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Fiber-optic Temperature Profiles Analysis for Closed-loop Geothermal Systems - A Case Study

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SUMMARY

In order to study the behaviour of shallow closed-loop geothermal systems four borehole heat exchangers equipped with fiber optics were installed on the campus of the University of Liege (Liege, Belgium) over a surface area of 32m². This paper presents the analysis of continuous, high-resolution temperature profiles measured along the boreholes length. The undisturbed ground temperature measurements indicate heat loss from ground structures located close to the boreholes. A 3D numerical model is presented to reproduce the measured temperature profiles. Temperature profiles during hardening of the grouting material indicate extended fractured zones in the rock mass. Temperature measurements during the recovery phase of a Distributed Thermal Response Test indicate the succession of rock layers with different mineral content. The results are in good agreement with those of the borehole televiewer logging method. The presented analysis could provide information on bedrock heterogeneity, on the anisotropic thermal behaviour of the rock mass and on the ground temperature variations due to heat loss from ground structures. These information could significantly contribute to the long-term behaviour prediction of the geothermal system and the geothermal reservoir potential.

Introduction

The undisturbed ground temperature field and the bedrock heterogeneity are important parameters for the design and the long-term behaviour of geothermal systems. In order to study the behaviour of shallow closed-loop geothermal systems and the interaction between them four double-U borehole heat exchangers of 100m long were installed on the campus of the University of Liege (Liege, Belgium) over a surface area of 32m². Usually a Thermal Response Test is conducted in-situ to obtain the mean undisturbed ground temperature and the mean thermal conductivity of the surrounding ground (Gehlin 2002). During the test temperature is recorded only at the entrance and the exit of the pipes. In our site fiber optics were attached along the pipe loops in the 4 boreholes, which allow us to obtain continuous, high-resolution temperature profiles along the boreholes.

The objective of this paper is to analyse temperature profiles at different phases (at the undisturbed state, during hardening of the grouting material, during the recovery phase of a Thermal Response Test) in order to obtain information on the undisturbed ground temperature field and on the possible heterogeneity and anisotropic thermal behaviour of the bedrock.

Methods

The four borehole heat exchangers installed in this site are located on the campus of the University of Liege (Liege, Belgium) at a minimum distance of 15m from neighbouring buildings and 6.6m from the university feeder pipe. The site bedrock, which starts at a depth approximately of 8m, is quite fractured and consists mainly of siltstone and shale interbedded with sandstone. The procedure applied in this site is as follows: The boreholes, of a diameter of 135 mm, were drilled by using a DTH hammer bit (destructive drilling technique) and cuttings were collected during the drilling. Then a borehole televiewer (Zemanek et al. 1970) was lowered into the boreholes. This instrument is composed of a transducer which transmits and receives ultrasonic pulses while lowered down inside the borehole. The amplitude and the travel time of the reflected pulses are recorded during the procedure and are presented as high-resolution images of the borehole wall (Radioti et al. 2013). Azimuth and deviation were constantly measured. Natural gamma radiation along the borehole was also measured to characterise the clay content of the rock formation. Based on these measurements and on cuttings observation a detailed bedrock characterisation in space is obtained including fracture characterisation, rock identification and layer dip angle determination.

After drilling the boreholes fiber optic cables were attached along the pipe loops and the double-U pipes were lowered into the boreholes. Fiber optics allow us to obtain continuous high-resolution temperature profiles along the pipe-loops. Temperature is measured along the fiber optics, by applying the Distributed Temperature Sensing technique (Soto et al. 2007). A laser pulse is injected into the optical fiber and the light is scattered and reemitted from the observed point. Based on the reemitted signal characteristics the temperature and the position of the temperature reading is determined. The temperature resolution (standard deviation) is of the order of 0.05°C.

Then the grouting material was injected inside the boreholes. Three different grouting materials were used: a commercial silica sand-based material, a commercial bentonite-based material and a homemade admixture with graphite (Erol and François 2014). Temperature was recorded along the borehole length during hardening of the grouting materials.

Temperature was also measured several days after hardening of the grouting material to obtain the undisturbed (before installing the borehole heat exchangers) ground temperature. Temperature was measured every three months for one year to investigate any possible variation of the undisturbed ground temperature profile through time.

Finally Distributed Thermal Response Tests (Fujii et al. 2006) were conducted in the borehole heat exchangers. The typical Thermal Response Test equipment consists of a pump to circulate to fluid inside the pipes, an electric resistance heater to inject constant heat, temperature sensors at the entrance and the exit of the pipes to measure the temperature and a data logger to record the measurements during the test (Gehlin 2002). During the test water is circulated inside the heat exchanger's pipe loop while constant heat is injected. After the heating period the system is left to recover to its undisturbed state. During the test temperature was recorded at the entrance and the exit of the pipes. Moreover temperature was measured along the pipe loops thanks to the fiber optics.

Undisturbed ground temperature

Temperature was measured every three months for one year with a sampling interval of 20cm and a spatial resolution of 2m. For the first approximately 18m the ground temperature is influenced by the outside temperature (unstable thermal zone). For the next meters until a depth of approximately 100m, the temperature remains constant through time. Due to the geothermal gradient a temperature increase through depth was expected. Though a negative temperature gradient is observed. This could be probably due to the heat loss through the foundations of buildings and the feeder pipe, that are located close to the boreholes.

In order to verify this a 3D numerical model is developed by using the finite element code LAGAMINE (Charlier et al. 2001, Collin et al. 2002). In this model the feeder is simulated with a surface heating element. The heat loss (150W/m length) is calculated based on temperature measurements inside the feeder pipes (Sartor et al. 2014). The heat loss through the foundations of the buildings close to the boreholes is simulated as follows: the temperature at the ground surface covered by the buildings is assumed fixed through time and equal to 16°C. Concerning the boundary conditions at the ground surface the following simplified assumptions are made: At bare ground temperature is fixed through time and is equal to the mean air temperature. Asphalt pavements are considered as isolating layers due to their much lower thermal conductivity compared to the ground (no-heat-flux boundary condition). Figure 1 shows the numerical results compared with the temperature profile measured in 2014. The numerical results are in good agreement with the experimental measurements.

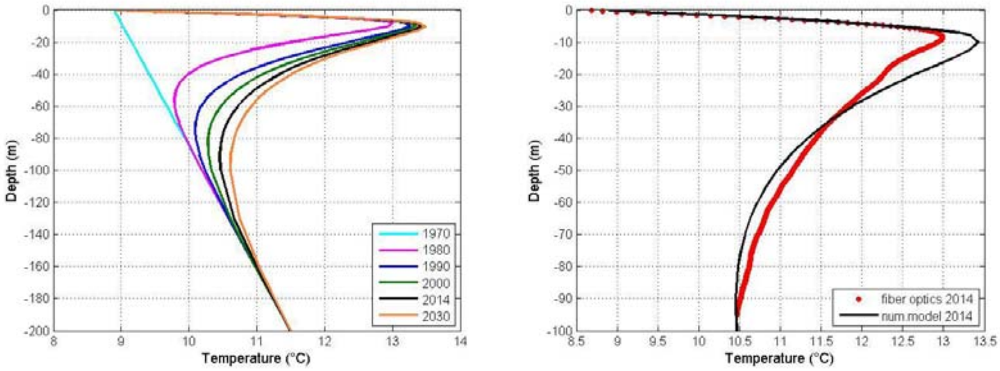

Figure 1 *Ground temperature profiles through time based on the 3D numerical model and measured temperature by fiber optics in 2014.*

Temperature during hardening of the grouting material

Hardening of the grouting material is an exothermic process and the heat generation results in a temperature increase inside the borehole. Figure 2 shows the measured temperature profiles for two boreholes, B1 and B4. The first 18m are not included in the analysis since they are influence by the air temperature. The temperature profiles during hardening of the grouting material for a depth greater than 18m are characterised by local maxima of a significantly increased temperature value at 26m for B1 and 29m for B4. These locations correspond to extended fractured zones more than one meter based on the borehole televiewer analysis (Radioti et al. 2015). These local maxima of the temperature curves are probably due to a local larger quantity of grouting material and/or local lower thermal diffusivity due to gathering of fractures.

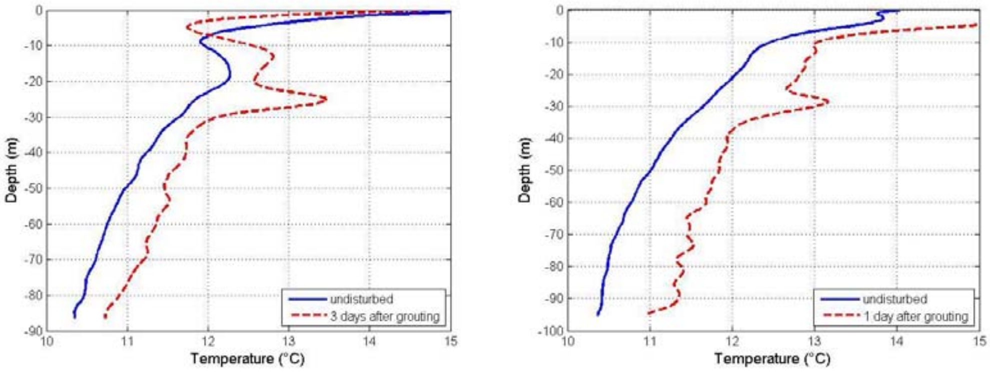

Figure 2 *Local maxima in temperature profile during hardening of the grouting material in B1(left) and B4(right).*

Temperature during the recovery phase of a Distributed Thermal Response Test

Temperature was recorded during the recovery phase of a Distributed Thermal Response Test with a sampling interval of 20cm and a spatial resolution of 2m. Figure 3 presents the temperature difference between the profile after 4h of recovery and the undisturbed temperature profile for B3. Local peaks in this profile indicate an uneven heat transfer through depth. Figure 3 also shows the gamma-ray data (moving average of 2m data) through depth measured by the borehole televiewer. High gamma-ray values indicate shale/siltstone layers while low values indicate sandstone layers. It is observed that temperature local minima correspond to gamma-ray local minima indicating sandstone/siltstone layers while temperature local maxima to gamma-ray local maxima indicating shale/siltstone layers. The higher thermal diffusivity of sandstone/siltstone is evident in the in-situ measurements despite the relatively small thickness of these layers. Moreover comparison of recovery profiles of all the boreholes can result to layer dip angle determination.

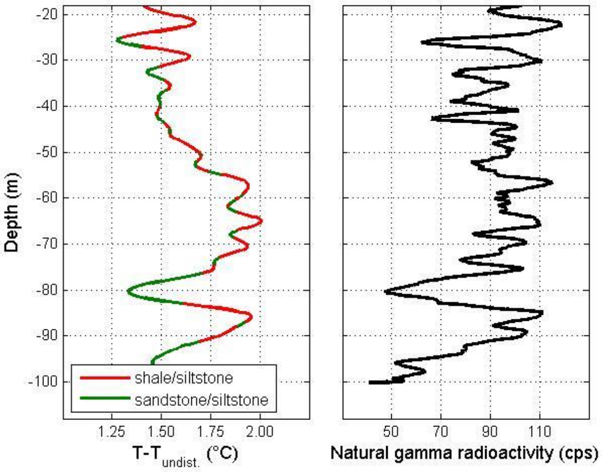

Figure 3 *Temperature difference after 4h of recovery and natural gamma radioactivity data for B3.*

Conclusions

A high-resolution temperature measurements analysis for shallow closed-loop geothermal systems is presented. Temperature profiles during hardening of the grouting material allow us to locate extended fractured zones, more than one meter in this specific case, probably filled with grouting material. The locally filled with grouting material fractures would affect the distribution of permeability, the mechanical strength and the effective thermal conductivity of the rock mass and hence the hydro-thermo-mechanical behaviour of the bedrock. Based on temperature measurements during the recovery phase of a Distributed Thermal Response Test we can detect layers, thicker than 1.2m in this specific case, with different mineral content since they display a different thermal behaviour. Comparison of the boreholes temperature profiles in a limited rock mass could also result in determination of the layer dipping. Moreover a 3D numerical model is presented to simulate the ground temperature due to heat loss from ground structures. The numerical results are verified by the experimental measurements of the undisturbed ground temperature.

The presented analysis could provide information on bedrock heterogeneity and the possible anisotropic thermal behaviour of the rock mass as well as on the temperature field variations due to heat loss from ground structures. These information could significantly contribute to the long-term behaviour prediction of the geothermal system and the geothermal reservoir potential.

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