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AQUIFER THERMAL ENERGY STORAGE IN THE FRACTURED LONDON CHALK. A THERMAL INJECTION / WITHDRAWAL TEST AND ITS INTERPRETATION

Ryan Law, Duncan Nicholson, Karen Mayo

Arup Geotechnics
13 Fitzroy Street
London, W1T 4BQ
e-mail: ryan.law@arup.com

ABSTRACT

To comply with current renewable energy targets substantial new building developments in London are using the water held within the Chalk aquifer as a source for heating or cooling. Owing to the fractured structure of the Chalk there is the possibility of rapid transport occurring between the abstraction and injection boreholes at a site. This has the potential to cause thermal interference between the boreholes and a consequent loss of performance and, ultimately, eventual failure of the system.

The nature of the thermal transport that occurs at a site will primarily be dependent on the fracture frequency in the aquifer. To help determine the frequency of the fractures beneath a proposed site in central London a thermal injection and abstraction test was designed and undertaken. The test was the first of its kind in the United Kingdom and its interpretation will be used to assist with the design of the proposed heating and cooling system.

The test consisted of heating and storing water on site, followed by injection into a packered section of a borehole. Once the hot water was injected the pump was reversed and the water abstracted. The temperature of the packered section of the borehole was monitored with thermistors throughout the test. The results were then interpreted with the United States Geological Survey (USGS) SUTRA 3D code.

The results suggest that the fracture frequency beneath the site is sufficiently high to limit the possibility of rapid thermal transport occurring between the two boreholes. The results have been used in further numerical models that predict the long term performance of the proposed system in this flow regime.

INTRODUCTION

There has been an increasing interest in using the water contained within the Chalk aquifer underneath central London as a source for heating or cooling a building, in combination with either ground source heat pumps or heat exchangers (Arup, 2006). This is in direct response to a change in the planning framework, instigated by the Mayor of London (Mayor of London, 2004). The Mayor's strategic policy on renewable energy states that substantial new developments should meet 10% of their total energy requirements from renewable sources. Indeed, it is anticipated that these targets may go further and require 20% from renewables and a 35% reduction in carbon emissions. Using the water within the Chalk aquifer is currently the principal method that developers have identified for meeting these targets.

Under the abstraction licensing legislation the Environment Agency currently requires that in order to maintain current water levels in the Chalk aquifer new abstractions must re-inject the majority of the water abstracted (Environment Agency, 2005). Re-injection of water at a different temperature to that at which it has been abstracted presents a number of problems including:

1. The possibility of heating or cooling the aquifer beneath the site during the lifetime of the building.
2. The possibility of rapid thermal transport between the injection and abstraction boreholes beneath the site due to the fracturing within the Chalk.

To better understand the long term performance of proposed ground source systems (problem 1 above) Arup has used a number of numerical models based on the USGS SUTRA 3D code (Law, 2005). The SUTRA code is well proven and is capable of coupling groundwater flow with convective and conductive heat transport. These models have to date treated the Chalk as a homogenous medium. The flow within the Chalk aquifer actually occurs through a number of fractures, with the Chalk matrix acting as an impermeable material (Price 1987, Bloomfield, 1996). Although the fracturing is often dense (Moench, 1995) there is the possibility that a small number of distinct fractures may link the abstraction boreholes with the injection boreholes (Figure 1.)

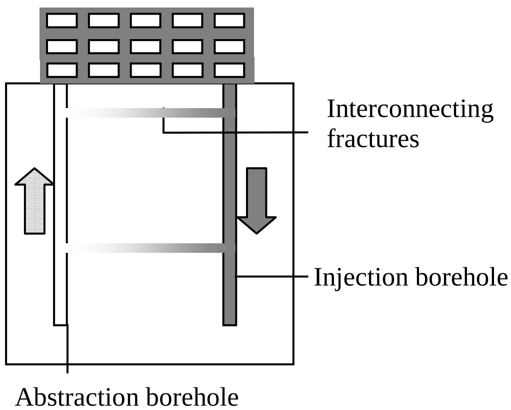

Figure 1. Illustration of the potential thermal interference caused by fractures linking abstraction and injection boreholes

The flow between the boreholes would, in such conditions, be channeled through a smaller volume or cross-sectional area of fracture. Flow rates would therefore be much faster than for a homogenous medium. The smaller the number of fractures that carry the flow, the faster the flow rates will be. Faster flow rates are likely to cause faster thermal breakthrough times between the injection and abstraction boreholes. Conversely, as the number of fractures carrying the flow increases, so does the volume and surface area through which the water flows, decreasing the velocity. In addition, the surface area of the Chalk matrix exposed to the hot / cold re-injected water is increased, causing greater energy dissipation from the fracture into the matrix. These two factors are the properties of the aquifer that need to be determined before a realistic appraisal of the proposed heating and cooling system can be made.

THERMAL TEST ASSUMPTIONS

The thermal test itself is based on the assumption that fluid transport within the Chalk can be represented by a number of parallel horizontal fractures. This is not an unreasonable assumption for the Chalk in which fractures, when observed, are often parallel and broadly follow bedding plane structures (Bloomfield, 1996).

As the operational flow rates will be fixed at a constant rate for a proposed system it is only the frequency of the fractures that will alter the thermal breakthrough times. The fracture aperture will only affect the head required to drive the flow.

The frequency of the fractures should theoretically determine the response of the aquifer to the injection and abstraction of heated water. The fracture frequency will affect both the fluid velocity and the dissipation of energy into the Chalk matrix. This theory was tested in a number of different numerical models previous to the actual test to prove that the response for different fracture frequencies would be sufficiently different to be measurable during the test. This work is in the process of being reported.

The longer the test, the greater the fluid penetration and therefore the more accurate the interpretation of the aquifer structure beneath the site. However, this has to be balanced with both the man hours required to undertake the test and the ability to heat sufficient quantities of water on site.

THE THERMAL TEST PROCEDURE

The thermal test consisted of heating a total of 6000 litres of water (by means of immersion heaters) in a number of thermally insulated containers (Figure 2).

Figure 2. Plastic insulated containers for heated water storage

Once the water was sufficiently heated to a temperature close to the likely peak injection temperature for the proposed system, the water was pumped into a 3.66m packered section of the borehole. The pump was placed within the packered section along with three thermistors; one at the base, one at the middle and one at the top of the section (Figure 3). The location of the packered section corresponded to the section of the borehole where peak flow rates had been observed in previous flow metre testing, in this case 144m below ground level. Figure 4 shows the equipment and packer being lowered into the borehole.

The flow rate from the heated containers to the packered section of the borehole was kept at a constant 5 l/s. Once the heated water had been exhausted the flow rate was reversed and the water abstracted at a constant 5 l /s.

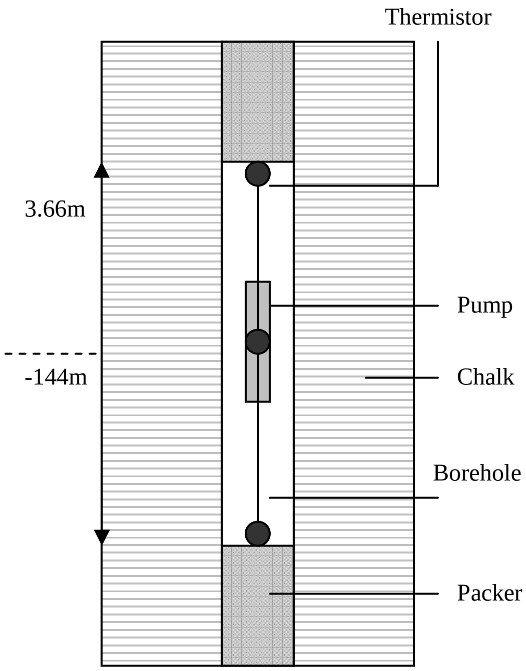

Figure 3. Schematic section of thermal test equipment

Figure 4. Equipment being lowered into the borehole

TEST INTERPRETATION

The principal method used to interpret the test was numerical modeling. Analytical solutions have been developed for an injection / abstraction test for the oil industry (Kocabas and Horne, 1990) for a constant injection rate and temperature followed by a constant abstraction rate. However, the injection rate for the test itself, although close to constant, did vary throughout the test. In addition, the temperature of the water within the packered section of the borehole was not constant throughout the test. Analytical solutions also become increasingly complex when dealing with radial flow (Moench, 1995). To represent the actual conditions that occurred during the test numerical modeling with time variable inputs was considered to be the most appropriate approach.

ANALYTICAL COMPARISON

To test the validity of the numerical model construction and the USGS SUTRA code for this type of problem a comparison was made between an analytical solution for thermal injection through a single fracture and the results derived from a numerical model. The analytical solution for thermal transport in a single fracture is well known and is based on the work by Lauwerier, 1955. The equations that need to be solved to determine the temperature at any point within the fracture are as follows:

$$(C\rho)_f \frac{\delta T}{\partial t} + \rho_w C_w V \frac{\delta T}{\delta x} = \frac{\lambda_m}{h} \frac{\delta T_m}{\delta z}$$

Eq.1

$$(C\rho)_f \frac{\delta T}{\partial t} + \rho_w C_w V \frac{\delta T}{\delta x} = (\lambda)_f \frac{\delta^2 T}{\delta x^2}$$

Eq.2

where:

ρ_w = density of water

C_w = specific heat capacity of water

ϕ_f = porosity of the fracture

$(C\rho)_f$ = total volumetric heat capacity of the fracture (includes any material in the fracture)

V = velocity of the water $V = \frac{q}{(\rho_w A \phi_f)}$

q = water injection rate

$\frac{\delta T}{\delta x}$ = temperature gradient in the water in the fracture

$(\lambda)_f$ = bulk thermal conductivity of the fracture

λ_m = bulk thermal conductivity of the material around the fracture

$\frac{\delta^2 T}{\delta x^2}$ = rate of change of temperature gradient in the fracture

h = the vertical depth of the fracture

$\frac{\delta T_m}{\delta z}$ = the temperature gradient in the material surrounding the fracture.

Equations 1 and 2 can be solved (Zabarnay, 1998) with the following boundary conditions:

$T_{(x,t)}$ = temperature within the fracture at any point

$T_{m(x,z,t)}$ = temperature of the impermeable surrounding material.

T_2 = initial temperature of the aquifer

T_1 = injection temperature

$T_{(\infty,\infty,t)} = T_2$

$T_{(x,y,0)} = T_1$

$T_{(x,0)} = T_1$

$T_{(o,t)} = T_2$

$T_{m(x,z,0)} = T_1$

$T_{m(x,z,t)} = T_1; x \to \infty, z \to \infty$

The solution then becomes:

$$\theta_{(x,t)} = erf\left(\frac{\frac{\lambda_m x}{C_w \rho_w V}}{h\sqrt{\frac{\lambda_m}{C_m \rho_m}\left(t - \frac{(C\rho)_f x}{C_w \rho_w V}\right)}} \right)$$

when $t > \frac{(C\rho)_f x}{C_w \rho_w V}$

Eq. 3

And

$\theta_{(x,t)} = 1$ when $t < \frac{(C\rho)_f x}{C_w \rho_w V}$

Where

$\theta_{(x,t)} = (T_{(x,t)} - T_2)/(T_1 - T_2)$

Equation 3 was solved in an Excel spreadsheet and the temperature at a number of different points along the fracture plotted against time. The parameters used are those shown in Table 1.

Parameter	**Value**	**Units**
C_w	4182	J/kg°C
ρ_w	1000	kg/m³
ρ_r	2800	kg/m³
λ_f	2.8	W/m
C_r	890	J/kg°C
q	0.5	l/s
ϕ_m	0.3	dimensionless
ϕ_f	0.98	dimensionless
t	variable	s
h	0.001	m

Table 1. Parameters used in the analytical solution

The numerical model in SUTRA consisted of a single fracture split horizontally by symmetry to save on model running time.

In order for the numerical model to treat the fracture as flowing water the dispersivity was set to zero. The model grid dimensions were set to comply with the Courant number which represents the relationship between the velocity of the fluid and the grid size of the model. A Courant number less than 1 is preferred for numerical accuracy:

$$C = v\frac{\Delta t}{\Delta l}$$

Where:
C = Courant number
v = average linear velocity of the fluid
Δt = numerical time step
Δl = dimension of the largest grid cell in the direction of flow

Fluid enters SUTRA through individual nodes and is then applied across a cell (Figure 5)

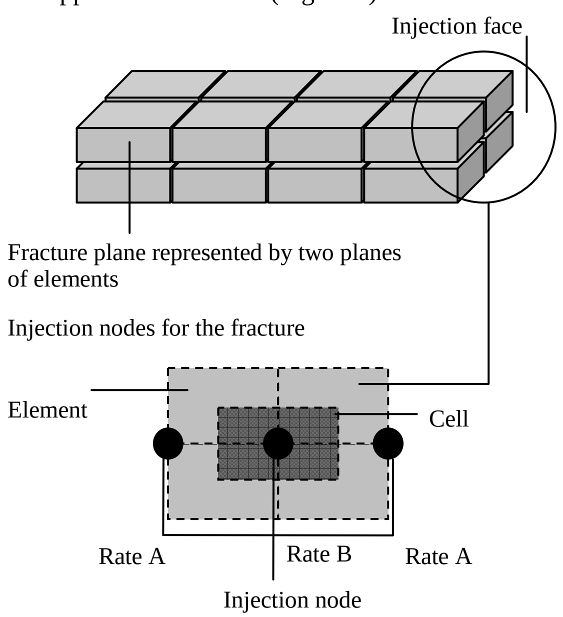

Figure 5. Representation of fracture plane in the numerical model

A single injection cell therefore spans four elements. The fracture plane itself was represented by two rows of elements to ensure that the fluid entered the model through the elements with the correct hydraulic and thermal parameters. In addition, nodes on the outer edge of the model were allocated half the injection rate of the other injection nodes (Rate A and Rate B respectively). The fracture hydraulic conductivity applied to the model was that derived from the cubic law for a 1mm fracture, although as the injection rate through the nodes is constant this parameter will only affect the pressure required to achieve this flow.

The results from the comparison between the analytical modeling and the numerical modeling can be seen in Figure 6. This shows that the correlation between the two results is extremely good for all distances from the injection point. The method used to represent the fracture and the model construction and running (time stepping, grid definition) are clearly acceptable.

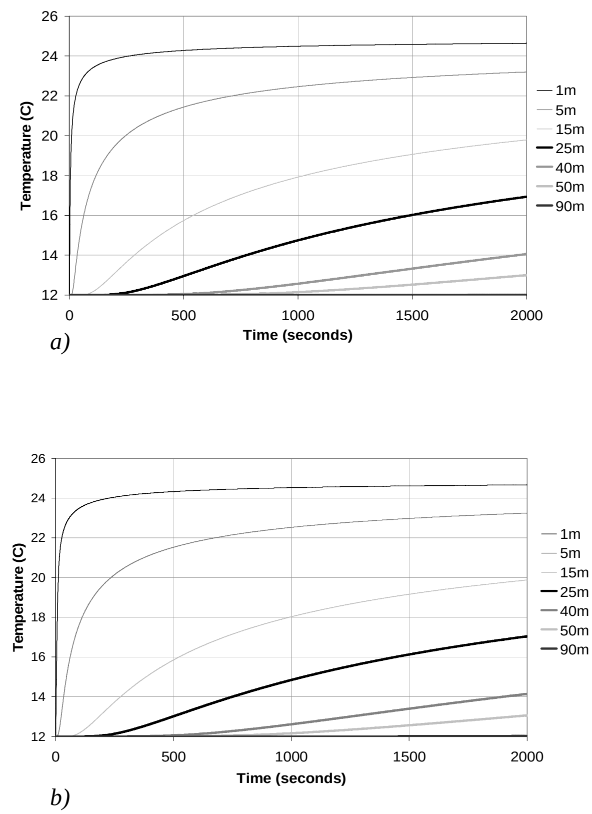

Figure 6. Comparison of results for a) analytical and b) numerical modeling for a single fracture

THERMAL TEST MODEL CONSTRUCTION

As with all numerical models a balance has to be maintained between the model resolution and the model running time. To reduce the model grid size and thus the running time, horizontal and vertical symmetry was used to split the packered section of the borehole (Figure 7). After this alteration, the model running time was reasonably fast.

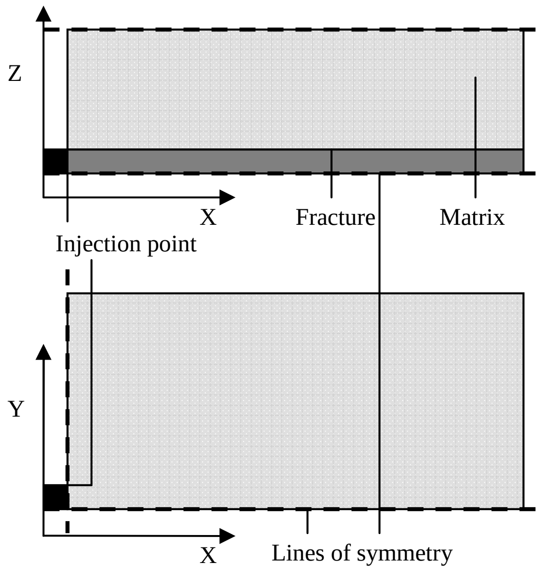

Figure 7. Lines of symmetry and model layout

MODEL OPERATION

The data from the injection period of the actual test was input as a time dependent variable into the SUTRA code. The average temperature recorded in the borehole during injection was used as the temperature input. The code was then recompiled using the Compaq Fortran compiler before being run. The dimension of the matrix above the fracture (X in Figure 7) was varied for each model run and the flow rate altered accordingly. The modeling commenced with a fracture frequency of one for the 3.66m packered section and was progressively increased by reducing the distance X.

RESULTS

The results of the thermal test can be seen in Figure 8. The results show that a near constant flow rate was achieved during the test. The moment when the flow is reversed can also be seen. The temperature recorded at the thermistors varied by up to a maximum of 3 °C during the test from which it is inferred that the water in the packered section of the borehole was not well mixed during the injection process. The temperature rose to a peak of 32 °C before the abstraction occurs and then dropped off during abstraction. Once the abstraction has finished there was a slight temperature rise in the borehole.

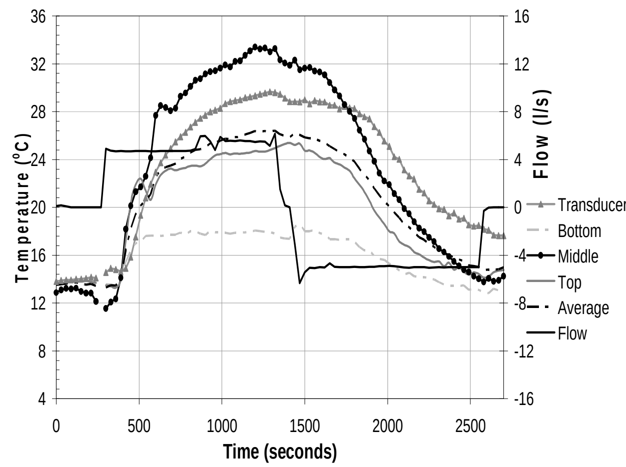

Figure 8. The results of one of the thermal tests

The results of the average temperature recorded during the test and those generated by the numerical model for different fracture frequencies can be seen in Figure 9. Fracture frequencies within the packered section of 2, 16 and 32 are shown to highlight the different predicted responses.

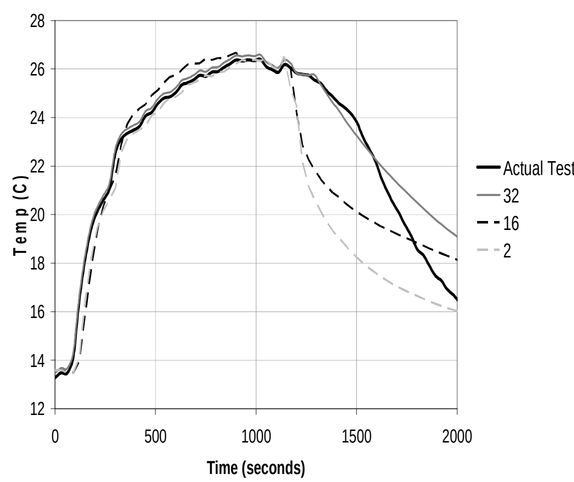

Figure 9. Thermal test results compared with numerical modeling results for different fracture frequencies

It can be seen from Figure 9 that the actual result from the test could not be matched exactly to a particular fracture frequency. However, it is clear that the response obtained from the test is more similar to the curve generated for a higher fracture frequency than for a lower frequency. Flow is clearly not occurring through a small number of isolated fractures (the response curve generated for a fracture frequency of 2 over the packered section, particularly in the early stages of abstraction, is markedly different to that obtained from the test). Even a fracture frequency of 16 still gives a more rapid drop in temperature during abstraction than that achieved during the test. A closer representation of the test is achieved when the fracture frequency rises to approximately 32 (one every 0.11m). Although this result is still not identical to that observed during the test it is much closer than those obtained with lower fracture frequencies.

The difference in the heat dissipation pattern for different fracture frequencies can be seen in Figures 10 and 11. Figure 10 shows the extent and nature of the thermal penetration for a single fracture. In this case, the penetration distance is approximately 7m from the borehole during the injection period. Conversely, for a fracture frequency of 32 (one every 0.11m) the penetration is closer to 3m and the thermal penetration pattern is markedly different.

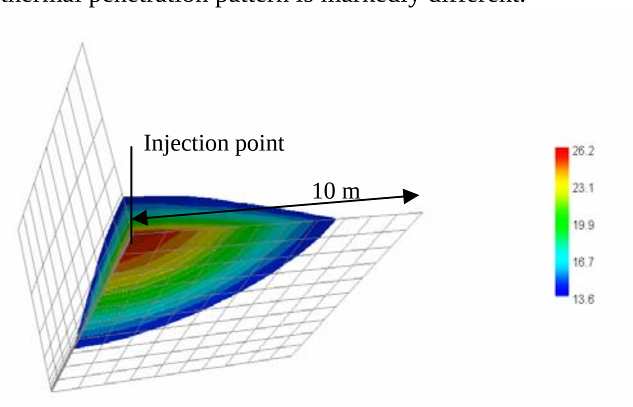

Figure 10. Thermal dissipation pattern for a single fracture

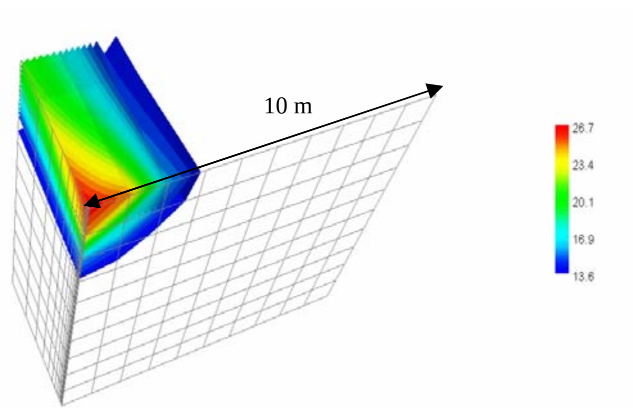

Figure 10. Thermal dissipation pattern for a fracture frequency of one every 0.1m

CONCLUSIONS

A thermal test was designed and implemented at a central London site to investigate the nature of the thermal transport. The results of the test indicate that the flow was not carried by a single or small number of fractures. The fractures that carry the flow can be approximately represented as a series of horizontal fractures with a frequency of one every 0.`1m (approximately 32 fractures over the packered section of the borehole). This result can be used in subsequent models that predict the performance of the system over the lifetime of the building.

DISCUSSION

There are some issues that arise from this sort of test and its interpretation. Of primary importance is the penetration that is gained during the test. With a penetration distance of approximately 3m it is likely that the test is, to a degree, representing the acidised portion of the Chalk aquifer. The flow in this acidised section of the aquifer will occur through preferentially enlarged channels. As the distance from the borehole increases the channels are likely to become less enlarged and the flow will travel through a greater number of fractures. The test will therefore be conservative and under estimate the fracture frequency.

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