RESEARCH ARTICLE

Temperature footprint of a thermal response test can help to reveal thermogeological information

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Borehole heat exchangers connected to a ground-coupled heat pump extract heat from the ground for the heating of buildings. Heat is transferred to the ground in cooling mode and can be extracted again during the next heating season. To dimension a large borehole field designed to meet the heating and cooling demand of a building, important ground parameters (temperature, volumetric heat capacity of the rocks, thermal conductivity, thermal borehole resistance) are needed. One important parameter is the effective thermal conductivity, which is measured with the help of thermal response tests (TRT). A temperature profile is measured before a TRT to find the undisturbed ground temperature. Rarely, temperature profiles are also measured after a finished TRT. Experience from about twenty TRTs shows, however, that important hydro- and thermogeological characteristics of the borehole may affect the measured ground parameters. These can be detected from temperature profiles after the TRT. Measuring the temperature profile in a well after a TRT can add valuable information to the study and about the nature of a borehole heat exchanger system. Four typical cases are discussed: a standard case of a borehole drilled in homogeneous and non-fractured rocks without any temperature anomaly and three more complicated cases, involving heat loss from buildings, groundwater flow through a single fracture and groundwater up-flow through the borehole from a confined artesian aquifer. Extra information about groundwater flow, open fractures and varying mineral content in the rocks can help to evaluate the TRT results and to suggest a better design of a ground-coupled heat pump installation. Based on the results of our study it is highly recommended to take temperature profiles after TRTs.

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Introduction

Geothermal energy is most often understood as heat that is accessible from the Earth's crust. This heat is mainly produced from radioactive decay of minerals but may also include residual heat from the formation of the Earth. Geothermal energy is used for electricity production in areas with an unusually high geothermal gradient (e.g., Iceland, Indonesia, Italy). These areas are mostly restricted to plate boundaries where heat is transported towards the Earth's surface via conductive and convective heat flow. A low-temperature variant of geothermal energy can be used, however, in most places and most effectively in regions with seasonal climate for the heating and cooling of buildings. In this case the energy is not generated in the ground but predominantly stored and renewed with the help of solar irradiation. A term frequently used to distinguish the heat source from pure geothermal heat is 'ground-source heat'. This term may be misleading as the main heat source is not the ground (e.g., average annual geothermal heat flux in Sweden: 0.6 kWh m^{-2}, Andersson 2011). The ground is predominantly a storage medium for the solar irradiative heat (e.g., average annual solar heat flux towards the ground in Sweden: 1500 kWh m^{-2}, Andersson 2011). Therefore, a more precise term should be used: 'ground-stored heat'.

To extract this ground-stored heat, borehole heat exchangers (PE collectors, mostly U-shaped in Scandinavia) are installed in shallow boreholes. A heat-carrier fluid circulates through the borehole heat exchanger and delivers heat to a ground-coupled heat pump which transfers the energy to the building in heating mode. In heating mode heat is removed from the rock. After a considerable removal of heat, a significant heat flow from the surface is established (Figure 1).

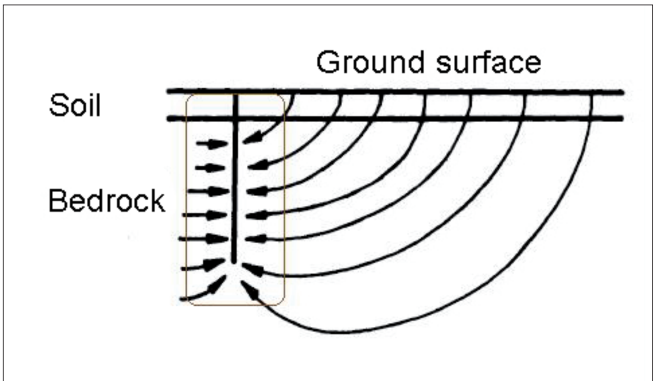

Figure 1. Energy refill around a shallow borehole from solar radiation under stationary conditions (minor geothermal refill is neglected in the figure; Nordell 2008, mod.).

Most commercial buildings have also a need for cooling in the warm season. This applies also to the Nordic countries because of the greenhouse effect of buildings with extensive glass facades or the heat production from computers and other electrical equipment. To satisfy the cooling needs, the heat pump can be reversed and heat can be transferred to the ground. This heat is then available to be brought up again in the next heating period. In this case waste energy is stored in the ground.

Ground-coupled heat pumps are used widely in single houses with a few wells and in commercial buildings or interconnected housing areas with up to 8006 boreholes like in Fort Polk (Louisiana, Hughes 2001). The largest well field in Europe until now is installed at Akershus University Hospital (Norway). There, 228 wells were drilled and furnished with borehole heat exchangers. About 40% of the building's heat load (ca. 20 GWh per year) is expected to be covered with energy mostly from ground-coupled heat pumps (www.fornybar.no, 11.04.2011).

The capacity of ground-coupled heat pumps worldwide has increased from around 1 800 MW (thermal) in 1995 to around 15 000 MW (thermal) in 2005 (Lund et al. 2005) and 35 000 MW (thermal) in 2010 (Lund et al. 2010). The market for ground-coupled heat pumps is also forced to increase in many countries as the use of renewable energy for heating and cooling of buildings is regulated by law. In new buildings in Norway, for example, technical regulation TEK07, § 8–22, requires that after 2007, 40% of the energy required for space and domestic water heating has to be delivered by other energy sources than electricity or fossil fuels.

The decision about how many metres of borehole have to be drilled to meet the heating or cooling load of a building is crucial for the successful and long-lived operation of the ground-coupled heat pump. The needed borehole length can be calculated if the thermal ground and well properties are known. Important parameters are temperature of the rock, volumetric heat capacity, thermal borehole resistance and effective thermal conductivity at a site. The knowledge of them will help to find a good compromise between costs (drilling and operation costs to run the ground-coupled heat pump system) and efficiency (supplying expected heat and cold loads). Thermal borehole resistance and effective thermal conductivity are measured with the help of a thermal response test (TRT, see Austin 1998 and Gehlin 1998). TRTs are applied as a standard procedure before a large well field is dimensioned and the results are considered to be essential for the proper dimensioning.

The objective of this study is to show the importance of temperature profiles before and after TRTs for the interpretation of the TRT results.

Before each TRT, a temperature profile is measured to find the undisturbed ground temperature which is a necessary parameter for the determination of the thermal borehole resistance (e.g., Gehlin 1998). Less attention, however, has been given so far to measure temperature profiles after a TRT. Experience from around 20 TRTs, with temperature profiles taken before and after TRTs, gives us an overview over the most common phenomena that can be observed. The temperature profiles can be grouped into four cases. Four illustrative examples are chosen where observed temperature variations and their implication on the TRT evaluation are discussed.

Materials and methods

Thermal response test

Thermal response tests are often applied in Scandinavia and many countries worldwide to evaluate the in situ or effective thermal conductivity in a borehole. For this purpose the TRT equipment is connected to the borehole heat exchanger of the energy well (PE collector pipes, most commonly U-shaped, see Figure 2).

Heating elements in a portable TRT trailer warm up the heat-carrier fluid that is circulating through the closed-loop system. The connection between the trailer and the borehole has to be well insulated, to avoid heat loss in cold weather or heat gain through sun irradiation. The circulation pump creates a turbulent flow in the pipes to get best heat transport from the collector towards the ground. The undisturbed ground temperature (measured before the TRT) and the temperature increase in the heat-carrier fluid during a test run are used to calculate the effective thermal conductivity of the ground (λ_{eff}) and the borehole thermal resistance (R_b). λ_{eff} is a parameter which integrates a) the ability of the bedrock surrounding the borehole to conduct heat (Fourier's law), b) buoyancy-driven convection in the borehole due to the heat input along the collector tubes (e.g., Gustafsson et al. 2010), and c) groundwater movement in or in the vicinity of the borehole (e.g., Gehlin et al. 2003).

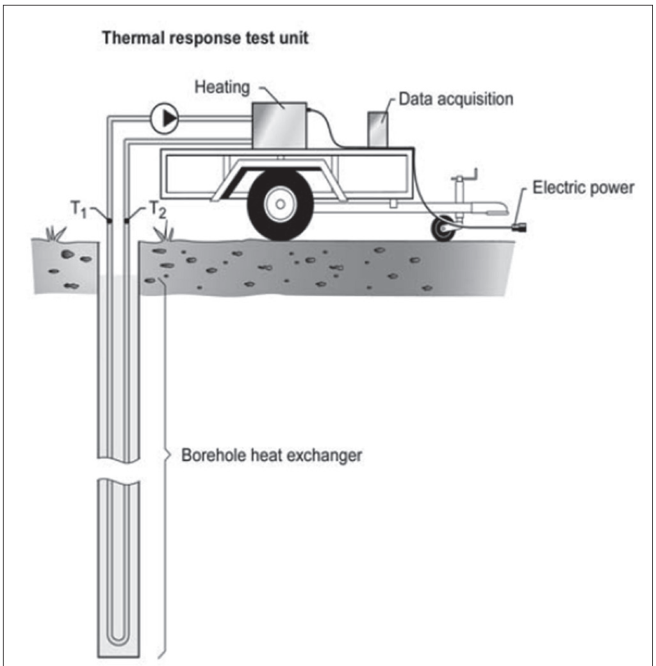

Figure 2. TRT rig connected to a borehole heat exchanger (Gehlin 2002).

The calculation of λ_{eff} follows the suggestions of Gehlin (2002) and Signorelli et al. (2007), which are based on the infinite line-source theory (Ingersoll 1948). The line-source model is based on a linear relationship between the average heat-carrier fluid in the collector and the natural logarithm of the time t, if the heat exchange rate per length unit, q, is constant (q is constant if the electric power supply to the heating elements is constant):

$$T_f(t) = k\ln(t) + m \qquad \text{[K]} \qquad (1)$$

where

$$k = \frac{q}{4\pi\lambda} \qquad \text{[K]} \qquad (2)$$

and

$$m = q\left[R_b + \frac{1}{4\pi\lambda}\left(\ln\left(\frac{4\lambda}{r_b^2\, S_{VC}}\right) - 0.5722\right)\right] + T_0 \qquad \text{[K]} \qquad (3)$$

r_b is the borehole radius, S_{VC} is the volumetric heat capacity of the rock/sediment, and T_0 is the undisturbed ground temperature. The average heat carrier-fluid temperature, T_f, is calculated from the inlet and outlet temperatures, T_{in} and T_{out}:

$$T_f = \frac{T_{out} + T_{in}}{2} \qquad \text{[K]} \qquad (4)$$

The thermal conductivity λ is found by plotting T_f against the natural logarithm of the time in seconds and by reading off the slope where the conditions have stabilized (e.g., Signorelli et al. 2007; normally between 20 (t_1) and 70 hours (t_2)):

$$\lambda = \frac{q}{4\pi} \cdot \frac{\ln(t_2) - \ln(t_1)}{T_f(t_2) - T_f(t_1)} \qquad [\mathrm{W\ m^{-1}\ K^{-1}}] \qquad (5)$$

A TRT typically lasts 72 hours (Gehlin 1998). In this time range the analytical solution of the infinite line-source shows a very low error level compared to the alternative solutions of the finite line-source and the infinite cylindrical-source theory (Philippe et al. 2009). Different international guidelines recommend durations of at least 36 hours (IGSHPA) or 50 hours (IEA). In Germany, commonly a TRT is considered to be long enough if the estimated effective thermal conductivity does not change more than 0.1 W m^{-1}K^{-1} within 24 hours (M. Sauer, pers. comm. 2011).

In case of strong groundwater flow through the borehole, the parameters of interest (in our case: λ_{eff}) can be approximated with a parameter estimation technique which varies the unknown variables in equations 1–3 to find the best fit between calculated and measured data for time-varying heat inputs (see also Shonder and Beck 1999, Wagner and Clauser 2005, Witte 2007).

Possible sources of error during a TRT are: 1) heat loss and gain (affects T_f), 2) variable electric power supply (affects q),

3) accuracy of the determination of the undisturbed ground temperature (affects T_0), 4) free convection of water in non-grouted boreholes (standard for energy wells in Scandinavia; affects λ; Gustafsson et al. 2010), 5) gradient-driven horizontal groundwater flow (affects λ; e.g., Gehlin and Hellström 2003) and 6) density-driven vertical groundwater flow (affects λ; e.g., thermosiphon effect, Gehlin et al. 2003, Gustafsson 2006, Gustafsson and Westerlund 2010). Typical levels of confidence of TRT results are about 9% for the thermal conductivity (Zervantonakis and Reuss 2006). If thermo- or hydrogeological situations are present that alter the effective thermal conductivity measurement, temperature profiles help to interpret the obtained TRT data or help to detect the special situation.

Temperature profiles

Temperature profiles were taken directly in one shank of the single U-shaped borehole heat exchanger before each TRT to determine the undisturbed ground temperature, T_0, and four to five hours after the end of the TRT. The local heat flux is the product of thermal conductivity and temperature gradient (Fourier's law of heat conduction). The heat flux is strongest in areas where the temperature decreased most during the recovery time after the TRT. In these areas a high effective thermal conductivity can be expected due to high thermal conductivity of the bedrock or due to groundwater flow.

The depth interval was two or four metres. It is necessary to keep the measurement time of a temperature profile short to avoid a further temperature recovery during the measurement after a TRT. Measuring a temperature profile for a 200 m long borehole took about 70 minutes. The temperature recovery during the temperature measurement depends on the heat input during the TRT and the thermal properties of the borehole and the surrounding bedrock (see also Javed et al. 2011). In a study recently presented (Liebel et al. 2011), the temperature recovery in a 138 m deep borehole was registered also after the TRT was finished. The temperature dropped within the first four hours by 2.6°C. Within the next hour the temperature decrease was 0.1°C only (heat input during the TRT: 3 kW for 94 hours). The temperature recovery is very fast in the first few hours before it slows down significantly. Therefore, four to five hours after a TRT seem to be a good timing for the temperature measurement after the TRT.

Fiber optic cables have recently been applied to observe temperature variations along the entire borehole (Fujii et al. 2009, Acuña and Palm 2010). They give very good control over temperature variations and temperature developments. However, their applicability is to date restricted to research due to the high costs of the analytical equipment. Therefore, economically attractive, ordinary temperature dataloggers are used in this study.

Results and discussion

Observations at the different sites

From a dataset of about 20 TRTs performed in Norway, four illustrative cases were chosen to be discussed in this study (see Figure 3).

All cases show phenomena that can be found frequently in temperature measurements related to TRTs and they have different implications on the evaluation of the TRT results. Some general data of the TRTs are presented in Table 1.

Fredrikstad

Outcrops close to the borehole in Fredrikstad show a rather homogeneous light reddish, biotite-bearing, medium-grained Iddefjord granite, which crystallised from magma in the Precambrian around 920–930 Ma ago (Pedersen and Maaloe 1990). The granite contains quartz, biotite, orthoclase, plagioclase, some muscovite and small amounts of apatite, titanite, magnetite and zircon (Holtedahl 1953) and it is interpreted as the continuation of the Bohus granite in Sweden. Outcrops around the borehole and information from the driller's well report indicate granite along the entire borehole length.

Regional fracture zones are present but show low hydraulic conductivity because of the appearance of swelling-clay minerals due to hydrothermal alterations and/or deep weathering in

Table 1. General data of the four TRTs presented in this study.

Location	Coordinates	Altitude m a.s.l.	Borehole depth (m)	Date of TRT	λ_{eff} (W m^{-1}K^{-1})	Duration of TRT (hr)
Fredrikstad	611848 E 6565630 N	17	200	26.07.– 29.07.2009	3.15	72
Nordstrand	600555 E 6637162 N	130	200	06.07.– 09.07.2009	3.23	65
Lade	572043 E 7037069 N	25	150	20.09.– 04.10.2009	4.11	333
Bjørnegård	583691 E 6639799 N	6	200	26.08.– 30.08.2010	4.81	95

Coordinates refer to UTM zone 32, WGS84.

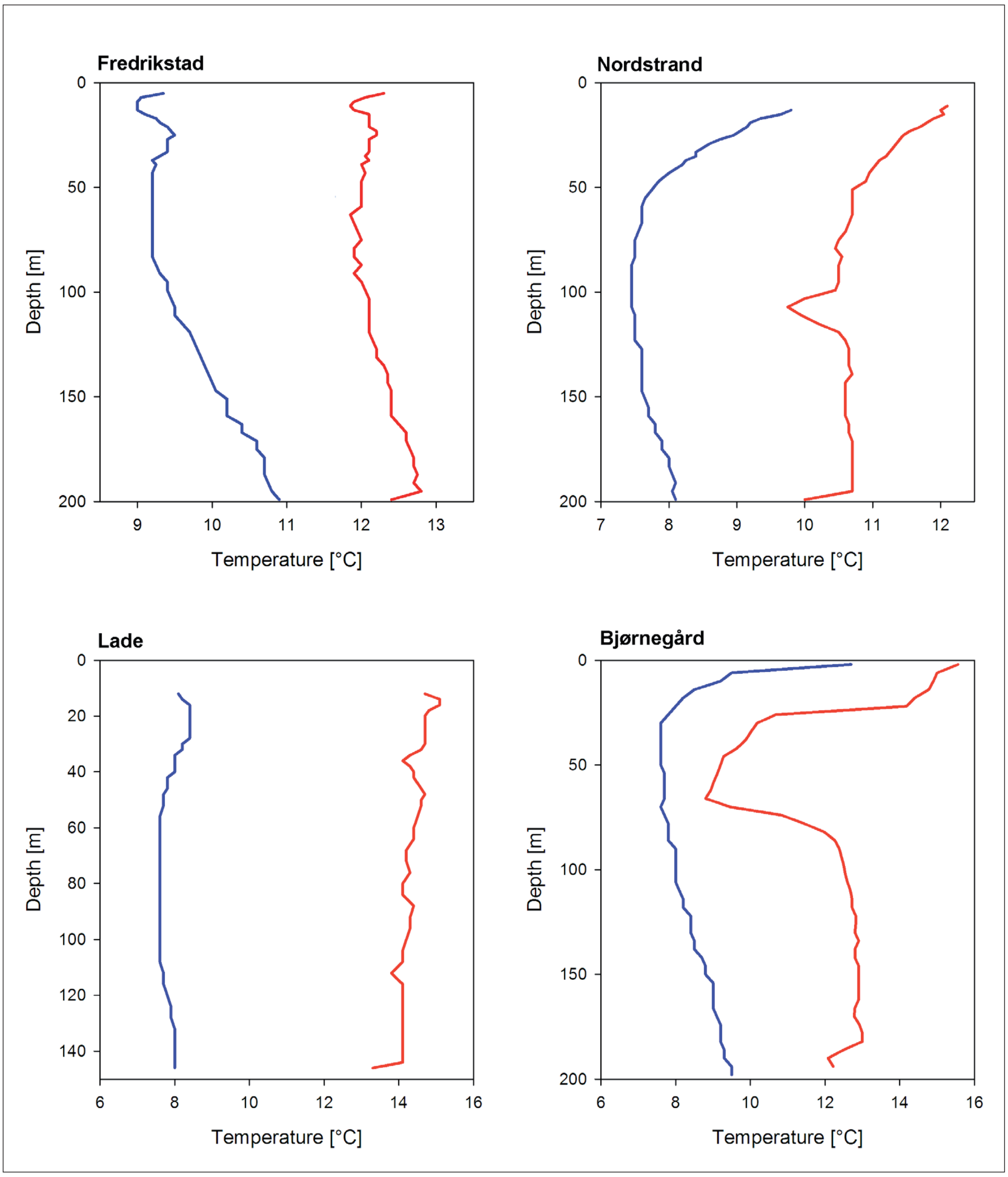

Figure 3. Temperature profiles before (blue) and after (red) a TRT at the four different study sites: Fredrikstad, Nordstrand, Lade and Bjørnegård.

the Triassic and Jurassic period (Banks et al. 1992a, b, 1994, Olesen et al. 2006).

Slagstad et al. (2009) measured a rock core thermal conductivity of 3.1 W $m^{-1}K^{-1}$ in the Iddefjord granite which is consistent with the TRT result: 3.15 W $m^{-1}K^{-1}$. The almost identical result indicates that the borehole is surrounded by granite only with negligible alteration of effective thermal conductivities due to groundwater flow. Also the temperature profile taken after the TRT supports this hypothesis (Figure 3). The uppermost ten metres of the borehole are influenced by seasonal variation while the following 60 m are influenced by (palaeo-) climatic effects as described by Slagstad et al. (2009), before a normal geothermal gradient is followed down to the base of the borehole.

The latter effects are most pronounced in the temperature profile before the TRT, but they are still detectable in the temperature profile after the TRT. The temperature profile shows no major variations along the borehole with the exception of a sudden temperature drop at the base. This effect can be explained with a stronger vertical heat flow at the bottom of the borehole due to heat flow from the sides and from below. As a consequence the cool-down is faster than in other parts of the borehole.

Nordstrand

The borehole used for the TRT at Nordstrand (borehole 3, see Figure 4) was drilled only two metres away from a large school building which dates back to the year 1926. Through the last 85 years, heat has been transferred from the building to the ground due to poor insulation.

The area around the investigated well field is dominated by garnet-rich tonalitic gneisses, a few kilometres west of the Mysen syncline (1660–1500 Ma; Graversen 1984, Lutro and Nordgulen 2008).

Sheet silicates like biotite are a main component of the gneisses at Nordstrand. They are responsible for a strong anisotropy effect in their thermal conductivity. Clauser and Huenges (1995) investigated the thermal conductivity of biotite and measured 3.1 W $m^{-1}K^{-1}$ parallel to the sheets and 0.5 W $m^{-1}K^{-1}$ perpendicular to the sheets. The strike and dip direction is expected to vary along the borehole as outcrops showed folding in the gneisses.

At an outcrop approximately 50 m west of the well field, another local rock type was discovered: a felsic pegmatite dyke (about 2 m thick). It is expected that the dyke cuts the borehole so that both gneiss and pegmatite are present in the well.

The thermal conductivity of the gneiss is expected to be somewhat lower than that of the pegmatite. Values recommended to be used in Earth Energy Designer for gneiss and pegmatite are 2.9 and 3.4 W $m^{-1}K^{-1}$, respectively (Eskilson et al. 2000). In the GEOS (GEOlogy of the OSlo region) database of the Geological Survey of Norway a median value of 3.04 W $m^{-1}K^{-1}$ for the gneiss present at Nordstrand was calculated based on 91 surface rock core samples. The effective thermal conductivity measured with the TRT in this study is 3.23 W $m^{-1}K^{-1}$ and is within the expected range. The driller's well report indicates a water-bearing fracture zone at 110–112 m depth.

Two different phenomena can be discovered while studying the two different temperature profiles related to the TRT: 1) the thermal influence of buildings on the temperature field in the ground, and 2) the presence of groundwater flow at 34 m depth.

The temperature increase in the temperature profile taken before the TRT is remarkably high in the uppermost 60 m of the borehole (see Figure 3). Therefore, three additional temperature profiles were taken in surrounding boreholes 1, 2 and 4 (see Figure 5).

The thermal disturbance in the ground decreases proportionally to the increasing distance to the main building of Nordstrand school. The same phenomenon was described for a building in Cambridge (Massachusetts, USA) where the influence was modelled to be down to almost 150 m, 50 years after the construction of the building (Roy et al. 1972). Roy et al. modelled the underground heat plume defining a Dirichlet temperature boundary condition for the building which was set to 15°C. This strategy was taken in a simple two-dimensional finite-element model for the thermal plume at Nordstrand school. The model was built up in FEFLOW 5.4 (DHI–WASY GmbH, Berlin, Germany). Using a transient model with a thermal conductivity of 3.23 W $m^{-1}K^{-1}$, a matrix porosity of 5% (used as pseudoparameter), a geothermal gradient of 0.7 K per 100 m and a simulation time of 82 years (time since the building was built), the temperatures measured in the uppermost 100 m can be simulated successfully (see Figure 6 and compare also with Figure 5).

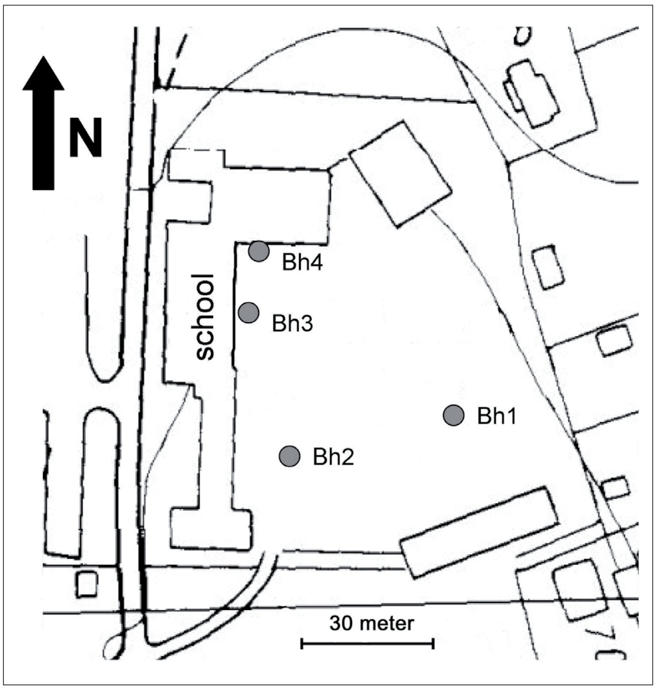

Figure 4. Map over Nordstrand school and position of boreholes (Bh) where temperature profiles were taken (map taken from www.norgeskart.no, 08.12.2009, mod.).

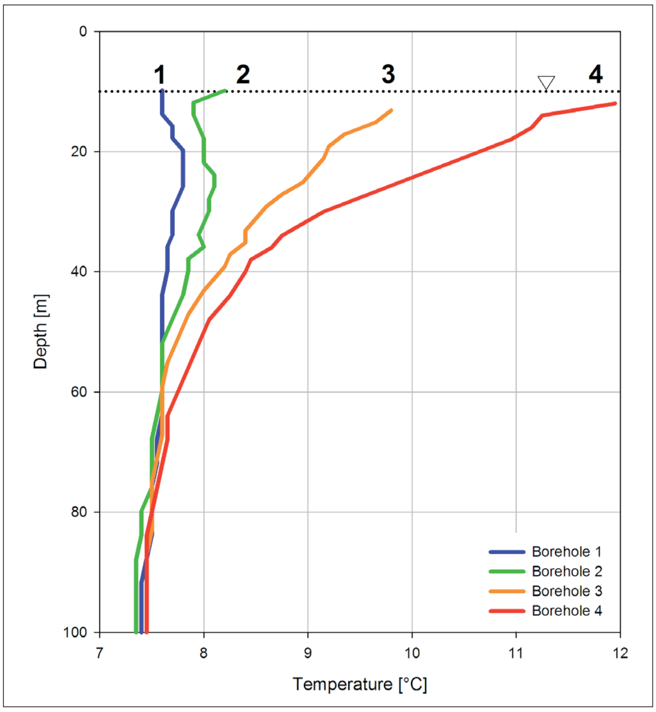

Figure 5. Temperature profiles in four boreholes at Nordstrand. The dotted line and the triangle show the groundwater level.

The heat loss through the foundations of the building over many years is significant and underlines the importance of good insulation.

Groundwater has an influence on the temperature recovery after the TRT. The driller's well report indicates a water-

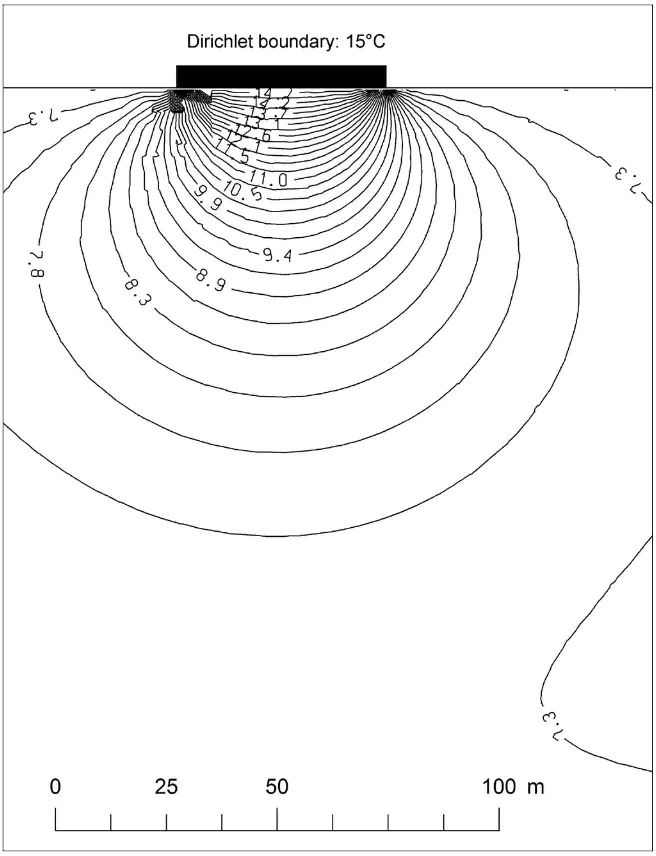

Figure 6. Simulated heat plume below Nordstrand school 82 years after the construction.

bearing fracture zone at 110 to 112 m depth and exactly there, the temperature decrease is fastest after the TRT. The effect of groundwater on the temperature profile was further investigated in a research borehole of the Geological Survey of Norway at Lade (see discussion below).

Lade

The upper 93 m of the borehole at Lade consist of Lower Ordovician greenstones while the lower part is characterised by trondhjemite based on driller's observations and an investigation with an optical televiewer. The borehole was tested for hydraulically active fractures with the help of a groundwater pump installed at 20 m depth. During pumping of water with a volumetric flow rate of 780 l hr^{-1}, a propeller was lowered in the borehole. The number of rounds per time interval can be used to detect and calculate groundwater flow through open fractures. In the depth around 34 m a pronounced fracture appears, which is visible in the flow measurement (reduction of number of rotations below 34 m) as well as in an optical televiewer image (see Figure 7). The televiewer image and the test data were made available by Harald Elvebakk who performed the measurements in 2003.

The effective thermal conductivity measured with the TRT is 4.11 W $m^{-1}K^{-1}$. This value is higher than the median rock core thermal conductivity measured in Norwegian greenstones (2.7 W $m^{-1}K^{-1}$, n=37, unpublished data, NGU) and trondhjemites (2.7 W $m^{-1}K^{-1}$, n=11, unpublished data, NGU).

The temperature profile at Lade is characterised by a negligible geothermal gradient and little variation along the borehole. However, the effective thermal conductivity measured at the borehole was higher than the laboratory measured thermal conductivities would suggest for greenstones and trondhjemites. A closer look at the temperature profile taken after the TRT reveals a faster recovery around 34 m than at the rest of the borehole (Figure 3).

As described above, the flow measurement showed a water-bearing fracture at this depth. A natural, regional groundwater flow can therefore be expected, similar as in the study of Liebel et al. (2011), which is responsible for an increased effective thermal conductivity. Even if the effect of the open fracture is rather small at Lade, it was chosen as an example because of the complete dataset comprising hydrogeological data for the borehole. A more pronounced effect of groundwater on the temperature profile than in this case can frequently be found (see e.g., Liebel et al. 2009).

Bjørnegård

The borehole at Bjørnegård (Bærum municipality, Oslo region) is drilled primarily in Ordovician limestones and shales according to the geological map and to outcrops from the area. The sedimentary cover is 28 m thick and consists of clays. The median thermal conductivity from rock core samples from the Ordovician limestones and shales is 2.7 W $m^{-1}K^{-1}$ (GEOS database, NGU 2011 unpubl.). The TRT result shows a pronounced higher effective thermal conductivity of 4.81 W $m^{-1}K^{-1}$. The driller's report indicates a water-bearing fracture at 60 to 62 m depth with a water yield of more than 1000 l hr^{-1}. The driller's estimate of the water yield for the entire borehole is 15000 l hr^{-1}. During drilling the borehole was artesian. After the drilling was finished, a tight plug was installed to stop the outflow from the borehole.

The temperature profiles at Bjørnegård show an anomalous temperature increase towards the surface (uppermost 10 m) which can be explained with two neighbouring injection wells where surface water is infiltrated into the aquifer with a total rate of ca. 38 litres per minute. Infiltration is done to avoid surface subsidence damages related to a lowered groundwater level as a consequence of the relatively new railway tunnel nearby. Figure 8 visually shows the hydrogeological situation at Bjørnegård.

The temperature profiles were taken in August 2010. The shallowest temperature field is altered due to solar irradiation on the parking lot and heat flow from the surface towards the ground (Figure 3). Elsewhere, the temperature profile before the TRT shows no unexpected variations. Very different, however, is the temperature profile after the TRT. The borehole cuts an open fracture at 60 m depth belonging to a presumably confined aquifer (artesian). Water intrudes the borehole and flows upwards to the next possibility where it can flow into the sur-

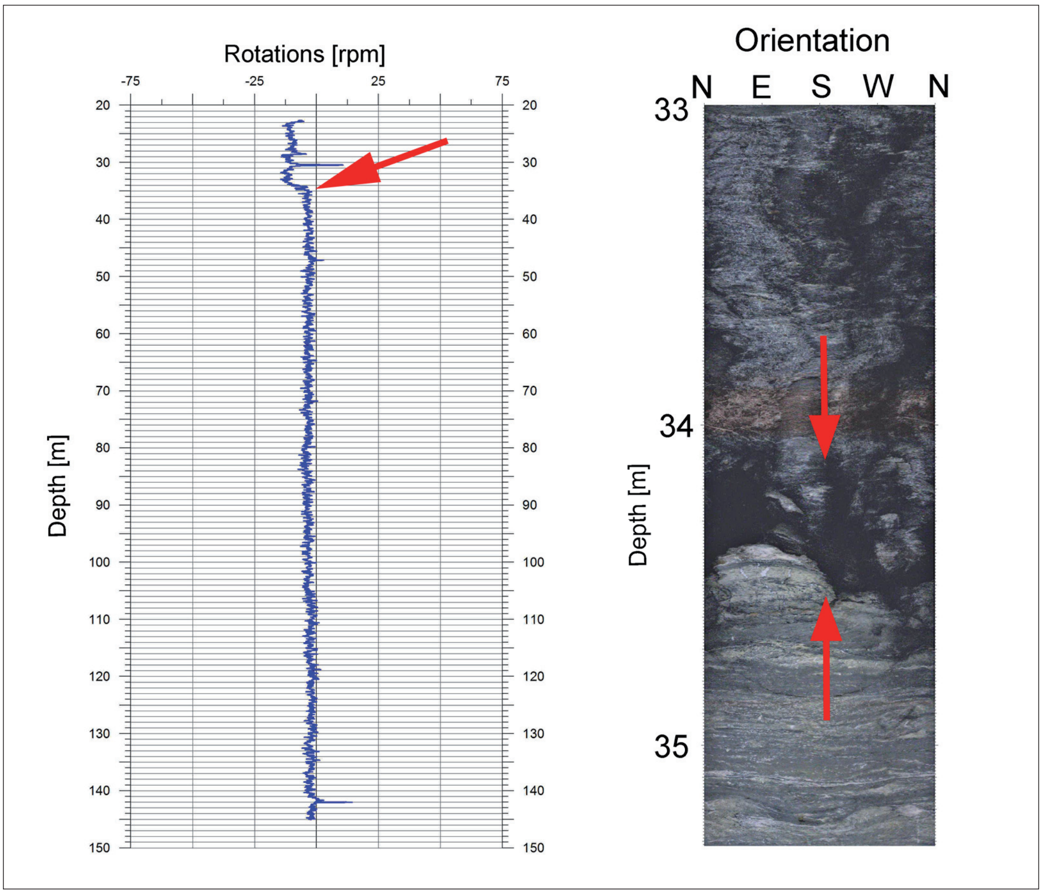

Figure 7. Results from the flow measurement (left) and optical televiewer image of the main fracture in the investigation borehole (right, H. Elvebakk, unpubl.); red arrows indicate the main fracture.

rounding formation, which is in this case at the contact between the bedrock and the sedimentary cover at about 28 m depth. Therefore, the temperatures recover fastest in the profile taken after the TRT in the interval between 60 and 28 m, while the heat takes longer to be dissipated in the other parts of the borehole. Similar temperature profiles were reported from Sweden (G. Hellström, pers. comm. 2011) and Germany (M. Sauer, pers. comm. 2011).

Conceptual models

Conceptual models of the four discussed cases are shown in Figure 9 and discussed in the following.

Case 1:

If the rocks in a borehole are homogeneous concerning mineral content and if no permeable fractures occur, a temperature profile may be measured after a TRT as shown in Figure 9. The temperature recovery after the TRT is fastest in the upper part of the borehole as the temperatures of the surrounding rocks are colder. Here the temperature gradient is largest resulting in a high heat flux according to Fourier's law. Further down in the borehole the undisturbed rock temperature increases according to a geothermal gradient. The temperature difference decreases between the heated borehole and the surrounding rock. Therefore, the temperature recovery is slow in the low part of the borehole (low heat flux). A temperature drop at the base of the borehole can be observed due to heat dissemination also in vertical direction.

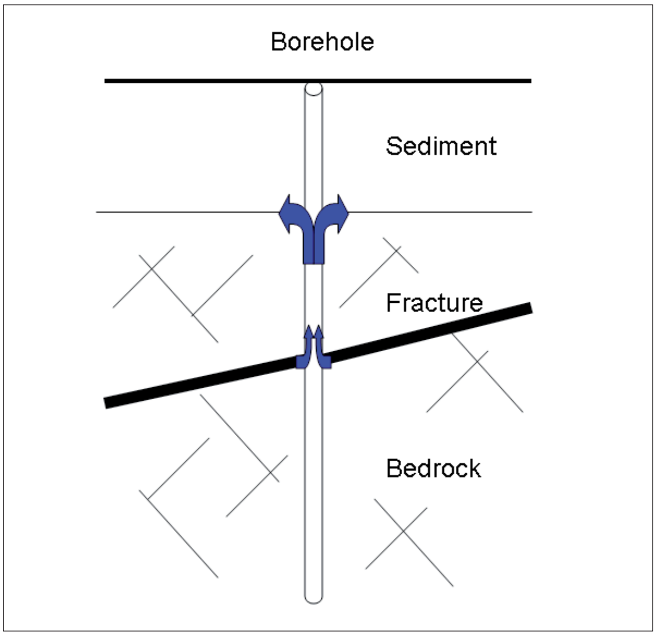

Figure 8. Schematic diagram showing the groundwater flow through the open fracture at Bjørnegård and the upward flow through the borehole with the final inflow into the sediments.

A temperature profile of this kind is the optimum for the TRT evaluation. The assumptions for the TRT analysis for example with the infinite line-source theory are met.

Case 2:
In case 2 the geological conditions are similar as in case 1 but the temperature in the upper part of the well is higher due to an increase in heat flow from the surface. Possible alterations may be due to the construction of a building with poor insulation towards the ground, a parking lot (pronounced effect with dark asphalt) or a forest clearing which increases the irradiation and the heat transfer towards the ground.

A temperature profile of this type does not implicate a special TRT evaluation. However, it gives valuable information on the expected operation of a ground-coupled heat pump installation. An increased heat transfer from the surface is positive for the heat extraction from the ground as the removed heat is restored fast from the surface.

Case 3:
If the borehole passes through a water-bearing fracture, a fast temperature recovery can be expected in the vicinity of the fracture (Figure 9).

If a temperature profile taken some hours after a TRT indicates a water-bearing fracture, the TRT results need a cautious interpretation. Groundwater flow through the borehole during the TRT can be discovered from the TRT results in certain circumstances. One possibility is that the effective thermal conductivity does not converge with time but does increase continuously (Witte 2002, 2007). If the groundwater flow volume through the open fracture is relatively small or if the total time of the TRT is chosen too short, this effect cannot be discovered

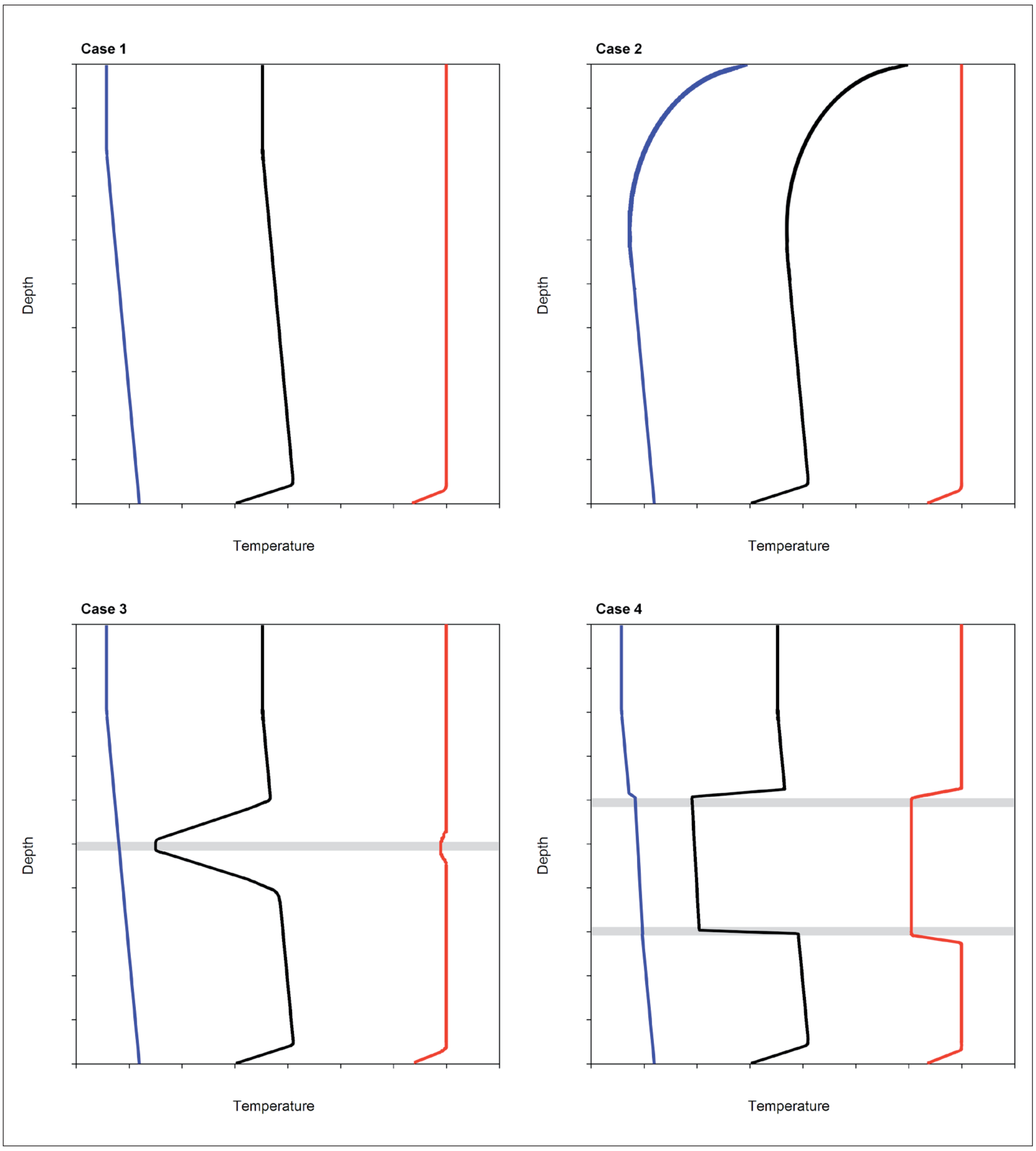

Figure 9. Fictitious temperature profiles before (blue), right after (red) and five hours after (black) a TRT in homogeneous rock for the four cases. Case 1: no water-bearing fractures; case 2: temperature anomaly towards the surface due to poorly insulated buildings or solar collectors (e.g., parking lot, pitch); case 3: one water-bearing fracture; case 4: two open fractures short-circuiting a confined lower aquifer with an unconfined upper aquifer.

in the TRT results. Results from a study in Bryn (Oslo region) show, however, that the effective thermal conductivity increased by 0.4 W $m^{-1}K^{-1}$ due to an increased groundwater flow through one fracture. In this case two TRTs were compared to each other, one without artificial groundwater flow and one with pumping of groundwater from a close-by well (for more details see Liebel et al. 2009).

Even if the groundwater flow is not detectable directly in the TRT results, it will transport heat away from the well during operation in cooling mode and it will transport heat towards the well in heating mode, which has to be taken into account for the dimensioning of a ground-coupled heat pump system.

The temperature profile after the TRT may indicate groundwater flow, even if the TRT results seem normal. In this case a more detailed hydrogeological investigation and a groundwater flow simulation should be performed to estimate the influence of groundwater on the borehole heat exchanger during operation. Parameter estimation techniques are a possibility to estimate the thermal conductivity based on the TRT results (e.g., Hellström 1997, Spitler et al. 1999).

A second explanation for a temperature profile with a fast recovery in one zone is a layer of improved thermal conductivity due to a different mineral content (for example a high quartz content). In most cases, the driller's observations of the colour of the drilling mud indicate different geological layers and mineral contents. If percussion drilling is applied, cuttings should be sampled in a regular interval (e.g., every three metres) to get more information about changing rock type and mineral content in the well. The driller's observations can be correlated to areas with fast temperature recovery in the temperature profile. In this case, the TRT results give effective thermal conductivities that converge and a standard data evaluation can be accomplished.

Case 4:
In this case the borehole penetrates two fractures where the lower one belongs to an artesian and the upper one to an unconfined aquifer. An upstream of groundwater towards the upper fracture is going to be established. Alternatively, the upper fracture can be replaced with the border between bedrock and permeable sedimentary cover.

A weaker upward flow might be established during the TRT if a thermosiphon effect appears (Gehlin et al. 2003).

The phenomenon of upwards flowing groundwater is easily discovered with the help of a temperature profile after the TRT as the temperature recovery will be fast in the area of flowing groundwater (Figure 9).

During a TRT, the temperature of the heat-carrier fluid in the borehole heat exchanger increases less if groundwater flow is present. The effect of upwards flowing groundwater on the effective thermal conductivity measurement may be stronger than of groundwater flow through fractures crossing the borehole. With up-flowing groundwater large areas of the borehole heat exchanger are affected by the contact with cold groundwater. In the case of horizontal fracture flow through the borehole, however, only limited areas of the borehole heat exchanger get in contact with cold groundwater. The measured effective thermal conductivity will be higher than the actual thermal conductivity of the bedrock in both cases, but highest in the case of upstreaming groundwater. Parameter estimation techniques are a possibility to estimate the thermal conductivity based on the TRT results (e.g., Hellström 1997, Spitler et al. 1999). For the dimensioning of a borehole field, further hydrogeological studies should be carried out, including a flow simulation for the influence area of the borehole field.

Conclusion

Temperature profiles before a TRT are taken as a standard procedure to calculate the undisturbed ground temperature and the thermal borehole resistance.

This study highlights the importance of taking temperature profiles also after the TRT is finished.

The temperature profiles yield important hydro- and thermogeological information based on a measurement that takes only about one hour. The driller's reports give an indication for areas of high probability for open fractures only. In the temperature profile after the TRT, the water-bearing fractures can be located precisely. Upcoming groundwater from confined artesian aquifers can be detected clearly. Layers of different mineral content showing varying thermal conductivities can be located and distinguished from zones of groundwater flow with the help of the driller's well reports.

Information gained from temperature profiles after a TRT, supplements the data obtained from various other sources such as: TRT, the driller's well report, rock core thermal conductivity measurements, the measurement of the undisturbed ground temperature, the geological map and so forth. The combined evaluation of all data available for a borehole can then be used to define the required capacity of a ground-coupled heat pump system and to predict the behaviour of the plant in operation. The extra information gained helps also to decide whether further site investigations or groundwater flow simulations are needed. Further work should focus on the quantification of the influence of groundwater flow on the estimate for the effective thermal conductivity.

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