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Temperature profile measurements – easy, cheap and informative

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ABSTRACT

Regular thermal response tests (TRT) are routinely performed to get data for sizing larger installations with borehole heat exchangers. The effective borehole thermal conductivity and the effective borehole thermal resistance are the two main parameters determined with the test, in addition, the undisturbed temperature of the borehole is determined, most often by measuring the temperature of the collector fluid during circulation before startup of the test.

The undisturbed temperature of the borehole can also be determined from the vertical temperature profile in the borehole. Such temperature profiles are easily obtained with manual measurements using a probe in one of the collector pipes.

In addition to an accurate measurement of the undisturbed temperature, the vertical temperature profile can be interpreted to find e.g. water bearing fractures, thermal pollution from nearby buildings and variations in geology. Temperature profile measurements after the TRT is performed can be used as an indicator of groundwater flow in the borehole that might affect the results from the response test and the performance of the borehole (Liebel 2012).

This paper presents data from temperature profile measurements performed in single boreholes and in borehole fields in Norway. The profiles are measured before (undisturbed temperature) and after TRTs on boreholes ranging between 50 to 500 m. Based on the data, cases where the temperature profiles have been used to indicate variations in geology, water bearing fractures and variations in temperatures within neighboring boreholes are presented. Together with thermal conductivity values from laboratory measurements on rock samples, the profiles are also used to explain the results from TRTs affected by groundwater flow. Temperature profile measurements from several boreholes within single borehole fields also show significant differences important for the design of the GSHP system. As a conclusion, it is shown that the regular measurement of temperature profiles is an easy and cost effective method to gain knowledge and insight beyond that of a standard response test. It is therefore recommended to measure the undisturbed temperature profile of all boreholes in a GSHP as a regular part of the documentation and as a basis for design of GSHP systems.

INTRODUCTION

Thermal response tests (TRTs) are routinely performed to determine the effective thermal conductivity of the ground (λ_{eff}) and the effective borehole thermal resistance (R_b), together with the undisturbed temperature of the ground, these are the key parameters when sizing borehole fields for ground source heat pump systems (GSHP). While the method is robust and widely used (Sanner et al. 2013) it is usually only for lager GSHP installations with more than 12-15 boreholes that TRTs are performed due to the cost involved, and for most of these larger installation

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only one test is performed. When performing a TRT, the undisturbed temperature of the borehole is determined either by measuring the temperature of the collector fluid during circulation before startup of the test, or by measuring the vertical temperature profile in the borehole by using a probe in one of the collector pipes (Gehlin and Nordell 2003).

In addition to an accurate measurement of the undisturbed temperature, the vertical temperature profile can be interpreted to find e.g. water bearing fractures, thermal pollution from nearby buildings and variations in geology. Temperature profile measurements after the TRT is performed can be used as an indicator of groundwater flow in the borehole that might affect the results from the response test and the performance of the borehole (Liebel 2012).

In contrast to the TRTs, the temperature profile measurements are simple and inexpensive, and can therefore be performed on several boreholes to complement the results from the TRT. This has also been pointed out in Raymond et al. 2016.

The temperature profile in the borehole can also be determined using distributed temperature sensing (DTS) with fiberoptic cable as described in detail in Acuna (2013). While these measurements are promising, the high cost of the measurement equipment limits the use of DTS for many GSHP installations.

Since 2011, Asplan Viak AS has analyzed 100 + TRTs performed in Norway. The borehole depths range between 50 to 500 m and are analyzed according to Gehlin (2002) and Signorelli (2004 and 2007). In addition to the standard TRT procedure, which usually follows the guidelines established by the Swedish Geoenergycentrum (2015), the vertical temperature profiles in the boreholes are routinely measured before, and in most cases, also after the test is performed.

The locations of the analyzed TRTs are shown in figure 1 where blue dots are TRTs accompanied by temperature profile measurements and red dots are TRTs without temperature profile. In the cases without temperature profile, the undisturbed temperature of the borehole is determined by measuring the temperature of the circulated collector fluid before the TRT is initiated.

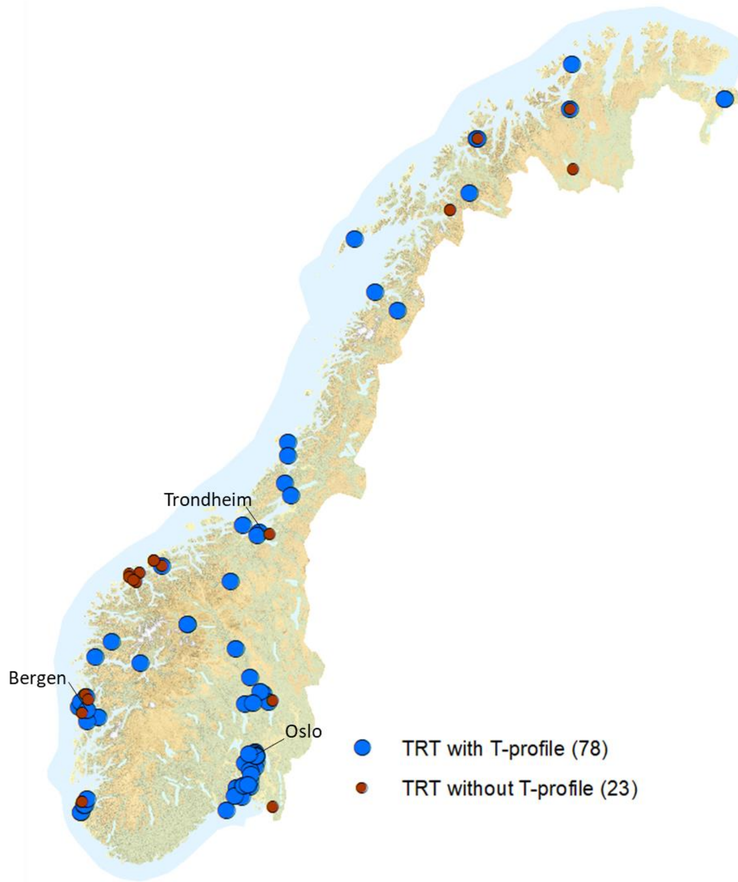

Figure 1. Location of most of the thermal response tests analyzed by Asplan Viak in Norway since 2011.

The aim of the present paper is to present data from temperature profile measurements and to demonstrate the usefulness of the temperature profiles for interpretation of TRT results and for the design of ground source heat pump systems (GSHP).

Specific cases have been selected to demonstrate the usefulness of the temperature profiles. Based on the data, cases were the temperature profiles have been used to indicate variations in geology, water bearing fractures and variations in temperatures within neighboring boreholes are presented. Together with thermal conductivity values from laboratory measurements on rock samples, the profiles are also used to explain the results from TRTs affected by groundwater flow. Therefore, the presented study can be regarded as an extension of the PhD-work of Liebel (2012).

METHODOLOGY

Temperature profiles presented in the present paper have been measured during the construction phase of GSHP installations. Measurements are usually performed by the drilling company and reported back to the consultant for sizing and documentation of the borehole heat exchangers (BHEs).

Undisturbed temperature profiles are measured after the borehole has rested a minimum of 3 days after the drilling is completed, in most cases the profile is measured after 5 to 7 days. When measuring the temperature profile there should not be any drilling in the area near to the borehole as this can disturb the measurements.

The temperature is measured inside one of the collector pipes with a probe, commonly of the type 110 from hydrotechnik GMBH. Such temperature probes have an accuracy of <0.1 K and a resolution of 0.1 K. This is a manual procedure were the value is noted for each 5^{th} to 10^{th} meter, at each step, the probe is held still until the temperature has stabilized. For a 250 m borehole, this takes about 30 - 40 minutes. Measurements are either performed from top to bottom, or from bottom to top. Provided that care is taken when performing the measurements, both measurement directions give the same results. When measuring from bottom to top, the probe is first lowered to the bottom of the borehole and then held still a few minutes until the temperature has stabilized before starting the measurements. This measurement direction is often more practical since it distributes the work involved with winding up the temperature probe.

For most cases, temperature measurements with a 5 m resolution is enough to capture effects such as groundwater movement in a 200 – 300 m borehole. For short boreholes (e.g. 50 m) is it natural to use a shorter measurement interval of about 2 m.

The temperature profiles after the TRT are measured while the temperature in the borehole is recovering. To avoid the rapid temperature changes directly after the TRT, the temperature should be measured after a few hours (Heiko et al. 2011). Due to practical considerations, the temperature profile is usually measured about 1- 5 hours after the heating period of the TRT is finished.

The temperature measurements presented in the present paper are derived from a series of GSHP projects involving several companies and with different temperature probes. While the measurements are expected to be influenced by the different operators, the temperature profiles are accurate enough to determine the undisturbed temperature of the borehole and to identify factors that are of importance for the BHE sizing and the interpretation of the TRT results.

The measurements are presented without any kind of post processing or corrections, e.g. as suggested in Raymond et al. 2016 for the rise of the collector fluid due to the added volume of the temperature probe.

TRT results presented in the paper are based on tests performed with a heating period of 72 hours, the tests are analyzed according to Gehlin (2002) and Signorelli (2004 and 2007).

THERMAL CONDUCTIVITY OF ROCKS BASED ON MINERALOGICAL COMPOSITION

Laboratory measurements on rock samples from the larger Oslo area, Norway, shows a variation in thermal conductivity typically from 2 to 4 W/m·K (Ramstad et al. 2014) representing the mineralogical composition and layering effects (foliation) on dry rock samples. The thermal conductivity is highest in rock types with a high content of quartz and parallel to the foliation of the rock. The rock types covered in the study above represent many of the most common rock types in Norway and thus gives a good basis of what to expect for the different rock types considering heat transfer with conduction only.

The geology at the TRT-site is usually determined by maps from the Geological Survey of Norway and supported by observations from detailed driller's logs, and observations from drilling cuttings. In cases where the TRT-measurements deviates significantly from the expected value it has to be determined whether the results are affected by groundwater flow. In these cases, the temperature profiles measured before and after the TRT provide valuable information, often in combination with observations from the driller's log.

WATER BEARING FRACTURES AND GROUNDWATER FLOW

Boreholes are often intersected by water bearing fractures and fracture zones. In some cases, this affects the performance of the borehole and the result of the thermal response test. Most often, this is observed as an unrealistic high value of effective thermal conductivity. As noted by e.g. Sanner (2007) and Liebel (2012) fractures and zones with cold water that intersects the borehole are easily identified in the temperature profile measured after the TRT. In most cases the fractures only affects a limited part of the borehole and therefore have little or no influence on the effective thermal conductivity as determined from a TRT. It is first when there is a groundwater flow vertically and along the collector in the borehole (e.g. between two fracture zones) that a significant contribution to the measured effective thermal conductivity can be seen. In these cases, the groundwater flow is pressure driven, typically with highest water pressure in the lower fracture and lowest pressure in the upper fracture. Pressure driven groundwater flow can often be observed in the undisturbed temperature profile as sections of the borehole where the temperature is constant (deviates from the conductive temperature profile). A groundwater flow can also be induced by the TRT itself due to density differences caused by different temperatures in the groundwater surrounding the collectors, also known as the thermosiphon-effect as described e.g. by Gehlin et al. 2003.

Pressure driven vertical circulation of water in the borehole

Undisturbed temperature profiles from two separate borehole fields in Norway are shown in figure 2 and figure 4. The profiles are selected to illustrate the influence from pressure driven vertical groundwater flow in the boreholes. The temperature profiles shown in figure 2 are from Vensmoen borehole field in Northern Norway, and are to a different degree affected by vertical groundwater flow. The profiles were measured in August 2016.

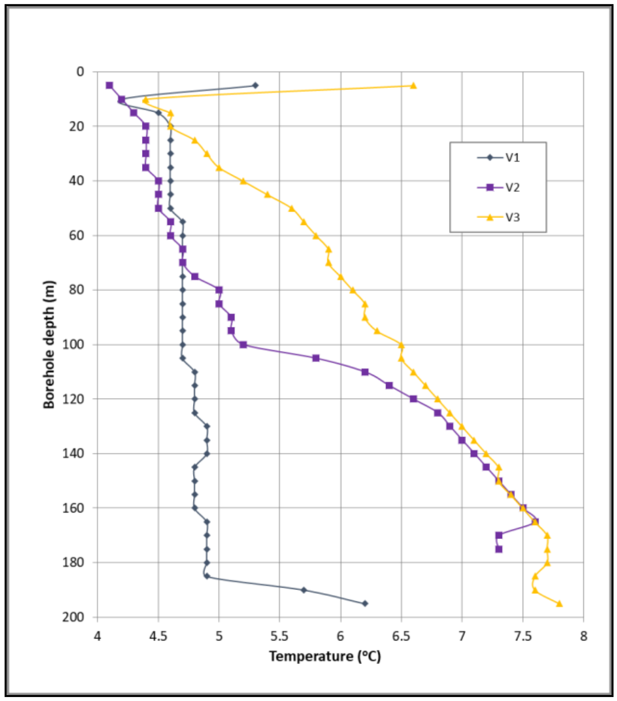

Figure 2. Undisturbed temperature profiles from Vensmoen borehole field, Nordland county in Norway. TRT performed in V1 yielded an λ_{eff} of about 60 W/ m·K. Temperature profiles V1 and V2 are affected by groundwater circulation while V3 is showing a conductive behavior. The profiles were measured in 2016.

In the first profile (V1), groundwater flows vertically along almost the entire length of the borehole (from around 185 m to ca. 15 m depth). Also in the second profile (V2), the upper 100 m of the borehole is affected by groundwater flow, while the third profile (V3) shows an almost ideal conductive profile for almost the entire borehole depth. The geology at the site is mapped as marble by the Geological Survey of Norway (NGU). It is not unusual that boreholes drilled in marble intersects large water bearing fracture zones and even caves (so-called karst) where the rock has dissolved. Borehole V1 (which was also the first borehole to be drilled) likely intersects such a karst with water at a higher pressure. A standard 72 hour TRT performed in borehole V1 in 2013 yielded a very high λ_{eff} of around 60 W/m·K. The unusually high λ_{eff} (even for TRTs affected by groundwater flow) can only be explained by a large vertical flow rate in the borehole. The temperature profiles measured before and after the TRT are shown in figure 3. The temperature profile that was measured 20-30 minutes after the test was finished resembles the undisturbed profile measured before the test.

It can also be noted that the undisturbed temperature profile measured in 2013, before the TRT, is about 0.8 K warmer than the temperature profile measured in 2016.

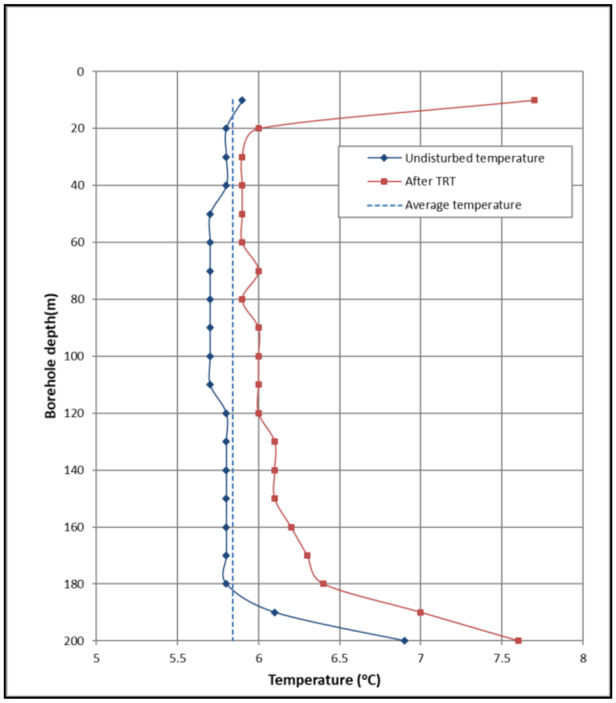

Figure 3. Measured temperature profile before and after the TRT in the test-borehole at Vensmoen, Nordland county, Norway

While no further TRT was performed in the project, a test performed in V2 would likely also give a rather high λ_{eff}, while a test performed in V3 would yield a more representative value for the thermal conductivity of the rock type on site reflecting the mineralogical composition only.

The temperature profiles shown in figure 4 are from Skjåk borehole field, in Norway, the first profile (S1) represents the undisturbed temperature in the first borehole drilled. The near constant temperature between 35 m to about 100 m indicates vertical flow of groundwater. A 72 h TRT performed in the borehole resulted in an unrealistically high thermal conductivity of 6.8 W/m·K. It was therefore concluded that the result was affected by the observed vertical groundwater flow. At a later stage in the project, observations from detailed driller's logs (water yield, observed fractures etc.) were used to select candidate boreholes for temperature profile measurements. A second 72 h TRT was then performed in the borehole with the least affected profile (profile S2 in figure 4). This test resulted in an λ_{eff} of 2.8 W/m·K which is more representative for the geology at the site which was mapped as granitic gneiss and migmatite by the Geological Survey of Norway (NGU).

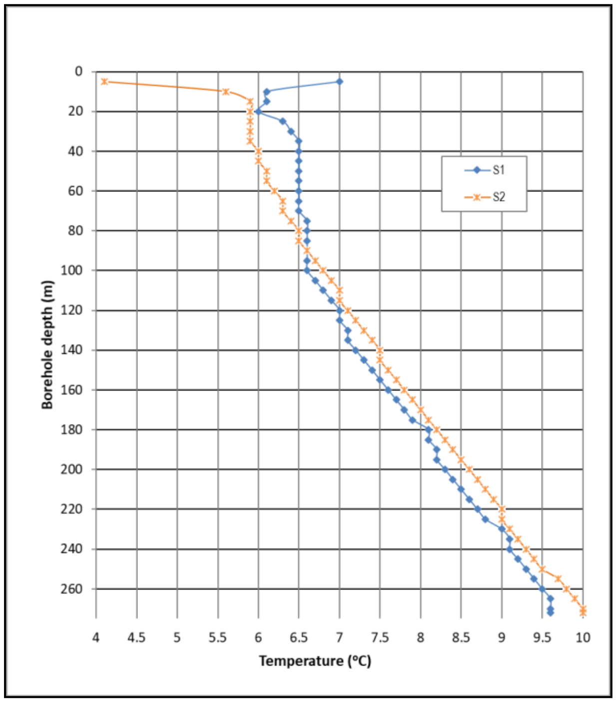

Figure 4. Temperature profiles from Skjåk borehole field, Oppland county, Norway. TRTs yielded an λ_{eff} = 6.8 W/ m·k in S1 and λ_{eff} =2.8 W/ m·k in S2.

Water-bearing fractures and induced water flow (thermosiphon effect)

Water-bearing fractures (where water crosses the borehole) are usually not visible in the undisturbed temperature profile, but can easily be identified in the temperature profiles measured after a TRT, as shown in figure 5 and figure 7. While showing as a distinct feature in the temperature profile, these fractures usually have little effect on the effective thermal conductivity (λ_{eff}) measured for a standard borehole (200 m – 300 m) since only a limited part of the borehole is affected. Temperature profiles measured before and after a TRT in a borehole with a single distinct fracture are shown in figure 5. The fracture, which was also observed in the drillers log at about 63 m, is clearly visible in the temperature profile measured 3 hours after the TRT. In this case the 72 hour TRT resulted in an λ_{eff} of 3.1 W/m·K which is a likely value for the rock type at the site, the influence of the groundwater passing through the borehole at about 60-70 m depth is therefore assumed to be limited.

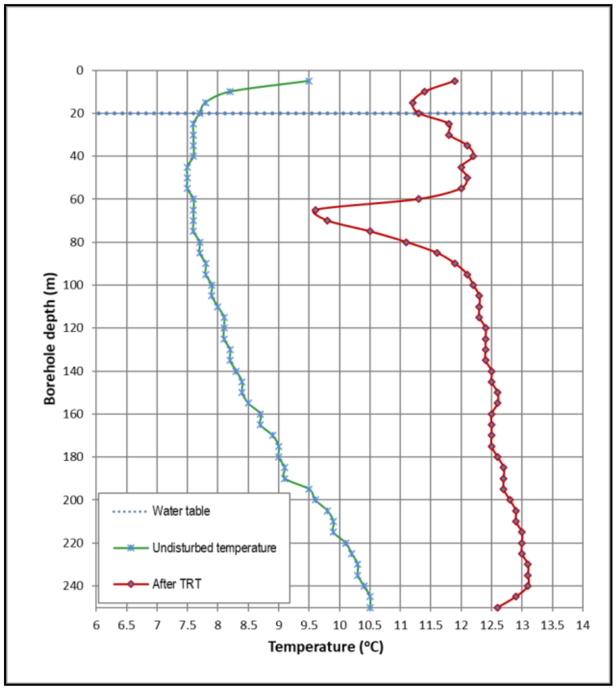

Figure 5. Temperature profiles before and 3 hours after TRT performed at Hovli, Oppland county, Norway. A single water-bearing fracture is observed after the TRT.

It seems that for groundwater to have significant effect on the results from the TRT there either has to be a vertical flow of water along the collector in the borehole or a larger amount of fractures and fracture zones intersecting the borehole. A vertical groundwater flow can also be induced by the TRT where added heat causes a thermosiphon effect, the phenomena is nicely described in Gehlin et al. 2003. In essence, the temperature increase causes the water to rise in the borehole; the warmed water leaves the borehole through fractures in the upper part of the borehole while cold water enters the borehole in fractures lower down. The result is an increase in λ_{eff} as measured by the TRT. Figure 6 show the development of λ_{eff} throughout a 72 hour TRT performed in a borehole in Skoppum, Norway. The borehole was intersected by two distinct fractures. The increase in λ_{eff} throughout the test indicates that the test is affected by the thermosiphon effect. The temperature profiles measured before and after the TRT are shown in figure 7.

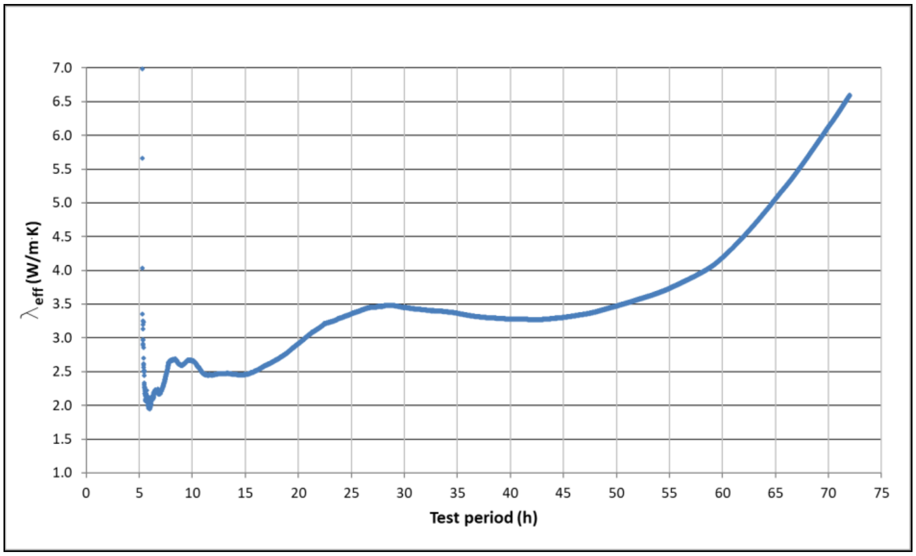

Figure 6. Development of λ_{eff} during a TRT performed in a borehole in Skoppum, Vestfold county, Norway. The test, which was influenced by the thermosiphon effect, is evaluated according to Signorelli (2007).

The undisturbed temperature profile in figure 7 is a near ideal conductive profile with a geothermal gradient of about 0.022 K/m which is high with respect to Norwegian conditions. The undisturbed temperature profile was measured one week after the drilling was finished. In the temperature profile measured 3 hours after the TRT (which was clearly affected by groundwater flow), two distinct fractures can be observed at about 30 m and 140 m depth. The fracture at about 30 m depth could also be interpreted as a reflection of the undisturbed temperature gradient in the borehole. Since the temperature profile was measured shortly after the TRT finished, it is, however, evident that the sudden temperature change is caused by groundwater flow. In the bottom of the borehole the temperature profile after the test crosses the undisturbed temperature, this might be a measurement error caused by the measurement procedure where the temperature probe is lowered to the bottom of the borehole before starting the measurements. The temperature profiles shown in figure 8 are from a second TRT, successfully performed in a neighboring borehole. The undisturbed temperature profile is measured on week after the borehole was drilled and the temperature profile after the test was measured 2 hours after the 72 hour TRT finished. This test yielded an λ_{eff} of 2.3 W/m·K, this is a low value, but it is not unlikely for the geology at the site which according to the Geological Survey of Norway (NGU) is mapped as rhomb porphyry. Laboratory measurements of rhomb porphyry presented in Ramstad et al. (2014) show a median thermal conductivity of 2.3 W/ m·K.

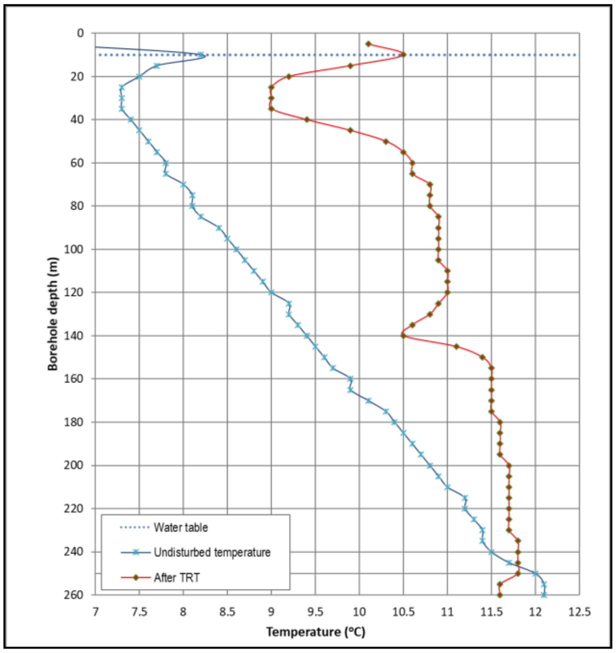

Figure 7. Temperature profiles before and after TRT performed in Skoppum, Vestfold county, Norway. Two distinct water-bearing fractures are observed at about 30 m respective 140 m depth.

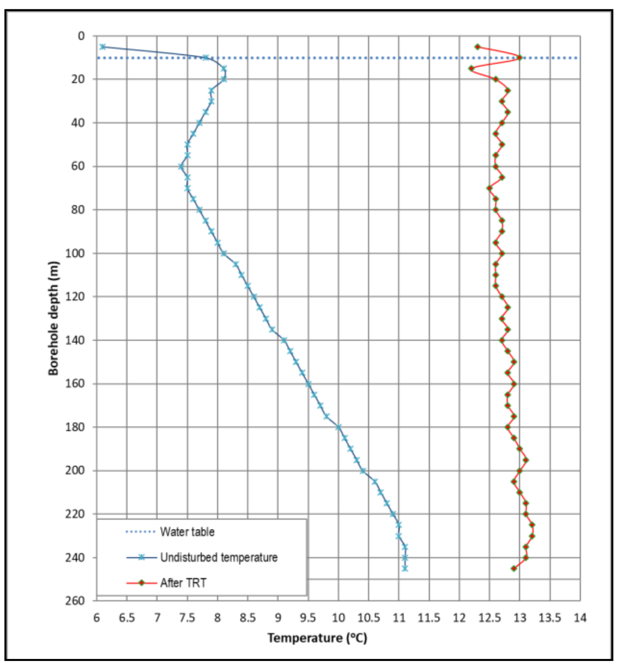

Figure 8. Temperature profiles before and after the second TRT (neighboring borehole for the borehole tested in figure 6 and figure 7) performed in Skoppum, Vestfold county, Norway.

It has been observed that pressure driven vertical ground water flow can be identified from the undisturbed temperature profiles measured before a TRT. Temperature profiles therefore provide an easy method to avoid tests that are affected by groundwater flow.

It is more difficult to avoid tests that are affected by induced ground water flow (thermosiphon effect); the undisturbed temperature profiles provide no information about groundwater flow horizontal to the borehole, e.g. fractures. These are, however, easily identified from the temperature profiles measured after the TRT. In addition, the induced thermosiphon effect shows as an increasing λ_{eff} throughout the test. The thermosiphon effect is more pronounced using higher specific heat effect during the test.

In most cases, the temperature profile measured after the test shows a conductive behavior (as in figure 8) and can be used to indicate that the test is successful and unaffected by ground water flow.

Temperatures within neighboring boreholes

When sizing a borehole field, the undisturbed temperature (as usually determined from the test borehole) is an important parameter, which have a large influence on the number of boreholes and the total amount of borehole meters drilled. The undisturbed temperature is usually determined either by measuring the temperature in the borehole (with a probe) or by measuring the temperature of the circulated collector fluid before the TRT is initiated.
The undisturbed temperature of the borehole can be affected by e.g. groundwater flow and thermal pollution from buildings, in addition, the undisturbed temperature reflects the deviation of the borehole, which is usually not measured. Here we present temperature profile measurements performed for two separate borehole fields. Figure 9 shows undisturbed temperature profiles from 13 boreholes at Vensmoen, in Nordland county, Norway. The boreholes were drilled on two parallel lines; about half of the boreholes, forming one of the lines, were drilled with a deviation, while the rest of the boreholes were drilled vertically. Temperature measurements were performed 5 days after the last borehole was completed. In this case, vertical circulation of groundwater and borehole deviation is thought to be the main cause of the variations in undisturbed temperature. Most of the boreholes stopped at about 165 m to 190 m due to high groundwater yields. Excluding the test borehole which had an average temperature of 4.8°C, the average temperature of the boreholes (in the depth range 20 m to 150 m) is between 5.08°C and 6.31°C with an arithmetic average of 5.81°C.

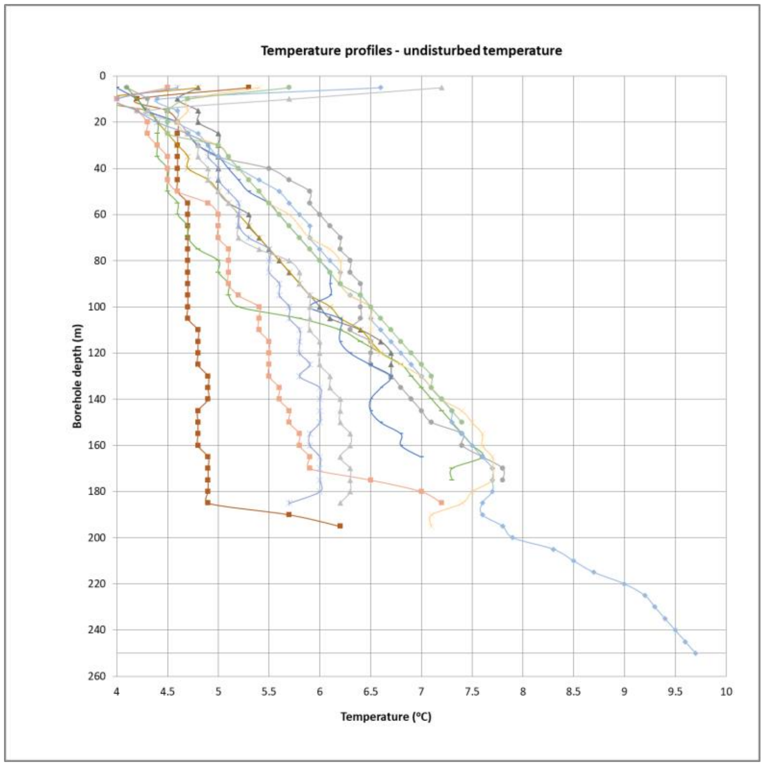

Figure 9. Undisturbed temperatures measured in 13 neighboring boreholes at Vensmoen, Nordland county, Norway.

The undisturbed temperature profiles measured from 18 neighboring boreholes at Revetal in Norway are shown in figure 10. The boreholes were drilled through several fracture zones, causing minor collapse in 8 of the boreholes. The boreholes had a well yield ranging between 30 000 l h^{-1} to 50 000 l h^{-1} and hydraulic connection was observed between about half of the boreholes. Due to high groundwater yields, most of the boreholes did not reach the target depth of 250 m. The temperature profiles were measured with a 10 m interval and the measurements were performed 5 days after the last borehole was completed. There are no direct signs of vertical groundwater flow in the boreholes but most of the boreholes intersected a large number of fractures and zones with fractured rock. The average temperature of the boreholes (in the depth range 10 m to 180 m) is between 9.07 °C and 10.57 °C with an arithmetic average of 9.62 °C. Although the boreholes were drilled on three lines parallel to an existing building, there are no obvious signs of thermal pollution in the temperature profiles. Though uncertain, the variation in temperature is more likely caused by a combination of groundwater flow and borehole deviation.

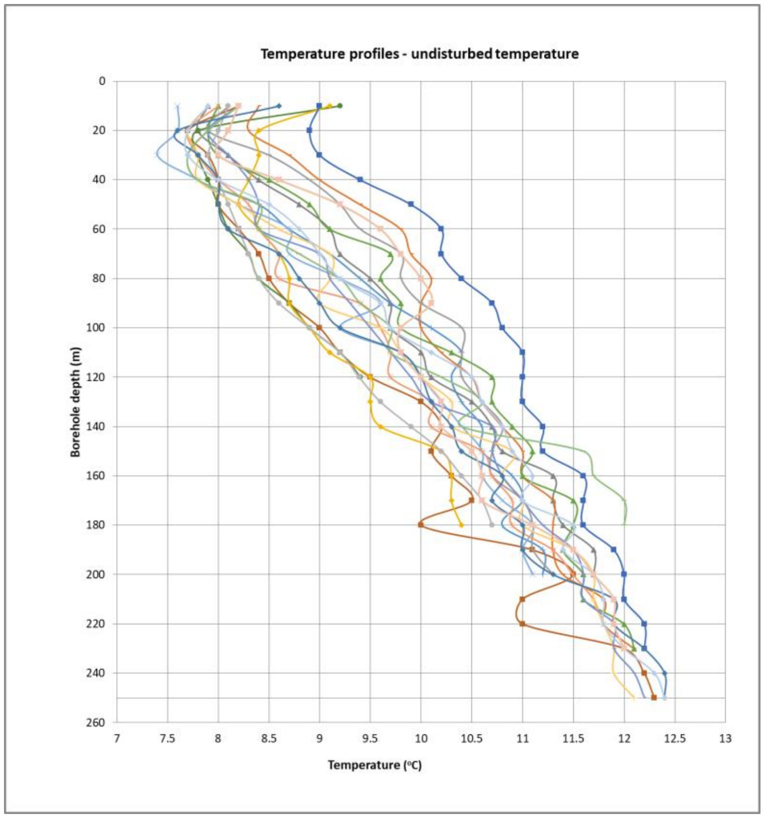

Figure 10. Undisturbed temperature profiles measured in 18 neighboring boreholes, Revetal, Vestfold county, Norway.

As seen in figure 9 and figure 10, the undisturbed temperature can vary significantly within neighboring boreholes. Therefore, the undisturbed temperature obtained either from circulation of collector fluid or from a single temperature profile, might in some cases not be representative for the undisturbed temperature of the borehole field. The temperature profile does, however, provide valuable information about e.g. groundwater flow and thermal pollution that can be used to estimate how representative the measured undisturbed temperature is. Temperature profile measurements can thereafter be performed during the progress of the project to validate that the determined undisturbed temperature is representative for the borehole field. By routinely measuring the undisturbed temperature profiles of all boreholes in a GSHP installation, it is possible to document that the installation is correctly sized.

DISCUSSION & CONCLUSIONS

Temperature profile measurements can be very useful for the planning of a TRT, the analysis of the test result, and finally, the sizing of the GSHP installation. By using temperature profiles actively to select suitable boreholes for TRTs, the risk for tests that are influenced by groundwater flow can be reduced.

As shown in the present paper and as also stated in Heiko et al. 2011, the temperature profiles measured before and after a TRT are an important supplement to the data required for sizing of a GSHP system. For each TRT, the plausibility of the calculated effective thermal conductivity has to be judged based on observations from the drillers log, the geology at the site (as determined on site or mapped by the geological survey), the test data from the TRT and the temperature profiles (preferably from both before and after the test).

Having a temperature profile that indicates conductive heat transfer both before and after the TRT is performed, is a good indicator that the results from the TRT are reliable.

It is shown that the undisturbed temperature can vary between neighboring boreholes. The cause of these variations is uncertain, but can be related to e.g. groundwater flow and borehole deviation. Temperature variations can also be caused by thermal pollution from buildings. The undisturbed temperature from one single borehole might in some cases not be representative for the borehole field.

While being far less detailed than e.g. DTS measurements (Acuna 2013) and in some cases less accurate due to the manual measurements procedure, which is prone to be affected by the operator, the big advantages of the temperature profile measurements are that they are cheap and easy. In many cases and due to minimal financial resources, these simple temperature profile measurements will be the only documentation for the undisturbed and "start-temperature" of the boreholes and the surrounding bedrock.

By routinely measuring the undisturbed temperature profiles of all boreholes in a GSHP installation, it is possible to document that the installation is correctly sized. This also makes the follow up of the GSHP in operation easier.

The strength of the method is the amount of data generated by the measurements. This contributes to a better understanding of the thermal behavior of the ground and the importance of groundwater flow in water bearing fractures in crystalline bedrock.

Further improvements would be to complement the temperature profiles with measurements of the borehole deviation or at least the borehole depth e.g. using a pressure sensor as in Raymond et al. 2016. For more complex GSHP installations with heating and cooling, the DTS measurements are recommended. DTS measurements will give a more detailed understanding of the heat production and behavior along the borehole profile, the influence of groundwater flow included.

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