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Thermal response testing through the Chalk aquifer in London, UK

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Thermal conductivity of the ground is an important parameter in the design of ground energy systems, which have an increasing role to play in providing renewable heat to the built environment. For larger schemes, the bulk thermal conductivity of the ground surrounding the system is often determined in situ using a thermal response test. Although this test method is commonly used, its limitations are often not fully understood, leading to an over-simplistic interpretation that may fail to identify key facets of the ground thermal behaviour. These limitations are highlighted using data from an instrumented thermal response test carried out in a 150 m deep borehole in east London. It is shown that a single, unique value of bulk thermal conductivity may not be appropriate, as stratification of the ground can lead to differences in thermal performance, depending on the direction of heat flow. Groundwater flow within the Chalk aquifer is also shown to have an important effect on the long-term heat transfer characteristics.

Notation

f	friction factor
h_i	heat transfer coefficient (between fluid and pipe)
Nu	Nusselt number
Pr	Prandtl number
p	power used to calculate p-linear average
q	heat flux per unit depth
R_b	borehole thermal resistance (mK/w)
R_{grout}	grout thermal resistance (mK/w)
R_p	pipe thermal resistance (mK/w)
R_{pcond}	pipe conductive resistance (mK/w)
R_{pconv}	pipe convective resistance (mK/w)
Re	Reynolds number
r	radial coordinate (m)
r_b	borehole radius (m)
r_i	pipe internal radius (m)
r_o	pipe outside radius (m)
S_{cv}	volumetric heat capacity (mJ/m^{3}K)
t	time since start of test (s)
t'	time since start of recovery phase (s)
t_{min}	minimum time after which line source approximation is valid (s)
u	integration parameter
α	thermal diffusivity (m^2/s)
γ	Euler's constant
ΔT_f	change in fluid temperature (°C)
ΔT_g	change in ground temperature (°C)
ΔT_{in}	change in loop inlet temperature (°C)
ΔT_{out}	change in loop outlet temperature (°C)
ΔT_p	change in pipe temperature (at r_o) (°C)
$\Delta T_{p\text{-linear}}$	change in fluid temperature (p-linear average) (°C)
ΔT_{rb}	change in temperature at $r = r_b$ (°C)
λ	thermal conductivity (W/mK)
λ_{fluid}	thermal conductivity of fluid material (W/mK)
λ_{pipe}	thermal conductivity of pipe (W/mK)

1. Introduction

The use of ground energy systems to provide renewable heat energy to buildings is increasing, with the UK government's renewable heat incentive (DECC, 2011) set to accelerate installation of systems for new building developments. Ground energy systems work by seasonal storage of heat in the ground. In closed-loop systems plastic pipes are cast into the ground (the ground loop), often in deep boreholes, and fluid is circulated through the pipes in order to transfer heat to or from the ground. The pipes are connected to the building heating and cooling system via a heat pump. In winter, a small input of electrical energy to the heat pump increases the temperature of the fluid to a level suitable for the delivery of usable heat to the building. In summer the heat pump can be used to reduce the temperature of the fluid returning from the air-conditioning system before recirculation through the ground loops.

1.1 Thermal response tests

Thermal conductivity is a key parameter for the design of closed-loop ground energy systems. It is often determined in situ by carrying out a thermal response test (ASHRAE, 2002; Sanner *et al.*, 2005). The test involves circulating a heated fluid around the ground loop in a single borehole heat exchanger for a period of 2–3 days. Changes in the fluid inlet and outlet temperatures are recorded over time, together with the heating power input. By assuming that the borehole heat exchanger is acting as an infinite line heat source, the thermal conductivity can be assessed. Although this is not a perfect representation of the real conditions in the ground, it has been shown that this assumption is appropriate in many cases. However, the limitations and any uncertainty resulting from the rest should also be assessed (Banks, 2008), and reported alongside the derived thermal conductivity.

For an infinite line heat source with a constant heat injection rate per unit depth of the borehole, q (W/m), the temperature change in the ground, ΔT_g (°C), with time, t (s), is given by (Carslaw and Jaeger, 1959)

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

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 (= 0·5772). To determine the average temperature change of the fluid (ΔT_f), the heat transfer within the borehole must be accounted for and therefore an extra term must be added

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

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

The first term gives the temperature change between the fluid and the edge of the borehole, and is calculated based on the thermal resistance of the borehole, R_b. The second term in Equation 2 is the temperature change at the borehole edge ($r = r_b$), calculated according to Equation 1.

In accordance with Equation 2, the gradient of a graph of 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 y-axis intercept, provided an assumption is made regarding the value of volumetric heat capacity (S_{cv} in J/m^3K) used to derive the thermal diffusivity

$$\alpha = \frac{\lambda}{S_{cv}} \quad (3)$$

1.2 Limitations

The line source theory underlying Equation 2 is based on some key assumptions. The first is that the borehole is infinitely long and thin. Although this is not the case in reality, analysis shows that for typical borehole geometries, where the length-to-diameter ratio is greater than 500, the finite length of the borehole does not become important until heat injection has continued for some decades (Loveridge and Powrie, 2013). Similarly, for a small-diameter borehole (<150 mm), the effect of the finite size of the cross-section results in less than 5% error in predictions of temperature change, provided the time period is greater than half a day (Philippe *et al.*, 2009).

The line source approach also assumes that the rate of heat transfer, q, is invariant along the length of the borehole, that the ground is homogeneous and isotropic, and that there are no external influences such as advection due to groundwater flow. How closely these conditions are approached for any individual test will affect the reliability of the test result. Typically, thermal response tests are considered to be accurate to within 10% (Pahud, 2000; Signorelli *et al.*, 2007; Spitler *et al.*, 2000) when analysed in this way. However, there is a tendency in practice to make a rapid, single-value determination of the ground bulk thermal conductivity, with little consideration given as to whether the boundary conditions of the interpretation method are met.

This paper examines in detail the results from a 150 m deep thermal response test carried out in east London. It is shown that although reasonable results can be obtained from using a line source method to interpret a thermal response test, these must be tempered by an understanding of the limitations of the test method and the interpretation techniques. In particular, a single-value approach to thermal conductivity may not always be appropriate.

2. Test details

2.1 Site description

As part of a new development in east London, a field of borehole heat exchangers was installed to 150 m depth. The boreholes are 127·5 mm in diameter, and were constructed through the full sequence of London Basin deposits (Table 1). Each borehole contains a single U-loop of plastic pipe, of internal diameter 33 mm. The boreholes are spaced at approximately 5·5 m, and were backfilled with fine to medium chert gravel below the base

Top of stratum: mbgl	Main stratum	Description	Thermistor levels: mbgl
0	Made ground (MG)	Fine to coarse brick and concrete gravel	0·5
		Soft to firm black sandy gravelly clay	2·0
3·3	Alluvium (Al)	Very soft clayey silt, sandy clay and peat	5·5
6·2	River Terrace Deposits (RTD)	Medium dense silty fine to coarse sand and fine to coarse gravel (mainly flint)	8·5
11·2	London Clay (LC)	Stiff thinly laminated fissured silty clay with silt partings	17·5
23·5	Lambeth Group (LG)	Laminated Beds: silty fine sand	25·5
		Lower Shelly Beds: fissured silty clay	38·5
		Lower Mottled Beds: clayey sandy silts and silty fine sands	
		Upnor Formation: very dense green sand	
43·3	Thanet Sands (TS)	Very dense, slightly silty fine sand	48·5
56·1	Chalk (Ch)	Medium density (grade B3 chalk)	63·5
		Subhorizontal and subvertical medium-spaced clean fractures	78·5
			98·5
			118·5
			133·5
			146·5

Table 1. Ground conditions and thermistor levels

of the Lambeth Group. This high-permeability backfill was used to take advantage of the potential for flowing groundwater to enhance the heat transfer characteristics of the borehole. Above the base of the Lambeth Group the boreholes were backfilled with thermally enhanced grout, comprising a bentonite and silica sand mix. Fourteen thermistors were installed over the full depth (Table 1) of one of the boreholes, being attached to the U-loop during installation. The borehole was then subjected to a thermal response test to determine the ground thermal conductivity and borehole thermal resistance.

2.2 Thermal response test rig

A schematic of the thermal response test rig is shown in Figure 1. The rig contains a pump for recirculating the fluid in the ground loop, a flowmeter to measure the recirculation flow rate, and a header tank to maintain the fluid level in the ground loop. Three electrical heaters, in this case of 6 kW, 3 kW and 2 kW, can be used in any combination to apply a fixed heat input to the fluid. A power meter is used to measure the electrical power input to the heaters and the pump. Temperature sensors measure the fluid temperature entering and leaving the ground loop, the external atmospheric temperature and the rig internal temperature. The temperature sensors, along with the flowmeter and power meter, are connected to a data logger for automated monitoring. Both the pipework within the rig and the rig enclosure are insulated to minimise external temperature effects.

2.3 Thermal response test procedure

A thermal response test typically consists of five stages, as shown in Table 2. To establish the ground thermal profile, a mobile thermistor string with measuring points at 5 m intervals is slowly lowered into one side of the ground loop, so as to cause as little disturbance as possible to the water column. The string is left in place until the readings have stabilised, and is then lowered progressively further until the whole depth of the borehole has been covered (stage 1). In this case, as the borehole is also equipped with permanent, cast-in-place thermistors within the borehole backfill (Table 1), these can be used to provide a further check on the ground temperature profile, albeit with less resolution. Once the mobile thermistor string has been removed, the thermal response test rig is connected to the ground loop. It is important that there is no trapped air in the loop, therefore the fluid is recirculated at a high flow rate to purge any air from the system (stage 2). To minimise external environmental effects, the pipes between the rig and borehole are kept as short as possible, and are well insulated.

After purging of the air, the initial circulation phase of the test starts (stage 3). This has two purposes: to ensure that the fluid and the ground have reached equilibrium, and to confirm the average ground temperature over the depth of the borehole. Initial circulation should continue until a thermal steady state is achieved, as measured by equal inlet and outlet temperature (T1 and T2 in Figure 1). These temperatures should also correspond to the mean value of the results from the thermistor string used in stage 1. Stage 3 typically requires 2–12 h. In this test, circulation was allowed to run overnight for approximately 15 h.

With circulation continuing, a fixed heat input is applied (stage 4) – in this case 8 kW. This phase should continue for a minimum of 50 h (Sanner *et al.*, 2005); in the current test, heat was applied for approximately 53 h. During the recovery phase (stage 5),

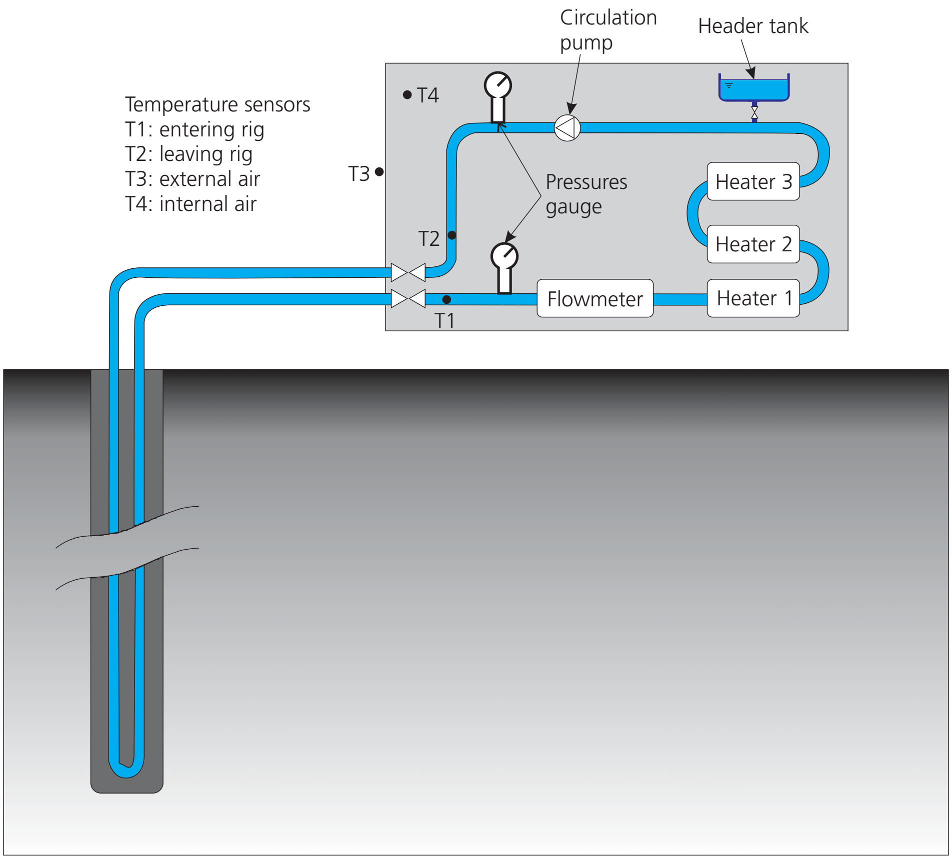

Figure 1. Thermal response test rig

Stage	Purpose	Method	Typical duration: h	Duration this test: h
1	Set up; establish initial thermal (temperature) profile in ground	Lower thermistor string down borehole	–	–
2	Purge air from system	Fluid circulation at high flow rate	–	–
3	Establish equilibrium between fluid and ground Confirm average ground temperature	Initial circulation of fluid	2–12	15
4	Determine thermal conductivity and thermal resistance during heat injection	Continued circulation of fluid with constant heat input	50–60	53
5	Confirm thermal conductivity during recovery	Continued circulation of fluid with no heat input	12–24	21

Table 2. Thermal response test stages

circulation of the fluid continues with no heat input. The duration of this phase of the test is typically 12–24 h, and in this case was approximately 21 h.

3. Test results

Figure 2 shows the test data; the heated fluid was subjected to a change in temperature of approximately 16°C before the heaters were switched off. While the nominal applied heating power was 8 kW, the actual applied power can be calculated from the temperature difference between the inlet and outlet pipes, the flow rate measured on the rig, and the specific heat capacity of the fluid. An hourly moving average of the actual applied power is also shown in Figure 2, with values in the range $8 \pm 0{\cdot}025$ kW for the main period of heat injection (the early part of the test data is not analysed, as described in Section 3.1 below).

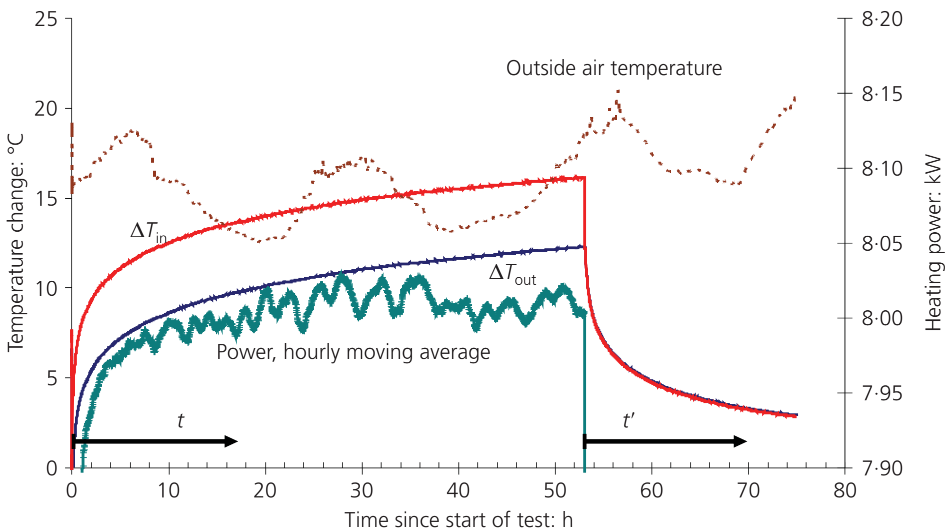

Figure 2. Thermal response test data

Figure 3(a) shows the undisturbed ground temperature profiles measured by the mobile thermistor string during stage 1 of the thermal response test, along with the permanent thermistor readings prior to the thermal response test. The permanent thermistors show greater scatter than the mobile thermistor string, but the trend is the same. There is an elevated temperature near the surface, reflecting the late summer period during which the test was carried out. Below this, there is a gradual increase in temperature with depth. The natural temperature gradient in the ground is greatest at depth, where it is about 1·5–2°C per 100 m. This is slightly less than the median UK geothermal gradient for 0–100 m of 2·2°C per 100 m (Busby *et al.*, 2011). Higher up, between approximately 20 m and 60 m depth, there is little temperature change. This may reflect movement of groundwater, or be part of a trend towards a reversal of the geothermal gradient due to heat losses from the urban environment. Similar and more extreme effects have been observed at other urban sites (e.g. Banks *et al.*, 2009). The mean temperature measured by the thermistor string over the test depth was 13·4°C. This is consistent with the fluid temperatures measured during the stage 3 initial circulation, which were between 13·3°C and 13·5°C.

3.1 Single-value interpretation

The standard technique for interpreting of thermal response data is to take the straight-line portion of the plot of ΔT_f against $\ln(t)$ and use the gradient and intercept to calculate the thermal conductivity of the ground and the thermal resistance of the borehole respectively. The early portion of the dataset is neglected, as at small values of time the mathematical simplification in Equation 1 is not valid. In addition, the assumption of a constant borehole thermal resistance is dependent on a thermal steady state within the hole, and this may take several hours to develop. Therefore interpretation commences after a minimum time, t_{min}, given by

$$4.\quad t_{min} = \frac{5r_b^2}{\alpha}$$

To estimate t_{min}, an assumption must be made regarding the thermal diffusivity, α. Taking a nominal value of $\alpha = 1 \times 10^{-6}$ m²/s for soils and rocks, t_{min} becomes 5·6 h.

3.1.1 Average fluid temperature

The average temperature of the thermal fluid is often taken as the mean of the loop inlet and outlet temperatures.

$$5.\quad \Delta T_f = \tfrac{1}{2}(\Delta T_{in} + \Delta T_{out})$$

This is on the basis that the rate of change of temperature of the fluid around the loop is uniform, and consequently the mean of the temperatures in the up and down sides of the U-loop is equal along the length of the borehole (Figure 3(b)). Unless the loop flow velocities are high, this is unlikely to be the case in reality. Rather, heat transfer becomes less efficient around the pipe loop, and thus the rate of change of the fluid temperature reduces. Consequently the true average fluid temperature decreases with depth. If this is not taken into account, then the borehole thermal resistance may be overestimated. To allow for this, Marcotte and Pasquier (2008) proposed using a power-linear (or p-linear) relationship to describe the fluid temperature changes with length around the pipe loop (Figure 3(b)). They found the best fit to numerical model data when the power p tended towards a value of -1. On this basis, the average fluid temperature for use with Equation 2 becomes (Marcotte and Pasquier, 2008)

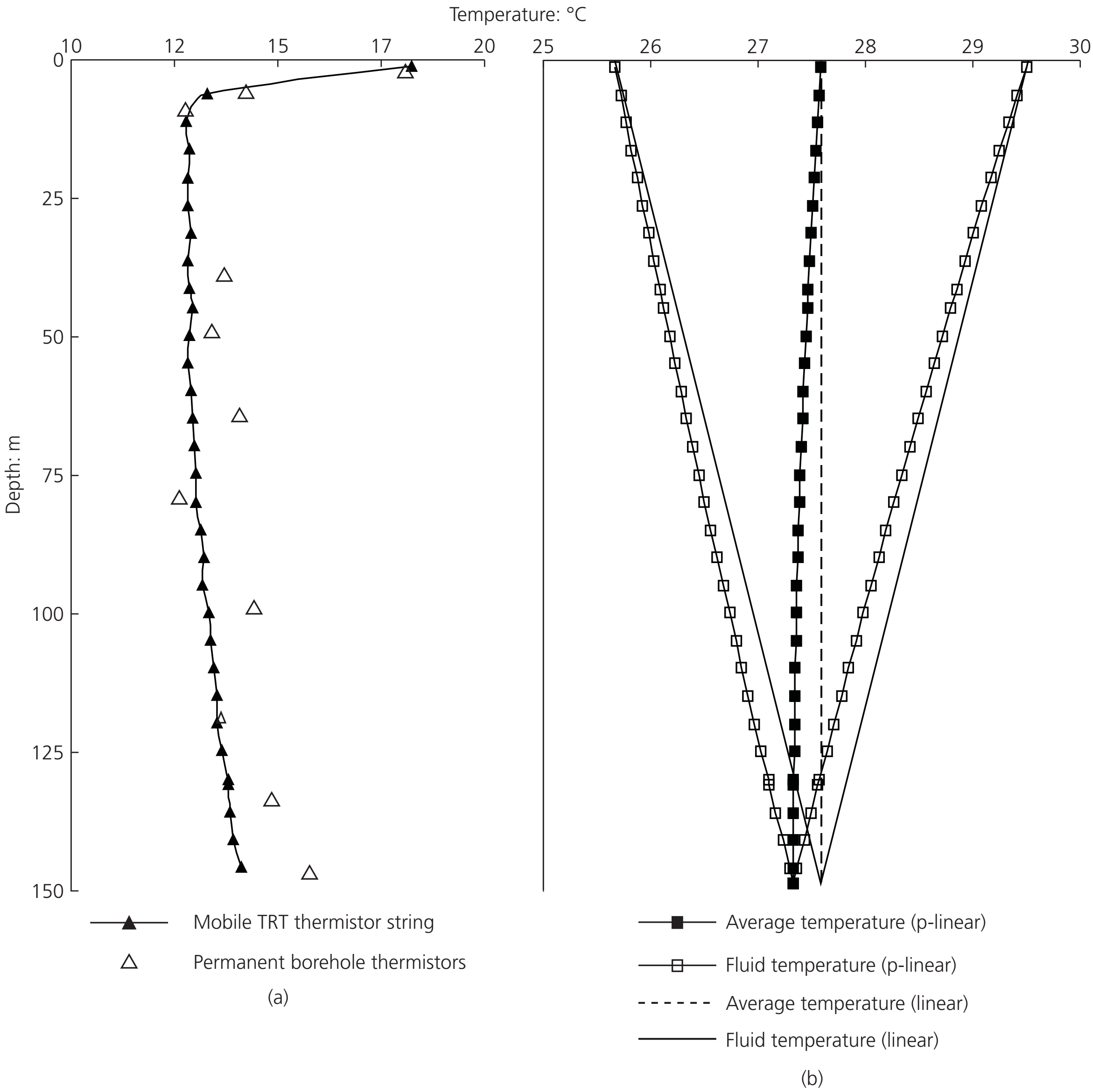

Figure 3. Temperature profiles: (a) undisturbed ground temperature; (b) theoretical fluid temperature profile at end of heat injection

6. $$\Delta T_{\mathrm{f}} = \left|\Delta T_{\text{p-linear}}\right| = \frac{p(|\Delta T_{\mathrm{in}}|^{p+1} - |\Delta T_{\mathrm{out}}|^{p+1})}{(1+p)(|\Delta T_{\mathrm{in}}|^{p} - |\Delta T_{\mathrm{out}}|^{p})}$$

Another consequence of the mean fluid temperature decreasing with depth is that the rate of heat transfer with depth is no longer constant. This means that stratification of the ground can influence the test results if a simple line source interpretation is used. This is discussed further in Section 3.2.

3.1.2 Test recovery data

Heat flow around a borehole heat exchanger is strongly analogous to groundwater flow to a well (e.g. Loveridge and Powrie, 2013). To interpret the recovery portion of the test data, the results have been analysed using the same techniques as applied to pumping tests. Taking the time from the start of the recovery part of the test, termed t' (Figure 2), it can be shown by superposition that the temperature of the fluid, ΔT_{f} (measured as a change from the undisturbed ground temperature), is given by

7. $$\Delta T_{\mathrm{f}} = \frac{q}{4\pi\lambda}\ln\left(\frac{t}{t'}\right)$$

Thus the recovery portion of the test data can also be used to determine the thermal conductivity by taking the gradient of a graph of the fluid temperature against ln(t/t'). The borehole thermal resistance cannot be obtained from this part of the test.

3.1.3 Results

The changes in average fluid temperature with ln(t) or ln(t/t') are shown in Figure 4. Using Equations 2 and 7 applied to the relevant portions of the heat injection and recovery data (the straight-line section from t_{min} to the end of the test phase under interrogation), single lumped values of thermal conductivity and thermal resistance have been calculated using both a mean temperature (Equation 5) and a p-linear fluid temperature (Equation 6). For the heat injection phase of the test the derived value of thermal conductivity is approximately 1·95 W/mK, with a small difference depending on the average fluid temperature used (Table 3). For the recovery phase of the test this increases to approximately 2·07 W/mK. During recovery, the temperature difference between the inlet and outlet is sufficiently small that the two measures of average fluid temperature are the same. It should be noted that the recovery graphs produce a small intercept value, when in theory this should be zero (Equation 7). This is a reflection of the small heat input that will be generated by the circulation pump as well as imperfect boundary conditions. Forcing the best-fit line through the axis origin fails to recognise these factors, and is therefore not appropriate.

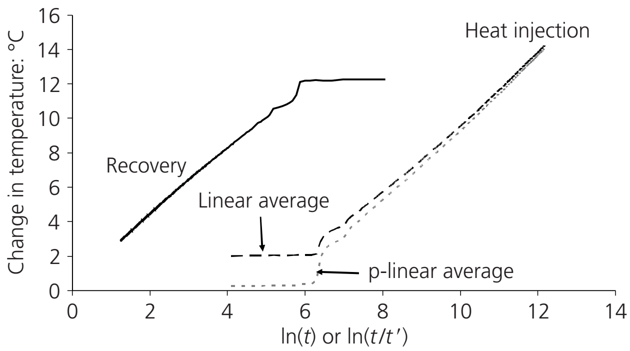

Figure 4. Changes in fluid temperature during heat injection and recovery

The derived thermal conductivities are in the upper part of the range typically reported for the Chalk (between 1·8 W/mK and 2 W/mK; Headon *et al.*, 2009). The difference between the values derived from heat injection and recovery is about 6%. While this is within the generally reported accuracy of the test, it is nonetheless significant, and will be explored further later in the paper.

The borehole thermal resistance is approximately 0·085 mK/W, which is at the lower end of the range of typical values for UK construction (Banks, 2009). This reflects the high thermal conductivity of the saturated siliceous gravel with which most of the borehole is backfilled, and may also include a contribution from both flowing groundwater (advection) and free convection cells developing within the gravel pore spaces. Research suggests that the latter mechanism, where temperature changes induce density-driven groundwater movements, can become important in coarse saturated soils. Pore spaces larger than a few millimetres and high temperature gradients, such as those next to heat exchanger pipes, are required for the effect to become significant (Farouki, 1986).

3.2 Dynamic interpretation

It is also possible to interpret the test data over a range of different timescales, starting from t_{min} and gradually increasing the analysis end time. This allows assessment of whether conditions are changing during the test, and also the uncertainties associated with a simple, single-value interpretation. Given that this analysis can be carried out without recourse to additional fieldwork, and is relatively rapid, it is recommended that the approach be adopted more routinely.

Figure 5 shows the derived thermal conductivity and borehole thermal resistance with time from the start of each phase of the test. In each case the start time of the analysis is t_{min}, and the end time varies. During heat injection the derived thermal conductivity is at first fairly stable, with only a small variation. These variations occur on a 24 hour cycle, and are likely to be related to small heat losses to the air at night when the surrounding temperature is less. However, at the end of the test period there is a marked fall in the thermal conductivity. It is not clear what is

Test phase	ΔT_f	Graph gradient	Graph intercept	R^2	Thermal conductivity: W/mK	Borehole thermal resistance: mK/W
Heat injection	$\frac{1}{2}(\Delta T_{in} - \Delta T_{out})$	2·1731	−12·257	0·9997	1·97	0·087
	p-linear	2·2147	−12·912	0·9998	1·94	0·082
Recovery	$\frac{1}{2}(\Delta T_{in} - \Delta T_{out})$	2·0669	0·307	0·9999	2·07	NA
	p-linear	2·0670	0·323	0·9999	2·07	NA

Note: thermal resistance values assume a ground volumetric heat capacity of 2·69 MJ/m^{3}K.

Table 3. Results of single-value interpretation

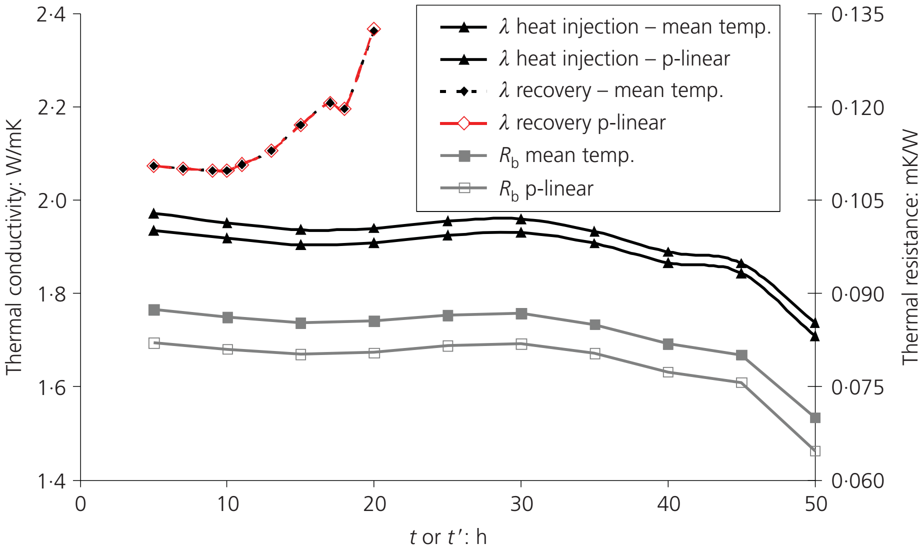

Figure 5. Changes in derived thermal conductivity and thermal resistance with time

causing this change, but it must reflect either a true change in thermal properties (e.g. reduced heat flow in the borehole due to grout cracking) or a change in boundary conditions. An example of the latter would be greater sensitivity to power fluctuations later in the test (when the rate of temperature change reduces), although in this case the power fluctuations are too small ($\pm$0·3%) to make this sort of impact (Figure 2). Alternatively, the fall in λ may occur because the soil around the upper part of the borehole (above the water table) has dried out during heating. A similar pattern is seen in the changing values of thermal resistance (Figure 5). While this behaviour cannot be satisfactorily explained, it serves to illustrate the uncertainties that can be associated with the test, and the dangers of restricting interpretation to a single value of thermal conductivity.

During the recovery phase of the test, the difference in behaviour compared with a conventional analysis is more significant. First, the derived thermal conductivity values are much higher, and, second, the values increase markedly with time. On the first point, theoretical differences between thermal conductivity derived from heat injection and heat extraction tests have been shown by Signorelli *et al.* (2007). They used a three-dimensional numerical model to demonstrate that the heat flow around borehole heat exchangers deviates slightly from the simple one-dimensional radial flow assumed by the line source model. Instead, the presence of a natural temperature gradient within the ground (Figure 3(a)) leads to a vertical component of flow.

During heat injection the average fluid temperature will decrease with depth (Figure 3(b)). The result is a greater temperature difference between the fluid and the ground at the top of the borehole than at the base (Figure 6(a)). Consequently, the thermal conductivity calculated from the test results will be biased towards the strata surrounding the top of the borehole. During a heat extraction test the situation is reversed: the average fluid temperature increases with depth, but at a lesser rate than the geothermal gradient. Therefore the greatest temperature difference between the fluid and the ground is at the base of the borehole, and the results will be biased to the strata at this location (Figure 6(b)). This means that in stratified ground, where a borehole heat exchanger passes through materials of different thermal conductivities, performance will be different in heat injection and in heat rejection. During recovery tests, when there is no applied heat flux, the fluid temperature is constant with depth. In these cases, the bias is considerably reduced, explaining the difference between the results from the two stages of the test (Figure 6(c)).

Figure 5 therefore implies that the top of the borehole is surrounded by soil or rock of lower thermal conductivity than the lower parts. The lower two-thirds of the borehole passes through saturated Chalk, while the top passes through a number of strata, including a significant thickness of London Clay. This would be expected to have a lower conductivity than the Chalk, with typical values for saturated clay being around 1·6 W/mK (Banks, 2008).

As well as being higher, the thermal conductivities derived from the recovery curve increase markedly with time (Figure 5). This is usually an indication of the presence of groundwater flow around the heat exchanger (Sanner *et al.*, 2008). However, it is unusual that this is noticeable only in the recovery phase of the test. This may reflect the fact that the main flow would be expected to be in the Chalk, in the lower part of the borehole, whose contribution would be less significant during the heat injection phase of the test.

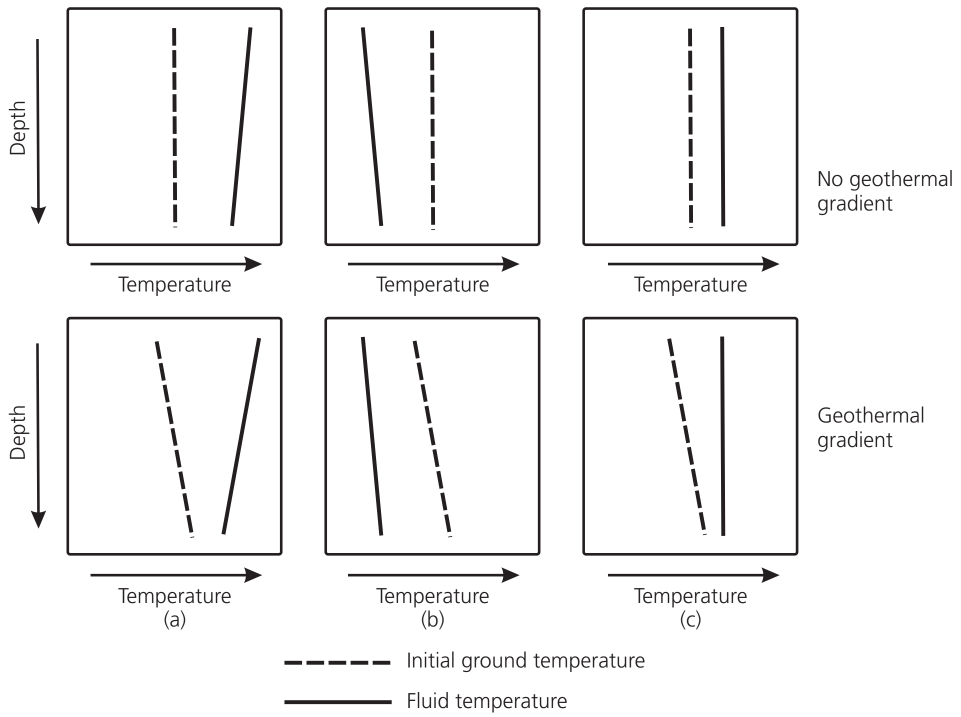

Figure 6. Schematic temperature profiles during: (a) heat injection; (b) extraction; (c) recovery (from heat injection)

3.3 Borehole instrumentation

Differences in behaviour due to vertical variation of ground properties can be investigated by considering the temperature changes with depth in the borehole, as measured by the permanent thermistors installed within the backfill (Table 1). Figure 7 shows the temperature changes in the borehole during heat injection compared with the p-linear fluid temperature (ΔT_f) and the theoretical temperature at the edge of the pipes (ΔT_p). The latter is calculated on the basis of the pipe resistance (R_p)

8. $$\Delta T_p = \Delta T_f - qR_p$$

Further details are given in the appendix.

In Figure 7 all the curves for the thermistors parallel the fluid and pipe temperatures, but at different offsets, depending on the distance of the thermistor from the pipes. Ideally, the thermistors would match the pipe temperature, but because of the high

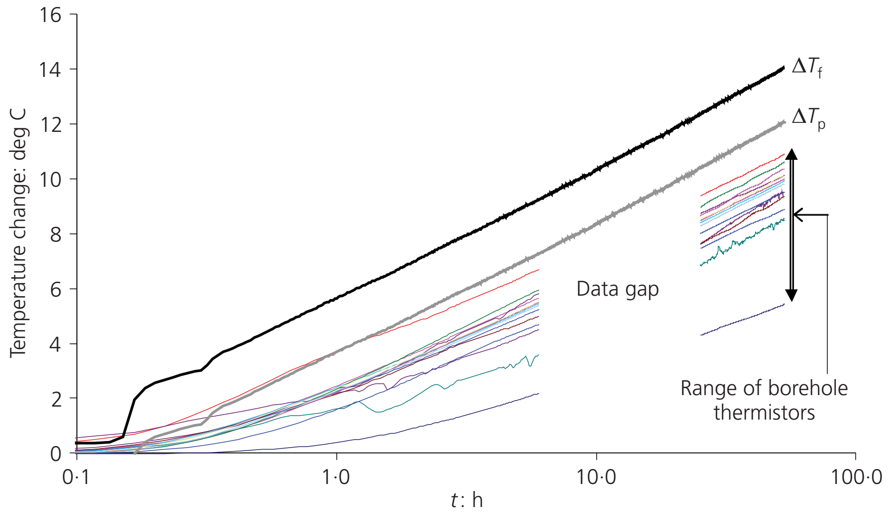

Figure 7. p-linear temperature change in borehole during heat injection

temperature gradients close to the pipes even a small variation in position will cause a noticeable difference in the value of the temperature readings. However, despite this, the thermistors will still record an accurate change in temperature resulting from the heat injection, and it is this value (i.e. the gradient of the lines in Figure 7) that is important for interpretation. The straight, parallel nature of the curves in Figure 7 also demonstrates this, and shows that the line source approach is still approximately valid, even for small sections of the borehole. This is because, overall, the principal flow direction is still radial. There will be small variations in this flow path, but any vertical components of the flow are secondary, and it is still possible to use each individual thermistor to calculate the thermal conductivity (e.g. Fujii *et al.*, 2006). This is done by taking the gradient of the lines and using Equation 2 to determine λ in exactly the same way as for the fluid temperatures. The main disadvantage of this approach is that, without the use of temperature sensors within the pipes (which in practice is very challenging, and was not feasible on this site), it is not possible to calculate the small changes in applied heat flux that occur with depth. This will add a small additional error to the results, especially near the borehole ends.

Figure 8 compares the resulting thermal conductivities calculated from the individual thermistors with the values presented in Table 3. Owing to a datalogging problem (see Figure 7) during the heat injection phase, the test has been interpreted from $t = 25$ h to $t = 53$ h during this phase. Large values of thermal conductivity are determined at shallow depth. However, these will not be true reflections of the thermal conductivity, as temperature gradients and heat flow paths in this area are influenced by the ground surface temperatures, and hence the infinite line source analysis is not valid. This will also be true for the base of the hole, but to a lesser extent.

The thermal conductivities determined from recovery are again greater than from heat injection. For both phases of the test the average of the results (neglecting the uppermost and lowermost values, owing to potential end effects) is greater than the value determined from the fluid temperatures, being 2·0 W/mK and 2·2 W/mK for injection and recovery respectively. There is also significant variability. With the exception of peaks in the Thanet Sands, near the top of the Chalk and also near the base of the Chalk, there is little consistency between the results from heat injection and recovery.

Figure 8 also shows the change in temperature in the borehole 30 h after the test has finished and the circulation pump has been switched off. Larger changes in temperature reflect a higher thermal conductivity, or perhaps the influence of groundwater flow. Distinct peaks are visible at 17·5 m depth, and between 48·5 m and 78·5 m depth. Surprisingly, the first peak corresponds to the London Clay, which would be expected to have a fairly low thermal conductivity and insignificant groundwater flow. The second, broader peak relates to the top of the lower aquifer, that

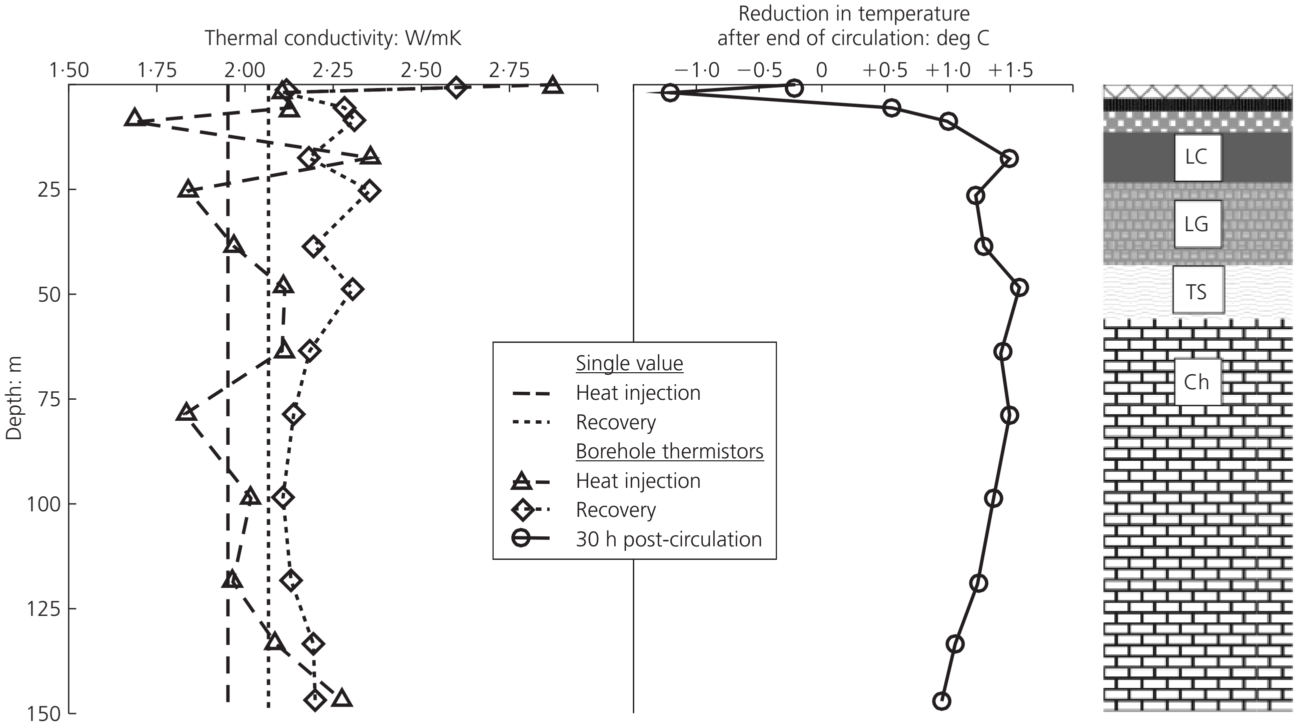

Figure 8. Thermal conductivity and post-circulation temperature change with depth

is, the Thanet Sands and upper section of the Chalk. There is then a reduction in temperature change with depth throughout the Chalk, which is broadly consistent with the thermal conductivity values calculated from the thermistors during recovery, although these also show an increase near the base.

Chalk has high matrix porosity but low matrix permeability, and groundwater movement is dominated by flow in fractures. Studies in the London area (e.g. O'Shea *et al.*, 1995) have shown that the most productive zone (and by inference the most fractured) is generally in the upper 30–40 m of the Chalk. This is consistent with the zone of higher thermal conductivity shown in Figure 8. A decrease in Chalk permeability with depth has also been reported (Williams *et al.*, 2006), which would explain the decline in temperature change for the lower part of the borehole after the end of the test (Figure 8).

To investigate the potential influence of groundwater further, the thermal conductivities derived from the borehole thermistors have been calculated as a function of time. In most cases the results show significant scatter (which is likely to be a reflection of the additional uncertainties introduced by assessing sections of the borehole individually), and definitive conclusions cannot be drawn. Figure 9 shows these results filtered for only those thermistors within the Chalk and at 25·5 m depth within the Laminated Beds of the Lambeth Group. The latter data are included as they show some increase in thermal conductivity with time during recovery. Overall, there is still significant scatter for the heat injection phase, but there is a small increase in thermal conductivity in the recovery phase. As well as at 25·5 m depth, this is especially clear for the thermistor at 63·5 m depth. The latter is not surprising, as it is near the top of the Chalk, where greatest groundwater flow would be expected. The increase in thermal conductivity with time for the Laminated Beds is less expected, although these beds were consistently associated with water strikes during the ground investigation at the site.

For the thermistors the apparent increase in thermal conductivity with time is less than shown for the fluid temperature in Figure 5. This confirms that the groundwater flow must be predominantly along major fractures that have not necessarily been intercepted by the discrete temperature monitoring points within the borehole.

4. Discussion

When carrying out simple single-value interpretation, the differences between performance of the borehole heat exchanger during heat injection and recovery could be considered to be within the limits of accuracy of the test. However, when the test data are considered in more detail, especially with respect to variations in time, the difference in performance is more striking. While the apparent thermal conductivity during heat injection is relatively stable, it increases markedly with time during recovery. This is a strong indicator of groundwater flow, which is important, owing to its significant impact on the heat transfer behaviour of the borehole over its lifetime.

Groundwater movement within the Chalk aquifer is known to be controlled mainly by fractures with the matrix having a much lower permeability. This is consistent with the data from the borehole thermistors. Thermal conductivities derived from these data, which are specific to precise horizons, show an increase during recovery of up to approximately 10%, compared with approximately 15% for the thermal conductivities derived from the fluid temperatures. This would be consistent with groundwater

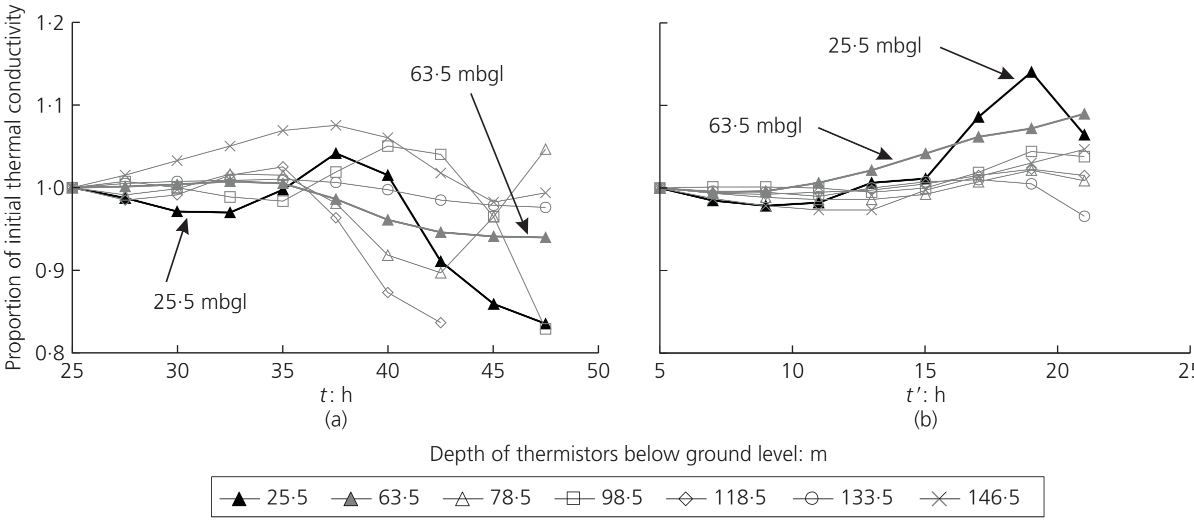

Figure 9. Change in thermal conductivity with time at different depths: (a) heat injection; (b) recovery

movement being dominated by one or two major fractures that have not necessarily been intercepted by the thermistors.

It is surprising, however, that the influence of groundwater flow is not seen during the heat injection phase of the test. In fact, the opposite appears to be true, with some reduction in thermal conductivity values with time during this part of the test. Thermal response tests are known to be biased towards the strata at the top of a borehole during heat injection, owing to a combination of the geothermal gradient and the variation in fluid temperature with depth. For the heat injection phase to be insensitive to groundwater flow would suggest that the main flow is happening near the base, or at least in the lower half, of the borehole. This is not consistent with the upper layers of the Chalk, less than halfway down the borehole, being the most productive in terms of groundwater extraction. Nonetheless, the thermal conductivities derived at different depths and shown in Figure 8 do show some increase near the base of the borehole, even discarding the lowest value because of end effects.

It can also be inferred from Figure 10, which plots the specific capacity (well yield divided by drawdown, l/s/m) of 353 wells in the London Basin, that although the upper 60 m of the Chalk aquifer is clearly the most productive, there is a subsidiary peak beyond 100 m depth where the specific capacity increases again. This suggests a fractured horizon at greater depth in at least some locations. The presence of such a feature, possibly a zone of fracturing related to hardgrounds in the Chalk, could explain the observed test results. It is unlikely that fractures at this depth would be as wide as the potentially solution-enlarged fissures higher up the sequence. However, it is possible that such fracturing could extend for a greater thickness, and thus make a significant contribution to flow.

5. Conclusion

Thermal response testing is an important technique for determining the thermal characteristics of both the ground and the borehole heat exchanger for use in the design of ground energy systems. However, the standard test measures only a bulk value of thermal conductivity for the ground, and owing to an imperfect fit with the assumed boundary conditions of the line source model there may be uncertainties in the results. Consequently it is recommended that these uncertainties be investigated and reported in routine practice; in particular, the following

(*a*) Both heat injection and recovery test phases should be carried out. This enables any difference in behaviour associated with the direction of heat flow to be determined. Differences in the bulk thermal conductivity between the two test phases are a reflection of different thermal properties at the top and base of the hole. This is because the results from heat injection are biased towards the upper part of the borehole.
(*b*) The test results should be interpreted over a range of time periods. This will help to identify external influences on the test data, such as groundwater flow, which could have a significant impact on the long-term performance of the energy system.

In the case study presented, evidence for groundwater flow is seen only in the recovery phase of the test. This would suggest that a flow horizon is present in the lower half of the borehole, possibly towards the base. This result was unexpected, as the upper layers of the Chalk, about halfway down the borehole in this case, are more typically associated with groundwater movement. Given the presence of groundwater throughout the lower aquifer, the use of high-permeability siliceous sand and gravel as borehole backfill material has been shown to be beneficial in terms of minimising borehole thermal resistance.

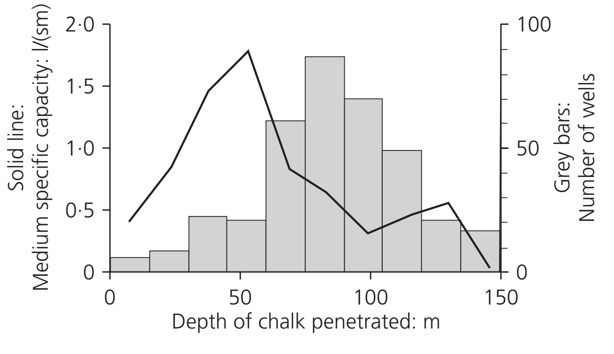

Figure 10. Specific capacity of wells installed in the Chalk in the London Basin (after Water Resources Board, 1972)

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Appendix: Thermal resistance of ground loop pipes

The temperature change across a borehole heat exchanger is the product of the heat flux, q (W/m), and the thermal resistance, R_b (mK/W)

$$\Delta T_f - \Delta T_{rb} = qR_b \quad (9)$$

The thermal resistance can be represented as the sum of its component parts, the resistance of the borehole grout (or other backfill material) and the resistance of the pipes, split into a conductive resistance and a convective resistance:

$$R_b = R_p + R_{grout}$$

10. $$= \frac{1}{q}(\Delta T_f - \Delta T) + \frac{1}{q}(\Delta T - \Delta T_{rb})$$

11. $$R_p = R_{pconv} + R_{pcond}$$

The conductive resistance can be calculated using the analytical solution for the thermal resistance of a cylinder and assuming the two pipes act in parallel

12. $$R_{pcond} = \frac{\ln(r_o/r_i)}{4\pi\lambda_{pipe}}$$

where r is the pipe radius, with the subscripts i and o indicating the inner and outer dimensions. The convective resistance is calculated based on the heat transfer coefficient at the fluid pipe interface, h_i. This is dependent on the flow conditions in the pipe.

13. $$R_{pconv} = \frac{1}{4\pi r_i h_i}$$

h_i can be calculated using the Gnielinski correlation (Gnielinski, 1976) for the Nusselt number (Nu)

14. $$h_i = \frac{Nu\lambda_{fluid}}{2r_i}$$

where

15. $$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12{\cdot}7(f/8)^{0{\cdot}5}(Pr^{2/3} - 1)}$$

where Re is the Reynolds number, Pr is the Prandtl number, and f is the friction factor. For turbulent flow in smooth pipes this can be calculated using this expression from Petukhov (1970).

16. $$f = [0{\cdot}79 \ln(Re) - 1{\cdot}64]^{-2}$$

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