Geothermal Response Tests with Heat Extraction and Heat Injection: Examples of Application in Research and Design of Geothermal Ground Heat Exchangers.

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ABSTRACT

A Geothermal Response Test (GRT) measures the temperature response of a closed-loop ground heatexchanger to an energy forcing. From the temperature response important thermal characteristics of the ground, such as the thermal conductivity and the borehole resistance, can be inferred. In this paper we will take a closer look at the Geothermal Response Test method that we have developed at Groenholland. Implications of the test results, with special attention to the effects of convection in the borehole and the influence of groundwaterflow on the testresults, will be presented.

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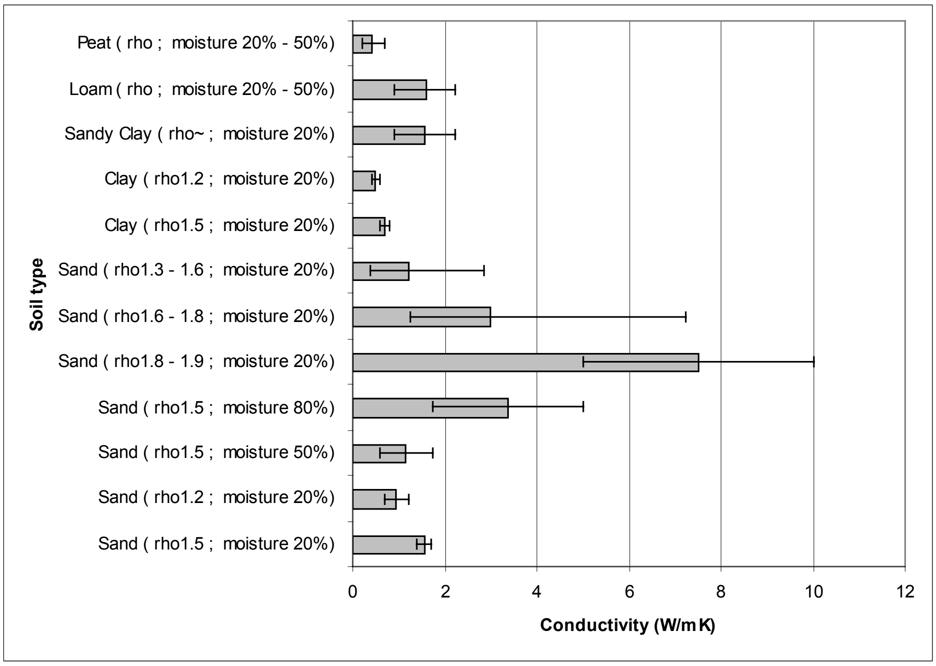
1 INTRODUCTION

The uncertainty in the thermal characteristics of the ground often is the most significant problem in the design of ground loop heatexchangers. The thermal characteristics of the ground will determine to a large extent the temperature response of a ground loop heatexchanger, and moreover are very variable and difficult to estimate from standard tables (Austin 1998). The most important ground thermal characteristic is the thermal diffusivity α , consisting of the ratio of the thermal conductivity λ and the volumetric heat capacity ρc. Especially the thermal conductivity is very difficult to establish with sufficient accuracy and has a significant effect on heat exchanger length and optimal spacing of individual heat exchangers (figure 1).

Figure 1. Some typical values and ranges for thermal conductivity of different soil types in the Netherlands.



A vertical closed-loop heat exchanger consists of a U-type or Concentric-type loop placed in a borehole in the ground. The borehole can be backfilled with the original (mixed) ground material or backfilled with a special mixture such as a grout. Along the length of the groundloop heat exchanger several different soil types may occur, and groundwater may be present or absent depending on the depth.
The rate of exchange of thermal energy between the ground and the fluid flowing in the tube depends on many factors. In general the different components of the system contribute as follows:

1. Groundloop and circulation fluid: fluid characteristics, flow rate, pipe material and pipe configuration. Determines the internal heat-exchange, usually expressed as the internal borhole resistance. See Hellström (1991) for a detailed account.

2. Borehole and backfill material: borehole material and borehole radius. Determines the contact resistance borehole wall – groundloop and a resistance between the ground – borehole. See Hellström (1991) for a detailed account.

3. Ground: far field temperature, thermal diffusivity of different soil types, groundwater flow. Determines the overall thermal response of the system to an energy forcing.

Although the first two components, the groundloop and borehole configuration, are important, both with respect to thermal efficiency and quality of the system, they are well known and can be controlled by the designer. To obtain information on the ground component information of the soil profile, together with tables of thermal classifications of soil types can be used. Alternatively laboratory analysis (with the needle probe method) of samples obtained at different depths can provide information on the thermal charactersitics. Both methods however do not provide any information on the borehole – groundloop configuration or the effects of groundwater flow. A Geothermal Response Test (GRT) measures the in-situ thermal response to an energy forcing, providing information on key parameters such as soil thermal condcutivity, far field temperature and borehole resistance. With such a test all components of the system are included, taking into account the groundwaterflow and borehole – heatexchanger construction as well.

The basis for a GRT is to inject in, or extract from, the ground a fixed and known amount of energy during a sufficiently long time. The equipment heats or cools a circulation medium (water or antifreeze) that flows through a closed-loop ground heatexchanger. The temperature response of the circulation fluid is measured at the same time and can be used to infer the soil thermal characteristics.
In principle two methods have been developed: one using electrical heater elements (Eklöf & Gehlin 1996, Austin 1998) and one using a reversible heatpump (van Gelder et al, 1999). The advantage of the latter being the ability to both inject or extract energy form the ground. The data obtained can be analysed by the line – source approximation (Mongesen, 1983), which is fast and easy. Alternatively a numerical parameter estimation technique (e.g. Eskilson 1987, Hellström 1989, 1991, Muraya 1995, Yavuzturk et al 1999) can be used that allows to estimate concurrently several parameters, but requires large amounts of computer time. The accuracy of the line source approximation depends on having a sufficiently long test and sufficently stable energy rate. In practice the main problem in application of the test is to keep the energy flux constant (e.g. Eklöf & Gehlin 1996). In the GRT systems using an electrical heater, fluctuations in the power grid may change the power input during the experiment. In practice outside conditions, such as passing weather fronts, may also influence test results. The test facility developed by Groenholland is not sensitive to power fluctuations, but may be influenced by outside conditions. Because either heating or cooling experiments can be performed, the difference between outside (winter/summer) conditions and temperature range of the circulation fluid can be minimised. Using good insulation and temperature sensors close to the borehole of course improve test quality as well.

2 THE GROENHOLLAND TEST FACILITY

Our testfacility (figure 2) was first developed in 1997. The system is built around a reversible water to air heatpump, with outside air serving as a heat source/sink. The heatpump either heats or cools a buffer vessel (0.5 m^3) , which acts as an energy store for the system, maintaining a temperature difference with respect to the circulation fluid returning from the ground. In practice two setpoints are used: when the temperature difference between the buffer vessel and the returning fluid drops below a certain threshold the heatpump is switched on, when it rises above a certain threshold it switches off. The temperature difference between the buffer vessel and the circulation fluid return temperature therefore varies within a certain bandwith.

Between the fluid entering the ground and returning from the ground a temperature difference is maintained as well. The amount of water mixed in depends on both the flow rate and the measured temperature difference. The required temperature difference between the entering and return fluid is calculated as a function of the measured flow and a selected “energy demand”. The calculated required temperature difference is compared with the measured temperature difference and adjusted by mixing in more or less water from the buffer vessel, by way of a three-way regulating valve. This allows a more stable energy flux during energy injection experiments, where the flow rate may rise due to changes in viscosity when temperature increases during the experiment.

Figure 2. The Groenholland In Situ Thermal Response Test facility.

During the experiment temperatures, flow rate and pressure are logged at regular intervals (usually 240 or 480 seconds). The pressure sensor is used to switch off the system automatically when a calamity occurs (when the pressure drops below a selected value). The whole system is controlled by an on-board computer and incorporates a GSM modem for remote system management and data logging.

The system is capable of a power rate of approximately 5 kW, with a temperature range between –5 and 45 ^{0}C. Flow rates can be varied between 0.5 m^3/hour and 3 m^3/hour, depending on head loss. The error observed in experiments is between 2% and 5% of the power rate selected.

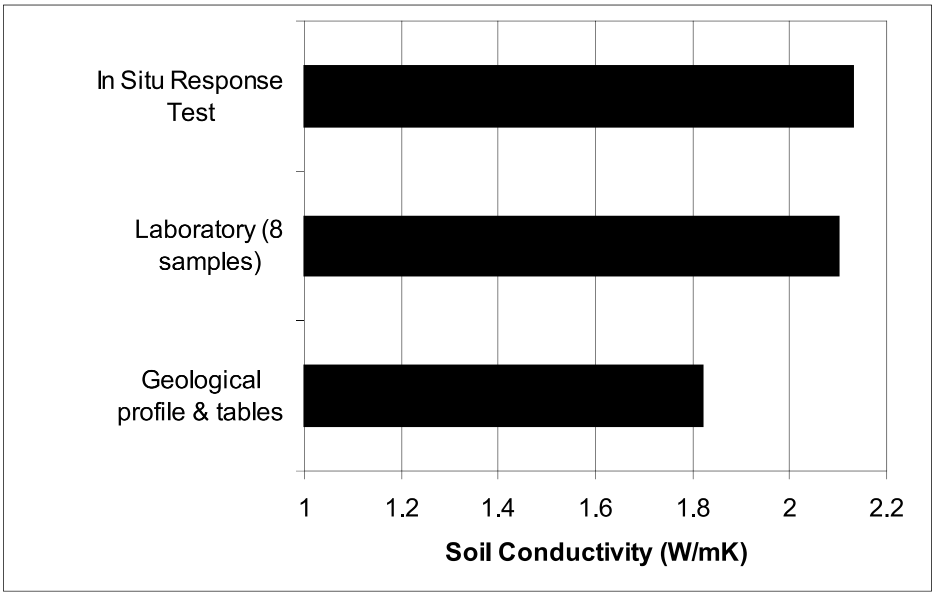
The advantages of this setup are:

1. Experiment type (injection/extraction) can be selected based on the outside temperature regime. Because differences between the outside temperature and circulation fluid temperature can be minimised, smaller errors can be achieved.
2. In experiments with heat injection convection may occur in the borehole, which may lead to over estimating the thermal conductivity.
3. In principle phase changes can be investigated.
4. With heat injection higher power rates are possible.

3 VALIDATION

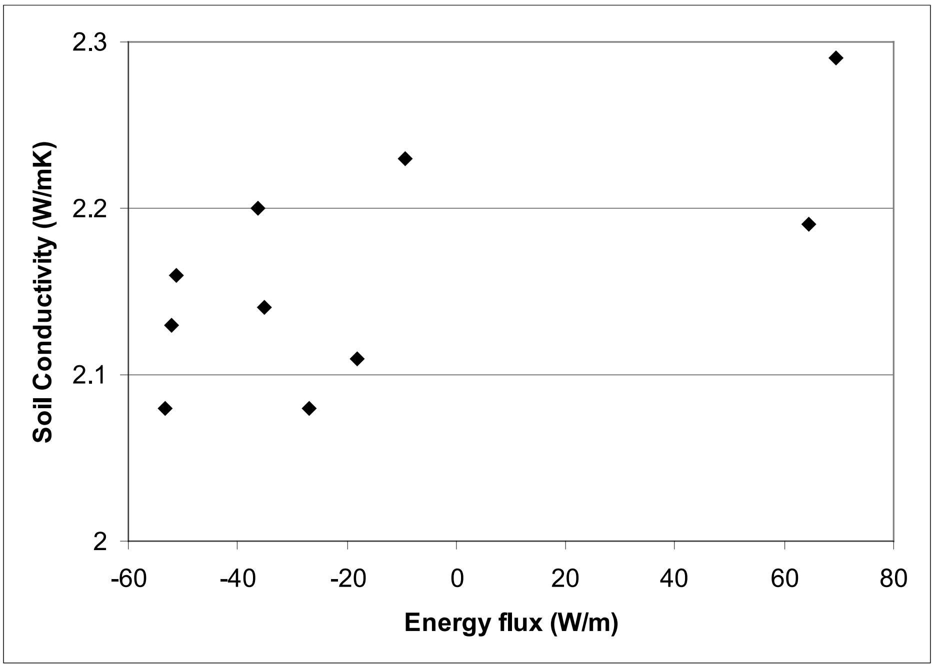
We first validated our test facility (Witte et al. 2002) by calculating a traditional estimate of ground thermal conductivity using a detailed geologic log, measuring ground thermal conductivity of a number of samples obtained from a drill core with the needle-probe method and performing a high-resolution test. Results (figure 2) show a very close correspondence between the conductivity values estimated by the laboratory method (2.1 W/mK) and the in-situ test (2.13 W/mK). The estimate based on the geologic log and reference tables yielded appreciably lower values (1.82 W/mK).

Figure 2. Validation of the GRT, comparison between conductivity values estimated by the In Situ respons Test, analysis of laboratory samples and the traditional method.



The second validation is based on ten tests that have been performed at the same site (located at the Groenholland offices in Amsterdam. The average thermal conductivity found is 2.16 W/mK, with individual measurements ranging between 2.08 and 2.29 W/mK. Interesting is that there appears to be a positive linear relationship between thermal conductivity and (positive) watts applied, which could be an indication of increasing convection in the borehole during heat-injection.

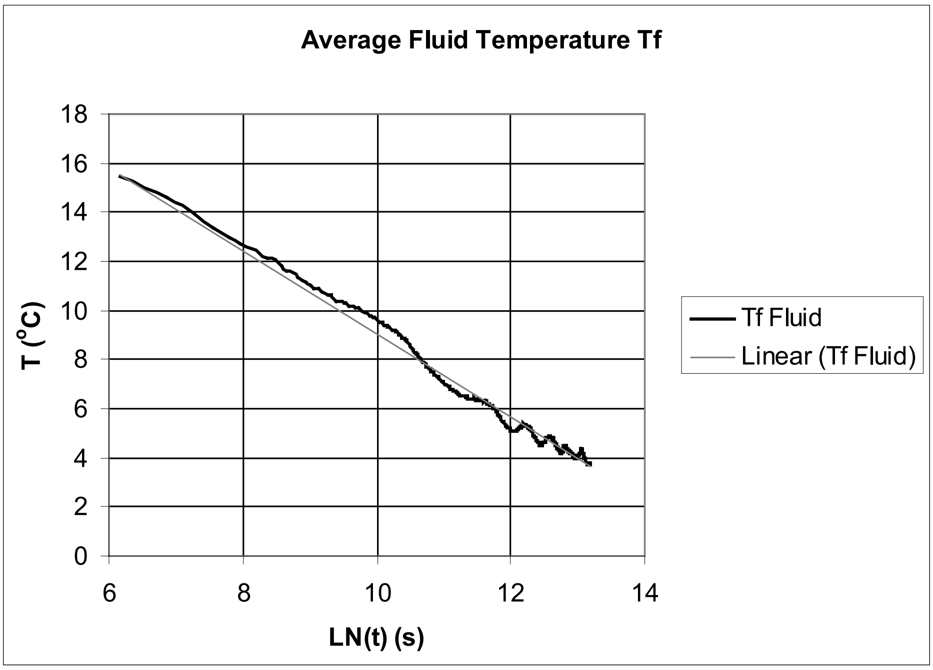
Figure 3. Validation of the GRT, results of ten tests with different energy rates.

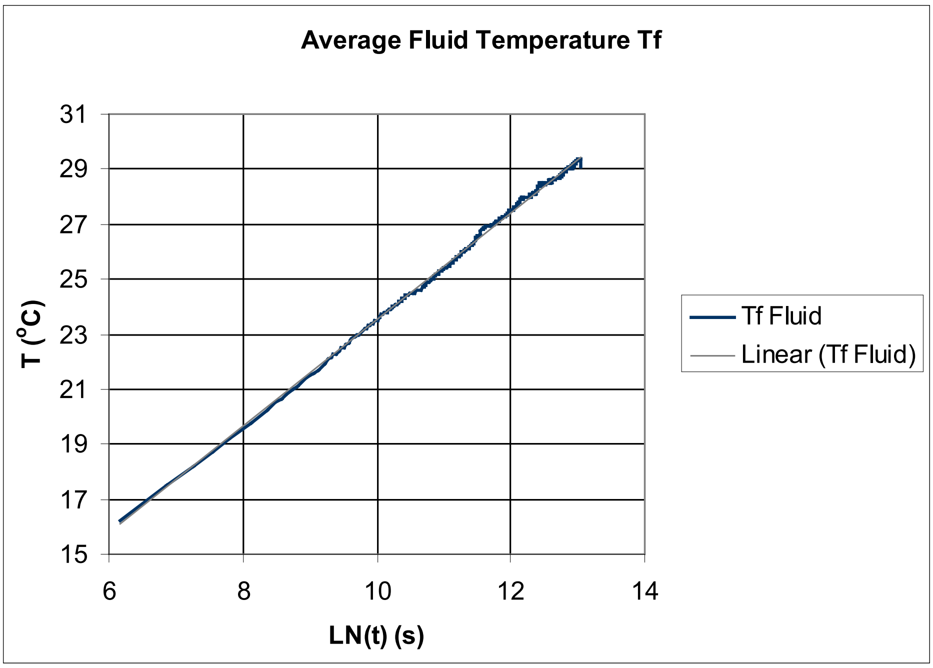


4 APPLICATION IN DESIGN

The first design case study is St Lukes Church in London. This derelict 18th century church is currently being redeveloped as a venue for the London Symphony Orchestra. Two tests were carried out (Witte et al. 2000a, 2000b), a heat injection experiment (33,2 W/m) and a heat extraction experiment (-27,1 W/m), on two 50 meters deep boreholes. Both experiments (figure 5) showed very comparable conductivity estimates (1.38 and 1.43 W/mK). As the soil profile did not reach the water bearing formations no groundwater flow or convection occurs. The measurements performed at the site showed appreciably higher conductivity values than were expected based on the geologic profile and the fact that no groundwater was present. The traditionally estimated ground conductivity was 0.8 W/mK. This difference resulted in a significant reduction of design length, and therefore project cost, of up to 25%.

Figure 5. Results from two tests (top: extraction, bottom: injection) performed at St Lukes Church, London (UK).





In the second design case study two boreholes, of 60 and 115 meters depth, were tested for the National Assembly for Cardiff (Wales). The picture on the right shows the drilling of one of the test holes. Both boreholes were tested with an injection and an extraction experiment, allowing sufficient time between the experiments for temperature regeneration.
Two important conclusions can be drawn on basis of the results (table 1):

1. As the conductivity estimates during heat injection are appreciably higher, convection in and around the (grouted) borehole apparently plays an important role.
2. The 60-meters borehole shows lower conductivity values. This is caused by the fact that the top part of the soil profile, comprising the dock infill and unsaturated soil with lower thermal conductivity, has a relatively higher contribution in the shorter borehole.

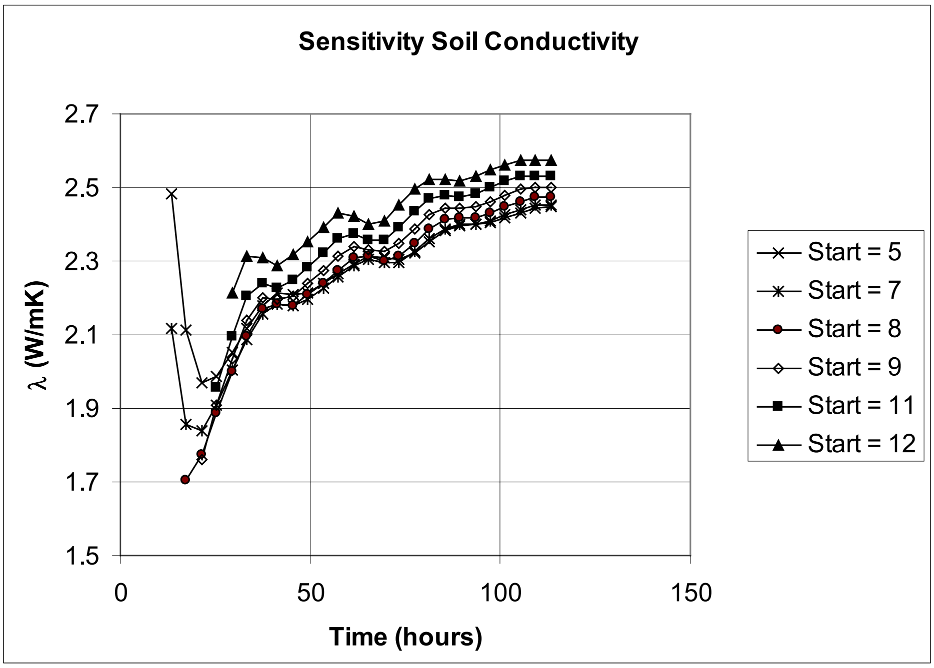
For the design this means that the (dominant) heat injection during summer should be designed differently than the heat extraction during winter. Moreover, borehole length in the final design has to be evaluated carefully as shorter boreholes have a lower overall conductivity.

Table 1. Traditional estimate and results of four tests, national Assembly for Wales.

source	energy flux (Watts)	λ (w/mK)
geologic log & ref tables		2,26
60-meters, injection	54.95	2.53 ± 0.042
60-meters, extraction	-27.47	2.21 ± 0.015
100-meters, injection	19.06	2.78 ± 0.028
100-meters, extraction	-15.24	2.57 ± 0.046

A third design case study was carried out in the Netherlands (Valburg) for a housing development (60 houses during phase I, up to 200 in phase II). In these projects the client (ITHO BV) uses solar collectors to thermally (re-)generate the ground during summer. The test showed relatively high estimates for the soil thermal conductivity, when compared to usual values for the types of sediments encountered.

Figure 6. Sensitivity graph of estimated thermal condcutivity values as a function of starting time selected and amount of data added.

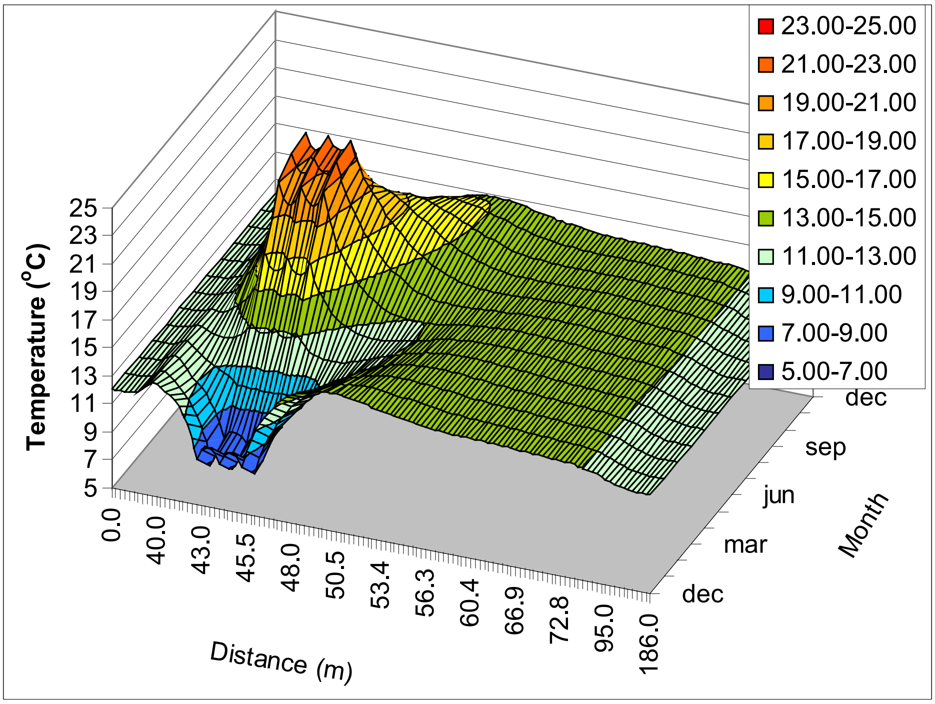


Especially when a sensitivity graph (figure 6) was constructed, where an estimate of the thermal conductivity is made with different starting points and measured data is added in small blocks in a stepwise fashion, it became clear that no stable estimate could be obtained. Estimates of soil conductivity became progressively higher when more data was added.

This behaviour can usually be taken as an indication of groundwater flow. A literature study of the geohydrology of the site showed that indeed high groundwater flowrates could be expected. Subsequently a detailed study was carried out for the site. In this study groundwater gradients were measured on the site itself and samples were collected from three boreholes. From the samples the soil conductivity for groundwater flow (K-values) were calculated. Using this information a thermal – geohydrological model was constructed in HST3D (Kipp 1986, Verbeek 2000) to study the effects of groundwaterflow on the thermal response of the system. There were two major concerns. The first concern was that downstream heatexchangers would experience colder circumstances due to the arrival of cold upstream water from a previous heating-season. The second concern were the possible losses in generated heat (active regeneration) due to the mass transport.

Results from the model calculations (figure 7) indicated that the downstream area that could be influenced was relatively small, about 30 meters with a maximum temperature response of about 0.5 ^{o}C. The generation of energy in the summer however was affected to a larger extent: losses of up to 20% of the heat generated are to be taken into account.

Figure 7. Results numerical model (HST3D) of influence of groundwaterflow on heat store.



5 APPLICATION IN RESEARCH

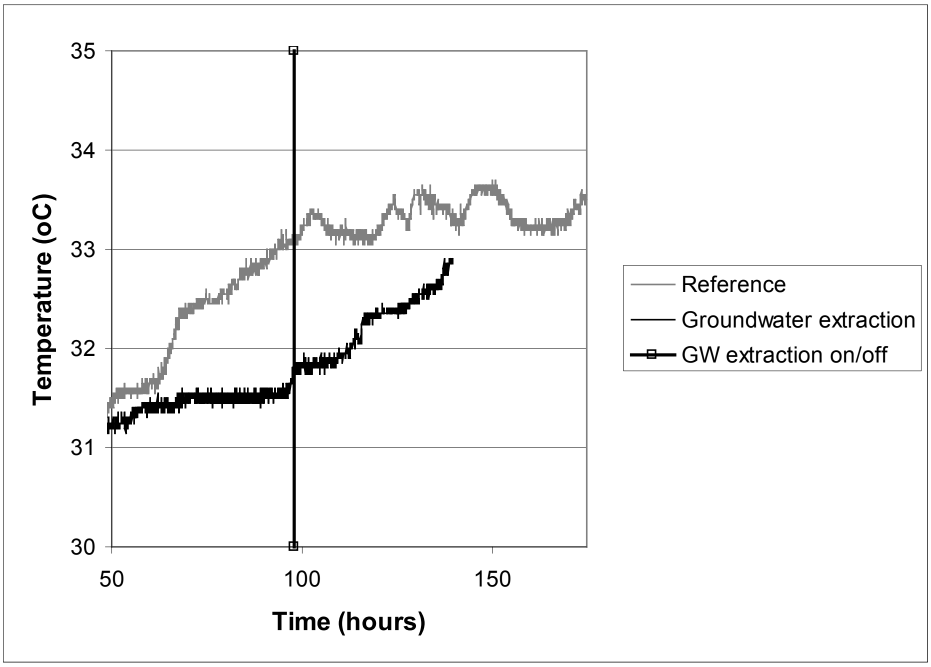
The influence of groundwaterflow on the soil conductivity measurements has been noted before (e.g. Sanner et al. 2000). To investigate this effect in a controlled manner we performed two Geothermal Response Tests on the same borehole. Experiment parameters are summarised in table 2. In one of the experiments a groundwater extraction was performed on an extraction well located approximately 5 meters from the thermal well.

The first question is if a significant effect of the groundwater extraction can be observed. Therefore, in the experiment without groundwater extraction (the reference experiment) the groundwater extraction was activated after 98 hours, if a significant effect is present the rate of temperature increase should become lower. In the experiment with groundwater extraction the extraction was turned off at about 95 hours, if there is a significant effect the rate of temperature increase should become higher. This is indeed what could be observed in the experiments (figure 8).

Table 2. Experiment parameters.

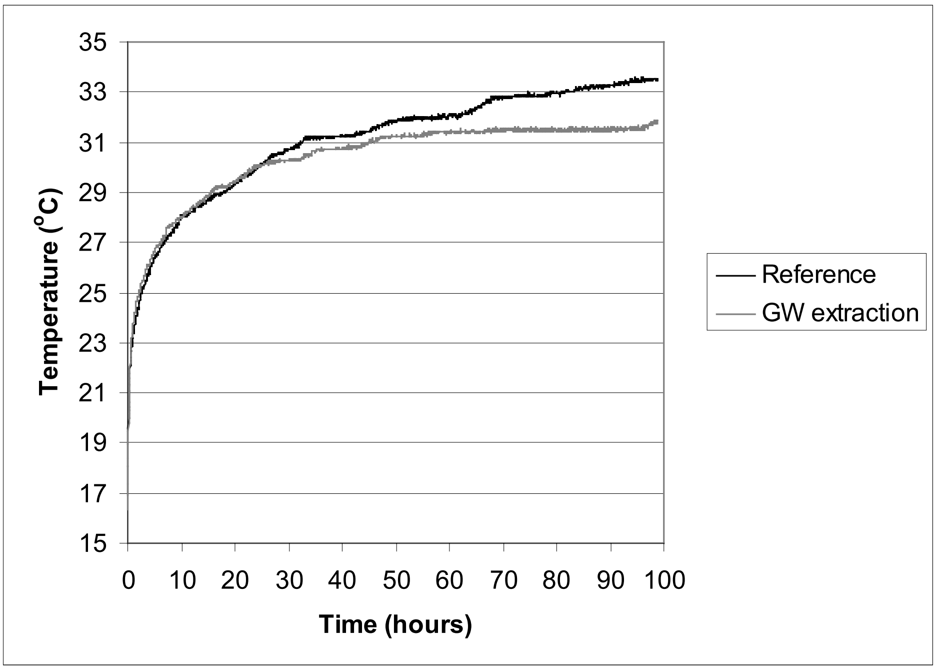
parameter	Reference experiment	Groundwater extraction experiment
circulation medium flowrate (m^3/hr)	0.85 ± 0.012	0.87 ± 0.0072
ΔT (°C)	2.18 ± 0.084	2.11 ± 0.068
energy rate (W/m)	69.23 ± 2.13	68.78 ± 2.23
Groundwater extraction rate (m^3/hr)	0	2.89

Figure 8. Thermal response to activating (reference experiment) or deactivating (extraction experiment) the groundwater extraction.



Comparing the temperature curves of the two experiments (figure 9) we can see that during the first eighteen hours there is little impact of the groundwater extraction. This can be attributed to the fact that either the borehole plays a larger role during that period, or to the fact that the temperature difference between the borehole and the groundwater is not yet sufficiently large to note an effect (the temperature in the borehole is about 5 – 7 ^{0}C lower than the circulation medium fluid measured). After 20 hours the experiment without groundwater extraction shows significantly higher temperatures and a higher rate of temperature increase. Using the data obtained to estimate the soil thermal conductivity a conductivity of 2.34 ± 0.007 W/mK was calculated for the reference experiment, while for the experiment with groundwater extraction a much higher conductivity, of 3.22 ± 0.018 W/mK, was estimated.

Figure 9. The thermal response during the two experiments.

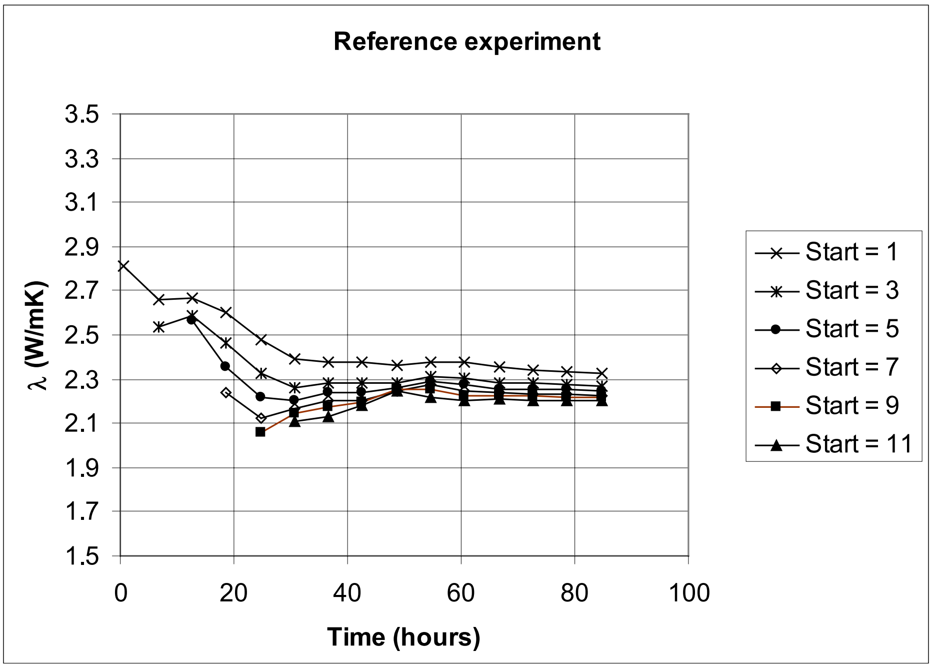


When we construct sensitivity graphs (figure 10) it is clear that the conductivity values estimated from the data of the reference experiment stabilise to values around 2.3 W/mK. For the experiment with groundwater extraction the estimated conductivity increase when more data is added.

To investigate the thermal response of the ground further we constructed a groundwater – heat transport model in HST3D. The model domain measures 500 x 500 x 50 meters and consists of a network of 100 x 100 x 8 nodes. The model consists of two vertical layers with different geohydrological characteristics: a clayey cover layer and a water bearing formation mainly consisting of sands. The thermal characteristics of both layers were kept the same in all calculations.
Node distances around the thermal and groundwater extraction well were made small (0.06 m) to obtain good approximations of the groundwater gradients and thermal gradients around the wells. Especially for the thermal well, the temperatures calculated at the well itself are depending on the node distances. The groundwater extraction model was calibrated using the measured heads from five observation wells. the calibration was performed for both the natural state of the system and for the heads measured during the extraction. Unfortunately the present version of HST3D does not allow the simultaneous simulation of both groundwater extractions and thermal injections/extractions with ground heatexchangers. Therefore the gradient resulting from the groundwater extraction was entered in a second model to model the thermal response.

The isotherms of the model simulations for the case with and without groundwater extraction clearly show the deformation of the thermal field. To compare the results of HST3D directly with the observations the temperature at the well is plotted along the observations. To do this one of the two series has to be translated along the temperature axis. HST3D does not properly model a heatexchanger as such, and therefore the temperatures approximate the temperatures in the borehole. From temperature observations in the borehole itself we know that the difference between the fluid temperature in the loop and the borehole temperature itself is about -5 to -7 ^{o}C. This value was used to shift the series along the temperature axis. In evaluating these graphs (figure 11) we should therefore consider the correspondence in angle for the different simulations. As we can see, this correspondence is quite good after about 30 hours.

Figure 10. Sensitivity graph of estimated thermal condcutivity values as a function of starting time selected and amount of data added. Top: reference experiment, bottom: groundwater extraction experiment.



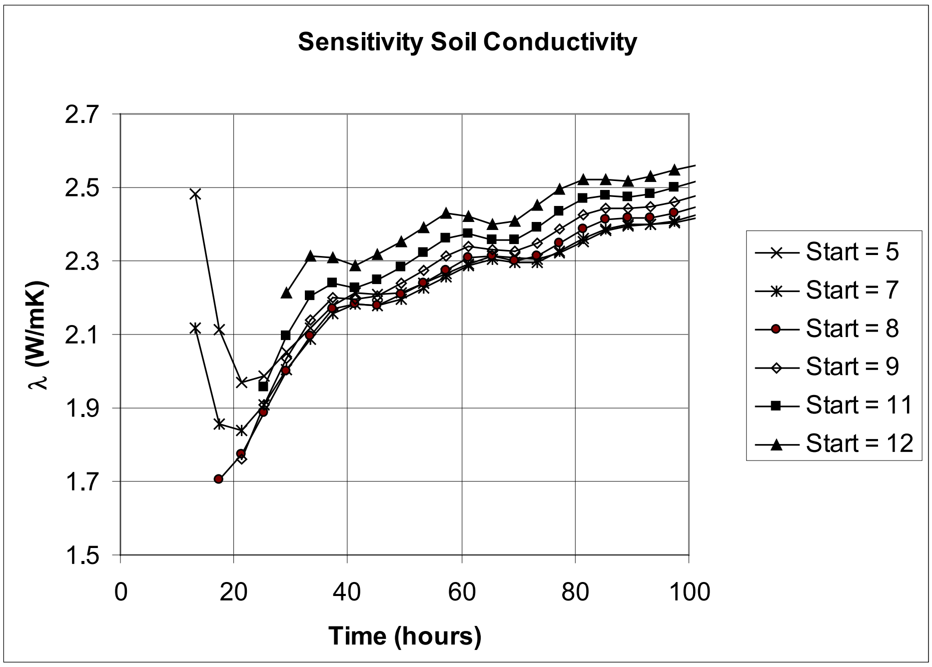
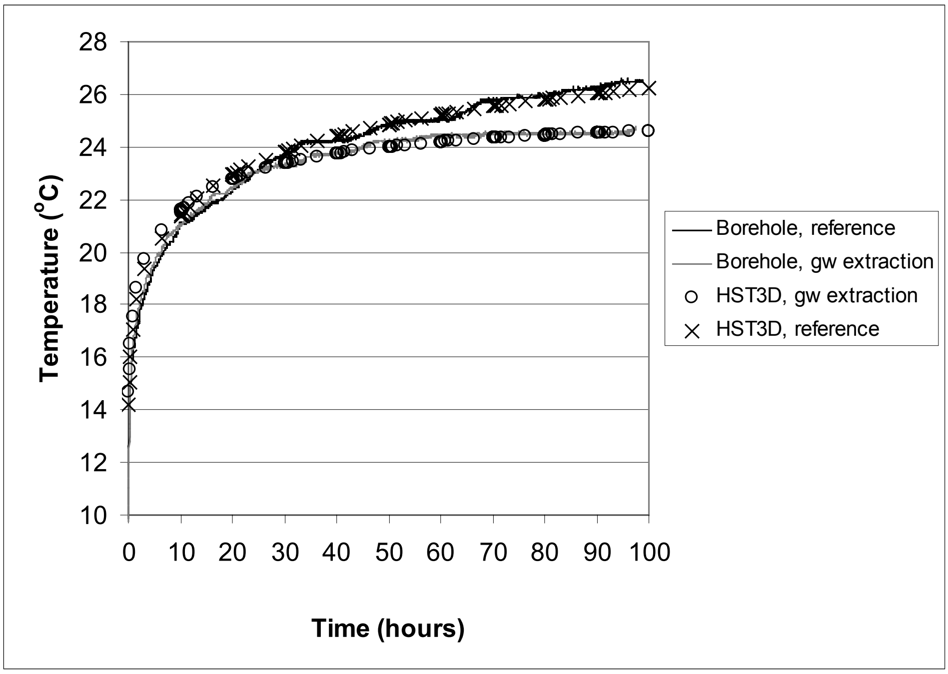


Figure 11. Correspondence between observed and simulated thermal response (HST3D) for the reference experiment and experiment with groundwater extraction.



Subsequently we used this model to calculate the response of a groundloop heatexchanger with different groundwater flow regimes (figure 12). When these temperature series are used to estimate the apparent thermal conductivity (figure 13) of the ground we can observe that the estimated ground thermal conductivity increases dramatically with groundwater flowrates. A significant effect is already noticible at small flowrates (Darcy flow < 3.5 m/yr, 6% higher conductivity estimate).

Figure 12. Simulated thermal response (HST3D) for different groundwater flowrates (Darcy flow 0 – 10; 65; 115 and 260 meters/year).

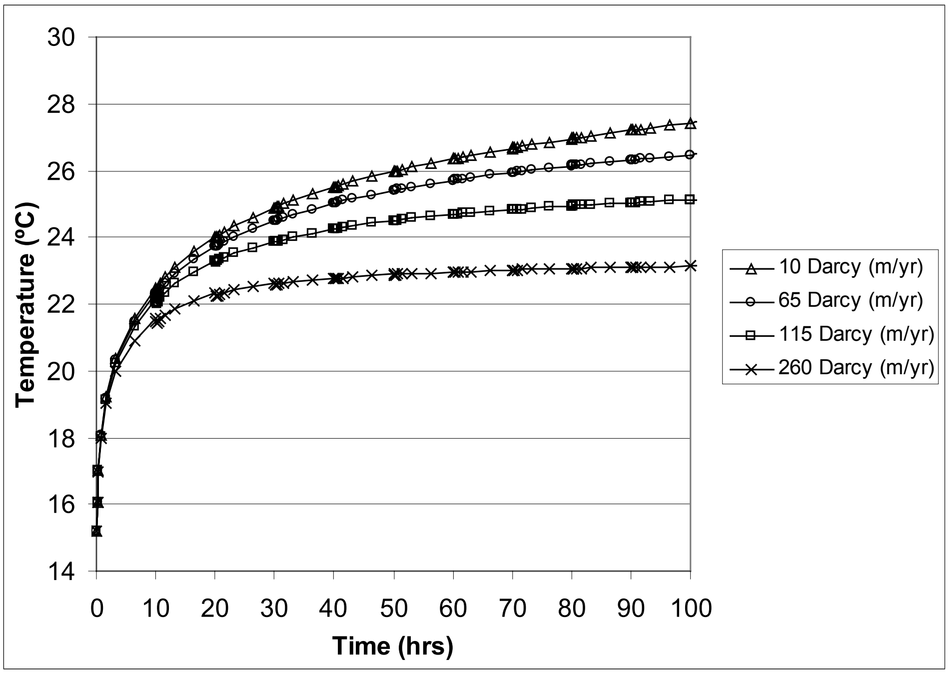
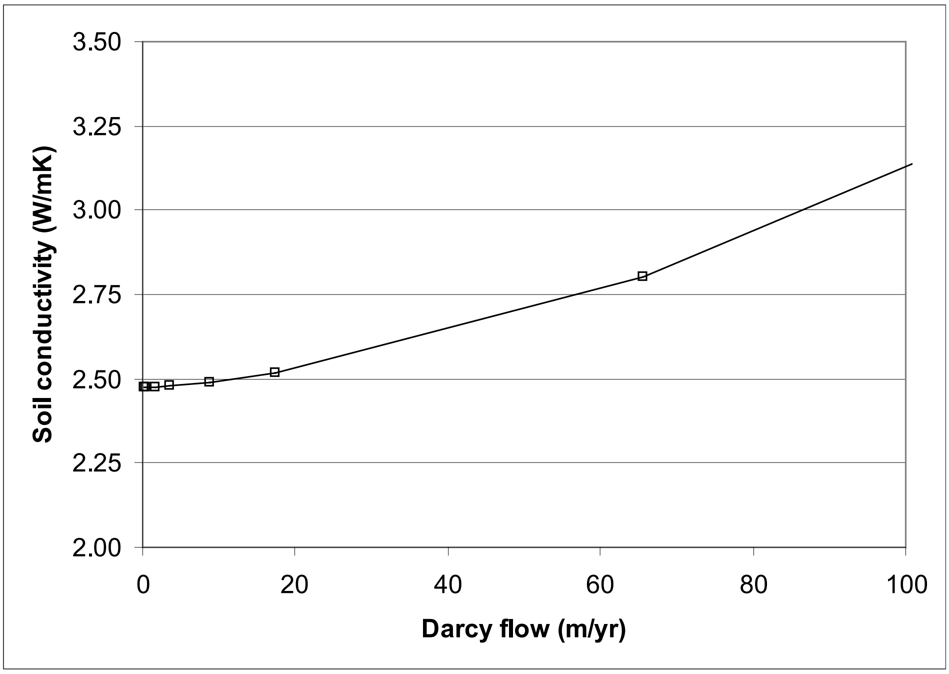


Figure 13. Estimated thermal conductivity with no groundwater flow and estimated apparent ground thermal conductivity simulated temperature response at different groundwater flowrates.



6 CONCLUDING REMARKS

In this presentation we have shown the Geothermal Response Test that Groenholland has developed. In practice (during the past 2 years about twenty tests have been performed) we have found that the machine is very reliable. We can run our tests for 2 – 3 weeks without having someone on site, as test management and data-logging can be done by remote access using a modem and connection to a mobile phone network.

The test allows accurate and reproducible estimates of the soil thermal conductivity. Test results are of importance in the design and implementation of groundloop heatexchanger systems. Better estimates of thermal conductivity, borehole resistance and far field temperature improve the quality of the design, especially with regard to total groundloop length required and distance between individual heatexchangers. Using additional information, such as detailed geologic logs obtained during the installation of the loops or temperature-depth profiles during the experiment, enables optimisation of drilling depth and costs. Moreover, the test can provide clear indications of convection in the borehole or the influence of groundwater flow.

Comparing the results of tests with heat extraction and heat injection, in saturated condictions, we note that the estimates derived from heat injection experiments may result in 10% to 15% higher estimates of ground thermal conductivity. This effect can probably be attributed to convection in or around the borehole. The ground thermal conductivity estimated with heat injection, in saturated conditions, is apperently not representative of the ground thermal conductivity, and can therefore probably not be used directly in modelling or design studies.

In a more research oriented test we have shown the influence of groundwater flow and how this translates to higher estimates for ground thermal conductivity. In our opinion a site investigation should normally include a description of the geohydrological conditions of the site and the test results should be evaluated with respect to convergence on an estimate of ground thermal conductivity. Especially in projects where the ground is used as a heat store, even moderate groundwater flow rates will introduce significant losses.

To improve the quality of the test results further research is required, especially with regard to:

1. Methods to estimate conductivities for the different formation in the soil profile (such as creating temperature logs at different depths along the borehole).
2. Effects of convection in the borehole and how to account for the influence on the estimated conductivity.
3. The effect of groundwaterflow on the conductivity estimates, and on how to incorporate groundwaterflow in the final design.

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