response. However, this only holds true while the concrete and soil have similar thermal conductivities as discussed further below.

6.4.2.2 Results for $\lambda_g = 2\lambda_c$

Figure 6–8 shows the temperature response of the fluid in the 600mm diameter pile models, where the concrete is less conductive than the ground. For the case with pipes positioned near to the edge of the pile, the temperature response curve moves towards the line source analytical model due to the extended time taken for the pile concrete to reach steady state. This is as a result of the lower thermal diffusivity of the concrete. Consequently, for thermal response tests carried out on piles of this diameter, and combination of pile and concrete conductivity, the results can appear surprisingly close (refer to the case in bold italics in Table 6-4).

On the other hand, for piles with centrally placed pipes the temperature response curve plotted in Figure 6–8 shows a gradual change in gradient. Here the initial gradient of the curve reflects the concrete conductivity while the later part represents the ground conductivity. Therefore if a thermal response test is interpreted over a range of timescales then the results will trend from the thermal conductivity of the concrete to that of the ground. This is illustrated in Figure 6–9. For the larger diameter piles (1200mm), the test appears to indicate accurately the thermal conductivity of the concrete (1 W/mK) up around 60 hours. After this period the derived thermal conductivity increases, but does not reach that of the ground (2 W/mK) within 1000 hours. For small diameter piles (300mm) the derived values of thermal conductivity increase throughout the test and come close to those of the ground within 60 hours. For intermediate diameter piles (600mm) the derived thermal conductivity increases markedly throughout the test but does not really represent either that of the concrete or the ground.

Figure 6—7 Fluid Temperature Response for 600mm Piles with $\lambda_g = \lambda_c$

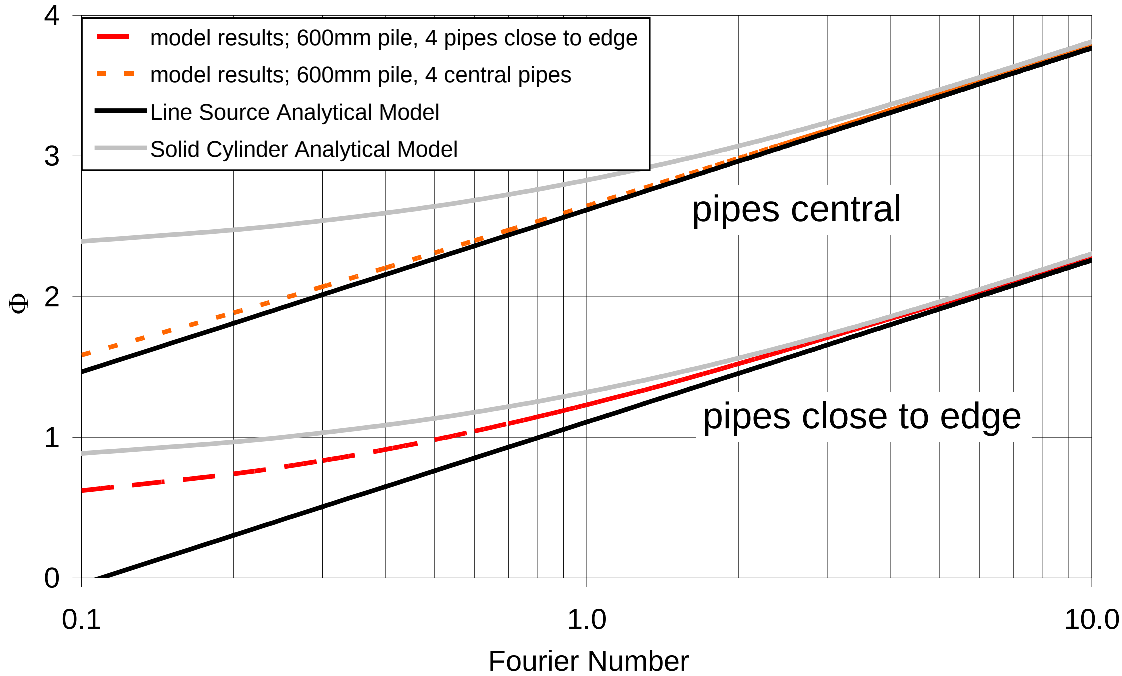
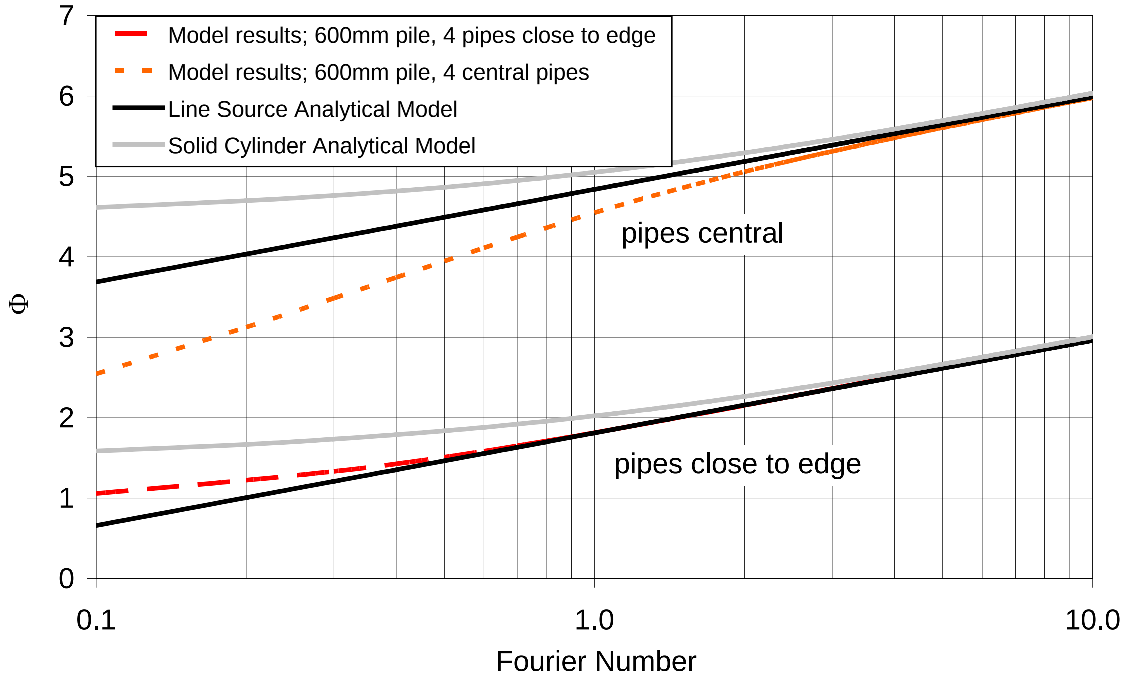


Figure 6—8 Fluid Temperature Response for 600mm Piles with $\lambda_g = 2\lambda_c$



6.4.2.3 Results for $2\lambda_g = \lambda_c$

Generally the difference between the derived thermal conductivity value and the actual model value is greater for the case when the ground is less conductive than the concrete (Table 6-4). This is because the greater thermal diffusivity of the concrete causes the temperature response function for the fluid to move away from the line source analytical model and towards the solid cylinder model. This is the opposite of the effect described in Section 6.4.2.2 and illustrated in Figure 6–8. As described above for piles with centrally placed pipes the derived value of thermal conductivity will vary between that of the concrete and that of the ground depending on the size of the pile and the length of the test and/or interpretation period (Figure 6–10). Figure 6–9 and Figure 6–10 together show the importance of interpreting the thermal response test results over a range of timescales, rather than just deriving a single value of thermal conductivity for the main straight line portion of the test data.

6.4.3. Derived Thermal Resistance

Determination of thermal resistance is dependent on having an intercept on the graph which is consistent with the analytical model as well as an appropriate measure of the thermal conductivity. This means that any significant errors in determining the ground thermal conductivity will also be reflected in the derived values of the thermal resistance (Table 6-4). Consequently, for large piles where the gradient of the graph is actually reflecting the concrete thermal conductivity (Figure 9 and Figure 10), then the graph intercept should not be used to determine the pile thermal resistance as erroneous values will result. However, as the thermal resistance of piles is a function of the concrete thermal conductivity and the pile geometry, if the concrete thermal conductivity can be reliably determined from the thermal response test this will allow calculation of the thermal resistance by empirical or numerical methods, such as those described in Chapter 5.

Figure 6—9 Derived Ground Thermal Conductivity for Piles with Centrally Placed Pipes with λ_g= 2 W/mK and λ_c=1 W/mK

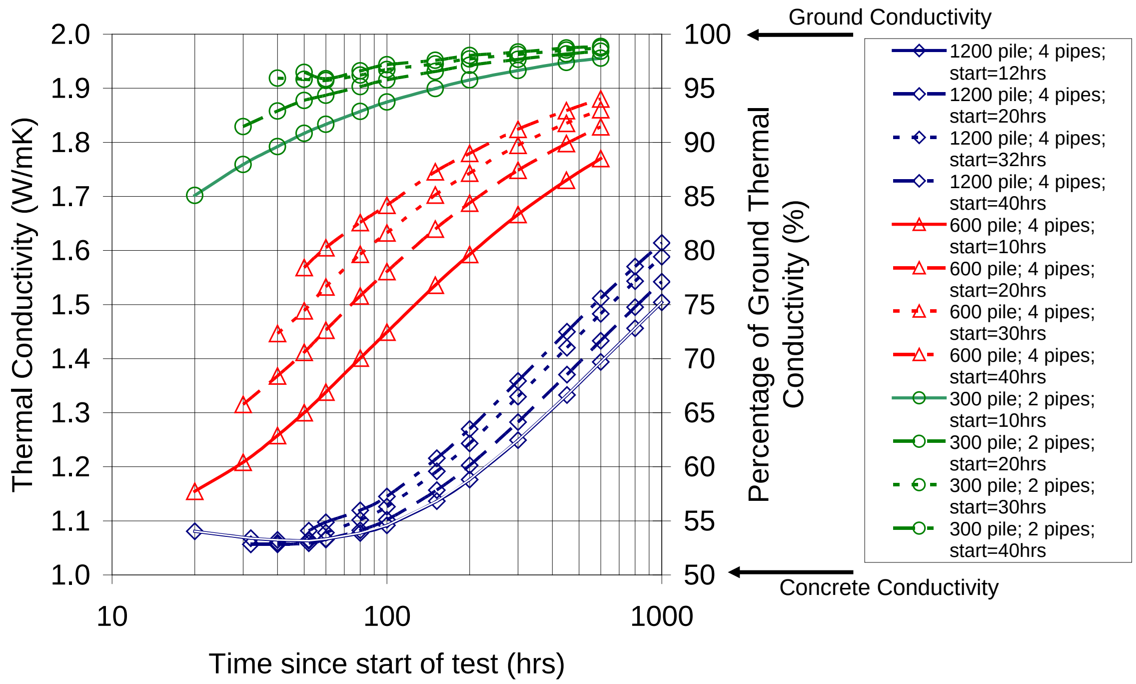
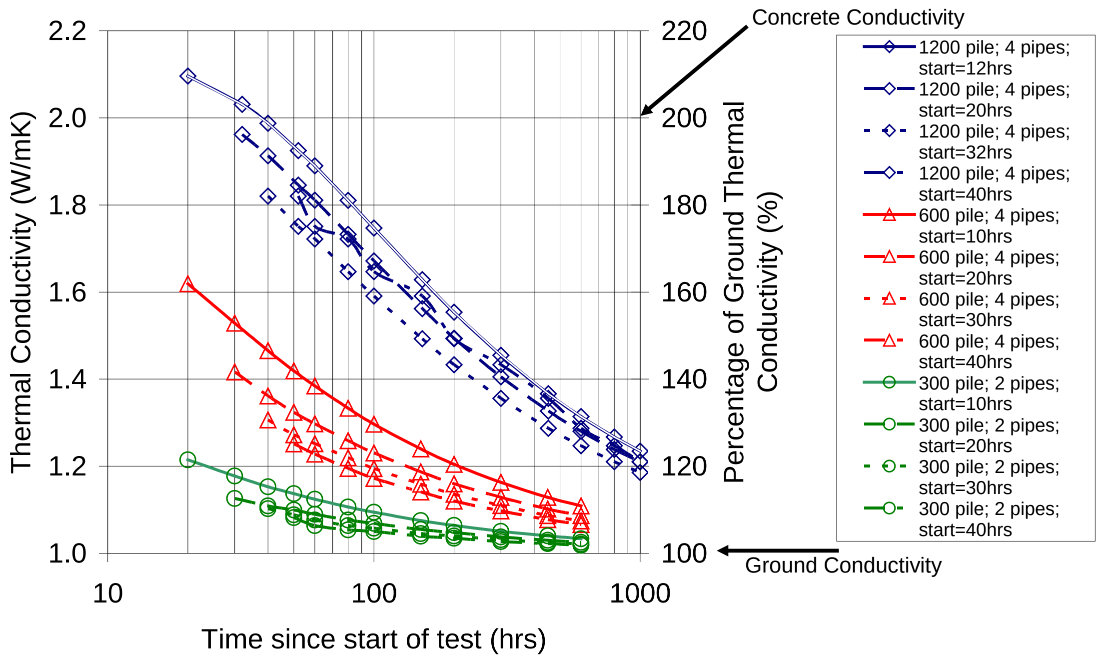


Figure 6—10 Derived Ground Thermal Conductivity for Piles with Centrally Placed Pipes with λ_g= 1 W/mK and λ_c=2 W/mK



6.5. Example Pile Heat Exchanger Thermal Response Tests

The following sections present results from three case studies of pile thermal response tests for different types and diameters of piles.

6.5.1. 300mm Diameter Domestic Dwelling Pile

A test plot of 300mm diameter, 10m deep contiguous flight auger type piles with centrally placed pipes was constructed as part of a research project described by Wood et al (2010a). The site was located on brown field land in the north of England, with variable geological conditions comprising made ground and natural clay soils. A thermal response test was carried out in one of the piles, which was installed with a single U-loop with the two shanks of the loop separated by 25mm. The results of the test are shown in Figure 6–11. Initially the graph of temperature with time is linear, but in the latter parts of the test the results are affected by fluctuations in the mains power supply caused by adjacent industrial users. This is reflected in dips in the fluid temperature profile approximately every 24 hours after about 18 hours.

Figure 6—11 Results of Thermal Response Test on a 300mm Diameter Domestic Dwelling Pile

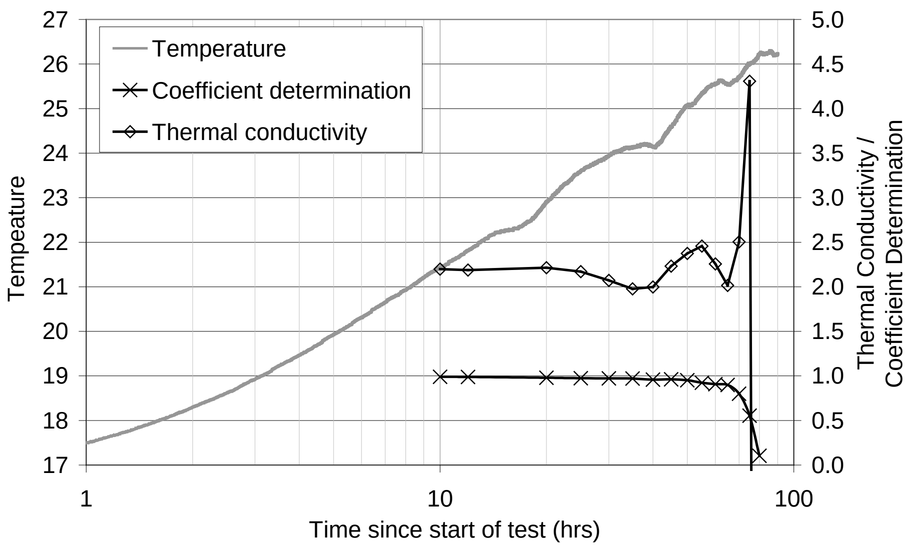


Figure 6–11 also shows interpretation of the test data over a range of timescales. The early part of the test data when the power input was stable suggest that the thermal conductivity of the ground is about 2.2 W/mK. Subsequently there is variation in the results due to the non linear nature of the data and this is reflected in a decrease in the coefficient of determination for the linear fit. The initial data suggests a constant value of thermal conductivity, perhaps indicating that the concrete and ground thermal conductivities are similar in this case.

However, given the variations in the dataset due to heat losses in the latter part of the test it is not possible to conclude this with certainty.

6.5.2. 300mm to 450mm Diameter Grouted Test Piles

Brettman et al (2010) report on thermal response tests carried out on three different 18.3m long auger pressure grouted piles installed as part of a test site in Texas. Three piles were constructed 4.5m apart in a triangular arrangement. There were two different diameters, 300mm and 450mm, and two different grout mixes, a standard cementitious pile grout and a thermally enhanced pile grout using bentonite and silica sand to improve the thermal conductivity. All piles were equipped with a pair of U-loops, which were attached to spacers so that the centres of the pipes were 76mm from the centre of the pile. This is approximately half way between the edge and the centre for the smaller diameter piles, and is closer to being centrally placed for the pipes in the larger diameter piles. Either one or both of the U-loops were used for the thermal response test in each case, with test times between 70 and 100 hours.

In the centre of the pile triangle a borehole was drilled to allow soil sampling and testing for thermal conductivity. The soil sequence is a complex one including sand, silt and clay deposits. Testing the different strata and averaging over the depths of the piles suggested a mean thermal conductivity of the ground of 2.98 W/mK. Samples of the two grout mixes were also tested and determined to have similar thermal conductivities of around 1.35 W/mK.

The derived thermal conductivity values for the pile thermal response tests as reported by Brettman et al (2010) are given in Table 6-5, from which a number of interesting trends are observed. For the piles constructed with standard grout, the derived thermal conductivity values are all within ±10% of the laboratory test results. Unsurprisingly, the smaller diameter pile shows closest agreement. The derived thermal conductivities tend to underestimate the laboratory values which is consistent with the thermal conductivity of the grout being less than that of the ground. There is one exception, however, which is for the 450mm pile where only one U-loop was tested, for which the derived thermal conductivity was higher than the laboratory measured value. This result is consistent with the results of the numerical parametric study presented in this paper, as highlighted by the bold italic text in Table 6-4. It also suggests that the U-loop tested in this case was probably off centre, towards the edge of the pile.

Table 6-5 Results of Auger Pressure Grouted Pile Thermal Response Tests (after Brettman et al, 2010)

Pile	Number of U-loops tested	Derived Thermal Conductivity (W/mK)	Coefficient of Determination
300mm – standard grout	1	2.98	0.999
	2	2.91	0.999
450mm – standard grout	1	3.27	0.996
	2	2.92	0.997
300mm – thermally enhanced grout	2	2.32	0.995

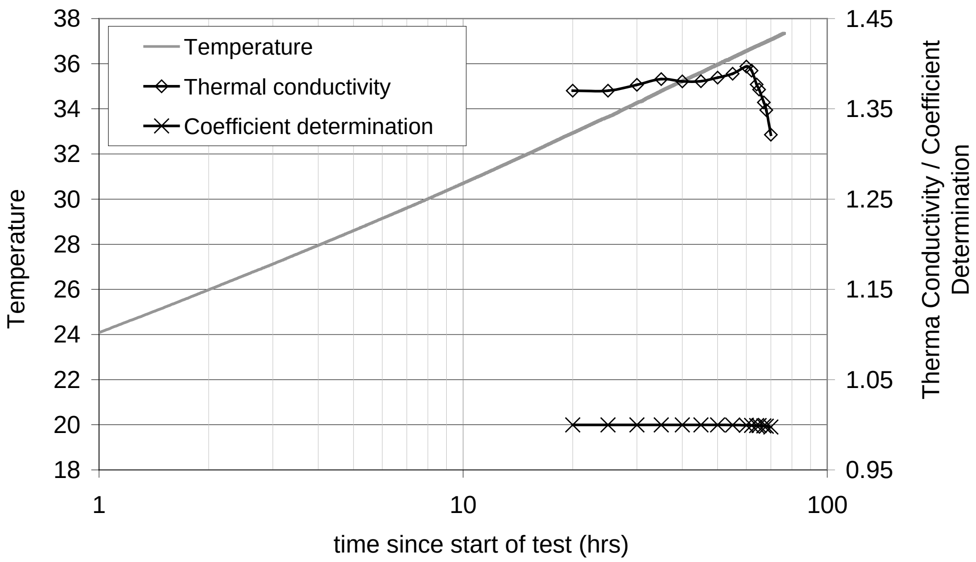
Another interesting result from Table 6-5 is that the derived thermal conductivity from the pile using thermally enhanced grout is significantly lower than that for the piles using standard grout, despite similar values of thermal conductivity being determined in the laboratory. There are two possible explanations for this. Either there is a lens of lower thermal conductivity ground in which this pile is installed or the thermally enhanced grout has a lower thermal diffusivity than the standard grout. This would mean that the thermally enhanced grout must have a higher volumetric heat capacity. However, without further details of the grout mixes it is not possible to confirm this.

Where only one of the two U-loops was tested the derived thermal conductivity was also higher. This must be because the problem is now asymmetrical and the shortest heat flow path to the higher thermal conductivity ground is dominating. In other words the piles where only one U-loop is tested behaved more like a pile with pipes near the edge than a pile with centrally placed pipes.

6.5.3. 1500mm Diameter Pile Group

A range of large diameter contiguous flight auger types piles, each with two centrally placed U-loops, have recently been constructed at a development site in East London. The ground conditions at the site comprise made ground over alluvial clays, river terrace gravels and over-consolidated London Clay. Two 1200mm diameter piles, each with the U-loops installed around a 40mm steel bar, were connected together in series and subject to a thermal response test. The temperature of the heated fluid plotted against time during the test is shown in Figure 6–12. The plot is very linear as the centrally placed pipes within a large mass of concrete are effectively testing the response of the concrete to the heat injected. The derived thermal conductivity of the concrete is also shown in Figure 6–12 and the majority of the test indicates a consistent value of around 1.37 W/mK. However, after about 60 hours the derived thermal conductivity falls markedly. The absolute change in value is small, but the inflection in the curve is marked. It is not clear what is causing this, especially as the ground is likely to have a higher thermal conductivity than the concrete at this location. It is possible that the results may reflect either fluctuations in the power supply or a change in the flow rate of the fluid, but no information is available to either verify or rule out this conjecture.

Figure 6—12 Results of Thermal Response Test on Two 1200mm Diameter Piles



6.5.4. Discussion

Taken together, the three tests described here generally support the numerical study presented in the earlier part of this paper. Where the pile diameter is small or where the volume of concrete is large, then consistent linear test data can be produced. The first case measures the thermal conductivity of the ground and the latter that of the concrete. In the case presented by Brettman et al (2010) it appears that tests can also be carried out successfully within 450mm diameter piles. However, caution must be exercised as the accuracy of the results will depend on the thermal diffusivities of both the concrete and the ground as well as the positioning of the pipes within the piles. These factors should be considered before commissioning a test and the length of the test increased if necessary to ensure an unambiguous outcome. The fact that the test by Brettman et al (2010) was carried out over an extended period of time may well have contributed to its success.

6.6. Conclusions & Recommendations

Thermal response testing has been reliably used to determine the thermal conductivity of the ground around borehole heat exchangers for several decades. This paper has assessed the potential for application of this test to larger diameter pile heat exchangers.

Numerical modelling has shown that the thermal response of the ground around a pile heat exchanger lies somewhere between the line heat source model and the solid cylinder model. Those cases where the response is closer to the line heat source will be most suited to thermal response testing. This includes smaller diameter piles and those with centrally placed pipes.

As the thermal resistance of a pile can be large compared to boreholes it can take several days for the concrete in the pile to reach steady state. This means that in some cases the temperature change of the fluid in a thermal response test may in fact be linear even though the pile is of large diameter. In such cases the thermal response test is measuring the thermal conductivity of the concrete rather than that of the ground.

As a result of this study it is recommended that:

1. Only piles up to 300mm diameter are suitable for standard thermal response testing of up to 60 hours duration. It may be possible to extend this to 450mm in some cases, but care needs to be taken according to the likely ratio of the ground and concrete thermal conductivities. Extending the test duration to 100 hours for 450mm piles would reduce the risk of erroneous results being produced. In such cases it would also be important to maximise measurement accuracy and minimise power fluctuations to reduce any other errors in the analysis.

2. For larger diameter piles, thermal response tests would need to be significantly extended in duration to be interpretable using standard line source techniques. However longer tests require greater care with respect to a constant supply of power and are also much more costly. A cheaper and more reliable alternative for determining the thermal conductivity of the ground may be to test a borehole of similar depth during the site investigation phase of a project. However, this has the disadvantage of providing no further information regarding the thermal resistance of the actual pile.

3. For piles 1200mm or more in diameter, where the pipes are placed in the centre of the pile, a standard thermal response test can be used to measure the thermal conductivity of the concrete. Once the concrete thermal conductivity has been determined in this

way it is possible to calculate the pile thermal resistance separately by empirical or numerical methods (refer to Chapter 5). However, the thermal response test itself should not be used to directly determine the thermal resistance directly as this will provide erroneous results.

In all cases interpretation of the test results over a range of time periods, rather than just calculating one value of thermal conductivity corresponding to the time period from t_{min} to the end of the test, will provide greater understanding of the behaviour of the heat exchanger. This will help inform judgements about the values of thermal conductivity and thermal resistance to be used in the design, as well as the ratio of the conductivities of the pile concrete and the ground, which is an important factor in controlling the short time step behaviour of pile heat exchangers.

Chapter 7. Discussion and Conclusions

7.1. Discussion

The preceding chapters of this thesis have considered in detail the thermal behaviour of foundation piles used as heat exchangers. They have highlighted a number of ways in which pile heat exchangers differ from borehole heat exchangers. These differences are important because much current design is based on methods previously developed for use with borehole heat exchangers.

7.1.1. Irregular Arrangement of Piles

Typically borehole field arrays involve regular arrangements of heat exchangers. For pile heat exchangers the layout is determined by the structural engineer and may be irregular, incorporating different sizes and lengths according to the building column locations and loads. Consequently, software tools developed for boreholes, which include only temperature response functions for regular arrangements of heat exchangers, may not be appropriate. In particular, care should be taken with the software PILESIM where highly irregular pile arrangements are used.

7.1.2. Pile Geometry

7.1.2.1 Pile diameter

Piles can have a much larger diameter than borehole heat exchangers, which are typically limited to around 200mm across. The larger diameter can have a number of consequences for the thermal behaviour:

1. The nature of the ground temperature response function. When considering the response of the ground in isolation it is clear than the diameter of the heat exchanger will be important, and that large heat exchangers will produce an increased temperature response in the ground at short times (Figure 4–4) compared with a line heat source (Chapter 4). Therefore analysis of pile heat exchangers using a line source analytical model will underestimate the temperature change in the ground at short

times, hence potentially underestimating the thermal energy available. This would suggest that use of a cylindrical heat source model to assess the temperature change in the ground would be a superior technique. However, subsequent work considering the ground and concrete together (Chapter 6) shows that when the temperature response of the system is treated holistically the overall response lies between that of a line heat source and that of a solid cylinder heat source (Figure 6–1 to Figure 6–3). The exact position of the response curve depends on the size of the pile and the number and arrangement of pipes installed (see Section 7.1.3 below).

2. Internal thermal behaviour. Larger diameter piles have a greater volume of concrete and hence greater thermal mass. This means that they may take much longer to reach steady state (Figure 6–10); up to several days compared with several hours for typical borehole heat exchangers. This has implications for both thermal response testing and the standard design approach of separating the thermal behaviour of the ground and the concrete, as both these methods assume steady state within the heat exchanger within a few hours.

7.1.2.2 Pile length

Piles tend to be significantly shorter than borehole heat exchangers which are usually greater than 100m in length. Therefore a thermal steady state can be reached much more rapidly than for borehole heat exchangers and consequently it is essential to have an analytical or numerical model which considers the finite length of the heat exchanger. Given the above discussion a finite line source model is clearly appropriate, but the finite solid cylinder presented by Man et al (2010), Equation 7–1, is also appropriate in this respect. The former has the advantage of being already adopted in a number of commercial software packages, but tends to be programmed for preset arrangements of heat exchangers which may not be applicable (see Section 7.1.1 above). The latter was introduced in its infinite form in Chapter 6. The finite form is given below and is far more complex to implement but would be more accurate in most cases.

$$t(r,z,t)=\frac{q}{\rho S_c}\int_0^t\int_0^h \frac{1}{8\left[\sqrt{\pi\alpha(t-t')}\right]^3} I_0\left[\frac{rr_b}{2\alpha(t-t')}\right]\cdot\left[e^{\left[-\frac{r^2+r_b^2+(z'-z)^2}{4\alpha(t-t')}\right]}-e^{\left[-\frac{r^2+r_b^2+(z'+z)^2}{4\alpha(t-t')}\right]}\right]dz'\,dt'$$

Equation 7-1

An alternative approach would be to use the simpler infinite solid cylinder equation (Equation 6–6) for short time periods (up to a Fourier number of 10) and then use a finite line source approximation for longer time periods.

7.1.2.3 Aspect ratio

The long term behaviour of energy piles is best represented by considering the aspect ratio rather than the length. The aspect ratio is the length divided by the diameter of the heat exchanger and allows the simplest characterisation of the long term behaviour of energy piles. Each aspect ratio will have a unique temperature response function for the long term response of the ground to heating or cooling. Depending on whether a finite line source model (Figure 4–7) or a finite solid cylinder model is adopted different temperature response function curves will be required according to the aspect ratio.

7.1.3. Pipe arrangements

Borehole heat exchangers tend to be installed with one or two pairs of U-pipes. The larger diameter of pile heat exchangers means that there is the potential to install many more heat exchange pipes. Within energy piles there is also the possibility of choosing between installation of the pipes in the centre of the pile or, by fixing to the steel reinforcement cage, nearer to the edge. The number of pipes and where they are installed can have a significant impact on the pile internal behaviour.

Given the wider range of possibilities than for borehole heat exchangers, it is not surprising that the pile thermal resistance can theoretically cover a much wider range than borehole thermal resistance (Chapter 5). Larger numbers of pipes installed closer to the edge of the pile will lead to relatively low resistance, while a smaller number of pipes installed in the centre of a large diameter pile will lead to much increased resistance. This latter scenario will also take the longest time to reach steady state and should really be treated as a transient problem as the concrete is making a significant contribution to the storage of heat as well as to its transfer.

Where pipes are installed near the edge of the pile, but their spacing is relatively wide, then there will be a significant spatial variation of temperature around the pile circumference. This means that simple means of determining the thermal resistance, which are based on a spatially constant temperature, will overestimate the resistance, potentially by up to 25% (Figure 5–5, Figure 5–6). Empirical equations to allow for this factor when estimating pile thermal resistance are included in Chapter 5. This presents a much simpler alternative compared with the accurate but complicated multipole method (Appendix A).

7.1.4. Fluid temperature profiles

All types of heat exchanger where the fluid pipes are installed in close proximity may be subject to interference between the pipes as they exchange heat with each other rather than with the concrete and the ground. This effect can reduce the efficiency of the heat transfer, often reflected in an increased resistance of the heat exchanger. Minimising interference depends on maintaining pipe circuit lengths below 300m, utilising high fluid mass flow rates and a using sensible pipe separation. For pipes installed at spacings in excess of 100mm on the pile cage interference should be minimal, except at very low flow rates (Figure 4–10). However, for multiple U-pipe installations in the centre of a pile it is possible for pipes to be touching each other and the potential for interactions and hence reduced performance may be high.

Piles also differ to boreholes as the pipe work from multiple shorter piles may be connected together in series. This means that the pipe circuit may start in one pile and finish in an adjacent one. Consequently the temperature of the first pile in the series will be different to the last pile. This can have heat transfer implications due to the relative temperature differences between the pile and the ground, leading to different rates of heat transfer being experienced by different piles.

7.1.5. Dual Structural Use

As well as functioning as heat exchangers, energy piles provide an essential structural function by transferring the loads from the overlying structure to the ground around the piles. It is therefore important that the thermal changes which may occur in the pile as a result of the heat exchange function do not adversely affect the load carrying capacity of the foundation system. In this respect the most important factor is making sure the ground does not freeze. This means that energy pile systems may well operate at a higher minimum temperature than other ground energy systems. Given the potential for temperature change of several degrees between the fluid and the ground (Chapter 5) it is, however, still possible to operate the ground energy system at temperatures below zero degrees, providing that a suitable design and control system is in place.

Temperature changes in the pile may also lead to additional stresses in the concrete and/or displacements of the foundations. It is important that these are assessed and allowed for in the design, although the nature of the pile restraint means that either displacements or additional stresses will occur and that excessive development of both in the same system is not possible. Case studies show that while large stresses are possible, these only develop when there is significant structural restraint to the piles. Where elevated stresses may be expected the capacity of the concrete to carry these must be confirmed.

7.2. Conclusions

This thesis has presented a framework for understanding the thermal performance of foundation piles used as heat exchangers. Appropriate methods for assessing the thermal response of the ground around the pile to heating and cooling have been presented. New methods have been developed for the determination of the thermal resistance of piles, often used to characterise their internal thermal behaviour. Rigorous assessment of the behaviour of energy piles during thermal response testing has also been carried out, resulting in important recommendations for practice. Based on this work and the discussion above, the following key conclusions can be drawn:

1. Standard vertical heat exchanger design methods, which for the purpose of analysis separate the thermal response of the ground from the internal temperature changes within the pile, are only valid for small diameter piles. In this context small diameter piles are taken to be those of 300mm and less. In some cases this could be extended to 450mm depending on the respective concrete and ground thermal properties, but this would need to be assessed on an individual basis.

2. For larger diameter piles it would be better to adopt a transient temperature response function that includes both the response of the concrete and the ground. Some initial work has been done towards this aim (refer to the short timescale temperature response functions shown in Figure 6–6 and Figure 6–7), but further analysis would be required to develop this concept fully.

3. In the absence of an overall transient temperature response function either a finite line source (Eskilson, 1987) or a finite solid cylinder (Man et al, 2010) analytical model in combination with a constant thermal resistance would be the most appropriate design approach. The finite line source is readily available in a number of commercial software tools, but the thermal resistance would need to be calculated in accordance with the methods described in Chapter 5.

4. For large diameter piles in which the heat transfer pipes have been installed in the centre of the pile the concrete is playing a far more significant role in the heat transfer process than the ground. Especially for a balanced system, which is operating as an

inter-seasonal store, the ground may have minimal influence on the system behaviour compared to the concrete thermal properties.

5. Where multiple heat transfer pipes are installed in the centre of a pile there is a question over reduced efficiency if those pipes are close together or even touching one another. This effect can be minimised by use of short pipe circuit lengths and high flow rate, but it would be better to ensure larger separation of pipes if possible.

6. While thermal response testing of boreholes is an important means of deterring the ground thermal conductivity in situ, it should only be directly applied to small diameter piles, typically 300mm or less. For larger diameter piles an extended duration test would be required, although this may prove uneconomic in many cases. An alternative would be to test a borehole of similar depth to the planned piles during the ground investigation stage of a project.

7. In the special case where the pipes are installed in the centre of a large diameter pile a thermal response test may be used to determine the thermal conductivity of the concrete. This can help with assessment of the pile thermal resistance.

The discussion and conclusions presented here form the basis for more detailed recommendations for practice which are set out in Chapter 8. It is also important that a number of themes from this work are developed further, and that in situ and laboratory testing data is used to validate some of theoretical findings. Recommendations for further work, based on the knowledge gained during preparation of this thesis, are contained in Chapter 9.

Chapter 8. Recommendations for Practice

8.1. Design for Heat Exchanger Thermal Capacity

The two main analytical solutions implemented in commercial design software for the temperature response of the ground are the finite line source (FLS) and the infinite cylindrical source (ICS). These are usually adopted with a constant steady state thermal resistance for the pile concrete. Use of a line source will underestimate the temperature change in the short term compared with a cylindrical source. This effect is greater for larger diameter piles. In the long term an infinite source will significantly overestimate the temperature response, with the effect being greatest for low aspect ratio piles. Therefore the ICS is conservative in the short term, but not conservative in the long term. Given that the long term is more significant with respect to the overall temperature changes in the ground, in the absence of other more sophisticated techniques a FLS rather than an ICS approach is recommended. A solid cylinder model, for which the temperature response lies between that of a line and cylindrical source would also be appropriate.

Where possible the following approach should be adopted:

1. For piles less than 300mm diameter a FLS approach in combination with a steady state pile resistance is recommended.

2. For piles greater than 300mm diameter a three dimensional numerical method which treats the pile concrete as transient is ideally recommended.

3. In the absence of 2, either the FLS or the Finite Solid Cylinder Model should be used to model the ground temperature response, in combination with a steady state pile resistance. However, it is important to appreciate that the use of a constant steady state resistance will overestimate the temperature response where the volume of concrete is large.

Where multiple piles are used as heat exchangers then their combined temperature response function, accounting for interactions, must be used in design. This is typically done by superposition and commercial software packages allow for this. However, many software uses built in pre-defined arrangements of heat exchangers, usually on regular grids. Pile foundations are more commonly irregularly arranged and therefore it is important to select a design approach with permits superposition based on coordinate locations rather than regularly spaced grids.

8.2. Design Parameters

8.2.1. Ground Thermal Properties

Where possible, the thermal conductivity of the ground and the initial undisturbed ground temperature should be determined *in situ* using a thermal response test (see 8.4 below). For small schemes this may not be economic in which case desk study and/or laboratory testing techniques can be adopted (refer to Appendix D, Section D.2.1).

Thermal diffusivity of the ground is also a required design parameter. This is often calculated based on the thermal conductivity and the volumetric heat capacity. The latter is difficult to determine by laboratory testing and assumed values are often used. Alternatively volumetric heat capacity may be calculated based on the phase proportions of the soil as described in Appendix D (refer to Section D.2.1).

8.2.2. Pile Thermal Properties

If a constant thermal resistance is to be used in the design (but see discussion in 8.1 above), the value can be determined either numerically or using the empirical equations presented in Chapter 5. Alternatively, given the role that pile concrete plays in heat storage (rather than just transfer) a transient design approach using the thermal properties of concrete should be considered. Concrete thermal conductivity has received much attention in terms of early age thermal behaviour and fire engineering applications. However, case studies which measure the thermal conductivity and record all the relevant influence factors (moisture content, aggregate volume and mineralogy, admixtures and cement replacement products) are rare. Consequently values of thermal conductivity in excess of 1.5W/mK are not recommended unless specific information about the concrete mix in use is provided. In such cases, the study presented in Appendix D, Section D.4 will provide guidance on parameter selection.

8.3. Pipe Arrangements and Flow Conditions

The efficiency of heat transfer from the pile heat exchanger to the concrete and the ground depends on the pipe and flow conditions. Longer pipe circuits and slower flow velocities will have reduced heat transfer characteristics, especially near the end of the circuit, compared to shorter pipe circuits with higher flow velocities. Interference between adjacent pipes, which further reduces the pipe efficiency, will also be more likely. in long pipe circuits with low flow rates. For these reasons it is recommended that pipes circuit lengths are kept to less than 300m with flow rates in excess of 0.5m/s.

The positions of the heat transfer pipes can also have an important impact on the heat transfer characteristics of the pile. Installing a larger number of pipes, closer to the edge of the pile will lead to a reduced thermal resistance. Pipes will also have increased potential for thermal interactions when they are installed immediately adjacent to one another towards the centre of a pile, rather than spaced at intervals around the circumference. Common practice of using a steel bar for stiffness during installation of central pipes is likely to exacerbate this effect. Consequently, where possible it is recommended that the use of centrally placed pipes is avoided.

8.4. Thermal Response Testing

The following approach is recommended for thermal response testing for pile heat exchangers:

1. For determination of thermal conductivity, only piles less than 300mm diameter are suitable for standard thermal response testing of 60 hours duration.

2. Larger diameter piles should only be tested if a bespoke testing regime is developed that takes account of the additional time taken for the pile to reach steady state.

3. In other cases the thermal conductivity of the ground can be determined in situ using a borehole during the site investigation phase of a project. It is important to ensure that this borehole is of a comparable length to the foundation piles.

4. For piles greater than 1200mm in diameter with centrally placed pipe loops thermal conductivity of the pile concrete can be determined by standard thermal response test methods.

More detailed recommendations for the procedure for thermal response testing techniques is contained within Appendix D, Section D.3.

8.5. Temperature Limits

In order to protect the structural capacity of the pile foundations it is essential that the ground surrounding the piles does not freeze. To ensure this the ground energy system must operate within agreed temperature limits. It is recommended that these are either:

1. The temperature of the heat transfer fluid leaving the heat pump (during heat extraction) must not fall below zero degrees Celsius. An appropriate margin of error, such as 2°C should also be applied; or

2. As approach 1 is very simple and therefore conservative it will be beneficial to the efficiency of a system to consider the problem in more detail. Lower temperatures may be accepted at the heat pump, subject to a suitable design which allows for the temperature difference between the fluid and the ground. This difference is typically a few degrees, but can be significantly higher for either large piles, with large thermal resistance, and/or short duration peak thermal loads where the thermal inertia of the piles means that the ground is not effected by the peak load.

More detailed discussion of this issue is included in Appendix D, Section D.5.

Chapter 9. Further Work

This work has provided new insight into the thermal behaviour of energy piles. However, it has also raised further questions which need to be addressed by additional research.

9.1. Temperature Response Functions

It would be of great benefit to develop a suite of temperature functions for energy piles, on a similar basis to the g-functions developed by Eskilson (1987) for borehole heat exchangers. Work presented in Chapter 6 of this thesis has shown that these temperature response functions will lie between the line source and solid cylinder models at short time periods. In the longer term the temperature response function would be equivalent to a finite line source.

Given the varied internal geometry of energy piles, a range of response functions would need to be developed according to likely pipe arrangements and pile sizes. The response functions would also need to encompass the transient behaviour of both the concrete and the surrounding ground, reflecting the more significant role concrete plays in energy storage for pile heat exchangers. Work has now commenced on this project and aims to provide lower and upper bound temperature response functions specifically for pile heat exchangers.

9.2. Fluid Thermal Interaction Model

The numerical models presented in this thesis are mainly simple two dimensional simulations. To capture the full three dimensional behaviour of energy piles it will be important to move to a more sophisticated model which encompasses the convective heat transfer related to the circulation of the heat transfer fluid. Such a model would allow:

1. Quantification of issues related to interaction between adjacent heat transfer pipes. This is an important and urgent question that needs to be addressed in order to assess the efficiency of piles with centrally installed heat transfer pipes.

2. Quantification of the impact of the variation of both undisturbed ground temperatures over the length of a pile and the changes in the surrounding ground temperatures throughout the year. This topic is of greater importance for piles compared to boreholes due to their shorter length.

3. Quantification of the importance of ground stratification. When the temperature in the ground varies with depth over the length of the heat exchanger the heat transfer will not be constant with depth and hence variation in ground thermal properties may become important.

9.3. Groundwater

Systematic quantification of the impact of groundwater flow on energy piles is still required. While it has long been known that groundwater flow has a potentially large impact on heat transfer, there is not a consensus about what flow regimes are likely to have a significant effect, nor the best means of assessing the impact analytically or numerically. To commence filling this knowledge gap in situ data is required. As a starting point instrumentation has been installed within and around a 150m deep borehole heat exchangers installed within the Chalk aquifer. Initial operational results are expected later in 2012.

9.4. Thermal Properties

There remains uncertainty about the likely range of thermal properties of concrete used in piling applications. Much of the testing published in the literature does not contain information regarding all of the important factors that influence the results: fine and coarse aggregate lithology, aggregate proportion, use of admixtures. This situation will hinder the selection of thermal resistance values for piles unless site specific testing is carried out.

While the thermal conductivity of soils is better understood than that of concrete, the UK database of values is not necessarily appropriate for use with shallow ground energy systems and this needs to be updated. There is also little guidance regarding specific heat capacity and this topic would warrant more detailed attention.

9.5. Monitoring of Energy Pile Systems

While it has been possible to make conclusions and recommendations regarding assessment methods for energy piles (Chapter 7), there is still scant monitoring data for energy piles with which to provide full validation for these recommendations. Gathering of detailed and thorough datasets from real energy pile installations or large scale laboratory tests are the only ways in which design methods can be fully tested and validated.

To make progress towards these objectives, a 1.2m diameter, 20m deep pile heat exchanger with centrally placed pipe loops has been instrumented as part of the EPSRC project

"Performance of Ground Energy Systems installed in Foundations" (reference EP/H049010/1). The design of the instrumentation for this scheme has been influenced by the understanding gained from the work presented in this thesis. Initial operational results from the scheme are expected later in 2012.

However, with many different pile heat exchanger configurations possible, more case studies will be important for fully validating the design approaches proposed in this thesis. It is recommended that this is considered an urgent priority for the industry.

Appendix A The Multipole Method

The Multipole Method for Thermal Resistance

Thermal resistances for the heat flow between the pipes and the ground can be calculated by using a line source to represent the position of each pipe. Superposition can then be used to determine the total resistance. For the idealised scenario of two symmetrically placed pipes Hellstrom (1991) demonstrated that:

$$R_b = \frac{1}{4\pi\lambda_c}\left[\ln\left(\frac{r_b}{r_o}\right)+\ln\left(\frac{r_b}{s}\right)+\sigma\ln\left(\frac{{r_b}^4}{{r_b}^4-\left(s/2\right)^4}\right)\right]+\frac{1}{2}R_p$$

Equation A-1

where $\sigma = \dfrac{\lambda_c - \lambda_{ground}}{\lambda_c + \lambda_{ground}}$

and in this case R_p is the resistance from the fluid to the material just outside the pipe for a single pipe. Hence for a pair of pipes the total resistance between the fluid and the outside of the pipe is $\frac{1}{2}R_p = R_{pconv} + R_{pcond}$

Multipoles are complex number derivatives of line sources. The computation required is therefore much more complicated than a line source, but otherwise the approach is similar. Full details of the multipole method are given in Bennet et al (1987). Multipoles may be expressed as expansion series and a first order multi-pole solution for the case of the two symmetric pipes in a borehole is given as (Hellstrom, 1991):

$$R_b = \frac{1}{4\pi\lambda_{grout}}\left[\beta+\ln\left(\frac{r_b}{r_o}\right)+\ln\left(\frac{r_b}{s}\right)+\sigma\ln\left(\frac{{r_b}^4}{{r_b}^4-\left(s/2\right)^4}\right)\right]-\frac{1}{4\pi\lambda_{grout}}\left[\frac{\frac{r_o^2}{s^2}\left\{1-\sigma\left(\frac{s^4/4}{r_b^4-\left(s/2\right)^4}\right)\right\}^2}{\frac{1+\beta}{1-\beta}+\frac{r_o^2}{s^2}\left\{1+\sigma\left(\frac{s^4{r_b}^4}{\left(r_b^4-\left(s/2\right)^4\right)^2}\right)\right\}}\right]$$

Equation A-2

where $\beta=2\pi\lambda_{grout}R_p$. This expression shows the line source method to overestimate R_b with the multipole method providing a corrective term (the second in Equation A–2) to address this.

Hellstrom (1991) shows that the relative error between the two methods is typically less than 10% providing the pipe diameters are less than 40mm. Greater accuracy still can be obtained from higher order multipoles, but the first order solution is quoted to be accurate to within 1% of the exact solution given from higher order assessments. Based on the results presented in Chapter 5, for the range of geometric parameters relevant to energy piles, the differences between the line and multipole methods appear much less than 1%.

Appendix B Shape Factor Look Up Tables

Shape Factor Look Up Tables

		Pile Only Model				Pile and Ground Model - Sf (by number of pipes)											
		Sf (by number of pipes)				$\lambda_c=\lambda_g$				$\lambda_c=2\lambda_g$				$2\lambda_c=\lambda_g$			
$r_b\backslash c$	$r_b\backslash r_o$	2	4	6	8	2	4	6	8	2	4	6	8	2	4	6	8
1.5	10	4.1666	5.0817	5.3740		4.1517	5.0691	5.3609		4.15	5.0691	5.3609		4.1537	5.0691	5.3609	
2	10	5.0653	7.1125	7.9191	8.3111	4.9964	7.0954	7.9020	8.2931	4.9774	7.0947	7.9020	8.2931	5.0164	7.0969	7.9020	8.2931
3	10	6.1242	9.9030	11.8928	12.9939	5.7806	9.8268	11.8587	12.9644	5.6801	9.8065	11.8586	12.9644	5.8868	9.8465	11.8621	12.9644
1.5	12	3.9944	4.9887	5.3146	5.4620	3.9810	4.9784	5.3022	5.4488	3.9793	4.9784	5.3022	5.4488	3.9834	4.9784	5.3022	5.4488
2	12	4.7888	6.9084	7.7790	8.2074	4.7195	6.8927	7.7627	8.1907	4.7004	6.8924	7.7627	8.1907	4.7398	6.8934	7.7627	8.1907
3	12	5.7228	9.4702	11.5459	12.7210	5.3916	9.3901	11.5116	12.6900	5.2947	9.3709	11.5077	12.6900	5.4937	9.4109	11.5146	12.6900
1.5	15	3.7901	4.8739	5.2408	5.4097	3.7761	4.8629	5.2279	5.3983	3.7741	4.8658	5.2279	5.3983	3.7785	4.8653	5.2279	5.3983
2	15	4.4759	6.6537	7.6020	8.0770	4.4072	6.6384	7.5856	8.0597	4.3873	6.6377	7.5856	8.0597	4.4262	6.6401	7.586	8.0597
3	15	5.2820	8.9524	11.1109	12.3756	4.9712	8.8725	11.0732	12.3482	4.8796	8.8526	11.0697	12.3479	5.0674	8.8935	11.07631	12.3484
1.18	20	2.7651	3.1076			2.7606	3.1024			2.7606	3.1024			2.7606	3.1024		
1.5	20	3.5407	4.7195	5.1424	5.3395	3.5285	4.7113	5.1320	5.3284	3.5268	4.7113	5.1320	5.3284	3.5314	4.7113	5.1320	5.3284
2	20	4.1134	6.3216	7.3603	7.8990	4.0485	6.3072	7.3436	7.8843	4.0302	6.3067	7.3438	7.8843	4.068	6.3096	7.3444	7.8843
3	20	4.7868	8.3161	10.5388	11.9063	4.5044	8.2366	10.5063	11.8782	4.4207	8.2167	10.502	11.8778	4.5923	8.2594	10.5102	11.8797
4	20	5.2842	9.6494	12.8239	15.0145	4.7186	9.4019	12.7291	14.9640	4.5599	9.3292	12.7052	14.9576	4.89	9.4771	12.7521	14.9721
6	20	6.0935	11.5821	16.1290	19.7006	4.9273	10.7497	15.6756	19.4678	4.638	10.5094	15.5408	19.4035	5.257	11.0062	15.8119	19.533
1.18	24	2.6903	3.0731	3.1761		2.6857	3.0679	3.1780		2.6857	3.0679	3.1780	0.0000	2.6857	3.0679	3.1780	
1.5	24	3.3923	4.6171	5.0762	5.2928	3.3798	4.6090	5.0664	5.2810	3.3782	4.6090	5.0664	5.2810	3.3828	4.6090	5.0664	5.2810
2	24	3.9062	6.1125	7.1992	7.7779	3.8446	6.0984	7.1847	7.7615	3.8266	6.098	7.1845	7.7615	3.8621	6.1008	7.1856	7.7615
3	24	4.5104	7.9359	10.1756	11.5959	4.2469	7.8595	10.1446	11.5700	4.1684	7.8395	10.1412	11.5695	4.3282	7.87971	10.1495	11.5718
4	24	4.9626	9.1490	12.2860	14.5256	4.4343	8.8998	12.1786	14.4537	4.2870	8.8289	12.1555	14.4475	4.5927	8.9724	12.2021	14.4619
6	24	5.6846	10.8745	15.2704	18.8094	4.6155	10.0871	14.8327	18.5762	4.3478	9.8587	14.7018	18.5126	4.9196	10.3279	14.9668	18.6406
1.18	30	2.5984	3.0304	3.1583	3.2145	2.5939	3.0250	3.1517	3.2074	2.5944	3.0250	3.1517	3.2074	2.5943	3.0250	3.1517	3.2074
1.5	30	3.2216	4.4885	4.9901	5.2320	3.2091	4.4795	4.9793	5.2206	3.2075	4.4799	4.9793	5.2206	3.2121	4.4804	4.9793	5.2206

		Pile Only Model				Pile and Ground Model - Sf (by number of pipes)											
		Sf (by number of pipes)				$\lambda_c=\lambda_g$				$\lambda_c=2\lambda_g$				$2\lambda_c=\lambda_g$			
$r_b\backslash c$	$r_b\backslash r_o$	2	4	6	8	2	4	6	8	2	4	6	8	2	4	6	8
2	30	3.6746	5.8618	6.9961	7.6208	3.6160	5.8480	6.9822	7.6051	3.5993	5.8475	6.9824	7.6051	3.6336	5.85	6.9831	7.6051
3	30	4.2067	7.4982	9.7375	11.2078	3.9648	7.4238	9.7042	11.1830	3.892	7.4048	9.701	11.1821	4.04	7.4454	9.7092	11.1846
4	30	4.6001	8.5625	11.6285	13.8774	4.1252	8.3359	11.5346	13.8272	3.9902	8.2686	11.5111	13.8205	4.2698	8.4064	11.5581	13.8342
6	30	5.2403	10.0877	14.2858	17.7543	4.2789	9.3579	13.8615	17.5220	4.0359	9.1446	13.7352	17.4576	4.556	9.5836	13.9917	17.5865
1.08	40	2.1187	2.3142			2.1187	2.3109			2.1187	2.3109			2.1187	2.3109		
1.18	40	2.4810	2.9725	3.1233	3.1902	2.4786	2.9679	3.1186	3.1857	2.4786	2.9679	3.1186	3.1857	2.4786	2.9679	3.1186	3.1857
1.5	40	3.0197	4.3201	4.8709	5.1621	3.0103	4.3145	4.8633	5.1375	3.0094	4.3145	4.8633	5.1375	3.0139	4.3145	4.8633	5.1375
2	40	3.4084	5.5517	6.7235	7.4060	3.3568	5.5392	6.7180	7.3928	3.3421	5.5392	6.7180	7.3928	3.3738	5.5429	6.7180	7.3928
3	40	3.8637	6.9803	9.1959	10.7041	3.6497	6.9135	9.1652	10.6809	3.5855	6.8947	9.1618	10.6809	3.7185	6.9339	9.1717	10.6809
4	40	4.1999	7.8935	10.8470	13.0906	3.7827	7.6861	10.7599	13.0453	3.6641	7.6233	10.7381	13.0391	3.9119	7.7515	10.7857	13.564
6	40	4.7457	9.1919	13.1293	16.4722	3.9106	8.5381	12.7337	16.2519	3.696	8.3446	12.6173	16.1906	4.1524	8.7414	12.8602	16.3189
8	40	5.2060	10.1992	14.8091	18.9318	3.9729	8.9974	13.9135	18.3361	3.6838	8.6651	13.6496	18.1584	4.3108	9.362	14.1942	18.5249
1.08	48	2.0745	2.2950	2.3565		2.0745	2.2916	2.3533		2.0745	2.2916	2.3533		2.0745	2.2916	2.3533	
1.18	48	2.4083	2.9333	3.0999	3.1740	2.4117	2.9288	3.0950	3.1673	2.4117	2.9288	3.0950	3.1673	2.4117	2.9288	3.0950	3.1673
1.5	48	2.9019	4.2138	4.7915	5.0873	2.8954	4.2071	4.7835	5.0790	2.8965	4.2071	4.7835	5.0790	2.8997	4.2071	4.7835	5.0790
2	48	3.2565	5.3646	6.5608	7.2651	3.2078	5.3524	6.5498	7.2524	3.197	5.3524	6.5498	7.2524	3.2285	5.3557	6.5498	7.2524
3	48	3.6709	6.6787	8.8629	10.3884	3.4718	6.6141	8.8373	10.3683	3.4141	6.5957	8.8346	10.3683	3.5393	6.6331	8.8441	10.3683
4	48	3.9763	7.5103	10.3848	12.6102	3.5919	7.3133	10.2999	12.5675	3.4825	7.2537	10.279	12.5621	3.714	7.3748	10.3257	12.5783
6	48	4.4711	8.6865	12.4618	15.7127	3.7060	8.0771	12.0882	15.4973	3.5078	7.8972	11.9758	15.4379	3.9312	8.2669	12.2063	15.5632
8	48	4.8875	9.5965	13.9807	17.9457	3.7607	8.4870	13.1391	17.3723	3.4937	8.1765	12.9005	17.201	4.0733	8.8218	13.3139	17.552
1.08	60	2.0194	2.2711	2.3422	2.3730	2.0194	2.2681	2.3389	2.3692	2.0194	2.2681	2.3389	2.3692	2.0194	2.2681	2.3389	2.3692
1.18	60	2.3220	2.8827	3.0690	3.1530	2.3221	2.8789	3.0642	3.1486	2.3221	2.8789	3.0642	3.1486	2.3221	2.8789	3.0642	3.1486
1.5	60	2.7678	4.0856	4.6919	5.0111	2.7618	4.0792	4.6850	5.0027	2.7613	4.0804	4.6850	5.0027	2.7659	4.0812	4.6850	5.0027
2	60	3.0863	5.1464	6.3570	7.0898	3.0412	5.1363	6.3470	7.0778	3.0313	5.1361	6.348	7.0778	3.0599	5.1397	6.3496	7.0778
3	60	3.4573	6.3366	8.4782	10.0104	3.2758	6.2760	8.4525	9.9913	3.2235	6.2598	8.4499	9.9913	3.3374	6.2943	8.4592	9.9955
4	60	3.7299	7.0808	9.8553	12.0469	3.3801	6.8998	9.7747	12.0029	3.2821	6.8464	9.7523	11.9965	3.4923	6.9571	9.7988	12.0134
6	60	4.1701	8.1267	11.7109	14.8426	3.4815	7.5683	11.3587	14.6350	3.3014	7.74048	11.254	14.5781	3.6849	7.4334	11.4699	14.6972
8	60	4.5394	8.9327	13.0575	16.8386	3.5297	7.9238	12.2816	16.2904	3.2871	7.6428	12.0506	16.1289	3.8119	8.2306	12.5245	16.4593

Appendix C Publications

Publications

Some of the material presented in this thesis has been, or is in the process of being, published elsewhere. The following sections provide details of these publications.

C.1 Journal Papers

The following journal publications have been produced based on the work contained within this thesis:

Loveridge, F. & Powrie, W. Pile heat exchangers: thermal behaviour and interactions, Proceedings of the Institution of Civil Engineers Geotechnical Engineering. Accepted for publication.

Loveridge, F. A. & Powrie, W. (in review) On the thermal resistance of pile heat exchangers, Geothermics.

Loveridge, F., Wood, C. & Powrie, W. (in review) Thermal response testing for pile heat exchangers, Journal of Geotechnical and Geoenvironmental Engineering.

C.2 Ground Source Heat Pump Association Thermal Pile Standard

During the compilation of this thesis the author has been involved with the production of a standard for thermal piles on behalf of the Ground Source Heat Pump Association. The sections where the author has played a leading role are indicated below[1] and extracts are included in Appendix D.

Section 5.7 GSHP Design – refer to D.1 & D.2

Section 6 Thermal Response Testing – refer to D.3

Section 8 Thermal Pile Concrete – refer to D.4

Appendix C: Guidance Regarding Fluid Temperatures in Energy Foundations – refer to D.5

Appendix D: Concrete Conductivity – refer to D.4.1

[1] Note: At the time of printing, the Thermal Pile Standard is still under production and some of the Section and Annex headings referred to may be subject to change before final publication.

Appendix G: Thermal Properties of Soils and Weak Rocks – refer to D.2.1

C.3 Other Publications

Other publications where the author has made a major contribution include:

Perry, J., Loveridge, F. & Bourne-Webb. P. (2011). Ground Sourced Energy, *Evolution*, Winter 2011, 20-23.

C.4 Invited Presentations

The author has made the following external oral presentation on this work:

The behaviour of foundation piles used as heat exchangers. Invited presentation to the Ground Source Heat Pump Association Technical Seminar, Cambridge, 16th November 2011.

Monitoring the Crystal Ground Energy System. Invited presentation to Arup Geotechnics, London, 6th December, 2011.

Progress of thermal piles. Invited presentation to the Piling and Foundations Conference, London, 9th May, 2012.

Appendix D Extracts from Thermal Pile Standard

This Appendix contains text extracts from the Ground Source Heat Pump Association "Thermal Pile Standard, Design Installation and Materials" version 16, 23rd February 2012, where the author is the main contributor.

Thermal Pile Standard

D.1 Thermal Pile Design Considerations

Thermal piles are different from borehole heat exchangers in a number of important respects and it is important that these are accounted for in the design.

1. The layout of thermal piles is usually fixed by the structural/geotechnical design. This means that the GSHP designer is often aiming to optimise the use of the thermal piles for a given building rather than ensuring all the heating and cooling requirements are met.

2. The thermal piles also provide essential structural support to the building. Consequently the temperature limits within which the pile heat exchangers operate must be agreed with the Pile Designer. In particular it is essential to ensure that the ground must not freeze. This can be achieved in one of two ways. The simplest and most conservative way to specify a minimum flow temperature at the heat pump of +2°C allowing for a tolerance of ±2°C. However, this is unlikely to lead to optimal thermal design and in practice lower temperatures can be achieved due to the transient thermal buffering offered by the pile concrete. In order to accept lower temperatures, analysis must demonstrate that for the planned operation of the heat exchanger system, temperatures at the concrete-soil interface will not fall below zero degrees Celsius. Further discussion of appropriate temperature limits and monitoring is given in Section 14.0 [*of the standard*] and Appendix C [*see D.5 below*].

3. Thermal piles tend to be both significantly shorter and of larger diameter than borehole heat exchangers. These geometric differences mean that (1) for short time step analysis it is important to take into account the actual size and shape of the heat exchanger, and (2) for long term analysis the short length should be considered in a 3D analytical or numerical model.

4. The large volume of concrete in the pile cross section, combined with generally 50mm offset of the heat exchange pipes from the ground means that the resistance of thermal piles can be significantly greater than that of borehole heat exchangers, depending on the number of pipes installed.

5. Especially for large diameter piles with centrally placed loops the thermal storage capacity of the piles themselves may be an important contributor to the thermal efficiency of the scheme.

6. It is common to connect a number of different thermal piles together into a single pipe circuit. This can affect the heat transfer characteristics of individual pile heat exchangers and can also lead to more variable temperature fields developing in the ground.

D.2 Design Parameters

The initial ground temperature and thermal conductivity should be determined in situ using a thermal response test where practicable. For smaller schemes this may not be economic, in which case in situ temperature profiling during the site investigation combined with laboratory testing for thermal conductivity would be recommended. If the local thermal conditions are well known then it may be possible to proceed on the basis of a literature review only, but this should be verified by subsequent assessment of the system performance.

Thermal diffusivity of the ground is also a required design parameter. This is often calculated based on the thermal resistance and the volumetric heat capacity. The latter is difficult to determine by laboratory testing and assumed values are often taken. Alternatively volumetric heat capacity may be calculated based on the phase proportions of the soil as described in Appendix G [*see D.2.1 below*].

Pile thermal resistance is best determined numerically due to the complex geometry of the heat exchanger. Alternatively, some guidance is given in the SIA document D0190 (Anstett et al, 2005). Care must be taken for larger diameter piles with large thermal resistance as these may not be at steady state and hence a constant value of thermal resistance may not always be appropriate. The thermal storage capacity of the concrete in such cases may be significant.

D.2.1 Appendix: Thermal Properties of Soils and Weak Rocks

(i) Introduction

The thermal conductivity and volumetric heat capacity of the ground are key parameters for the design of thermal pile systems. The following sections contain information about typical values and also testing techniques for determining site specific values of thermal properties. The information has been restricted to soils and weak rocks as piled foundations for buildings are unlikely to be required where there is an underlying competent rock unit.

(ii) Thermal Conductivity

Typically the thermal conductivity of soils and rocks varies from around 0.2 W/mK to 5 W/mK in the most extreme cases. The thermal conductivity is controlled by the nature and proportions of the soil and rock constituents with the solid particles being the most conductive, followed by water and then air. Quartz is the most conductive mineral and soils which are rich in quartz and also saturated will have the highest thermal conductivity. MIS3005 (DECC, 2011b) provides guidance on the likely range of values to be encountered, a summary of which is given in Table D-1. In addition Downing & Gray (1986) provide details of testing on selected UK lithologies (Table D-2). However, caution should be exercised when using these numbers as most of the source boreholes used for the testing were deep exploration holes for petroleum or geothermal resources. It would therefore be expected that the samples would be of lower porosity and higher saturation than would be representative of the range of conditions relevant to shallower thermal pile systems.

Given the uncertainty in using the literature as a source of information for the thermal properties of soils, site specific testing is preferable where possible and economic. In situ thermal response testing is the most suitable means of testing (refer to Section 6.0 [D.*3 below*]) but in situ needle probe and laboratory testing may also be carried out.

Table D-1 Thermal Conductivity of Soil and Weak Rock (after DECC, 2011b)

Soil or Weak Rock	**Thermal Conductivity (W/mK)**	
	Range of quoted values	**Recommended Values**
Sand, dry	0.3 – 0.8	0.4
Gravel, dry	0.3 – 0.4	0.4
Peat, soft lignite	0.2 – 0.7	0.4
Clay/silt, dry	0.4 – 1.0	0.5
Clay/silt, water saturated	0.9 – 2.3	1.7
Gravel, water saturated	1.6 – 2.0	1.8
Claystone, siltstone	1.1 – 3.5	2.2
Sand, water saturated	1.5 – 4.0	2.4
Gypsum	1.3 – 2.8	1.6
Marl	1.5 – 3.5	1.8
Sandstone	1.3 – 5.1	2.3

Table D-2 Thermal Conductivity Values for Selected UK Lithologies (after Downing & Gray, 1986)

Formation	**Number of Tests**	**Thermal Conductivity (W/mK)**
London Clay – sandy mudstone	5	2.45 ±0.07
Lambeth Group – sandy mudstone	4	2.33 ± 0.04
Lambeth Group – mudstone	10	1.63 ± 0.11
Chalk	41	1.79 ± 0.54
Upper Greensand - sandstone	18	2.66 ± 0.19
Gault – sandy mudstone	32	2.32 ± 0.04
Gault – mudstone	4	1.67 ± 0.11
Kimmeridge Clay	58	1.51 ± 0.09
Oxford Clay	27	1.56 ± 0.09
Mercia Mudstone	225	1.88 ± 0.03
Sherwood Sandstone	64	3.41 ± 0.09
Westphalian Coal Measures – sandstone	37	3.31 ± 0.62
Westphalian Coal Measures – siltstone	12	2.22 ± 0.29
Westphalian Coal Measures – mudstone	25	1.49 ± 0.41
Westphalian Coal Measures – coal	8	0.31 ± 0.08
Millstone Grit	7	3.75 ± 0.16
Carboniferous limestone	14	3.14 ± 0.13
Old Red Sandstone	27	3.26 ± 0.11
Hercynian Ganites	895	3.30 ± 0.18
Basalt	17	1.80 ± 0.11

(iii) Laboratory Testing

Most laboratory testing techniques for soils are based on establishing steady state conditions in the sample and measuring the temperature gradient and/or heat flow across the sample. In 2008 Clarke et al developed a testing method specifically for use with samples resulting from current UK site investigation practice. This method, available from testing laboratories in the UK is recommended for the laboratory testing of most soils and weak rocks.

An alternative method, based on more rapid transient techniques may also be used. The needle probe (IEEE, 1996) can be used either in the laboratory or *in situ* on site and involves pushing the probe into a specimen. The needle is then subject to a heat pulse and the resulting temperature changes are recorded and used to calculate the thermal conductivity. The principal of operation is identical to that of an in situ thermal response test, but the scale of the test is much smaller. The advantages of this method over the Clarke et al (2008) test are its speed and the ability to carry out testing in situ. Being transient the test is also less likely to cause moisture migration, which may affect the test result in unsaturated soil. However, given the size of the needle (typically no more than a few millimetres) the test is only applicable in fine grained soils.

(iv) Volumetric Heat Capacity

Volumetric heat capacity for most minerals and impervious rocks is around 2.3 MJ/Km^3 ± 20% (Roy et al, 1981). Given that water has a volumetric heat capacity almost twice this (around 4.2 MJ/Km^3) and air around three orders of magnitude less, then the phase proportions of a soils are important in determining the overall volumetric heat capacity.

Measuring volumetric heat capacity directly is extremely challenging (Waples & Waples, 2004) and can lead to unreliable results. Rock fragments can be tested relatively rapidly and accurately according to the method of Scharlie & Rybach (2001). However, for soils, it is recommended to use the following equation based on the proportion of soil components:

$$S_{cv} = \chi_{solid} S_{cv(solid)} + \chi_{water} S_{cv(water)} + \chi_{air} S_{cv(air)}$$

where χ is the volume proportion of the phase component and S_{cv} is the volumetric heat capacity. Given the low value of $S_{cv(air)}$ it is common to neglect this phase.

D.3 Thermal Response Testing

(i) Aim of the Test

Thermal Response Testing is carried out to provide accurate information about the thermal properties of the ground where thermal piles are being constructed in order to enable the GSHP designer to optimise the energy exchange for a specific installation. For small schemes it may not be economic to carry out a test compared to adopting conservative thermal properties during design. However, for larger schemes, or in situations where there is uncertainty regarding the in situ thermal properties then it is recommended that a thermal response test is carried out. Using test measured thermal conductivity increases the thermal loop thermal modelling precision and therefore assists with optimising the running efficiency of the heat pump system.

For thermal piles it is also desirable to gain an understanding of how the pile will respond structurally and geotechnically to the thermal changes imposed on it during operation. This can be achieved by extending the scope of a thermal response test to include measurement of strain and temperature within the pile over a heating and cooling cycle.

(ii) Testing Strategy

As piles have a larger diameter and hence a greater heat storage capacity than borehole heat exchangers, it is not always possible to carry out thermal response test directly on a thermal pile heat exchanger within an economic timescale. Consequently the following options are recommended:

1. Where the potential for use of thermal piles have been identified at an early stage, a site investigation borehole may be equipped with a single U-tube and used to carry out a thermal response test. This will allow determination of the ground thermal properties. Refer to Section (iii) for further details.

2. Where the thermal piles are to be no greater than 300mm in diameter then a thermal response test may be carried out using the pile, adopting the same methods as for a borehole heat exchanger. Refer to Section (iv) for further details.

3. Where the thermal piles to be constructed are larger than 300mm in diameter then a bespoke thermal test, likely to be of greater duration and requiring more sophisticated interpretation techniques can be carried out. Refer to Section (v) for further details. Alternatively, a borehole can be tested at site investigation stage as indicated above.

4. Pile thermal load test. To determine the stress-strain behaviour of a pile during heating and cooling one of the test types above could be extended to include both heat injection and heat rejection to the pile while it is maintained under load. Monitoring of the temperatures and strain developed within the pile itself then allows assessment of the stress-strain response of the pile as well as its thermal characteristics. Refer to Section (vi) below for further details.

Where thermal response testing is carried out in a thermal pile it is recommended to do so in a preliminary test pile if possible. This provides time in the construction programme to allow for the pile to reach equilibrium with the surrounding ground temperature before testing and also allows time for the findings of the test to be incorporated into the design.

If a working (or contract) pile is to be subject to a thermal response test then it may not be possible for any assessments of the stress-strain behaviour to be incorporated into the design of the structure. Thermal properties may still be incorporated into the assessment of heating and cooling capacity at this stage.

(iii) Borehole Thermal Response Test

Borehole thermal response tests should be conducted in accordance with the procedure set out in Section 5 of the Vertical Borehole Standard (GSHPA, 2011) and European Committee for

Standardization document TC 341 WI 00341067.6 (submitted to CEN Enquiry) prepared by CEN/TC 341 'Geotechnical Investigation and Testing'. The test hole should comprise a U-bend pipe grouted in a borehole no larger than 200mm diameter with high thermal conductivity grout. Heated water is pumped through the thermal loop under turbulent flow and feed and return temperatures are monitored over a specified duration in order to determine the thermal properties of the soil.

Key determinants of the test are:

1. Average undisturbed formation temperature
2. Average ground thermal conductivity

With additional knowledge of the geology, other parameters such as specific heat capacity can be derived from other tests and/ or published values. Density would also be determined from other site investigation work. These parameters along with the test derived thermal conductivity can be used to calculate the ground thermal diffusivity.

In order to use the information from a borehole TRT in the design of thermal piles, the depth range over which the test is carried out should be similar to the depth of the proposed piles. If the piles are to have a cut off level below the existing ground level then it may be necessary to insulate the top section of the borehole which is above the cut off level, such that this does not affect the test result. If the thermal piles are likely to be of varying length then the GSHP Designer will need to make a judgement about an appropriate test depth and range, or if the pile length variation crosses geological boundaries, then consideration should be given to conducting more than one test in boreholes of different depths.

As thermal piles are typically much shorter than boreholes greater consideration must be given to the surface effects of heat loss from the thermal pile and also the above ground test equipment. The heat injection creates a thermal funnel effect around the pile, where isotherms are significantly curved at the ground surface due to the effect of this boundary. This effect results in increased error within the accuracy of the calculated thermal conductivity. Test methods must also be employed to determine the extent of the heat loss from the above surface test apparatus, so this can then be accounted for in the calculations.

It is also possible to use borehole thermal response tests to determine the borehole thermal resistance. This interpretation is not necessary in this case as the thermal piles will have a different thermal resistance.

(iv) Pile Thermal Response Test (Up to 300mm Diameter)

Due to cost and time constraints it is only practicable to physically test thermal piles up to 300mm diameter. Such tests are closely allied to the common borehole TRT except the pile itself is considered to be the borehole thermal resistance element.

Key determinants of the test are:

1. Average undisturbed formation temperature

2. Average ground thermal conductivity

3. Pile thermal resistance (calculated with additional knowledge of the soil density and specific heat capacity.

This test is therefore broadly as detailed in Section 5 of the Vertical Borehole Standard (GSHPA, 2011) with the exceptions and variations described in the following paragraphs.

The test duration shall be extended to allow the thermal resistance of the pile to be overcome and evaluated, and thereafter to allow an accurate measurement of the thermal properties of the ground. Consideration should be given to installing a thermistor and strain gauge array within the pile, with thermistors attached to a lantern detail to allow temperatures at the soil/pile interface to be measured together with temperatures and strains within the pile.

The test should not be started until 60 days after the concrete has been poured to allow the pile temperature to reach equilibrium with the standing temperature of the ground. It may be possible to use a shorter wait period if thermistors are cast into the concrete to allow monitoring of the temperature stabilisation.

The thermal response test shall be initiated without heating elements switched on. The temperature measurement shall be logged as the liquid enters and exits the loop, immediately after start-up and for a minimum of 60 minutes, or until equilibrium has been reached.

Testing shall comprise the application of controlled heat to the closed-loop for the duration of the test. Specific requirements for the monitoring and provision of heat and power to the circulated fluid are that:

1. The collected data shall be analysed using the line source method. Other methods, such as the cylindrical heat source method or using a numerical algorithm may be considered.

2. If the test is interrupted during the heating period or needs to be retested, a re-stabilisation period shall be allowed before a further test is conducted. The re-test shall not begin until the thermal loop temperature has returned to within 0.28°C of the average undisturbed temperature of the thermal pile at the commencement of the test.

3. The results of the test shall be analysed by personnel fully conversant and trained in the line source analysis method with suitable qualifications.

(v) Pile Thermal Response Test (Greater than 300mm Diameter)

In most cases, for piles above 300mm diameter, either a standard TRT should be carried out in a traditional borehole of appropriate length (see Section (iii)), or data from a detailed desk study of the geology, hydrogeology & thermogeology augmented by site sample testing should be used. In such cases, post installation monitoring should always be used to refine the design and confirm the assumptions used by the designer especially if no in situ TRT has been conducted.

Alternatively, if economically viable on a large scheme, bespoke pile thermal response testing may be carried out.

Large Diameter Bespoke Pile TRT

For large schemes where it may be considered beneficial to test the thermal behaviour in situ then larger diameter piles may be subject to a thermal response test, providing that the test duration can be extended sufficiently to allow the thermal resistance of the pile to be overcome. This should generally be regarded as a bespoke test, where the method is to be developed according to the piles to be tested and the proposed interpretation technique. Greatly extended test times could be required, as it is generally recommended that for times less than t_1 the initial test data should be discarded when using line source interpretation methods.

$$t_1 = \frac{5{r_0}^2}{\alpha}$$

Other interpretation methods may allow the testing time to be reduced, but this would need to be demonstrated for the situation being considered.

Large Diameter Piles with Centrally Places Loops

For the special case of large diameter (>1200mm) piles where the thermal loops are placed in the centre of the pile, then a standard thermal response test, as described in Section 5 of the

GSHPA Vertical Borehole Standard (September 2011), can be utilised to measure the thermal conductivity of the concrete rather than the ground. This may be useful in determining both the thermal resistance of the borehole and any contribution which the pile makes to diurnal heat storage.

It is important that such thermal response tests are not used directly to determine the thermal resistance of the pile as a steady state will not have been reached within the timescale of the test and hence any results would be erroneous.

(vi) Pile Thermal Load Test with Strain Measurement

A fully instrumented load test (e.g. as carried out at Lambeth College and described by Bourne-Webb et al, 2009) on a thermal pile will provide the most precise and realistic data for both the geotechnical and thermal design of thermal piles. Strain gauges and temperature gauges positioned down the length of the pile can be used to show the combined effect of applied load with heating and cooling cycles on shaft friction, axial force and pile head movement. The test pile diameter and materials used should be similar to the proposed thermal piles so that the interface effects at the soil/pile boundary can be accounted for. A prolonged period of monitoring with temperature variations similar to that of the proposed scheme is recommended so that the long term performance of the pile can be assessed rather than the short term effects that would be produced by a rapid load test with extreme temperature fluctuations. Instrumentation types (including strain gauges, thermistors and piezometers) and positions should be chosen to ensure that sufficient data is available for back analysis of the pile test.

D.4 Thermal Pile Concrete

(i) General

Concrete thermal conductivity is an important aspect of thermal pile design as it will influence the transfer of heat within the pile. Where possible the designer should ensure high conductivity materials are used in the concrete mix design. However, it is recognised that the final mix design will be a balance of the structural, constructability and thermal needs of the pile. The viability of importing aggregate over long distances should also be considered.

(ii) Concrete Thermal Conductivity

Concrete thermal conductivity depends mainly on the aggregate lithology, aggregate volume ratio and concrete water/cement ratio. In order to maximise the thermal conductivity high aggregates volumes with high quartz content should be used. Generally the use of admixtures and cement replacement products may reduce the thermal conductivity. However, initial research suggests that use of PFA may enhance the thermal properties.

In the absence of specific information regarding the aggregate type and proportions then experience suggests that thermal conductivity of pile concrete should not be assumed to be greater than 1.5 W/mK. Where it is known that a high volume of siliceous aggregate has been used in the concrete mix then higher values may be adopted (refer to Appendix D [D*.4.2 below*]). If the design of the thermal pile scheme is shown to be sensitive to the concrete thermal conductivity then consideration should be given to testing of the design mix.

Concrete thermal conductivity can be determined by the following tests:

- BS EN ISO 12664:2001 Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Dry and moist products of medium and low thermal resistance.
- BS EN ISO 12667:2001 Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Dry and moist products of high and medium thermal resistance.
- ASTM C177 Test method for steady state heat flux measurement and thermal transmission properties by means of the hot guarded plate apparatus.
- ASTM C518 Test method for steady state heat flux measurement and thermal transmission properties by means of heat flow meter apparatus.
- ASTM C1363 Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus

As these test methods involve samples in an oven dry conditions and pile concrete is likely to be saturated once installed in the ground, correction of the test results will be required. Suggested methods are given in the American Concrete Institute Report 122R-02, "Guide to Thermal Properties of Concrete and Masonry Systems" (ACI, 2002) and CIBSE "Guide A, Environmental design, Chapter 3: Thermal properties of building structures" (CIBSE, 2006).

D.4.1 Appendix: Concrete Conductivity

The thermal conductivity of concrete is a key material parameter in controlling the internal heat transfer behaviour of thermal piles. Along with the geometry it determines the thermal resistance of the pile when it is at a thermal steady state. For shorter term transient heat fluctuations, the thermal conductivity, along with the volumetric heat capacity, dictates the temperature changes within the pile due to imposed heating or cooling power.

There is a general impression that concrete has advantageous thermal properties which encourage heat transfer. However, the thermal conductivity of concrete can cover a wide range of values, from little over 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 (Tatro, 2006). Concrete piles installed in clay soils or in any geological conditions below the water table are likely to be saturated. Neville (1995) reports typical values of saturated concrete thermal conductivity between 1.4 W/mK and 3.6 W/mK. Piles installed in dry sands may have a lower thermal conductivity than these values owing to the reduced water content.

Many studies have considered the thermal conductivity of concrete, but few studies record all of the important variables (cement-aggregate ratio, aggregate type, moisture content). In addition cement replacement products can also affect the thermal conductivity. Assuming that pile concrete is typically saturated, the following sections consider the impact of the different variables on thermal conductivity before some recommendations are made about values for use with energy piles.

(i) Aggregate Type

Concrete thermal conductivity is dependent on the thermal conductivity of its constituents. Consequently, aggregates which can range in thermal conductivity from 2 W/mK to 7 W/mK, play an important role in determining the overall thermal conductivity of the material. Typical concrete aggregates in order of their thermal conductivity are given in Table D-3 below. Quartz rich aggregate will lead to a higher thermal conductivity aggregate compared to limestone rich aggregate concrete. Many publications, e.g. Neville, (1995), Tatro (2006) and Barmforth (2007), give values for the thermal conductivity of concrete containing different aggregate lithologies (see also Table D-4), but without also providing details of the aggregate proportions it is not possible to compare these sources.

Table D-3: Aggregate Thermal Conductivities (after Lane, 2006, Clarek, 1966, Khan, 2002, Cote & Konrad, 2005)

Rock type	Thermal Conductivity (W/mK) Range of quoted values
Quartzite	5.0 – 7.4
Dolomite/Dolostone	3.8 – 5.0
Siltstone	3.5 – 5.2
Sandstone	3.0
Granite (quartz monzonite)	2.8 – 3.6
Granite	2.5 – 3.8
Granodiorite	2.6 – 3.5
Amphibolite	2.6 – 3.8
Diabase (dolerite)	2.3 – 3.4
Gneiss	2.0 – 4.4
Limestone	2.0 – 3.0
Shale	2.0
Basalt	1.7 – 4.3

Table D-4: Thermal Conductivity by Aggregate Type (Bamforth, 2007)

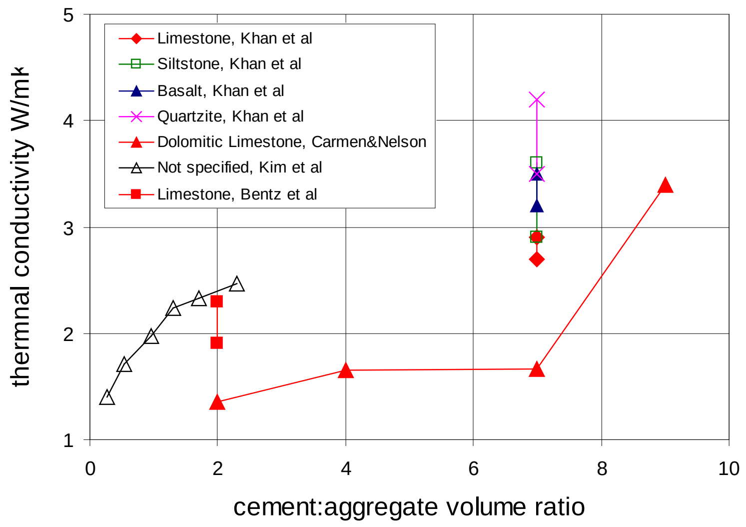
Aggregate Type	Thermal Conductivity of Concrete (W/mK)	
	Sand and aggregate from same rock type	Aggregate from defined rock type with siliceous sand
Quartzite and siliceous gravels with high quartz content	2.9	2.9
Granite, gabbros, hornfels	1.4	2.0
Dolerite, basalt	1.3	1.9
Limestone, sandstone, chert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

(ii) Cement Aggregate Ratio

Neat cement paste has a thermal conductivity of around 1.2 W/mK (Tatro, 2006). Consequently, the higher the aggregate proportion in a concrete mix the greater thermal conductivity it will have. Figure D-1 plots the thermal conductivity of different concrete mixed where both the cement :aggregate volume ratio, and in most cases the aggregate lithology are know. The total aggregate volumes has been used in this assessment, i.e. both coarse aggregate and fine aggregate (sand).

For typical piling mixes high strength, and therefore high cement contents will be required. This means that pile concrete is likely to fall in the centre or on the left hand half of Figure D-1 depending on the cement:aggregate volume ratio. Although this may vary depending on the project specific requirements, 1:4 would be typical. It is also important to consider that the main coarse aggregate and the sand used in the mix may have different sources. The potential effect of this is highlighted in Table D-4 (although it should be noted that these data not provide information pertaining to the overall aggregate proportions used).

Figure D-1: Concrete Thermal Conductivity by Aggregate Type and Ratio (after Carmen & Nelson, 1921, Kim et al, 2003, Bentz et al, 2011 and Khan, 2002)

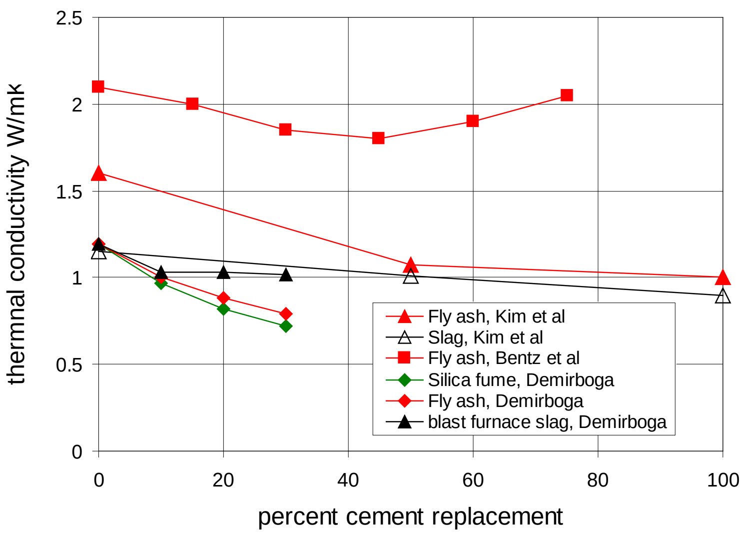


(iii) Cement Replacement Products

Figure D-1 and the foregoing text assume that no cement replacement products have been used. Recent studies (Kim et al, 2003, Bentz et al, 2011, Demirboga, 2007) have shown that use of fly ash or silica fume as a cement replacement will reduce the thermal conductivity of the concrete by up to 25%. The effect of blast furnace slag is less conclusive, with smaller changes in properties observed.

Studies of heat transfer rates by Patel & Bull (2011) suggest that concrete mixes using fly ash as a cement replacement product will absorb more heat in a shorter time. This may be because, while the thermal conductivity is reduced due to the presence of the fly ash, the reduced density of the material results in a higher thermal diffusivity. Xu & Chung (2000) also attempted to determine appropriate mixes which would improve the thermal properties of concrete. They confirmed that the use of silica fume would reduce the thermal conductivity, but found that used in combination with small amounts of silane, both the thermal conductivity and the specific heat capacity would be increased. Silane has previously been used to coat admixtures, but is rarely used as an admixture itself. Inclusion of 2% silane was shown to increase the thermal conductivity by 38% and increase the specific heat by 50%. Given that many concrete mixes for pile applications use cement replacement products to improve workability, further research into the overall effect this has on heat exchanger effectiveness would be beneficial.

Figure D-2: Concrete Thermal Conductivity by Cement Replacement (after Kim et al, 2003, Bentz et al, 2011)



Note: assumes cement aggregate ratio of 1:2, except Kim et al (2003) where no aggregate used; aggregate type not specified, except Bentz et al where limestone used.

(iv) Temperature Dependence

Thermal conductivity of concrete reduces with temperature (Morabito, 1989). The results present in the above sections consider testing at ambient laboratory conditions (around 20°C). Kim et al (2003) carried out testing in the range of 20°C to 60°C and found the results to vary by less than 0.2 W/mK within this range. More detailed studies have shown the variation in thermal conductivity to be proportional to temperature within the range of -20°C to 100°C (Morabito, 2001). The proportionality constant is not influenced by the type of cement but is dependent on the type of aggregate. Values up to around -0.004 K^{-1} were reported. This is consistent with the Kim et al results and suggests a potential variation of less than 0.2 K^{-1} over the range of operation of ground energy systems. This is likely to be less in magnitude than uncertainties relating to other factors.

(v) Recommendations

Based on the proportion and type of aggregates likely to be used in pile concrete mixes, it is unlikely that the thermal conductivity would be in excess of 2.5 W/mK. In many cases, with low thermal conductivity aggregate, low aggregate ratios and the presence of admixtures, the value may in fact be much lower. Consequently, for conservative design purposes, with no recourse to specific testing, values less than 1.5 W/mK are recommended. Where the aggregate is known to be siliceous, with a cement:aggregate volume ratio of at least 1:4, then larger thermal conductivities, in the range 1.5 W/mK to 2.0 W/mK may be used.

D.5 Guidance Regarding Fluid Temperatures in Energy Foundations

A number of publications (eg Brandl, 1998, 2006) highlight the need to prevent freezing of the soil or the soil-pile interface during operation of thermal piles or other foundation heat exchangers. However, there are few sources of guidance with respect to control limits for fluid temperature to prevent this occurring. Below, the relevant criteria from three sources of design guidance are summarised. Whilst one provides no guidance about the means to prevent freezing, two suggest the approach of ensuring that the fluid returning from the heat exchangers does not fall below 2°C. Exceptions from this simple and conservative approach should only be given if design calculations can demonstrate that lower fluid temperatures are possible without freezing the ground and that operational control systems are in place to prevent minimum fluid temperatures from being exceeded.

To understand the temperature difference between the fluid and the ground an appreciation of the internal behaviour of the pile is required, and this is often characterised in terms of thermal resistance. The thermal resistance will depend on the size of the pile and the number and arrangement of pipes within the pile cross section. Some guidance in this respect is given by the Swiss Society of Engineers and Architects (Anstett et al, 2005). The temperature difference is then the produce of the heat flux (per metre length of the pile) and the thermal resistance. In extreme cases the temperature difference can be up to 10°C (Anstett et al, 2005), but is more likely to be only a few degrees.

To apply a thermal resistance to the analysis of the temperature difference between the fluid and the pile assumes that the pile is at steady state. This is reasonable for longer timescale temperature variations. However, for short duration thermal pulses, which are most likely to result in lowering of the fluid temperature below 0°C, then the pile concrete will behave in a transient manner and act as a buffer to transfer of the heat to/from the ground. In effect, for such short duration pulses, the short term heat storage capacity of the pile is important. This contributes to the ability of the pile to protect the ground from freezing as long as the peak thermal heating requirements are short lived. It is due to these effects that it has been shown to be acceptable to use fluid temperatures as low as -1°C (Brandl et al, 1998) and still prevent ground freezing.

(i) SIA D 0190 (Anstett et al, 2005)

Under principles of design, the SIA guide takes the approach that the return temperature of the fluid in circulation should not fall below zero with a 2°C safety margin. However it later states that a lower return temperature could be permitted if an appropriate control system is in place to prevent to pile-soil interface freezing. Later in the text the guide is more ambiguous simply stating the minimum fluid temperature must be fixed at 0°C. Relevant quotations are given below:

Paragraph 2.7:

"In all cases, except with special permission from the civil engineer, the temperatures imposed on the geostructures must remain positive, with a margin of 2°C.

"Operational returning temperatures of the fluid will be maintained with a 2°C safety margin with absolute reliability. This is for the security of the foundations and hence the security of the structure of the building which they support.

"A lower return temperature is eventually possible if a control system can guarantee that at all times the pile soil boundary does not fall below 0°C."

Paragraph 7.2

"Variation of the temperature of the heat transfer fluid must be compatible with the static mechanical design of the foundation.

"Minimum temperature fixed at 0°C to prevent freezing of the structure. It should be higher than this unless antifreeze is also used."

(ii) VDI 4640 Blatt 2 Entwurf (Design) 1998

The VDI document "Thermal use of the underground" (VDI, 2009) does not extensively discuss use of piles as heat exchangers. It considers the design to be analogous to that for boreholes, but with the exception that freezing temperature should never be reached.

(iii) NHBC Efficient design of piled foundations for low-rise housing Design guide

The NHBC guide (NHBC, 2010) also outlines the principle of prevention of freezing and recommends that fluid temperatures do not fall below 2°C:

"One particular precautionary principle, however, is that the pile must not be allowed to freeze. If the coolant is circulated at temperatures below freezing point, then it will be necessary to demonstrate that the freezing front does not reach the soil interface. It is recommended that geothermal pile fluid circulation temperatures range from ambient ground temperatures down to no less than 2°C."

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