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Determining fracture properties by tracer and thermal testing to assess thermal breakthrough risks for ground source heating and cooling in the Chalk

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Abstract

Numerous open loop ground energy systems are under construction or have been constructed in central London. The majority of these systems use the Chalk aquifer as a water source. A significant proportion of the abstracted water must be returned to the aquifer to maintain groundwater levels. If the ground system is to function correctly, the temperature of the abstracted groundwater must not be altered significantly by early thermal breakthrough of the returned water. Groundwater flow within the Chalk is predominantly through fractures and these provide the primary route by which thermal breakthrough might take place. The nature of the fracturing and its impact on the thermal transport beneath a proposed site must be understood to provide confidence that the ground energy system will function correctly. Two tracer and thermal test methods to determine fracture properties are examined. The results suggest that the flow in the Chalk is carried by a small number of fractures and that careful modelling and interpretation can provide valuable constraints on the frequency of fractures, their spatial pattern and their hydraulic aperture. The results highlight difficulties for designing within borehole temperature monitoring systems for fractured aquifer thermal experiments.

Main Text

Ground energy systems use the ground and groundwater as a heat 'source' during the heating (Winter) cycle and a heat 'sink' during the cooling (Summer) cycle. Ground and groundwater temperature is normally equal to the average annual air temperature, making it cooler than the average air temperature during the summer and warmer than the average air temperature during the winter. Ground energy systems usually consist of a ground loop connected to ground source heat pumps (GSHPs). GSHPs operate in a similar way to conventional air sourced systems but capitalise on the fact that the ground temperature is close to that required for space heating or cooling. GSHPs therefore have to do much less work than a conventional air sourced system to achieve the required room temperatures and therefore operate at much higher efficiencies.

There are two primary methods of linking the ground to the GSHP: 'closed loop' and 'open loop'. Closed loop systems consist of a number of tubes buried beneath the ground through which a fluid is circulated. There is no direct contact between the heat conducting fluid and the ground or groundwater. In the case of open systems, the groundwater is used as the heat conducting fluid and pumps are used to abstract groundwater before passing it through a heat exchanger and /or a GSHP. The waste groundwater is then either recharged to the aquifer or disposed to a surface water source. Open loop systems yield significantly more energy per borehole than closed loop systems.

A common strategy in London has been to install open loop systems that use groundwater from the Chalk aquifer. Recent regulations from the Environment Agency in England state that licenses for abstraction from the Chalk are unlikely to be granted for abstractions greater than 0.2 Mega litres/day (525 gallons per minute) (Environment Agency, 2005). Therefore, for an open loop ground energy system of any significant size, the majority of the water abstracted from the aquifer will have to be re-injected to the aquifer. To avoid high costs for piping and to restrict possible interference with other schemes, reinjection will normally take place within the footprint of the building . Thus, the injection and abstraction boreholes are normally in close proximity (<100 m) to one another and the risk of interference between the boreholes is of potential concern.

The injected water will be at a different temperature to the aquifer and the interaction between this water and the aquifer can affect the sustainability of the system in both the short and long term. This paper is concerned with short term sustainability issues caused by rapid thermal breakthrough due to a small number of fractures connecting the injection and abstraction boreholes. Identification of the fracture frequency and apertures of the fractures is an essential requirement for predictive assessment of breakthrough risks.

Geology and hydrogeology of London

The central London area falls within the London Basin, an asymmetric syncline in Cretaceous and Tertiary deposits. The Basin is faulted in a number of places. The faulting affects aquifer continuity and the flow of water. A typical sequence of strata at a site can be summarised as, Made Ground, Alluvium & Gravels, London Clay / Lambeth Group, Thanet Sand Formation and the Chalk (Figure 1). The Chalk is located at approximately 90m below ground level and forms the main aquifer. The Chalk aquifer is typically hydrogeologically linked to the Thanet Sand Formation which is a fine grained sandstone. The intact chalk is generally considered to be impermeable (Bloomfield 1995, Macdonald 2001) but fissures and fractures can make the overall rock mass highly permeable. Water flow can be rapid where significant fracturing occurs.

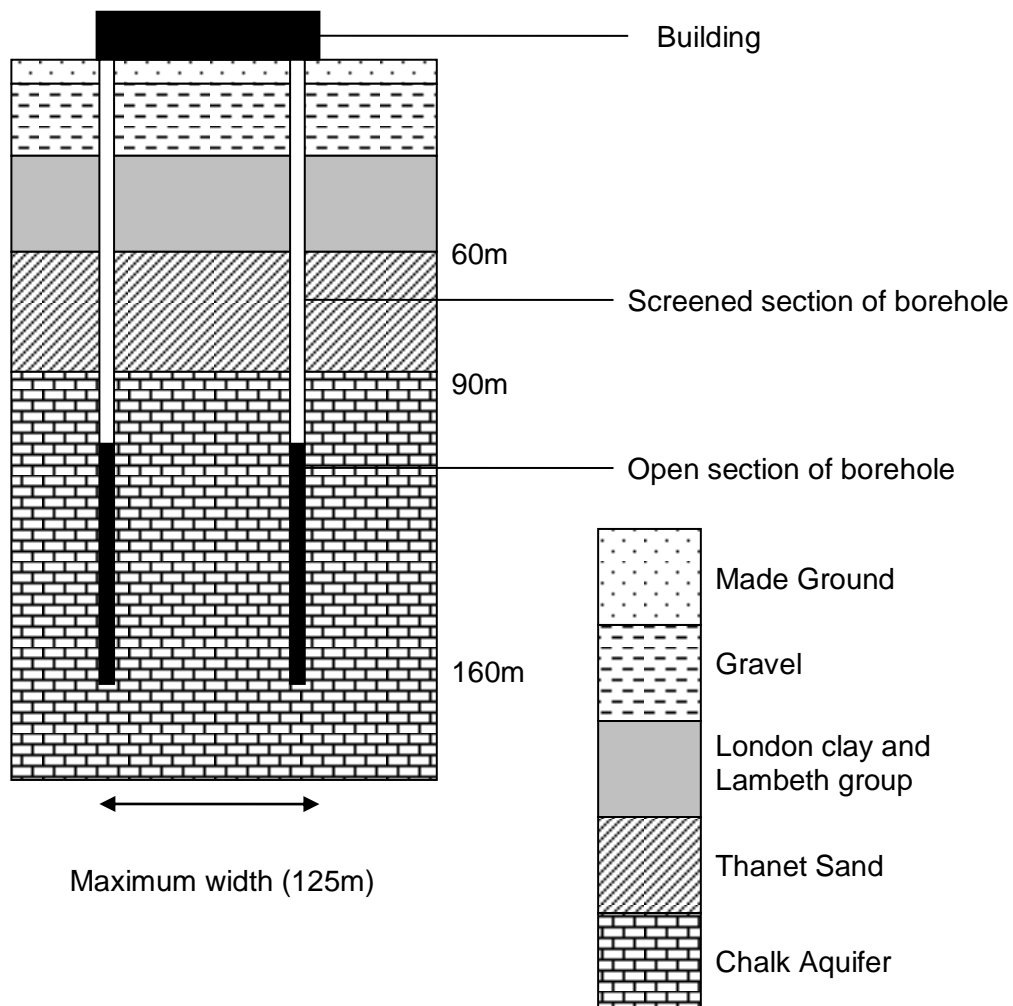


Figure 1 Summary of the geology in central London and an open loop configuration

The degree of fissuring in the Chalk can be highly variable. The mass permeability of the Chalk typically decreases with depth and it is generally considered, for engineering purposes, that almost all the water is yielded by the upper 60–100 m of the chalk. The Chalk is widely exploited for water abstraction in Central London with typical borehole yields of 15 litres/second (240 gallons/minute). The background hydraulic gradient in the Chalk of the London basin is typically 1/1000 with

groundwater flow in the direction of the central London groundwater depression (Environment Agency, 2005).

Short term sustainability

Short term sustainability problems are caused by short circuiting between the injection and abstraction boreholes. Short circuiting will primarily be caused by fractures within the aquifer through which water can flow at rapid rates. It is conceivable that a single (1mm) fracture could carry the majority of the flow between an injection and abstraction borehole, causing rapid thermal interference (potentially in a time frame under 48 hours). This process is illustrated in Figure 2.

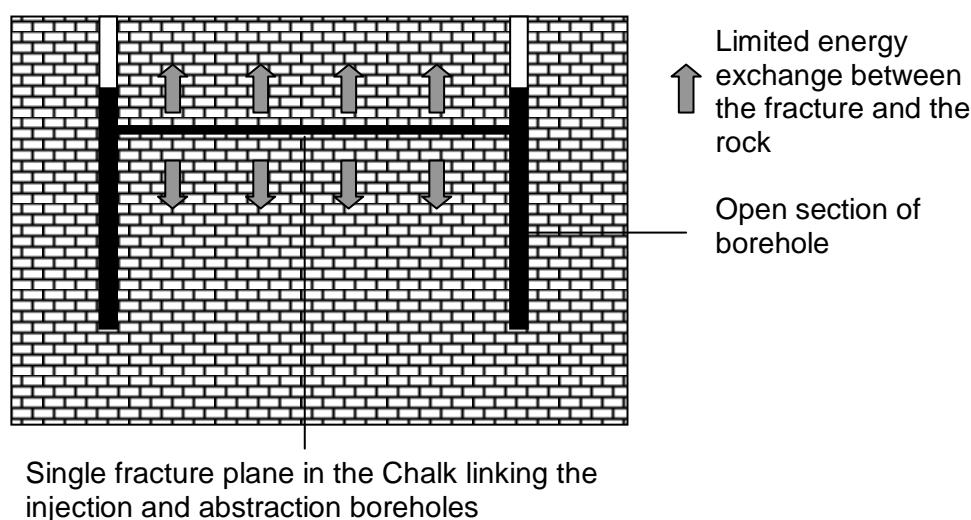


Figure 2 Thermal breakthrough caused by a single fracture

It is our opinion that the issue of short term sustainability and thermal breakthrough in fractured aquifers has not been given sufficient attention during the design of open loop systems. As this technology is relatively new in the United Kingdom few data have been published to corroborate this thesis.

The data presented below (Figure 3) are from an abstraction and injection borehole at an operational site in central London. The data points are for July and August and show the rapid response of the abstraction temperature to the injection temperature. The peaks in abstraction temperature directly correlate to the injection temperature of the day before, implying that thermal breakthrough is taking place in under 24 hours. This breakthrough time can only be caused by fracture flow. In addition, the abstraction temperature rises even when injection temperatures are comparatively low, implying that little heat is being lost to the Chalk matrix during transport between the boreholes. In these cases, as the temperature difference between the injected water and the matrix is as little as 2°C the water transport time must be too fast for the heat to be absorbed by the matrix. Over the summer period of approximately 3 months, the average temperature in the abstraction borehole has increased by 1°C.

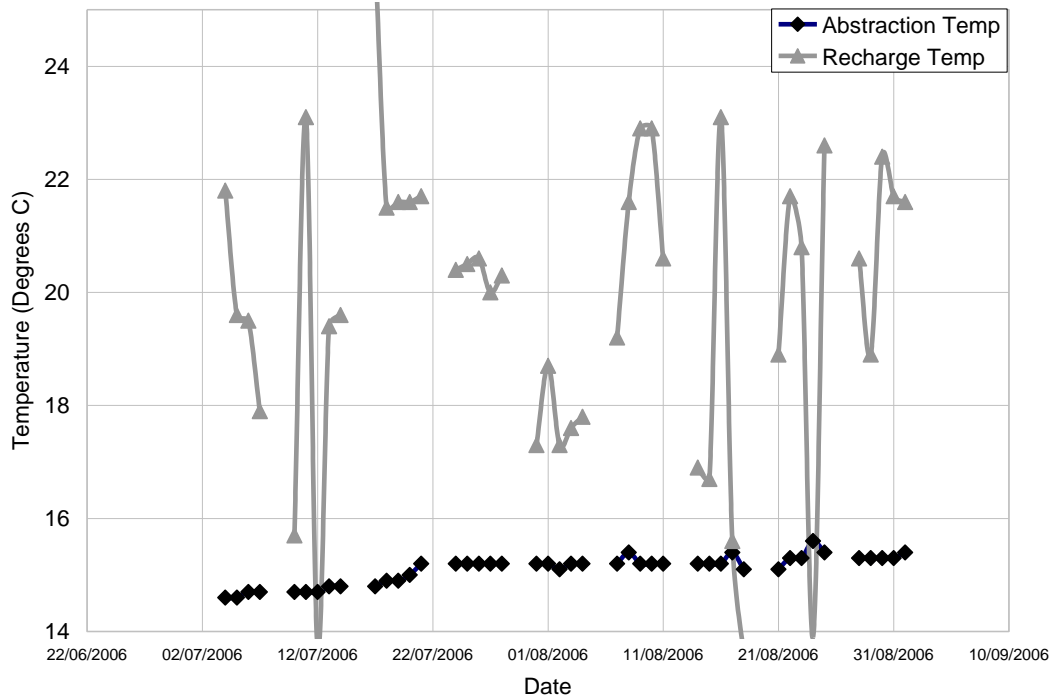


Figure 3 Temperature data from an existing open loop system, London

General approach to designing a system

Sustainability issues should be addressed before the system is installed. Long term sustainability problems can be resolved by ensuring that the energy demands placed upon the aquifer are approximately balanced throughout the year. This can only be achieved through dialogue between the building designers, M&E engineers and the ground energy system designer.

Short term sustainability issues are more difficult to resolve as they require prior knowledge of the aquifer. This paper considers a suite of field tests and their interpretation aimed at predicting the thermal transport characteristics at a site. The field testing regime and interpretation was undertaken at a site located in central London to assist with the design of a proposed open loop system.

Testing

The aim of the testing regime was to provide sufficient data to predict the nature of the thermal transport beneath the site. The tests conducted were as follows:

- CCTV survey
- Flow logging
- Pumping tests
- Tracer testing
- Thermal testing

All these tests require at least one and in some cases two test boreholes to be drilled at the site. If the trials are successful, the boreholes can later be used for the ground energy system. However, this represents something of a Catch 22. Test boreholes are expensive to install. This implies that a client is already committed to a ground energy system even though no tests have been undertaken at the site. However, the client can only finally commit once the tests have been undertaken and an assessment of the performance of the aquifer completed.

CCTV survey

A CCTV survey was conducted over the entire length of the boreholes drilled at the site. A CCTV survey serves two purposes: a method of checking the way in which the borehole has been drilled and cased and as a method of locating likely fractures. An image from the CCTV survey conducted in one of the boreholes at the site is shown in Figure 4. The image is taken at a depth of approximately 86m and clearly shows a fracture plane. The aperture of the fracture is varied in size but is of the order of 2 millimetres. Although the fracture can be clearly seen, it may not be flowing.

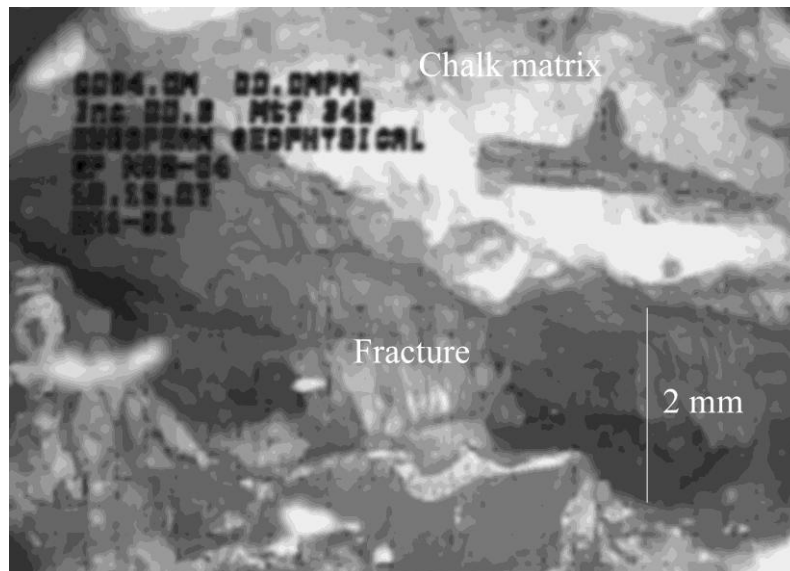


Figure 4 CCTV survey showing a potential fracture in the Chalk (86mbgl)

Flow logging

Flow logging was undertaken in both static and pumped conditions. A flow log measures the flow at all points along the depth of the borehole. Flow rates in the borehole increase where fractures occur. If the increase in flow is fairly regular over the entire depth of the borehole then it can be assumed that many fractures are carrying the flow and the aquifer can be treated for analytical purposes as a homogenous medium. Conversely, if the flow rate jumps at certain points along the length of the borehole then only a few fractures are likely to contribute to the flow. Figure 5 is the flow log at the site during pumped conditions, at a depth of between 68 and 98 mbgl. There is a clear influx horizon where the flow rate increases, at approximately 86 mbgl. This corresponds to the fracture detected at this level by the CCTV survey and helps to confirm that this particular fracture is not only flowing but carrying a significant quantity of the flow.

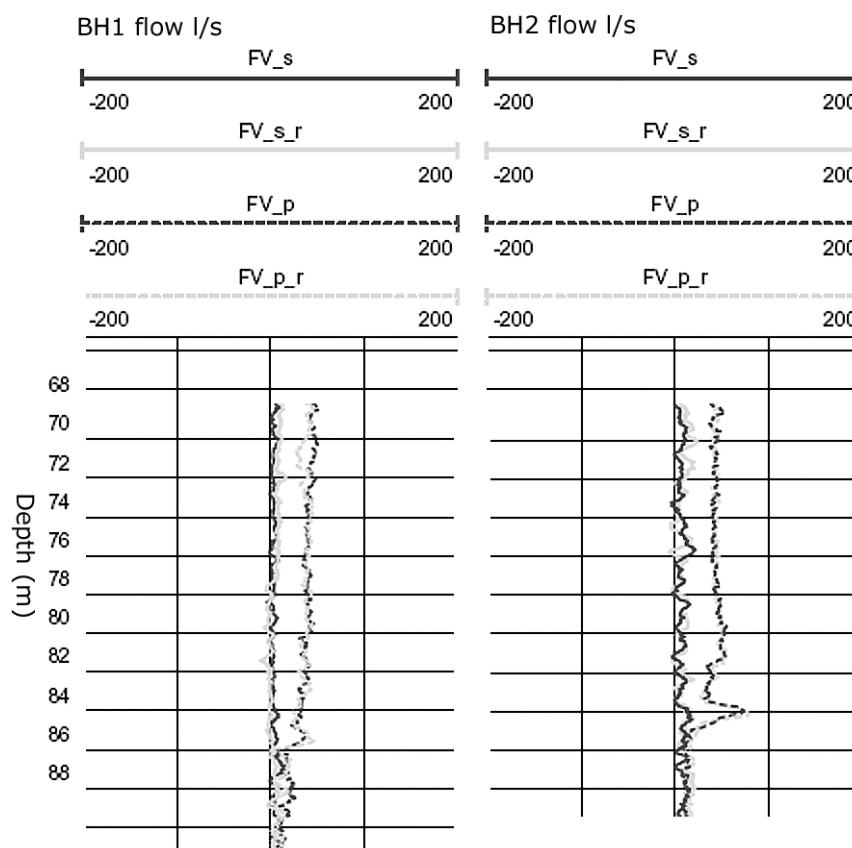


Figure 5 Results from the flow logging (_s_ unpumped conditions; _p_ pumped conditions; _r_ recharge)

Although CCTV and flow logging have suggested that the majority of the flow to both boreholes during pumping is through a single fracture plane, the properties of the fracture are not possible to determine using this test alone and the detailed effect of other flow contributions at greater depths requires further evaluation.

Pumping tests

Pumping tests are used primarily to prove the flow rate for a borehole. In addition, constant rate pumping tests enable the transmissivity of the aquifer to be estimated. The transmissivity calculated from a pumping test in the Chalk is important because it provides an indication of whether the aquifer is significantly fractured. This is because most of the transmissivity of the Chalk is due to the presence of fissures and fractures, so that a high transmissivity is evidence of significant fissuring.

At the test site in central London the transmissivity was estimated to be between 700 m²/day and 1000 m²/day. This is significantly above that which would be expected for the chalk in this area (250m²/day) (Monkhouse, 1995) implying the presence of a significant fracture or series of fractures.

Tracer and thermal test

Tracer testing offers a method of measuring the velocity of water as it travels between an injection and abstraction borehole. The most effective test requires two boreholes to be drilled; one injection and one abstraction. At the injection borehole a known quantity of tracer (in this case fluorescein) is deposited in the borehole. A detector is placed in the discharge line at the abstraction borehole and the amount of time that the fluorescein takes to travel from the injection borehole to the abstraction borehole is measured. This can be used to estimate the velocity of the water which allows the transmissivity of the aquifer and a range of possible fracture numbers and apertures to be deduced. See Barker(1993) for a full description of the method of interpretation.

The thermal test consists of isolating a section of a borehole (using packers) where flow zones were identified (from CCTV and flow metering). A large volume of water is heated at the surface and injected into the isolated section of the borehole before being withdrawn. The thermal absorption properties of the aquifer can then, theoretically, be back calculated.

Thermal and tracer test results and interpretation

Tracer test

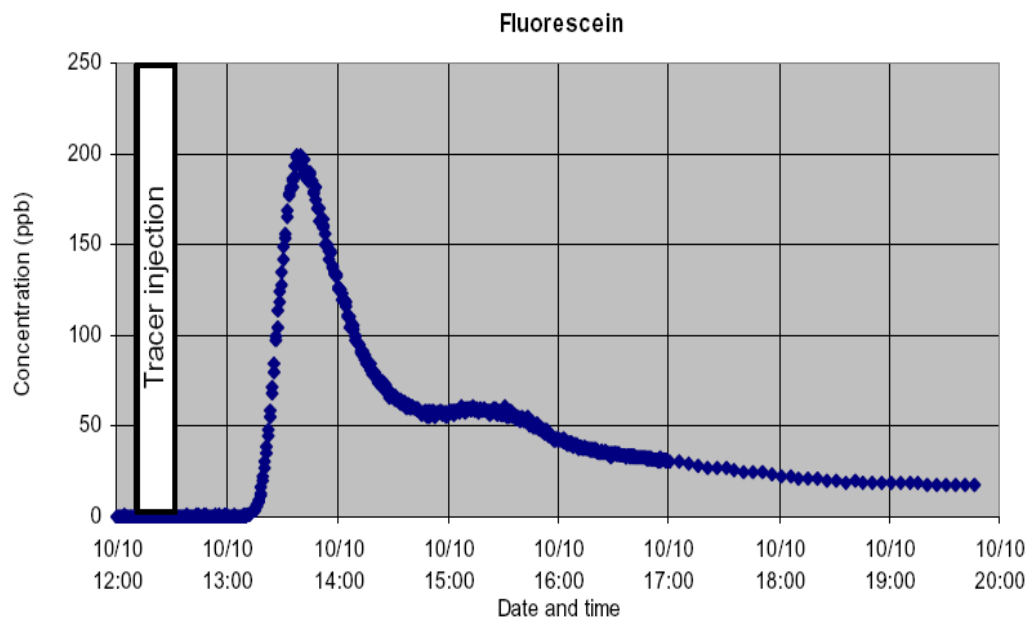


Figure 6. Tracer test results.

The results from the tracer test are shown in Figure 6. The spacing between the doublet boreholes is 122 m. The results show three interesting features. First a clear rapid early breakthrough curve at the abstraction borehole. The first breakthrough occurs at 65 minutes after start of injection, which is approximately 60 minutes after the tracer is first injected to the aquifer (as a result of the delay in transmission down the borehole in the injection pipe). The second is the apparent secondary breakthroughs at later times. Closer inspection of the secondary breakthroughs show a periodic pattern with decaying amplitude. The secondary breakthroughs imply the recycling of the tracer around the injection/discharge loop. The third, and somewhat surprising result, is the smoothness of the breakthrough curves. A fracture network would be expected to give a 'noisier' response and this suggests flow in continuous and relatively uniform planes or channels.

The formula for the first breakthrough time across a doublet borehole system with constant rate injection/discharge of Q with no mechanical dispersion and separation distance L in a homogeneous medium is:

$$t_b = \frac{\pi \phi b L^2}{3Q} \quad \text{Eq. 1}$$

where ϕ is the porosity of an aquifer of thickness b . For clean fractures we can re-interpret the porosity as unity and the b as the aperture. The first breakthrough occurs about 1 hour after initial injection of the tracer to the aquifer (note injection time to the aquifer has been adjusted from start of injection at ground surface to account for the injection procedure adopted). Using equation 1 yields an apparent aperture of 5.8mm

A transmissivity of about $1000 \text{ m}^2/\text{d}$ has been calculated based on the interpretation of the head differences between the boreholes during pumping. To satisfy the combined transmissivity and aperture constraints presented by the pumping and tracer tests implies that about 4 equal fractures of approximately 1.5mm would yield the appropriate breakthrough. This calculation assumes that the hydraulic aperture and the mechanical aperture for the fractures are the same. Whilst this condition is not confirmed, it has been adopted as an appropriate initial working hypothesis for the modelling interpretation.

This calculation also assumes that the fractures are planar rather than channelled and it assumes that all the flow is through the upper horizon. To test these assumptions it is necessary to do more than simply investigate the first breakthrough time, it is necessary to model the full breakthrough curve. This has been carried out using a particle tracking model to model conservative tracer breakthrough to the discharge borehole in steady-state flow conditions (analytically modelled) around a doublet borehole in an infinite aquifer. The adoption of a steady-state approximation for the flow geometry should be sufficiently accurate given the low storage coefficient for confined fractured chalks and the lateral extent of the chalk.

Breakthrough curve analysis was undertaken assuming no rock matrix diffusion. Dispersion, the potential for flow loss down the borehole to the deeper flow horizons and recycling of the fluorescein was allowed. The modelled properties obtain a good calibration (Figure 7) assuming that there is a flow loss of about 30% to the lower horizons of the injection well (this is consistent with the flow data shown earlier in Figure 5). The calibrated model presents the following features:

1. The shape of the first breakthrough curve is well matched to the observation data.
2. The timing and amplitude of the secondary breakthrough curves is well matched to the observation data.
3. The decay of the secondary breakthrough curves is only slightly lower than the decay rate observed in the actual tracer response but the total loss of tracer is less than indicated in the observations.

The results indicate that the assumption of Darcian flow in homogeneous planar fractures is a good approximation of the real conditions for this particular site. The required magnitude of the longitudinal dispersivities indicates that the fracture apertures show some heterogeneity but that this is most likely not derived by large scale channelling features. The results also indicate that the tracer lost to the lower borehole section does not reach the discharge borehole during the first 7 hour period of the tracer test. Feature 3 suggests a further net loss of material that is not identified by the model. During calibration it was not possible to increase the downflow loss of 30 percent further without underestimating the magnitude of the first breakthrough peak. Two possible causes for this are rock matrix diffusion and possible regional scale heterogeneity increasing the lengths of some flow paths between the boreholes during pumping.

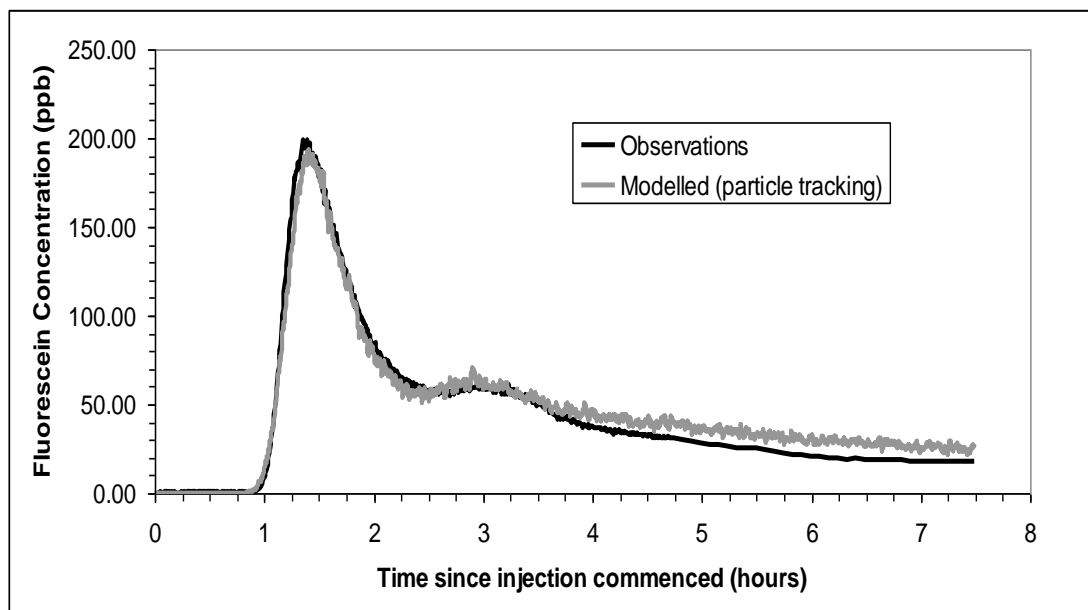


Figure 7. Calibrated versus observed breakthrough tracer concentrations at the outlet of the doublet discharge borehole.

The results of the modelling indicate that about 70% of the injected water is travelling through the fractures in the upper section of the Chalk. The model suggests a total aperture of 7 mm and, therefore, assuming that 70% of the transmissivity (ie 666 m²/d) is provided by the upper section and uniform fracture properties, then roughly 7 fractures of aperture 1.1mm are required to meet both the transmissivity and fracture porosity constraints. This figure is rather different from the first breakthrough time analysis (ignoring the full tracer response) and will have the affect of increasing the time to thermal breakthrough under the operation of the doublet borehole for thermal energy storage.

Typical values for rock matrix diffusion at fracture walls for limestone have been estimated in a study by Greswell et al. (1998) to be around 3×10^{-6} m²/d. Based on this value, it is possible to estimate the maximum amount of tracer that could be lost by this process over the duration of the test if 7 fractures are assumed. When calculated this amounts to about 28 percent of the injected volume after 7 hours. A figure of 30 percent is needed to explain the apparent loss and therefore rock matrix diffusion could provide a possible explanation for the enhanced decay.

Whilst each of these results must be considered cautiously, the tracer test has provided potentially very useful information for the determination of the physical system that controls thermal breakthrough.

Thermal test

Thermal testing between packers was carried out on the upper and lower sections of the borehole but only useful results were obtained for the lower section and these are shown in Figure 8. The borehole diameter was oversized in the upper part of the chalk making it impossible to locate and fix the packers to carry out a test. Five cubic metres of warm (35°C) water was injected at 5 litres per second into a 3.66m packered section of the borehole over a period of twenty minutes. The packered

section was then pumped at 5 litres per second to recover the injected water. Temperatures were monitored at 30 second intervals with thermistors at the top middle and lower sections of the borehole to observe the heat loss into the aquifer and to examine the form of the response to establish whether the expected thermal properties for the chalk are consistent with the observations.

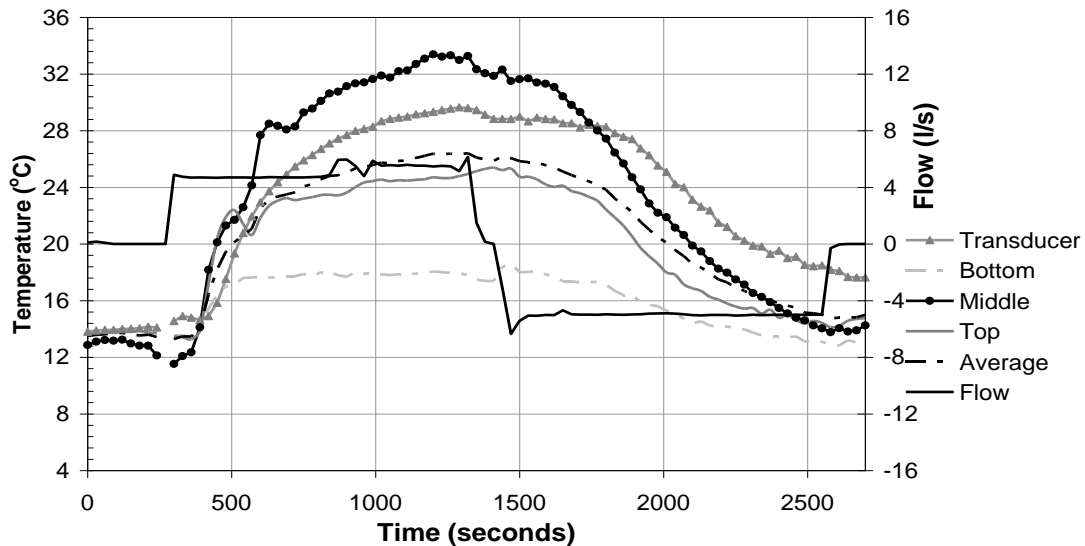


Figure 8 Field observations during the thermal energy injection withdrawal tests.

The results for the 3 thermistors are intriguing in so far as they show remarkably different magnitudes of response. The highest temperatures are recorded in the mid section while the lowest are recorded at the lower section with the upper section showing a rise in temperature intermediate between the other two. The heated water was injected at the mid point of the packed section. In addition, the temperatures only gradually increase towards the injected water temperatures during the test and on cessation and reversal of flow, they show a gradual response to the reversal that is rather different from the typical recovery shape as would be expected for simple heat injection and withdrawal in a single fracture. The gradual rise in temperature cannot be explained by thermal losses in the injection pipe and as there is apparently little mixing in the open section of the packed borehole and the volume of the open section is much smaller than the injected volume, it cannot be explained by manifold type mixing. Another explanation is required to resolve the apparent thermal behaviour of the experiment.

Figure 9 shows the arrangement of the packers, pipework and the pumps in the borehole. This figure provides the clues to the processes controlling the form of the temperature observations. If it is assumed that flow is to one or a few localised fractures below the inlet to the pump, then the water in the borehole between the packers will be effectively stationary other than between the outflow from the pump and the fractures. It is important to note that this interpretation ignores local thermally driven flow cells, which may play a role in determining the temperature distribution within the packed section. The pipework transmitting the inflow down to the midpoint of the packed section permits heat to be transmitted by thermal conduction to the stationary water in the annular space surrounding it. Thus, during injection the upper half of the packed section will be heated. As the pump has a larger diameter than the pipework above and because heat transmission of metals is high relative to water (and the annular space around the pump is smaller), the water

in the annular space around the pump will be heated more quickly than the water above the pump, leading to higher temperature rises. At the base of the packed section, a similar heat source is not present and the temperature rises will therefore be much lower. To test whether the concepts identified here explain the results, a highly simplified model (excluding thermal convection in the annular space) was built to include the main elements of the borehole as shown in Figure 9. The thermal properties used are presented in Table 1. The data used in this Table are taken from standard values presented in the literature and on the web (The Engineering ToolBox, 2005) The modelling results are shown in Figure 10.

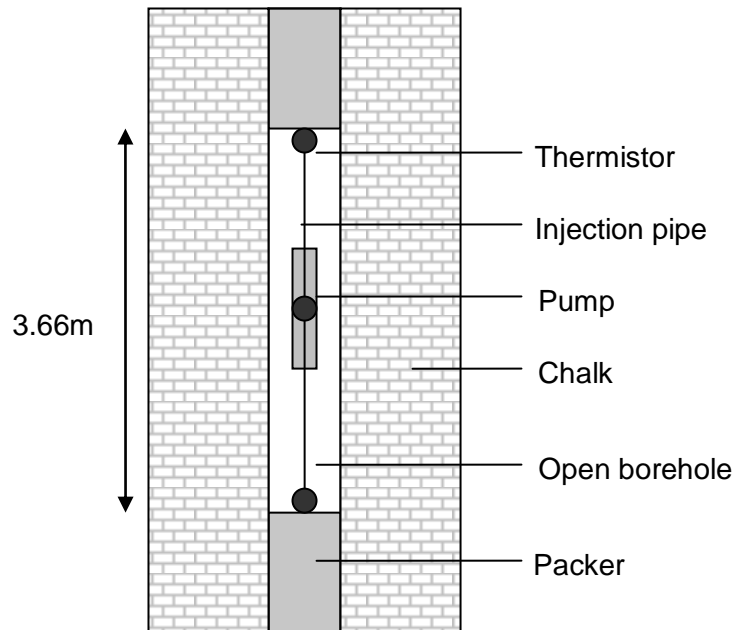


Figure 9. Basic elements of the thermal test

Table 1 Material properties used to model the thermal injection test

Material	Thermal Conductivity kJ/m/s/°C	Thermal Capacity kJ/m ³ /°C
Water	6.1×10^{-4}	4.18×10^3
Limestone matrix	2.0×10^{-3}	1.56×10^3
Steel	9.2×10^{-2}	3.62×10^3

Whilst the results are imperfect, as the model does not account for convective processes, the similarity in the response of the upper and middle temperature sensors to the model results suggests that the explanation given here for the observed results is probably correct. The model failed to reproduce the lower temperature profile suggesting that either a part of the internal construction of the packer/pump system is not properly represented in the model or alternatively there is a very slow discharge to the aquifer close to the base of the packed section. Neither will have a strong influence on the use of the model results.

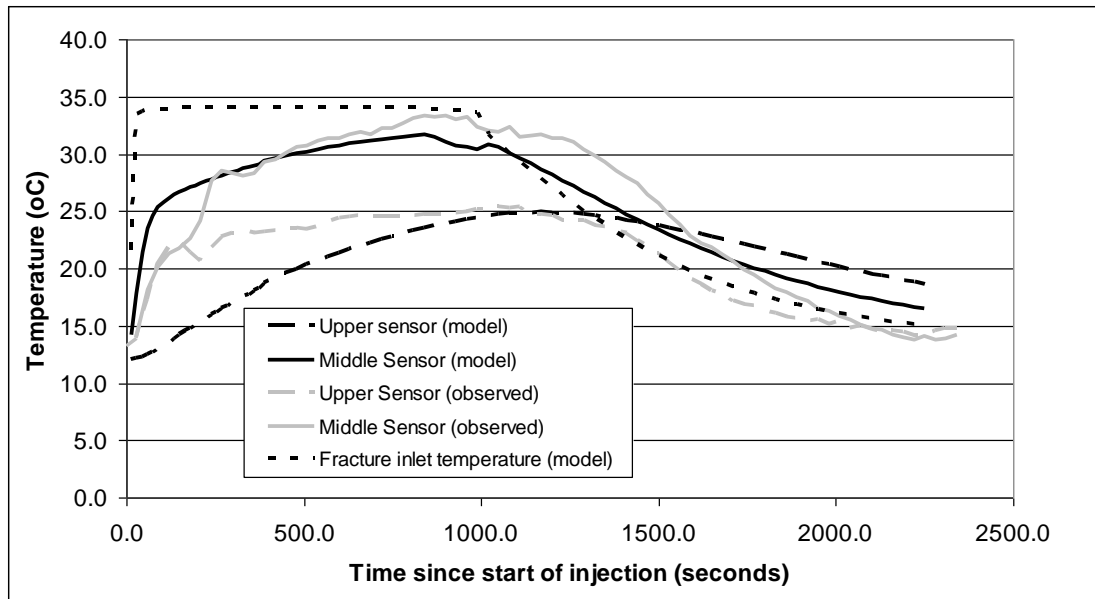


Figure 10. Modelled versus observed response for the thermal test.

The thermal modelling analysis carried out here illustrates two rather important points and words of caution. First, the sensitivity of the modelled temperature variations to sensor location in the annular space and to the modelled processes taking place that drive heat flow in this region is very large and therefore caution is needed when drawing inferences from the modelling for the interpretation of thermal properties. For fractured rock masses, the adoption of within packer monitoring is essentially inappropriate under these circumstances. Second, the recovery of the temperature in the borehole provides some evidence for the degree of fracturing in the packered section only if the thermal properties of the rock are known.

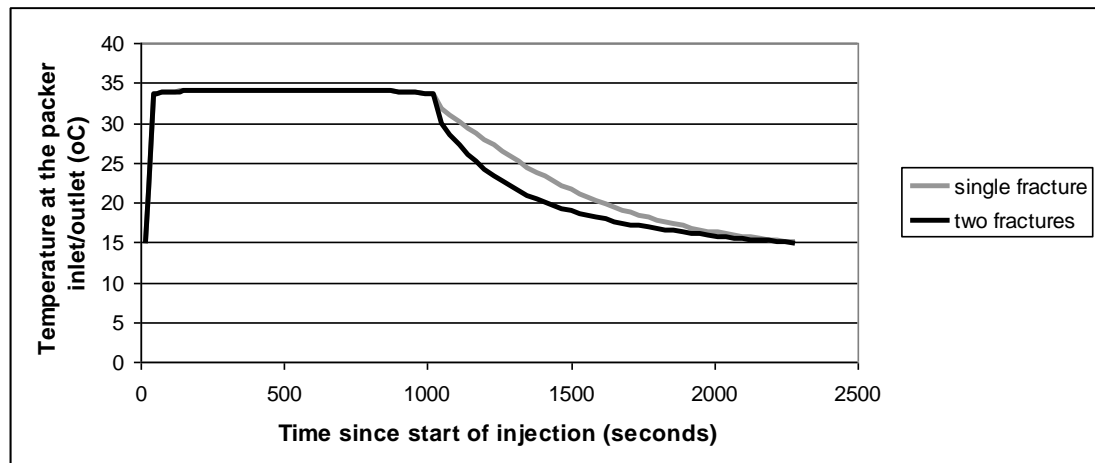


Figure 11. Modelled results for a single fracture and two fractures.

The different responses during recovery for one and two fractures is shown in Figure 11. There is a marked increase in the thermal losses to the matrix from the two fractures compared with the single fracture case, indicating that this test can support the assessment (at least locally to the injection well) of the frequency of fracturing. However, for a valid interpretation of the fracture frequency, the modelling does require *a priori* knowledge of the rock thermal properties. Such knowledge does appear to be available and the current experiments show that in this case the

adoption of standard literature values for the thermal properties of the chalk and the borehole construction materials yield similar results to those observed . Nevertheless, the full results suggest that thermal heating tests are most useful when they are accompanied by a tracer test to acquire an initial appraisal of the fracture frequency and property data. Thus, the thermal test does provide a valuable confirmation of the applicability of the literature derived values for thermal conductivity and heat capacity once an understanding of the flow geometry is available. It is also reasonable to infer from the combination of the tracer and thermal test results that an adequate understanding of the fracture systems is essential to prove the value of a fractured rock site for geothermal energy storage and recovery. Moreover, it appears from the present results that a combination of tracer and thermal testing supported by use of existing data on thermal properties for many of the UK rock types is sufficient to provide the required information for assessment of both the short term risks and the longer term behaviour of the aquifer under an applied cyclical thermal loading.

Conclusions

A suite of tests were undertaken at a site in central London to determine the fracture flow in the Chalk. The results were used to help design an open loop ground energy system. The testing identified that a small number of fractures (<10) carried the majority of the flow between the two boreholes. CCTV and flow logging identified the approximate location of some of the fractures. Tracer testing (fluorescein) proved to be the most successful method of categorising the fractures.

Two methods were used to interpret the results of the tracer testing. The first method used a simple interpretation based on the breakthrough time. This interpretation concluded that 4 fractures, each of 1.5mm would be a good approximation for the flow. The second interpretation, that modelled the full breakthrough curve, concluded that flow was carried by 7 fractures, each of 1.1mm.

A thermal test was also devised in an attempt to mimic the actual response of the Chalk to thermal injection. However, an interpretation of the results of the test showed that the results were inconclusive. For a thermal test to provide conclusive results, observations of the integrated thermal outputs during recovery (ie the temperature of the recovered discharge) would be needed. The results also suggest that a thermal heater test of the type described would on its own provide insufficient evidence for assessing the risk of adverse thermal breakthrough and that the combination of the tracer and thermal testing is the most effective testing regime for a fractured rock such as the Chalk.

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