Undisturbed ground temperature for closed-loop geothermal systems: a case study in a semi-urban environment

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RÉSUMÉ: *La température non perturbée du sol est un paramètre important pour le design des sondes géothermiques verticales en système fermé. Cette étude présente des mesures de température sur quatre sondes géothermiques d'une longueur de 100m, installées sur le campus de l''Université de Liège (Liège, Belgique). Les tuyaux géothermiques ont été équipés de câbles à fibres optiques, qui nous permettent d'obtenir des profils de température continus et haute-résolution avec la profondeur. Les profils mesurés sont caractérisés par une température élevée et un gradient négatif avec la profondeur. Notre hypothèse est que le champ de température mesuré est le résultat du chauffage de sol par les bâtiments existants. Pour investiguer cette hypothèse, un modèle numérique 3D a été développé avec le code aux éléments finis LAGAMINE. Les résultats numériques sont comparés aux profils expérimentaux et l'impact sur le design des systèmes géothermiques est analysé sur base des résultats numériques.*

ABSTRACT. *The undisturbed ground temperature is an important parameter for the design of closed-loop geothermal systems. This study presents temperature measurements in four Borehole Heat Exchangers of 100m long, installed on the campus of the University of Liege (Liege,Belgium). The geothermal pipes were equipped with fiber optics, which allow us to obtain continous, high-resolution temperature profiles along the borehole length. The measured ground temperature profiles, which are in good agreement with those of lowering a temperature sensor inside the pipes, are characterised by elevated temperature and a negative temperature gradient through depth. It is argued that the measured temperature field is the result of the heating of the ground by structures located close to the boreholes. To further investigate this argument, a 3D numerical model was developed by using the finite element code LAGAMINE. A comparison between the in-situ measurements and the numerical results is presented and the impact on the design of closed-loop systems is investigated based on the numerical results.*

MOTS-CLÉS : *température non perturbée du sol, mesure de température par fibres optiques, modélisation numérique, effet de l'urbanisation, sondes géothermiques en système fermé*

KEY WORDS: *undisturbed ground temperature, fiber-optic temperature measurements, numerical modelling, urbanisation effect, closed-loop geothermal systems.*

Introduction

Among the various categories of direct use of geothermal energy, geothermal heat pumps is the most frequent worldwide application with an increasing number over the last years [LUN 11]. Shallow closed-loop geothermal systems are widely used for heating and/or cooling of buildings, since they require little land space for installation, can be applied in many geological contexts and provide lower environmental impact compared to open-loop systems. The undisturbed ground temperature is a critical parameter for the optimisation and the design of vertical closed-loop geothermal systems, also known as Borehole Heat Exchangers (BHEs), since it directly limits the amount of power extracted from the ground [DEC 12]. The ground temperature close to the surface is influenced by the air temperature, while at greater depth temperature is invariant with time and increases slowly with depth due to the geothermal gradient effect. Though, in urban areas elevated ground temperatures have been internationally observed, which are characterised by a zero or negative geothermal gradient extending to depths more than 50 m [BAN 13].

This study presents undisturbed ground temperature measurements in four BHEs, namely B1 to B4, installed on the campus of the University of Liege (Liege, Belgium) over a surface area of 32 m² [RAD 13]. The four BHEs, equipped with double-U geothermal pipes of 100 m long, are located at a distance of approximately 15 m to a building (SEGI) and 6.6 m to an underground structure (feeder pipe) (Figure 1). After drilling the boreholes, a borehole televiewer was lowered inside the four boreholes. A detailed bedrock characterisation was conducted based on acoustic borehole imaging data, gamma-ray logging data and cuttings observation [RAD 16]. The site geology is characterised by deposits of sand and gravel until a depth of approximately 8 m. The bedrock follows which consists mainly of siltstone and shale interbedded with sandstone. Fractured zones are detected in the rock mass mainly until a depth of 35 m. The mean layer dip angle is approximately 45° SE. During the installation of the geothermal pipes, fiber optic cables were attached along the pipe loops. Fiber optics allows us to obtain continous, high-resolution temperature profiles along the pipes length by applying the DTS technique [HER 14]. The temperature resolution (standard deviation) of the DTS instrument used in this study is in the order of 0.05 °C. Temperature was recorded every 20 cm (sampling interval) with a spatial resolution of 2 m. The boreholes were backfilled with the following grouting materials: B1 and B3 with a silica sand-based commercial material (Geosolid, λ=2.35 W/mK), B2 with a bentonite-based commercial material (Füllbinder, λ=0.95 W/mK) and B4 with a homemade admixture with graphite (λ=2.5 W/mK) [ERO 14].

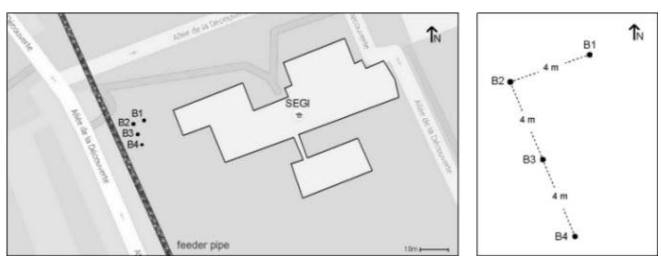

Figure 1. *Site location on the campus of the University of Liege (Liege, Belgium).*

1. In-situ measurements

Figure 2 shows undisturbed temperature profiles measured in the four boreholes in a period of two years. The upper 18 m correspond to the thermally unstable zone, where ground temperature is influenced by weather conditions. Below this depth, measured temperatures appear invariant to time in the two-year period. The temperature decreases through depth at a mean rate of approximately 0.25 °C/10 m and the depth-average temperature of this zone is 11.0 °C. Moreover, the temperature profiles in B2, B3 and B4 coincide with each other, in each case, and display a higher temperature in the first 20 m compared to B1. Temperature profiles were also obtained by lowering down a Resistance Temperature Detector (RTD) probe inside the U-pipe and measuring the temperature at a depth interval of mainly 10 m. The RTD probe measurements can fairly reproduce the corresponding fiber optics profiles.

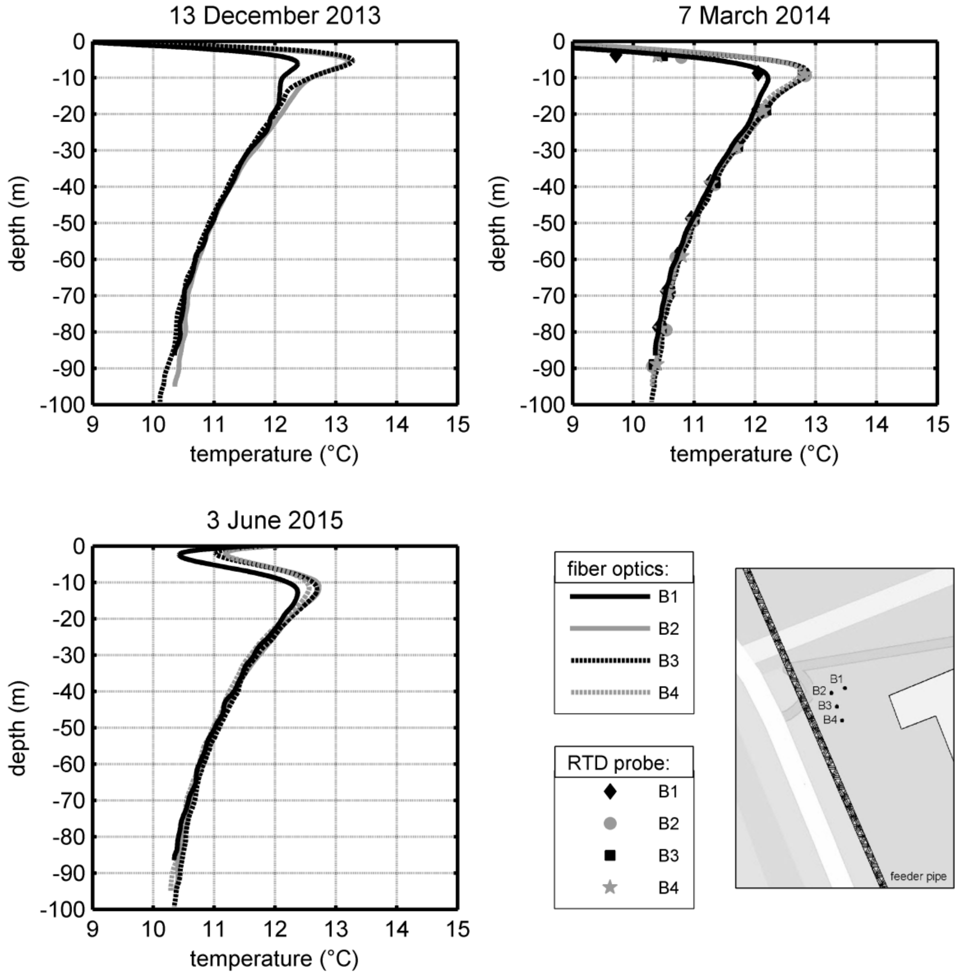

Figure 2. *Undisturbed ground temperature measured by the fiber optics and by lowering a RTD probe inside the U-pipe in the four boreholes.*

Temperature was also measured by a RTD probe in a borehole well, which is located 150 m southeast from the site (Figure 3). The influence of the air temperature (3.26 °C) is evident in the first meters. Below approximately 14 m, temperature oscillates around a value of 10.1 °C, lower than the corresponding temperature in the four boreholes. Moreover, contrary to what is observed in the four boreholes, the temperature is not decreasing through depth. Though, it should be noted that measured temperature in this zone might not be representative of the ground temperature slope, due to convection effects inside the well which is filled with water below 10.6 m.

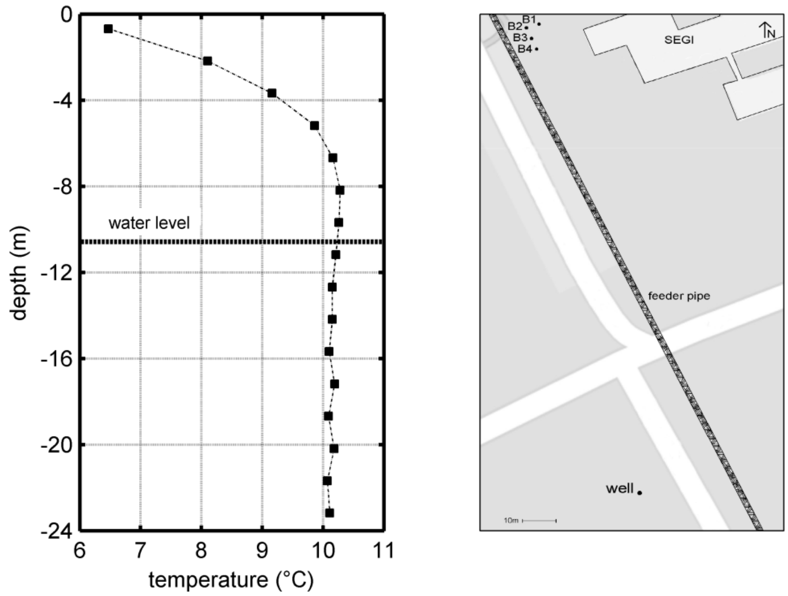

Figure 3. *Undisturbed ground temperature measured by lowering a RTD probe inside the borehole well (24 February 2016).*

2. Numerical modelling

A 3D numerical model was developed, by using the finite element code LAGAMINE [CHA 01, COL 02] to investigate if the measured ground temperature profiles could be a result of the heating of the ground due to structures heat loss into the subsurface. The feeder pipe was simulated with a surface heating element. The heat loss (150 W/m length) was calculated based on temperature measurements inside the feeder pipes for the year 2011 [SAR 14]. The heat loss through the foundations of the SEGI building was simulated by imposing a constant temperature through time (17.7 °C) at the whole building surface, as measured by temperature data loggers at the basement of the building. The ground was simulated with 4-node 3D finite elements until a depth of 220 m, covering a surface area of 0.11 km². The initial ground temperature (before the presence of engineering structures, in 1970) was calculated analytically based on air temperature data and on the ground thermal properties [TIN 12]. The air temperature parameters used in this calculation are based on statistical data for the Sart-Tilman area for a period of 20 years and the mean ground thermal conductivity on Thermal Response Tests conducted in situ in the four boreholes. The influence of the air temperature variations, first 18 m, was not included in the numerical model. The temperature at bare ground surface is influenced by several phenomena such us solar radiation, air convection due to wind and long wave radiation. The temperature under an asphalt pavement is also influenced by several factors including the thermal diffusivity and the thickness of the pavement layer, which usually displays a much lower thermal diffusivity than the ground in this case study. In this model, the simplified assumptions were made that at bare ground the temperature is constant through time, equal to the average annual air temperature, and that the ground surface under the pavement can be simulated by a no-heat-flux boundary condition. These simplified boundary conditions result in an approximation of the ground temperature field. Though, the aim of this modelling is not to explicitly reproduce the experimental measurements, but to investigate if an elevated ground temperature and a negative temperature gradient can be attributed to structures heat loss into the subsurface. Advanced boundary conditions, that take into account wind convection effects, solar radiation effects and the geometry or thermal characteristics of the asphalt layers, could improve the accuracy of the model. An analysis for an investigated period of 60 years (1970-2030) was conducted.

Figure 4 presents numerical results of the ground surrounding the four boreholes. The initial ground temperature (before the existence of structures, in 1970) is dominated by the geothermal gradient effect. According to the numerical results, the heating of the ground, due to the feeder and the SEGI building operation, modifies the temperature gradient at the location of the boreholes until a depth of 100 m after 20 years (1990). The heating effect becomes progressively evident at greater depth, reaching a depth of 130 m after 45 years

(2015). Moreover, the curvature of the temperature profiles is clearly evolving with time, with the increasing amount of heat added to the ground. The depth-average temperature of the ground which is not influenced by the weather conditions (below 18 m) increases at a mean rate of 0.03 °C/year for the first 45 years (1970-2015).

Figure 5 shows temperature measurements and numerical results at the location of the four boreholes. The influence of the air temperature variation is not taken into account in the model, and hence any quantitative comparison with the fiber optic measurements is inconsistent for the upper 18 m. Based on a qualitative comparison among the four boreholes for this zone, B1 displays a lower temperature compared to the other three boreholes. This is also observed in the fiber optics measurements, as presented above in Figure 2. The lower temperature could be attributed to the distance of each borehole from the feeder pipe, which is located at an average depth of 2.5 m. Given that B2, B3 and B4 are 4 m closer to the feeder pipe than B1, the heat loss effect from the feeder pipe will be more enhanced in the location of theese three boreholes. Below 18 m, the temperature profile given by the numerical model is in good agreement with the experimental one. The numerical results satisfactory predict the depth-average temperature in the period 2013-2015 (mean overestimation of 0.11°C). It should be noted that based on the numerical results the ground temperature increases at very low rate of 0.017 °C/year for the two-year measurement period. This low temperature increase is not clearly evident in the fiber optics measurements, given the short measurement period in combination with the accuracy of the fiber optic measurements.

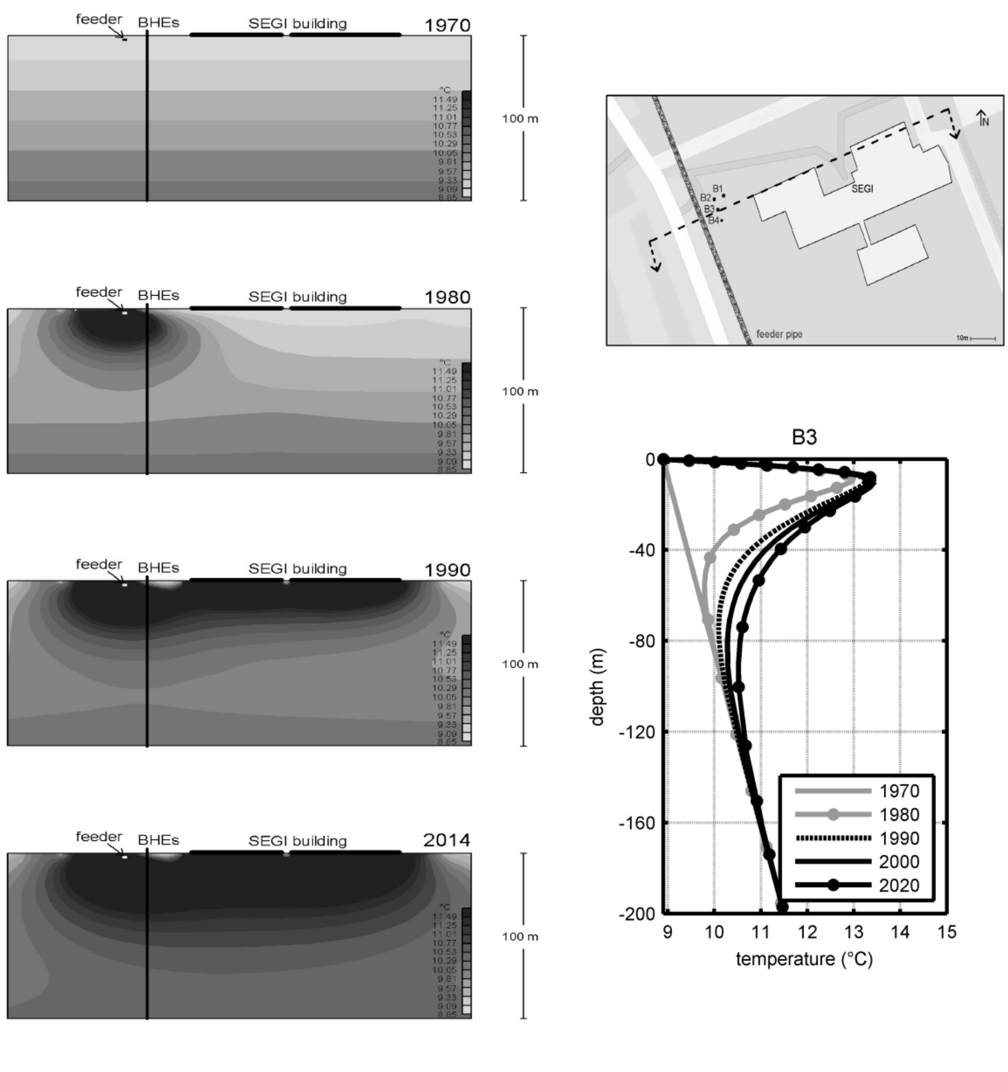

Figure 4. *Ground temperature field evolution based on the numerical results*.

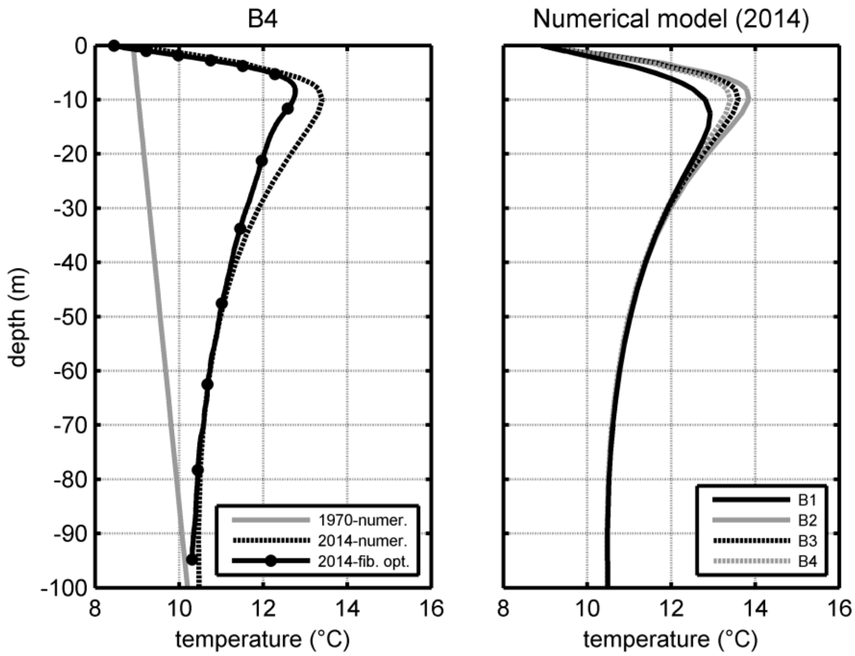

Figure 5. *Experimental and numerical results of the ground temperature at the location of the four boreholes.*

Figure 6 presents the numerical results and the temperature measurements in the well. According to the numerical results, the heat loss through the feeder shell modifies the temperature field at the location of the well, despite its great distance to the feeder (27 m). Below 20 m, temperature is almost invariant with depth and reaches a value of 10.1 °C in 2016. This is in good agreement with the measured temperature in the well for this depth.

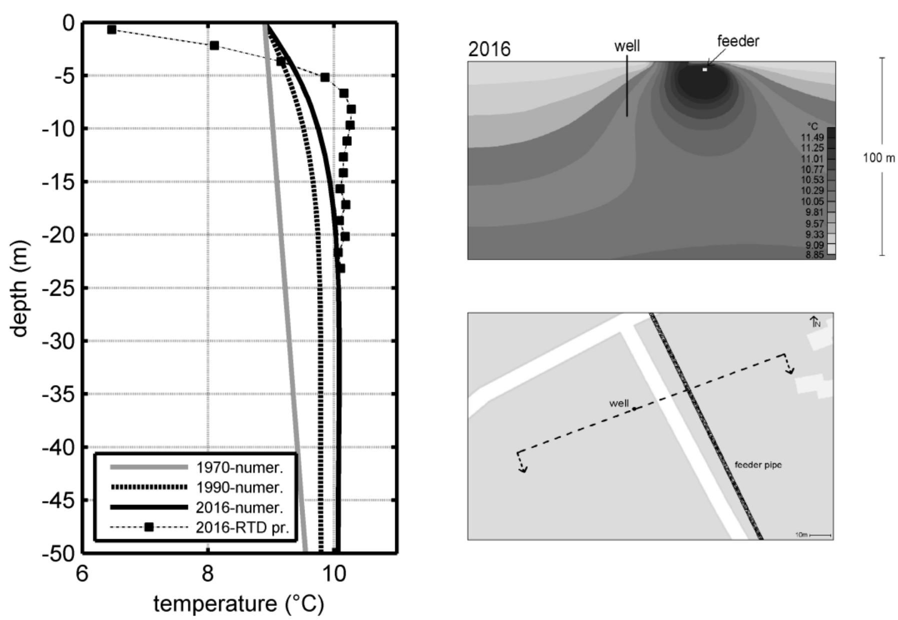

Figure 6. *Experimental and numerical results of the ground temperature at the location of the well*

Given the good agreement between the temperature measurements and the numerical results, the measured temperature profiles can be attributed to the heat loss through the surrounding structures. The undisturbed temperature directly affects the design of BHEs since it controls the maximum power to be extracted per unit length of the BHE. Table 1 shows the depth-average temperature at the location of the boreholes during time and the impact on the design. The maximum extracted power increases of 9% after 10 years of the feeder operation and 17% after 50 years. These results indicate that heat loss through buildings and underground structures can have an important effect on the design of closed-loop systems since they continuously recharge the geothermal reservoir.

Table 1. *Numerical results of the depth-average temperature evolution and impact on the design*.

year	T_{avg} (°C)	Q_{extr} * (W/m)
1970	9.6	45.3
1980	10.5	49.3
1990	10.9	51.0
2000	11.1	52.0
2020	11.4	53.1

* [DEC 12], 1200 FLEQ run hours

3. Conclusions

In this case study, the undisturbed ground temperature profiles are characterised by an elevated temperature and a negative temperature gradient. This could be attributed to the ground heating by structures located close to the boreholes (feeder pipe at a distance of 6.6 m and a building at a distance of 15 m), as indicated by the numerical model analysis. The heat loss into the subsurface has a significant effect on the design of BHEs. After 10 years of the feeder operation, the maximum extracted power at the location of the boreholes increases of 9% and after 50 years of 17%.

In urban areas, the heat loss through buildings foundations and underground structures (feeder pipes, sewage pipes etc.) recharges the geothermal reservoir. This is enhanced by the existence of pavements (roads, parking lots etc.) and the elevated air temperatures observed in these areas. Recharging the geothermal reservoir is a continuous phenomenon which could significantly affect the design and the long-term behaviour of the geothermal systems. Taking this effect into account could contribute to a sustainable geothermal reservoir management in a city scale, as well as to an optimisation of the geothermal systems design. The urbanization effect on the ground temperature could be revealed by temperature monitoring along the borehole length. Apart from fiber optic measurements, the temperature distribution through depth can be fairly obtained by lowering a temperature sensor inside the pipe and measuring the temperature at intervals. This is a cost-effective and easy to implement approach.

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