Published in: 2006. Proceedings Ecostock, the Tenth International Conference on Thermal Energy Storage. May 31 - June 2 2006, the Richard Stockton College, New Jersey (USA).

GEOTHERMAL RESPONSE TESTS USING CONTROLLED MULTI-POWER LEVEL HEATING AND COOLING PULSES (MPL-HCP): QUANTIFYING GROUND WATER EFFECTS ON HEAT TRANSPORT AROUND A BOREHOLE HEAT EXCHANGER

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ABSTRACT

Classical Geothermal Response Testing depends on applying a constant energy forcing to a Borehole Heat Exchanger and analysing the temperature response in terms of ground thermal conductivity and borehole resistance using the line source or similar analytical approach. In the test the only heat transport mechanism accounted for is conduction, and the principle aim of the test is to measure accurately the ground thermal conductivity.

Although the test is very useful in practice, there are several drawbacks. First of all, only the conductivity and borehole resistance can be estimated. Other parameters (borehole geometry, heat capacity etc) remain unknown. Secondly, to achieve high accuracy in a limited amount of time, a good idea of the thermal response of the ground is needed beforehand. If this information is not available, the test may saturate too quickly (too large energy forcing) or the thermal forcing may be too small, leading to an insufficient temperature response. In both cases the required accuracy of the test is not achieved. Thirdly, other heat transport mechanisms, such as ground water effects, are not considered. However, ground water flow affects and even may invalidate the test results, as has been shown in experiments performed by us where ground water flow conditions could be controlled.

We recently developed a new test protocol that is based on the idea of using a numerical model and parameter estimation procedure to obtain estimates of any parameter of interest. In this test protocol the thermal pulse is modulated to achieve different energy levels. Pulses of about 24 – 40 hours are used, and both heating and cooling pulses are combined. The analysis procedure can be carried out by basically any model capable of calculating the energy transfer between a Borehole Heat Exchanger and the ground. In this case we employ a model based on TRNSYS with SBM, which was specifically adapted for this purpose.

To develop the data analysis procedure we carried out a reference experiment, where ground water flow is virtually absent, and in exactly the same conditions an experiment where ground water flow was forced. In this paper we will present the results of this experiment and develop the methodology to quantify ground water effects using a Type III MPL-HCP geothermal response test.

1. INTRODUCTION

For the design of thermally efficient and economically sized borehole heat exchanger systems the soil thermal characteristics, especially the thermal conductivity, borehole resistance and undisturbed ground temperature, are essential parameters. As these parameters are difficult to estimate from general literature values, Geothermal Response Test's (GRT) have been developed to accurately measure these parameters in the field. The most widely used analysis method is based on the response of an infinite line source model (Ingersoll and Plass 1948, de Vries 1952, Mogeson 1983).
The principle of the GRT experimental procedure is to apply a constant thermal forcing to a borehole heat exchanger and measure the temperature change in time. From the rate of temperature change, given a constant heat

rate, the thermal conductivity can be inferred. Using measurements of the undisturbed ground temperature with the estimate of soil conductivity, the Borehole Resistance can be calculated. The first mobile tests (Type I test, "TED"), based on resistance heating, were introduced in 1995 in Sweden (Eklöf & Gehlin, 1996) and the USA (Austin, 1998).
In the Netherlands a somewhat different approach was followed, and the first Type II test allowing both heat injection as well as heat extraction became operational in 1998 (van Gelder et al., 1999, Witte et al. 2002). The reason to include heat extraction was to allow tests to be performed in temperature ranges that were comparable to the actual temperature bandwidth of heat pump systems used for space heating and to prevent convection around the borehole, that would otherwise affect results.

Although the GRT experimental method as described above has been applied successfully in many different settings (see Sanner et al. 2005, Gehlin & Spitler 2003 for an overview), the test method has a number of important limitations:

- The thermal energy rate needs to be constant. With the Type I test, using direct electrical resistance heating without any active control of the heat rate, variations in the electrical power supplied to the test rig affect results. Numerical models using parameter estimation techniques have been developed to overcome this problem (e.g. Shonder and Beck 1999, Austin et al.. 2000, Yavuzturk et al. 1999). More recently a de-convolution method has been described to remove the variable heat effects (Beier and Smith 2003). The Type II test as developed by us does not experience the problem of varying heat flux, as the energy flux to the ground is maintained constant by an active control system.
- The soil conductivity is considered to be completely homogeneous. Clearly, in practice this is not the case as usually the geological profile along the borehole heat exchanger will comprise several different layers. Also, there can be marked anisotropy, where the conductivity in the vertical or horizontal direction can be different. Additional temperature measurements at different depths in the heat exchanger pipes or in the borehole can be taken to analyze the response in different layers, but this will usually be cumbersome and too expensive to realize. A temperature profile made just after finishing the test can provide at least a qualitative indication of differences in the response of different layers.
- The undisturbed soil temperature is considered to be completely homogeneous. Effects of temperature gradients near the surface or geothermal gradients are not considered. Based on numerical analysis, Signorelli et al. (2004) have shown that these gradients affect the estimated soil conductivity and that the results depend on whether an extraction or injection test is performed.
- The only heat transport mechanism considered is conduction. Other possible heat transport processes such as lateral groundwater flow or convection are not considered, but can be important (Chiasson et al. 2000, Witte 2001). Witte (2001) showed that local convection around the borehole would enhance heat transfer and result in lower borehole resistances and higher soil conductivities. In the same paper results from an experiment with controlled lateral groundwater flow were presented. The presence of lateral groundwater flow can be evaluated using the line source analysis method by examining the constancy of the regression (Witte, 2001).
- In practice, to obtain high quality data, as large an energy forcing as possible should be applied to obtain accurate results, while maintaining sufficient run length of the test. In this respect, the maximum power output of the GRT equipment can be limiting. Especially when insufficient information on the geological profile under investigation is available (which is usually the case as that is one of the main reasons to perform a GRT), it is difficult to select optimum test conditions. A test method that allows heat rates at different levels would be helpful, as the results from the first (constant heat rate) pulse can be used to select parameters for a second or even third pulse.

Recently (Witte, 2005) we developed a new test protocol, based on the application of several energy pulses, with both heat injection (positive energy flux) and heat extraction (negative energy flux). This multi-power level heating and cooling pulses (MPL-HCP) Type III test is based on using a numerical model with a parameter estimation technique to obtain estimates of the relevant soil parameters. The test protocol was developed for two main reasons. First of all, it is able to deal with the problem of reaching the temperature limits of the test equipment too quickly, as it is possible to perform a first pulse at lower energy rate. Using a revised estimate of the soil thermal conductivity from the first pulse, a second pulse can be applied at a higher energy setting, with improved accuracy. The second reason is the fact that the effects of convection and lateral groundwater flow are temperature dependent. More specifically, the magnitude of the effect depends on the difference between the temperature of the fluid flowing through the borehole heat exchanger and the temperature of the groundwater. Therefore, having GRT temperature pulses that approach the temperature plateau at different temperatures may provide additional information. Moreover, combining heating and cooling pulses are thought to allow evaluating the effect of convection. The idea being that the temperature induced density difference driving convection will be aided by higher temperatures, as viscosity will decrease, but will be counter-acted by extraction as the colder water will have a higher viscosity (Witte 2002, Gustafsson 2005).

In this paper we extend the work presented in Witte (2005) and include analysis of a new test that was performed where groundwater flow was enhanced by pumping groundwater from an extraction well.

2. ANALYSIS METHOD AND EXPERIMENT SETUP

In addition to the generally applied line-source or cylinder-source analytical models used to evaluate test results, several different numerical models have been used to analyse GRT data. Shonder and Beck (1999) developed a 1D numerical model based on the cylindrical source representation. Yavuzturk et al. (1999) developed a numerical short time step two-dimensional finite volume model (Austin 1998, Austin et al. 2000, Yavuzturk et al.. 1999) that uses a Nelder-Mead Simplex parameter-estimation method (Nelder and Mead 1965, Austin et al.. 2000) to obtain estimates of several parameters of the ground loop heat exchanger. Gehlin and Hellström (2003) present an explicit one-dimensional finite difference model with a short time step. Signorelli et al. (2004) present a full 3D numerical model, including groundwater flow, for thermal response tests. Wagner and Clauser (2005) developed a parameter estimation technique based on the SHEMAT code (Clauser 2003) to concurrently estimate ground thermal conductivity and ground heat capacity.
We adopted an approach based on the transient simulation model TRNSYS (Klein et al. 1976). The parameter estimation procedure is carried out using the GenOPT (Wetter 2004) package, offering several parameter estimation procedures. We use the Hooke and Jeeves minimization algorithm (Hooke and Jeeves 1961) with the Generalized Pattern Search with Particle Swarm Optimization (GPSPSOCCHJ, Wetter 2004). To calculate the borehole response we utilized first an adapted version of the Lund DST borehole model (Hellström, 1989), but have recently switched to the Superposition Borehole Model (SBM, Eskilson 1986).

The Superposition Borehole Model (SBM) was developed in Sweden by Eskilson (Eskilson 1986, 1987) specifically for the design of borehole heat exchanger systems used as a heat source or heat sink for a heat pump. The model is able to calculate the three dimensional temperature field for a system with any number of vertical (or even graded) boreholes, using an explicit forward differencing numerical technique. The local problem (in the borehole) can be parameterized either by specifying the borehole geometry and composition or by two resistance terms (internal borehole resistance Ra and borehole thermal resistance Rb). As, for the calculation of many boreholes with steep temperature gradients near the borehole, would require a locally very dense mesh, symmetries of the system are used and the final solution is achieved by superposition.

The TRNSYS model (figure 1) uses a data reader to read the relevant experiment data (entering water temperature, return water temperature, air temperature, flow) from a text file. The thermal inertia due to the heat capacity of the fluid is taken into acount by including a fully insulated buffer tank. A delay component is included to account for the fluid travel-time and improve convergence. The model can be forced directly with the measured borehole entering water temperature, or by subtracting the measured ΔT from the calculated SBM borehole return water temperature. The calibration error is defined as the sum of the squared differences between measured and calculated BHE return temperature. The SBM model was adapted to allow the use of different values for the soil conductivity and borehole resistance for different simulation times. Moreover, in the calibration procedure the error is calculated for a selected time window only. The procedure proceeds by having the model calculate the temperature response, using the previously calibrated values for soil conductivity and borehole resistance up to the pulse that is currently being calibrated. For the pulse currently being calibrated, different parameter values are selected and the SSE error calculated repeatedly until the GenOpt optimization algorithm has identified the parameter values yielding the minimum error.

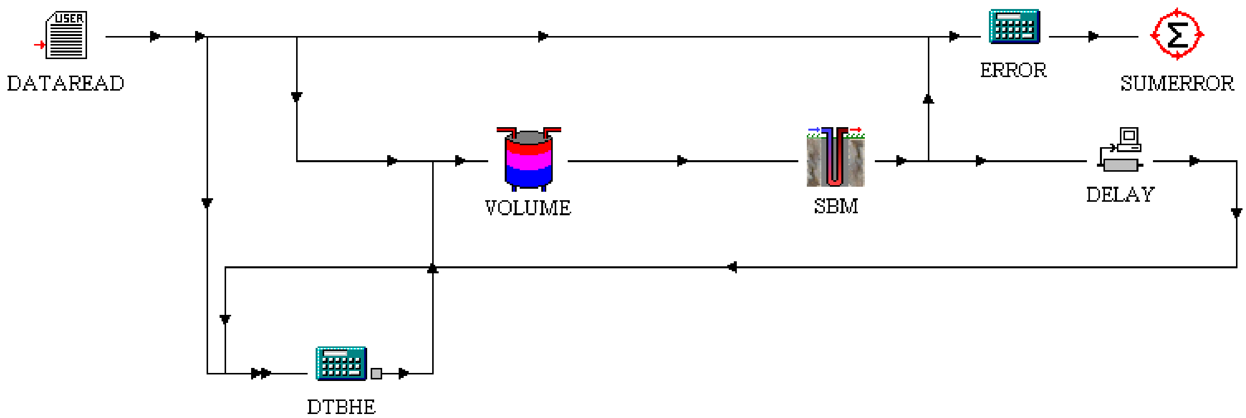

Figure 1. TRNSYS model used for the calibration procedure.

This approach offers a very flexible solution, as several different parameters (soil thermal conductivity, borehole resistance or borehole conductivity and shank spacing, ground temperature, ground temperature profile) can be included easily for the concurrent calibration. Also it is quite easy to extend the model to include the total heat capacity of the volume of fluid in the system or to take into account the travel time of a specific volume of water. Moreover, as this model will be subsequently used for the actual design of the borehole heat exchanger system a calibration using the same model will add confidence to the design results.

The experimental data was obtained by performing two Geothermal Response Tests on the Groenholland reference borehole heat exchanger (BHE), in the second test water was extracted from an extraction well. The BHE is the same borehole used in previous investigations (Witte 2001, Witte et al. 2002, Witte 2005). The borehole heat exchanger is installed in a 30 meters deep borehole. The soil profile consists mainly of a cover layer of low hydraulic conductivity (confined aquifer) with below a sequence of fine sands with clay and coarser sands. A detailed description of the soil profile and borehole configuration is given in Witte et al. (2002). Located at a relatively small distance (2.5 meters) of the BHE there is an extraction well, where water can be pumped from a filter at a depth of approximately 20 meters. Several observation filters are present, at different radial distances from the borehole heat exchanger and extraction well. With the exception of one shallow filter located in the cover layer, all filters are located in the first aquifer. A general schematic and radial profile is presented in figure 2. The first experiment was conducted without any groundwater extraction, the second experiment was conducted with groundwater extraction. Natural groundwater flow at the location is negligible.

Before the test commenced, measurements of undisturbed temperature were made. During the test the flow and temperatures in the BHE are recorded at 240 s intervals. In the test with the extraction well active regular measurements of groundwater levels and total volume extracted from the extraction well have been made. Thermal recovery was also recorded in both experiments, but is not evaluated in this study. Heat transfer fluid in the BHE was a 17% ethylene glycol solution.

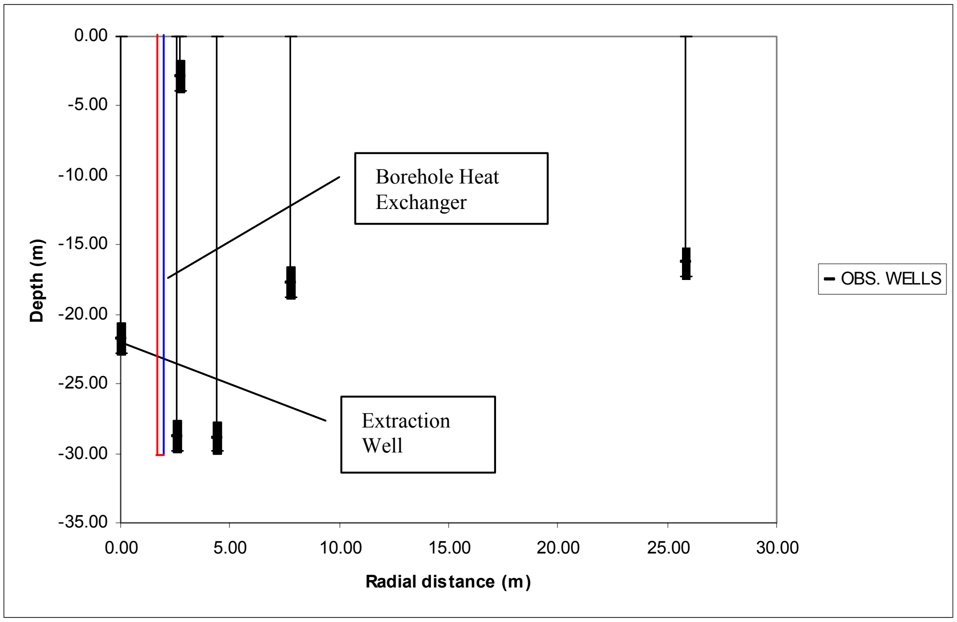

Figure 2: Observation well positions: filter depth and radial distance to extraction well.

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3. RESULTS

Each test comprises three energy-pulses: two heat injection pulses at different energy levels and one heat extraction pulse. Duration of the pulses was kept virtually the same in the two experiments. The relevant experiment parameters are summarized in table 1. Between the heat injection and extraction pulses a short recovery period was allowed, also needed to switch the system from heat injection to extraction mode. The reference experiment was carried out between 03/10/2005 and 07/10/2005, the experiment with groundwater extraction between 31/10/2005 and 4/11/2005. The temperature evolution of both experiments is shown in figure 4.

Groundwater was extracted at a rate of 3.26 $\pm$ 0.0049 m^3/hr. The groundwater extraction lowered the piezometric head in the observation wells by 7.5 - 9.5 meters. From figure 3 it is evident that the lowering of the piezometric head is stable during the experiment. Also clear is the fact that although the nearest filters show decreased lowering of head, the furthest filter has a significantly stronger lowering. This is due to the filter being positioned closer in depth to the extraction well, in combination with some anisotropy in hydraulic conductivity. The hydraulic conductivity of the top few meters (cover layer) is very low (< 0.05 m/day), the hydraulic conductivity in the aquifer has been calculated using the data from the pumping test and ranges from 5 - 10 m/day. At the position of the borehole heat exchanger the Darcy groundwater flow is calculated to range between 3 - 6 meters/day during the experiment. Of course, the flow pattern will not be uniform along the borehole heat exchanger and the calculated value is the maximum expected flow rate.

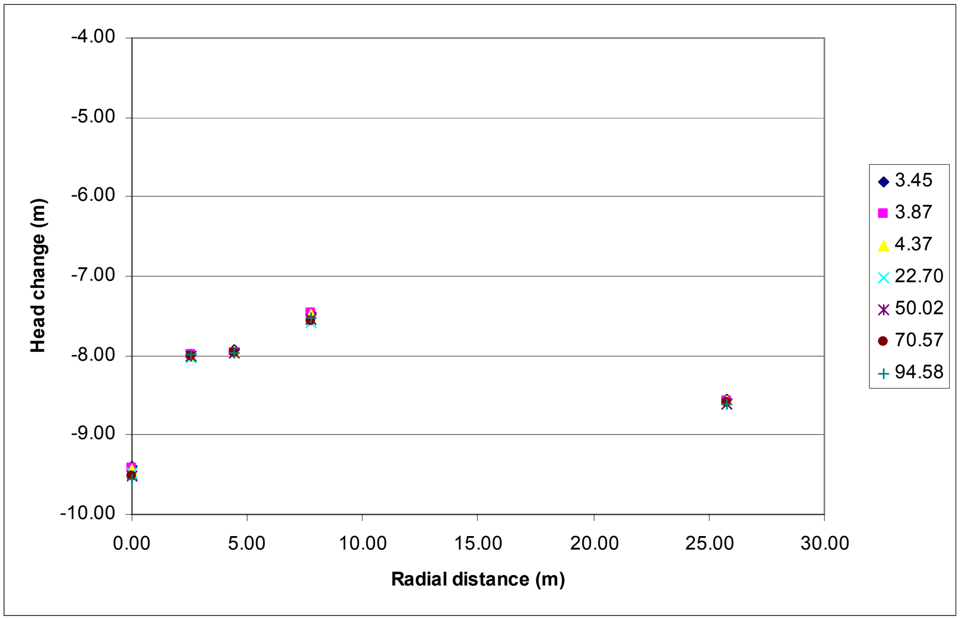

Figure 3. Change in piezometric head in the different observation wells, for different times (hours, see legend) during the experiment.

Experiment	Pulse duration (hours)	Flow rate (m^3/hour)	ΔT (K)	Energy flux (W)
REF – PULSE 1	0 – 24	0.71 ± 0.0074	2.04 ± 0.175	1602 ± 174.5
REF – PULSE 2	24 – 47	0.72 ± 0.0053	3.09 ± 0.145	2446 ± 119.4
REF – RECOVERY	47 - 51	0.70 ± 0.0124	0.00 ± 0.185	4 ± 63.77
REF – PULSE 3	51 – 95	0.70 ± 0.0046	-2.51 ± 0.113	-1947 ± 87.66
GW – PULSE 1	0 - 24	0.69 ± 0.0061	2.09 ± 0.144	1606 ± 108.8
GW – PULSE 2	24 - 48	0.68 ± 0.0066	3.29 ± 0.064	2477 ± 45.72
GW – RECOVERY	48 – 52.4	0.69 ± 0.0151	0.02 ± 0.0902	11 ± 70.05
GW – PULSE 3	52.4 - 95	0.70 ± 0.0047	-2.52 ± 0.117	-1945 ± 91.52

Table 1. Experiment parameters and standard deviations for the different pulses, reference and groundwater extraction experiment.

The difference in temperature response is quite obvious (figure 4). The experiment with groundwater flow shows a lower rate of temperature increase, which is more, pronounced during the second heat injection pulse.
An overview of the results from the calibration runs for the different thermal energy pulses are shown in table 2. Previous experience (Witte 2005) showed that the calibration error is especially large during the first hours of an energy pulse, when there is a transient borehole response that cannot be adequately represented in the model. The same observation was made with the SBM model where the errors when the first few hours are included are larger by an order of magnitude. The first hours representing the transient borehole response are therefore excluded from the error calculation. The calibrated values for the complete data series show a higher overall conductivity (2.31 W/mK) for the groundwater extraction experiment. For the reference experiment there is no great difference between the estimated values for the different periods. For the groundwater extraction experiment there is clearly a trend of increasing conductivity with the progression of the experiment.

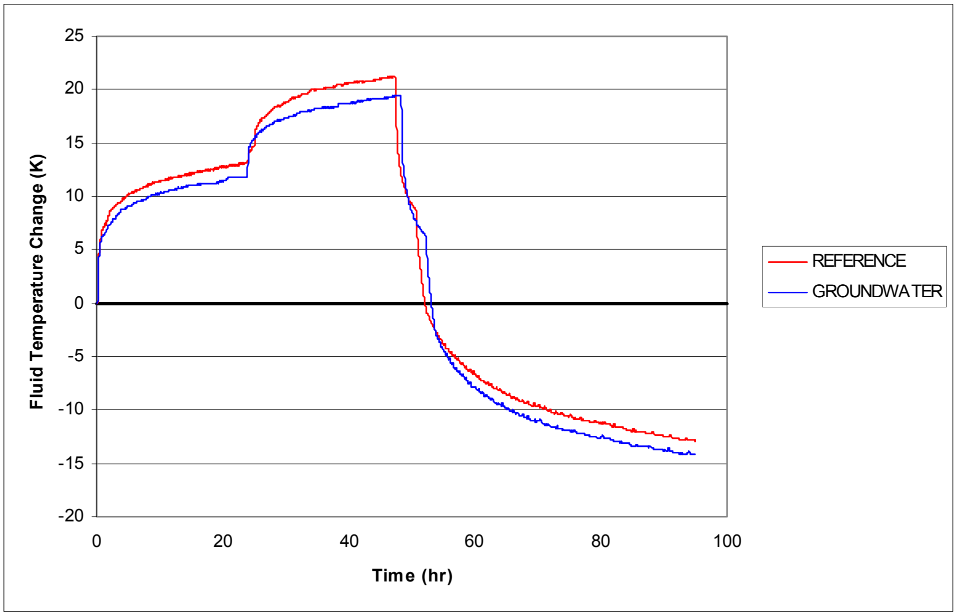

Figure 4: Temperature change of heat transfer fluid temperatures for the reference and groundwater extraction experiment.

Experiment	Pulse duration (hours)	Soil conductivity (W/mK)	Borehole Resistance (K/(W/m))	Error
REFERENCE	5 – 95	2.09	0.086	14.75
REF – PULSE 1	5 – 23	2.11	0.148	0.264
REF – PULSE 2	27– 47	2.01	0.126	0.384
REF – PULSE 3	55 – 95	2.18	0.038	1.428
GW EXTRACTION	5 - 95	2.31	0.09	15.8
GW – PULSE 1	5 - 23	2.03	0.146	0.299
GW – PULSE 2	27 - 47	2.22	0.130	0.321
GW – PULSE 3	55 - 95	2.32	0.045	1.54

Table 2. Overview of the calibration runs for the different thermal energy pulses, reference and groundwater extraction experiment.

Borehole resistance values are in the same range for both experiments, notable is that the borehole resistance is lower during the later heat-extraction pulse. The three heat pulses were further subdivided in periods of 10 hours long, the heat injection pulses in two and the longer heat extraction pulse in four periods. The conductivity and borehole resistance values were calibrated for each period separately, periods of transient response were excluded. The results are shown in figure 5 and 6, here the conductivity and borehole resistance are plotted with respect to the difference between the undisturbed ground temperature (12.3 ^{o}C) and average fluid temperature during the period. The calibrated conductivity values for the reference experiment all fall within a relatively narrow bandwidth (2.0 - 2.2. W/mK) where the calibrated conductivities for the later heat extraction pulses are higher. For the groundwater extraction experiment, the calibrated conductivity shows a relation with the temperature difference. Especially during the second heat injection pulse, the estimated conductivity is higher during the second part of the pulse. For the calibrated borehole resistances (figure 6) no such dependence on the temperature difference is evident. Borehole resistance values during the heat extraction period is somewhat higher for the groundwater extraction experiment.

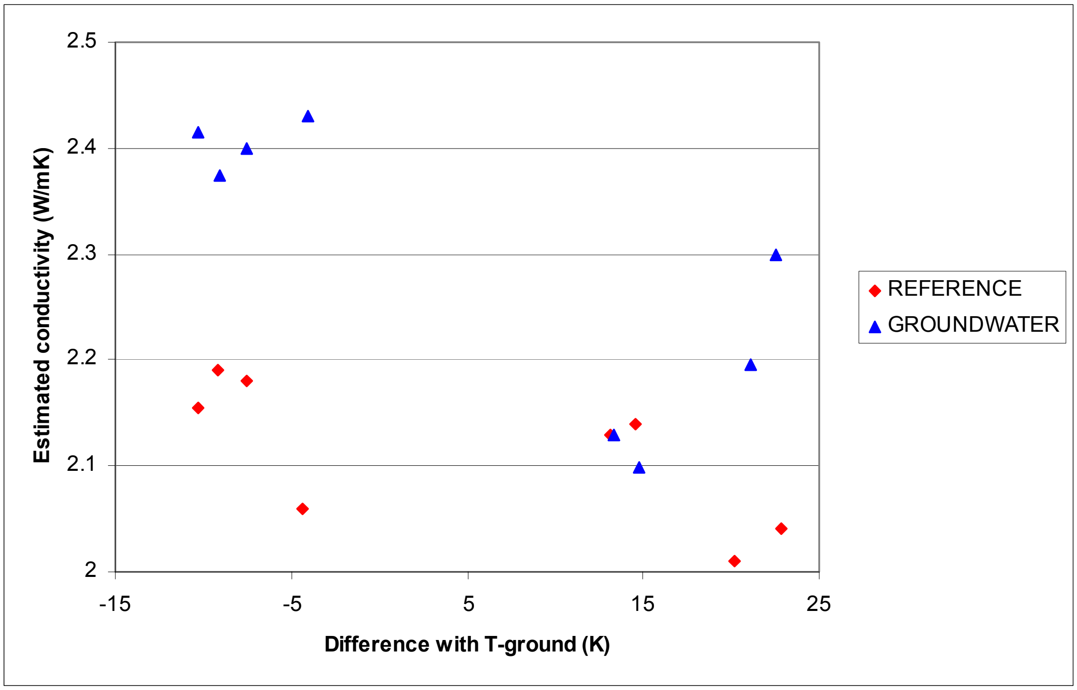

Figure 5: Calibrated conductivities for 10-hour periods of the heat extraction and heat injection pulses plotted against the difference in average period temperature and undisturbed ground temperature.

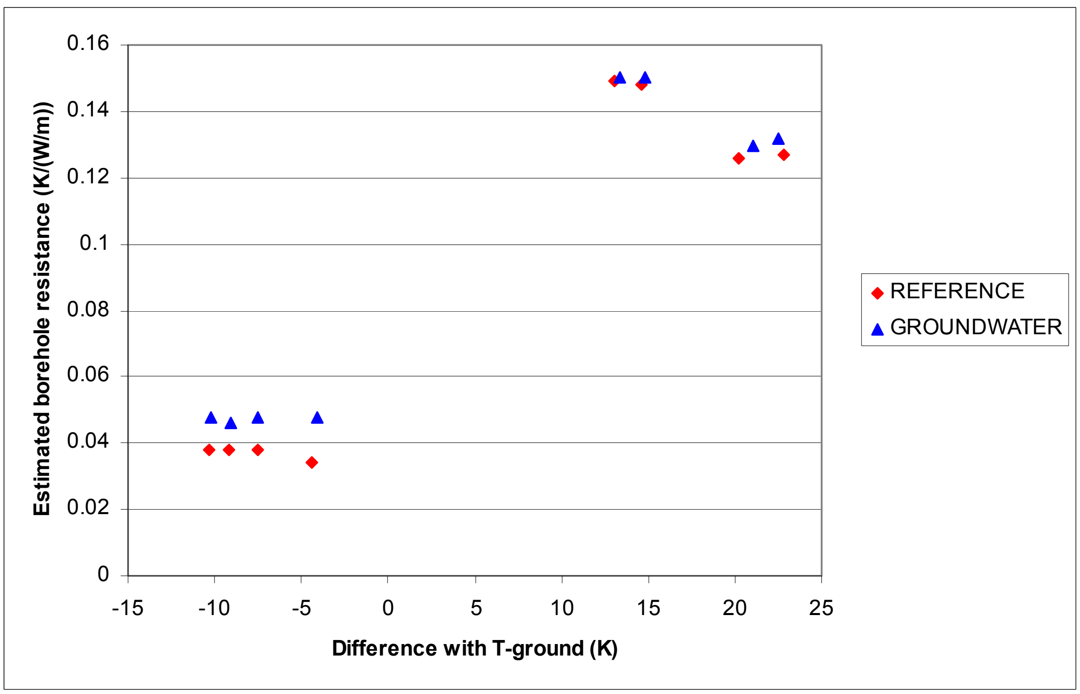

Figure 6: Calibrated borehole resistance values for 10-hour periods of the heat extraction and heat injection pulses plotted against the difference in average period temperature and undisturbed ground temperature.

4. DISCUSSION AND CONCLUSIONS

In this paper we presented the results of two Type III Geothermal Response Tests where in one of the experiments the groundwater flow was enhanced by pumping water from a nearby extraction well. The Geothermal Response Test used is an extension of the classical GRT, where several heat injection and heat extraction pulses are combined in one test. This new test protocol, with calibration based on the Duct Ground Heat Store (DST) model was previously discussed in Witte (2005). In this study we use the Superposition Borehole Model (SBM) to calculate the thermal response of the borehole heat exchanger. A sensitivity analysis of the calibration procedure with the SBM model showed that the parameters soil conductivity, borehole resistance and also ground temperature can be estimated concurrently, there is a global minimum in the parameter space. The estimates usually converge within about 200 - 300 iterations, which will take about 30 minutes for a 95-hour dataset (240 seconds logging interval, 1425 data points) on a 3.2 GHz Intel Xeon processor.

The idea of the multi-level heating and cooling pulses GRT with regard to the effects of groundwater flow is that the apparent or effective conductivity will increase when the difference between the fluid temperature and groundwater temperature is larger. The "true" conductivity can then be estimated from the experiment period with the smaller temperature difference. At greater temperature differences the effect of groundwater flow (if present) will become bigger and the magnitude of the effect is a measure of the groundwater flow rate. If groundwater flow does not play an important role in the heat transport, the estimates of soil conductivity should be the same at least within the heating or cooling pulse. We have shown that it is possible to distinguish the effects in the different thermal energy pulses under no groundwater flow and groundwater flow regimes. Moreover, within the same pulse differences in heat transfer occur during earlier and later times. Using both heating and cooling pulses is interesting because it widens the range of the experimental temperatures. Also, convection effects, if present, can be distinguished by comparing the heat injection with heat extraction results. If there is an appreciable vertical temperature gradient (near the surface or near the bottom of the heat exchanger), effects on the heat transport will be different for heating and cooling pulses (Signorelli, 2004). The test described here would be able to separate such effects as well.

The highest conductivity values were found for the groundwater extraction dataset during the heat extraction pulse, even though the difference between fluid and ground temperature was not very great. As temperatures were still well above freezing, no heat of fusion was released. Perhaps some residual heat from previous heat injection pulses is transported to the borehole heat exchanger, but then the effect would be expected to diminish with time, which was not the case. We plan to repeat the experiments described here with the order of heating and cooling pulses inversed so that the dependence on the pulse order can be investigated.

The datasets we have assembled using groundwater extraction can be used to calibrate numerical models incorporating both heat and mass transport. Using such models, the effects of more uniform groundwater flow, for several typical geohydrological situations can be simulated. Using such simulated GRT data, the effects on actual test data can be better predicted and optimal energy levels for an experiment can be selected.

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