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A Comparison Between Traditional and Hybrid Optic Fibre Based Ground Thermal Response Tests

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ABSTRACT

The importance of analysing and understanding the entity of the ground thermal conductivity aimed at evaluating the heat exchange capability in ground-source heat-pump (GSHP) applications is crucial. The subsoil represents the limiting factor in borehole heat exchanger (BHE) field design for building conditioning, due to its immutability and the cumbersome expenses associated with the installation drilling phase. Currently, there are several methods for assessing the thermal properties of a geological setting: laboratory analyses on sample corings, thermal response tests (TRTs) and distributed TRTs carried out with fibre optic sensors.

In this regard, a GSHP system of more than 60 BHEs 120m deep has been realized at the new humanistic campus of the University of Padova (Italy). The coring provided a detailed stratigraphic sequence of unconsolidated alluvial deposits. Besides, the monitoring well has been equipped with a hybrid optical fibre cable integrating some electrical wires conductors and a bundle of fibre optics, sealed into the well. The fibre optic cable has been used here in an active mode to perform an Enhanced Thermal Response Test (ETRT) by injecting a constant heating power through the electrical wires contained within the cable structure and by measuring the transient thermal behaviour of the borehole. This kind of TRT has distributed features because exploits the optical fibre sensing technology to provide a spatial distributed representation of the behaviour of the subsoil along the stratigraphic succession.

In the paper, the data acquired from the distributed ETRT have been analysed with two different method (analysis of the measured temperature by applying the first-order approximation of the infinite line-source model and the derivative analysis); the results are compared each other and to the global thermal conductivity provided by the traditional TRT in relation to the local stratigraphic succession.

1. INTRODUCTION

Ground Source Heat Pumps (GSHP) are well-established systems for building conditioning, thanks to their high energy efficiency. The closed-loop ground borehole heat exchanger (BHE) is the most widely used configuration for heating and cooling purposes (Sarbu and Sebarchievici, 2014). The assessment of the local heat exchange capability is crucial for the correct sizing of new borefields because the subsoil represents the limiting factor, due to its immutability and the cumbersome expenses associated with the installation drilling phase. Hence, the local thermal exchange capacity has to be evaluated to finally calculate the required total borehole length. An overestimation or an underestimation of the thermal exchange capacity of the ground could strongly affect the installation and running costs of the ground heat exchanger as well as the energetic efficiency of the whole heating and cooling system over the years.

The ground heat exchange capacity depends on the local geological settings such as the stratigraphy succession and the groundwater/water table condition. Each geological layer contributes depending on its granulometry, mineralogical composition, state of consolidation and saturation.

The Thermal Response Test is currently the most diffuse method for assessing the thermal properties of the ground where a new borehole field has to be installed. During the TRT, water is continuously injected into the borehole and the inlet and outlet temperature are continuously measured; this way, a global value of thermal conductivity for the whole borehole is extrapolated (ASHRAE, 2011). In the first phase of the test, the TRT provides the local ground undisturbed temperature. In the second phase, when the water injected is heated (or cooled), the outputs can be elaborated by applying several analytical methods (Gehlin and Spitler, 2001; Zarrella et al., 2017) and provides a global thermal conductivity value, that takes into account the whole stratigraphy and the in-situ conditions of groundwater, temperature and state of confinement of the ground. In addition, the TRT test involves a wide volume of ground in the probe's surroundings, depending on the geometry of the well and on the thermal behaviour of the materials used in the BHE construction (Banks et al., 2008; Luo et al., 2016).

Conventional TRT performed on closed-loop ground heat exchangers requires the use of a specific TRT unit, cause the system and the TRT testing procedure were established by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Gehlin and Nordell, 2003).

Usually, in the software used for the design of new borefield, the input required are the buildings thermal loads, the undisturbed temperature of the ground and the global thermal conductivity provided by the TRT. The outputs are the borefield total length, that can obviously be composed with different combinations of probes number and length. Conversely, in particular geological settings where different layers have different thermal exchange capacity, for example an aquifer with intense groundwater flow enclosed between aquitards with very low thermal conductivity, the borefield design optimization could be reached only by distinguishing the different contribution of each geological layer. Due to the procedure of measuring the temperature variations of the fluid circulating in the whole borehole, the TRT procedure provides a global value of thermal conductivity for the entire length of the borehole, and it cannot distinguish the contribution of each geological layer.

Recently, a new method for evaluating the ground thermal properties with a higher spatial and temporal resolution, called Distributed Thermal Response Test (DTRT) has been developed (Vieira et al., 2017). This new measurement is carried out by means of a hybrid cable integrating some copper wires and a bundle of fibre optics, sealed into a well. The signal is emitted and received by a proper interrogator from the surface. The fiber optic cable is usually used in passive mode, for the monitoring of the ground temperature variations along the borehole depth induced by the functioning of the borehole field. Alternatively, the fiber optic cable can be used in an active mode to perform an Enhanced Thermal Response Test (ETRT) by injecting a constant heating power through the electrical wires contained within the cable structure and by measuring the transient thermal behaviour of the borehole. This kind of TRT has distributed features because exploits the optical fibre sensing technology to provide a spatial distributed representation of the behaviour of the subsoil along the stratigraphic succession, which is more accurate than the standard TRT.
ETRT and DTRT allow the measurement of the vertical ground temperature distribution along the entire length of the borehole with high spatial and temporal resolution. This way, this technique can distinguish the different thermal behaviour of each geological layer and drive the design optimization of the borehole length.

This paper reports the results obtained in a test site located in Padova, Italy. Here, a DTRT hybrid optical fibre cable has been installed into a borehole down to the depth of 125 m in one of the courts of the new humanistic campus of the University of Padova. The DTRT data has been elaborated by applying the first-order approximation of the infinite line-source model to the measured temperature and, in addition, the derivative analysis recently developed (Pasquier, 2018). The obtained results have been finally compared to the traditional TRT.

2. METHODS

2.1 The test site

The test site is located in the city of Padova, in Northern Italy in the Po Plain, which is the largest alluvial plain in Western Europe (Fig. 1a). The geological setting of the site is typical of lowland areas, consisting in a continuous alternation of unconsolidated sediments. The coring, made on purpose, provides the complete local stratigraphy of unconsolidated fluvial sediments, as described in Chapter 3.

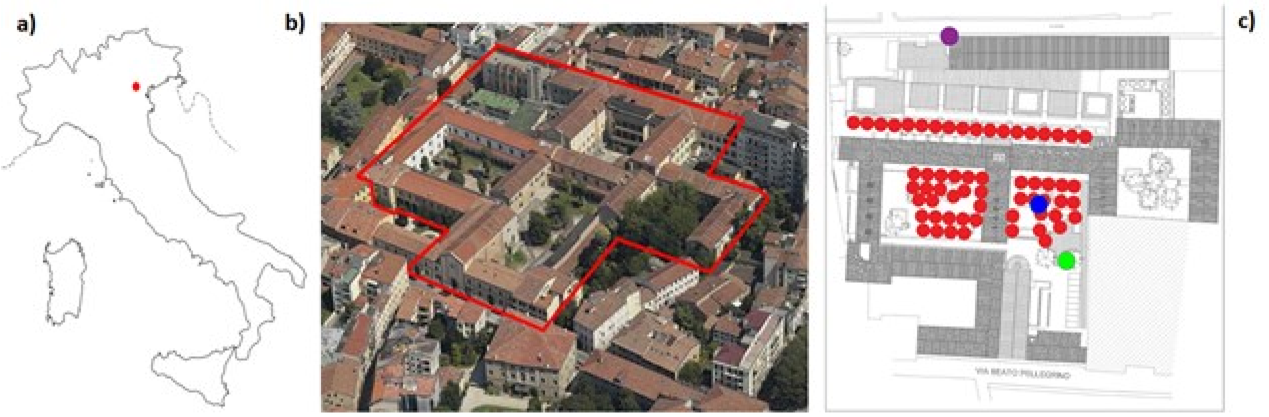

Figure 1: a) The location of the test site in Padua, Italy; b) The overview of the complex of building constituting the test site and c) the borefield layout (in red) with the position of the monitoring wells (in purple, blue and green).

In the site, the University of Padova concluded a conversion of an ancient historical hospital into the new humanistic campus by means of a deep retrofitting intervention (see Figure 1b). The complex is composed by 15 buildings devoted to teaching rooms, offices, 2 auditoriums and a very large library devoted to the collection and conservation of the ancient books of history, philosophy and arts.
The GSHP borefield consists in 60 double-U BHEs of 120m. The system is hybrid, with 2 geothermal heat pumps (168 Kw cooling - 177 kW heating) coupled with 2 air/water heat pumps (470 Kw cooling - 330 Kw heating). The site is one of the demonstration sites of the EU founded project named Geo4Civhic, about the application of the shallow geothermal systems in renovations of historical buildings.

2.2 The Thermal Response Test

First, a traditional Thermal Response Test was performed in a Double U probe 120m long in HDPE De32 PN16, 32 mm external diameter. The diameter of the well was 152 mm and the sealing grout was Fassa Geo 100, with a declared thermal conductivity of 2 W/m K. The test was conducted on 16th September 2016, after about two months from the realization of the borehole. The testing time was of 77 hours, with an injected mean power of 7kW, equal to 58W/m, and a discharge of 1234 l/h. The obtained results show a global thermal conductivity of the ground equal to 1.68 W/mK and a Thermal capacity of 2.6MJ/m^3 K. The undisturbed temperature of the ground was equal to 17.5°C.

2.3 The monitoring system and the DTRT with fiber optic cable

The whole borefield is monitored by means of 3 monitoring wells 125m long, one upstream, one downstream (in terms of groundwater flow) and the other in a central position, corresponding to the coring well (see Figure 1c); each of them is equipped with 2 thermal sensors chains installed every 10 meters along the whole well. In addition, the central well of the monitoring system has been completed with a hybrid fibre optic cable. This is composed of 4 copper wires and one bundle of 5 optical fibres, sealed together into the well with thermally enhanced grout with declared a thermal conductivity of 2 W/mK (Thermocem plus). Fig. 2 reports some pictures of the installation procedure. After the installation, a proper Distributed Temperature Sensing interrogator has to be connected to the cables in order to perform the test.

The DTRT has been performed by heating the ground by means of the current injected into the copper wires (i.e. Joule effect), while the vertical ground temperature distribution has been measured by the optical fibres. The use of the optic fibre cable allows the acquisition of temperature profile along the entire length of the borehole, due to the signal emitted into the fibre and backscatterd through the acquisition system being sensitive to temperature, thus exploiting the Raman scattering occurring in optical fibres (Schenato, 2017). The working principle is quite simple; when an optical pulse is injected into a fibre, three signals are generated (I) the Rayleigh backscattered signal at the same wavelength of the input light, (II) the Stokes component at a longer wavelength, and (III) the anti-Stokes component at a shorter wavelength. In particular, only the anti-Stokes signal intensity is temperature-dependent (approximately 0.8%/K at room temperature), while the Stokes is not. The ratio between the two intensities is, therefore, a measurement of the temperature at which the backscattered signals have been generated.

The use of Distributed Temperature Sensing (DTS) in thermal response testing allows measurements of high spatial (0.2-5m), temporal (1-10 min) and temperature (0.1-0.5K) resolution (Selker et al., 2006; Vieira et al., 2017). In this work, to perform the DTRT we used a commercial DTS interrogator by AP Sensing with sampling interval of 0.5 m, spatial resolution of 1m and a temperature repeatability of few tenths of a Kelvin degree.

The DTS has been firstly used without heating in order to collect the undisturbed temperature of the soil, which was 17.50°C. Then, the thermal solicitation of the well and the surrounding ground has been provided by injecting into the copper wires an almost constant heating power of 3707.7 W for about 4 days (from 5th March to 8th March 2018). After the heating phase, the fibre optic cable continued measuring the ground recovery phase for 5 days. The heating power is assumed to be constant along the cable for its entire length (equal to 248 m).

Figure 2: a) One phase of the installation procedure, with the hybrid fibre optic cable clamped to a rigid shaft and to the thermal sensor chains before the installation; b) the Distributed Temperature Sensing interrogator during the test.

During the DTRT, the temperature along the fibre optic cable has been recorded every two minutes during the heating period and the subsequent 5 days, to measure the recovery thermal phase of the ground. At the end of the heating test, the profile temperature was almost constant for the entire profile (around 37°C). During the subsequent recovery phase, the temperature measured at different depths corresponding to different geological layers cooled down at different rates, depending on the thermal properties of the surrounding deposits.

2.3 The analytical method

Given that the hybrid fiber optic cable was deployed in the well in a looped configuration (duplexed), both the heating than the measuring systems consist in two parallel lines. First of all, the raw temperature data, staked in time to form a 2D-dataset, have been numerically filtered to reduce the noise using 2D-wavelet transform. This approach benefits the effectiveness of 2D image processing and it allows for improved signal-to-noise ratio in both dimensions, i.e., time and space, simultaneously. A more rigorous approach would consist in using the algorithm directly to the Stokes and Anti-Stokes signals intensity (Soto et al., 2016) but here it was not applicable as they were not available. The same procedure has been already applied and described in Galgaro et al., 2018.

To analyse TRTs performed on closed-loop ground heat exchangers, the first-order approximation of the Infinite Line-Source model (Ingersoll et al, 1954) is usually used. The interpretation method consists to perform a linear regression on the mean late temperatures of the heat carrier fluid. The coefficients of the regression being related to the heating power and to the thermal conductivity of the surrounding ground, the method provides the ground thermal conductivity around the ground heat exchanger (Gehlin and Spitler, 2001). Recent works also suggested using temperature derivative methods to interpret TRTs (Pasquier, 2018).

In this work, the two same interpretation strategies are used to analyse the high spatial resolution temperatures acquired during the DTRT. Both approaches consist to fit a linear regression model to the signals of temperature and derivative measured at each depth along the cable. Hence, two values for the thermal conductivity of the surrounding ground are obtained for a given depth. The hybrid cable being a U-loop, each soil layer is heated by two wires that interact with each other. Such interaction is easily taken into account by the superposition principle. The analysis of the DTRT then been achieved by the following two methods:

Temperature Analysis

Using the spatial superposition principle and the first-order approximation of the infinite line-source model, the temperature around two heat sources emitting a constant power q (W/m) according to the depth is given by:

$$T(z,t) = T_0(z) + qR_w + \sum_{i=1}^{n} \frac{q}{4\pi\lambda(z)} \left(\ln\left(\frac{4\alpha t}{r_i^2} \right) - \gamma \right) \tag{1}$$

where $T_0(z)$ is the initial temperature (K) at a depth z (m), R_w is the thermal resistance of the ground heat exchanger (mK/W), $\lambda(z)$ is the thermal conductivity (W/mK) measured at a depth z (m), α is the thermal diffusivity (m^2/s), t is the time (s), r_i is the distance (m) between source i and an evaluation point and finally γ is the Euler number equal to 0.5772.

Reorganizing equation (1) highlights a linear relationship between the temperature (T), the natural logarithm of time ($ln\ t$) and the thermal conductivity λ. After a few simple manipulations, equation (1) is reorganized to:

$$T(z) = T_0(z) + qR_w + \frac{2q}{4\pi\lambda(z)} \ln(t) + \frac{q}{4\pi\lambda(z)} \sum_{i=1}^{n} \left(\ln\left(\frac{4\alpha}{r_i^2} \right) - \gamma \right) \tag{2}$$

From equation (2), the thermal conductivity at a depth z when two interacting heat sources are present is given by:

$$\lambda(z) = \frac{q}{2\pi m(z)} \tag{3}$$

In equation (3), $m(z)$ is the regression coefficient obtained when using the logarithm of time as the regressor and the mean temperature measured by the optical fibres of the DTRT as the dependent variable.

Derivative Analysis

The analysis of the temperature derivative is based on a constrained first-order approximation of the derivative proposed recently (Pasquier, 2018). The idea consists to take the derivative, with respect to time, of the temperature provided by the infinite line source model. The logarithm of the temperature derivative $\ln(\dot{T})$ being linked to $\ln(t)$ through a negative unit slope, use of a constraint on the slope helps obtaining accurate estimations of the thermal conductivity by the linear regression. Using the experimental temperature derivatives $\dot{T}$ for times $t \geq 5\alpha/r_i^2$, the coefficient of the constrained regression is obtained by:

$$\widetilde{b} = E[\dot{b}] = \frac{1}{n_t} \sum_{k=1}^{n_t} \left(ln(\dot{T}\ (t_k)) + ln(t_k) \right)$$

Finally, assuming a constant heating power q with respect to time and depth, a second estimation of the thermal conductivity is obtained by

$$\lambda(z) = \frac{q}{4\pi e^{\widetilde{b}}} \tag{5}$$

3. RESULTS

Equations 2 and 4 were used and applied to interpret the 200 temperature signals (one every 0.5 m) acquired during the DTRT. Prior the analysis, a Nuttall low pass filter was applied to the raw temperature signal to remove the high frequency content of the signals and thus ease their analysis. The analysis focused on the evaluation of the initial undisturbed temperature profile, and on the data provided during the heating phase.

First of all, the DTRT provides an interesting vertical profile of the undisturbed temperature along the whole depth, reported in Figure 3. From 0 to 12m, the seasonal variation is clearly visible. From 12 to 70m there is a zone of low gradient, followed by a zone where the geothermal gradient increases significantly. The segmentation of the signal acquired by means of the fiber optic cable allows the identification of different temperature status at different depths, thus highlighting, in this case, that longer boreholes can get higher yields of heat extraction given the higher geothermal gradient in the deeper strata.

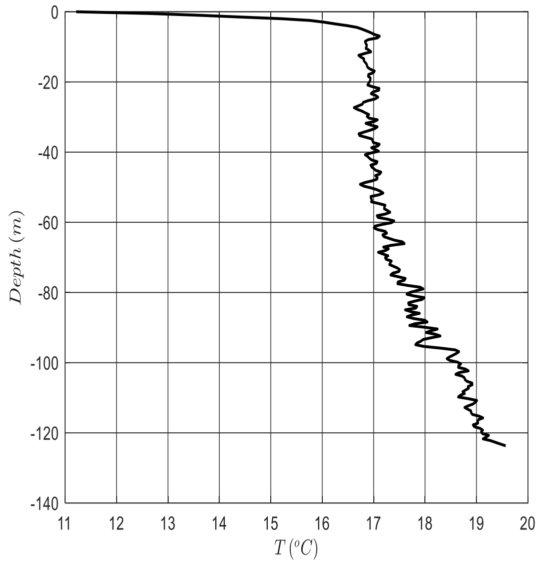

Figure 3: Vertical temperature profile measured in the first part of the DTRT test performed in March 2018 in Padova, Italy.

The heating phase has than being analysed both by applying the first-order approximation of the infinite line-source model and the derivative analysis. The resulting 200 signals of temperature and derivative are illustrated in Figure 4. Note the clear linear relationship in the semilog and loglog plots during the heating phase. For each sensitive segment of the fiber optic cable, corresponding to a segment of 0.5m depth, the temperature data recorded during the heating phase and the derivative can be directly compared, as show in Figure 5.

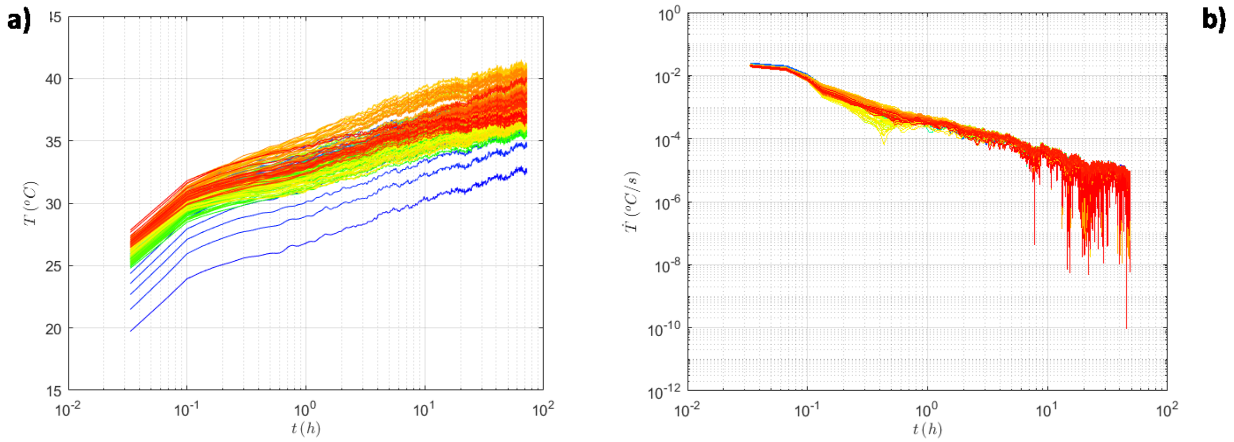

Figure 4: Temperature (a) and derivative (b) measured during a DTRT performed in March 2018 in Padova, Italy. The redder the line and the deeper the measurement. Conversely, the bluer the line and the shallower the measurement.

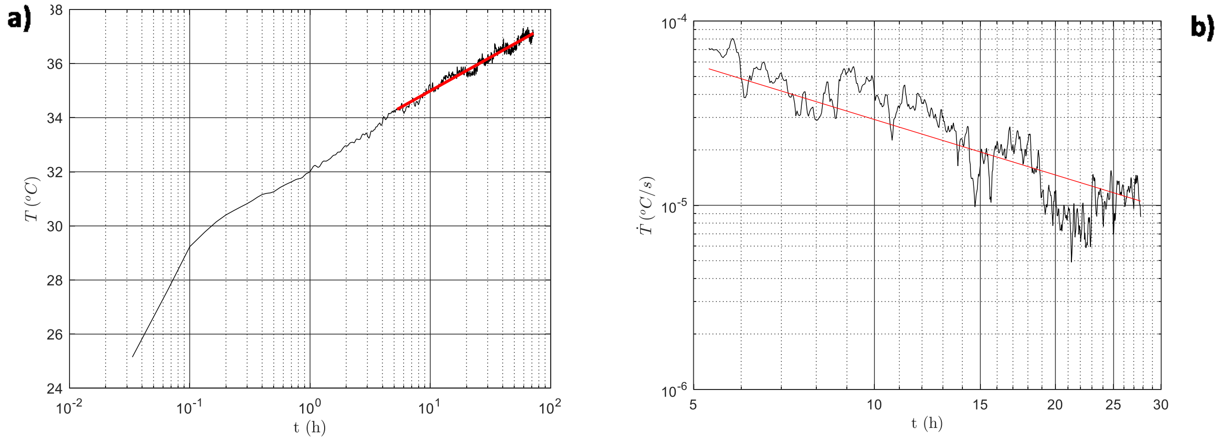

Figure 5: Example of the temperature (a) and derivative (b) measured at a depth of 49.17 m (in black) and regression model fitted to the experimental measurements (in red).

Hence, for each segment of 0.5m the thermal conductivity value can be calculated by applying the temperature analysis as well as the derivative analysis. The comparison of the obtained values is represented in Figure 6a over the entire vertical profile. In the picture, also the schematic stratigraphic sequence is represented (see Fig.6b). The stratigraphic sequence has been derived directly from a 130m deep well coring made on purpose in the test site; the cored materials have been collected in specific catalogue boxes. The lithological sequence can be described as a dominantly horizontally layered structure, typical of a quaternary floodplain deposition environment, dominated by sandy deposits alternated with silty and thin clay layers. The main aquifer has been identified from 119m down to 130m; the aquifer is constituted by coarse gravel in a sandy matrix and presents a no negligible water flow due to the high permeability of the materials despite the very low hydraulic gradient. Moreover, another sandy aquifer has been detected between 62 and 72 m depth. The other layers present low permeability. During the coring, the water table was 1.5m below the ground level.

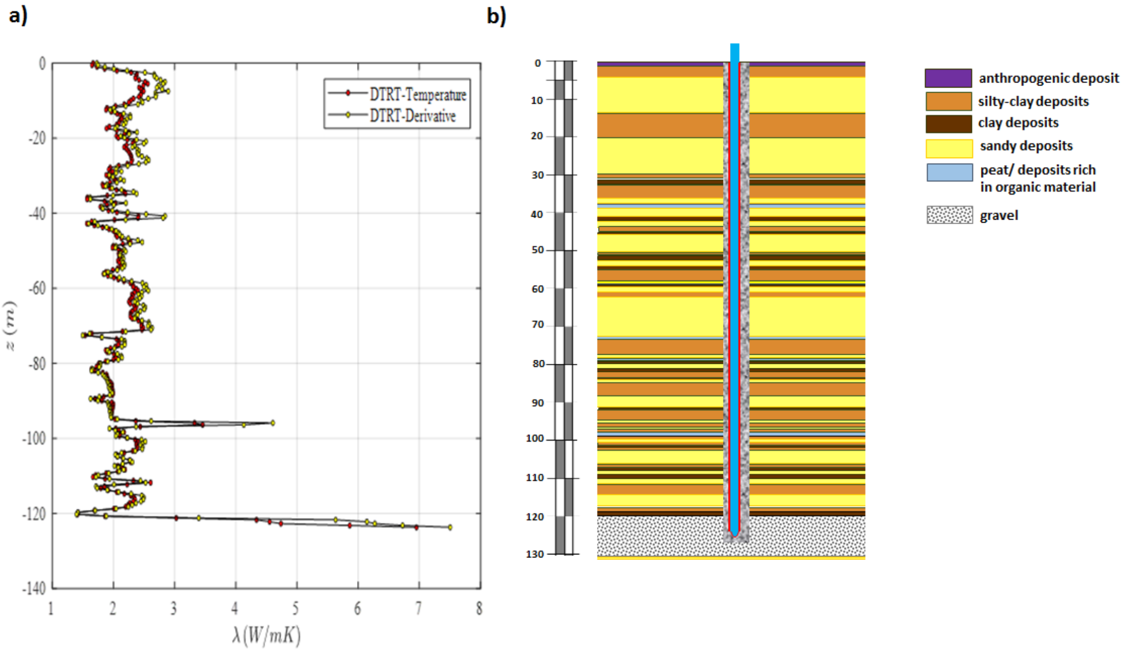

Figure 6: a) Vertical variation of the thermal conductivity obtained by the interpretation of the DTRT both with the temperature and the derivative analysis. The profile is directly compared with b) the schematic local stratigraphic sequence provided by the coring.

The direct comparison shows a very strong accordance between the thermal conductivity values obtained by applying the two interpreting methods. In addition, there is a clear visual correlation between the thermal conductivity values and the geology. It is important to take in mind that the spatial resolution of the DTS interrogator (1 m), is twice the distance among sensing points (0.5m). Hence, the DTRT performs a vertical spatial average of the signal and the thermal conductivity value inferred for each measurement point is correspondingly averaged over 1m fiber optic cable.

For this reason, the good correlation is more evident for the deposits of significant thickness: the values corresponding to the sandy layers, represented in yellow, are higher than that corresponding to silty and clayey deposits. The presence of organic material and peat lowers down the corresponding values. Finally, the DTRT correctly identify a very high heat exchange capability in correspondence to the gravel deposit (starting from the depth of 120m), supplied by the presence of groundwater flow within this coarser deposit characterized by high permeability. Only at the depth of around 98 m, a high value of thermal conductivity is detected, without appearing correlated to the geological sequence. It is possible that this value is affected by a local water infiltration or by an incorrect local sealing of the well or, finally, by a local alteration of the fiber optic cable functioning.

In Table 1, the global values of thermal conductivity evaluated by applying the two interpreting methods are compared with the one obtained from the traditional TRT. It has to be noted that the well where the TRT has been carried out is 120 m long, hence the effective borehole is probably about 1 m shorter due to the presence of the ballast. The difference between the values acquired by means of the DTRT performed in a 125m monitoring well and the traditional TRT performed in a 119m borehole, highlights the significant contribution to the global heat exchange supplied by the aquifer at 120m.

Table 1: Mean thermal conductivity obtained.

Method	Thermal conductivity λ (W/mK)	Monitored length (m)
TRT	1.68	119
DTRT - Temperature	2.17	124
DTRT - Derivative	2.28	124

CONCLUSION

The results obtained highlight that the two interpreting methods applied, the first-order approximation of the Infinite Line-Source model and the recently proposed temperature derivative methods, provide very similar values. Secondly, the obtained results demonstrate the potentiality of the DTRT to estimate, in addition to the global value of the thermal conductivity, also its variability along the vertical profile.

Despite the DTRT performs a vertical spatial average of the signal (1m), the thermal conductivity profile is clearly correlated to stratigraphy succession, especially for the deposits of major thickness. The thermal conductivity vertical profile clearly identify higher values for sandy deposits and lower values for the cohesive ones, whilst outstanding values are detected in correspondence to the gravel deposit (from the depth of 120m), thanks to the convective contribution to the heat transfer provided by groundwater flow. In this case, the difference between the thermal conductivity global value provided by the traditional TRT and the ones provided by the DTRT can be ascribe to the different length of the tested stratigraphy: the aquifer present at the depth of 120m provides a very significant contribution to the heat exchange between the ground and the borehole.

This result highlights the importance of distinguishing the different thermal behaviour of the different geological strata.

Further development of the analysis method, currently on-going, will allow the interpretation of the recovery phase and deeper evaluation of the relationship between the stratigraphic units and the thermal conductivity measured by the DTRT.

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