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Ground temperature profile while thermal response testing

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ABSTRACT

In the context of a project funded by the Spanish Ministry of Science and Innovation, a reference borehole heat exchanger installation was constructed in the Universitat Politècnica de València campus. Its purpose was to improve the procedures to characterize thermal properties of Mediterranean area grounds. Borehole depth is 40 meters, with two independent U-pipes inside, first one 29 meter depth and second one 39 meter depth. First thermal response test executed in this installation was started on December-15-2010 at 11:00am and inserts 2449 W of thermal power to the shorter U-pipe. Test duration was seven days, finishing on December-22-2010 at 10:30am. Second U-pipe was used to measure ground temperature profile while the test was performed, by inserting a temperature sensor in this pipe several times, measuring ground temperature every meter. This contribution presents these experimental measurements. First temperature profile was measured one day before the test was started and second one when thermal power was switched on. Then, temperature profiles were acquired one day, two days, five days and seven days after, when thermal power was switched off. Main conclusion of this contribution is the clear identification of layers with quite different thermal behaviour, indicating the presence of ground water flows at several depths (10, 18 and 25 meters). This contribution also analyses thermal response test data to estimate effective ground thermal conductivity and borehole thermal resistance, and presents measurements of the temperature profile after the test was finished, showing the time that the ground needs to recover from this injection test.

1. INTRODUCTION

The characterization of ground thermal properties using in situ Thermal Response Tests is a common procedure for designing HVAC systems based on ground coupled heat pumps. The purpose of this test is the measurement at site of the three critical parameters for system design: ground thermal conductivity, borehole thermal resistance and undisturbed ground temperature (Austin, 1998; Eklöf, F. & Gehlin, S. 1996). Thermal Response Test is particularly necessary in large size installations, where an inappropriate design of the borehole heat exchanger will mean a poor performance of the system in the case of being undersized, or an unjustified cost overrun in the case of being oversized.

Thermal Response Test is based on the study of the thermal response of the borehole heat exchanger (BHE) to an injection or extraction of constant thermal power. Most relevant variables measured in a thermal response test are the temperature of the heat carrier fluid at the input and output of the heat exchanger, taken throughout the execution of the test. With these experimental data, and a model that adequately describe the heat transfer problem between the fluid and the ground, thermal properties of the ground can be estimated. Kelvin infinite line source (ILS) model of heat transfer by thermal conduction is the most widely used for evaluation of the data acquired in a Thermal Response Test for reasons of simplicity and speed (Hellström, 1991; Witte et al, 2002).

The shallow geothermal energy research group of the Valencia Polytechnic University has spent several years studying procedures to improve the estimation of ground thermal properties, necessary for the design of ground coupled heat pump systems. A possible approach is to refine the model describing underground heat exchange to include effects not taken into account. Finite size effects can be incorporated to the analysis procedure as shown in Bandos, 2009. A filtering technique of the effects produced by ambient temperature fluctuations in measurements of the temperature of the fluid at the inlet and outlet of the exchanger was presented in Bandos, 2011a. Finally, the impact of ground anisotropy in the measurement of effective thermal conductivity of the ground using thermal response test technique was analyzed in Bandos, 2011b.

Other approach to improve in situ estimation of ground thermal properties is the development of new devices able of measuring quantities relevant to the proper characterization of the heat transfer between the fluid and the ground. This characterization can be made if the evolution of the fluid temperature along the heat exchanger is known. A measuring device encapsulated in a sphere of diameter 25 mm, which includes a temperature sensor, data acquisition, temporary storage and wireless communication system was developed to obtain this characterization (Martos, 2011).

To contrast all the work developed by our research group in the improvement of procedures for in situ measurement of ground thermal properties, the construction of an experimental facility was included in the request for a project of the National Research Investment Plan. This facility will allow assessing the validity of the developed models, as well as to improve the characterization of thermal properties of the ground in Mediterranean areas, affected by the abundant presence of groundwater flows. This facility was constructed during 2010 year at the Polytechnic University of Valencia, and was funded by the project of the National Research Energy Plan ENE2008-00599.

This contribution presents the analysis of the data obtained in the first thermal response test performed at the facility. Also, shows the evolution of the ground temperature profile throughout the execution of the test as well as after its completion, showing clearly a different behavior of each layer of the ground, indicating the presence of ground water flows at different depths.

2. THE BOREHOLE HEAT EXCHANGER FACILITY

The BHE facility is composed of two independents U-pipes inserted in a 40 meters borehole and filled with a mixture of one part of bentonite and twelve parts of cement (CEMEX 32.5 raff). First U-pipe depth is 29 meters and second U-pipe depth is 39 meters. The whole borehole is protected with a metallic cylinder, inserted while drilling.

A picture of this borehole facility is shown in Figure 1, with the data acquisition system at the end and a permanent thermal injection system coupled to the borehole.

Diagram in Figure 2 shows the vertical layout of the borehole, indicating the different strata of the ground, with two layers of clay (from 0 to 4 meters, and another from 26 to 27 meters), a layer of peat (from 4 to 12 meters), two layers of gravel (from 12 to 26 meters and from 36 to 40 meters) and one layer of sand (from 27 to 36 meters).

The diagram in Figure 3 shows the cross-sectional structure of the exchanger.



Figure 1: Picture of the facility after finishing construction.

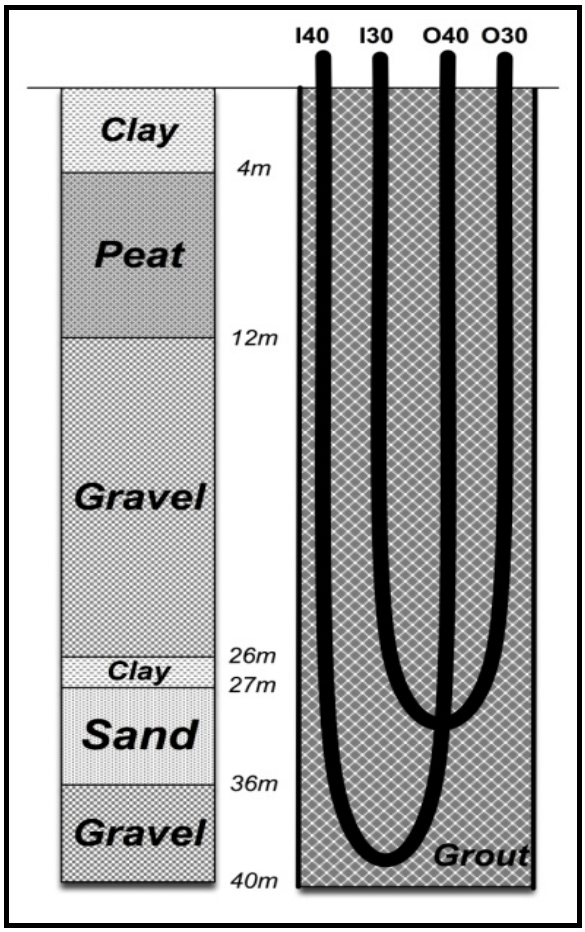

Figure 2: Diagram showing the vertical layout of the borehole, indicating the different strata of the ground.

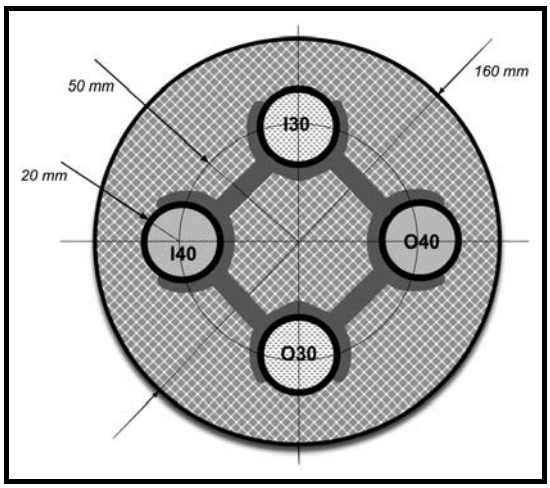

Figure 3: Diagram showing the horizontal structure layout of the borehole.

3. THERMAL RESPONSE TEST

The experimental facility incorporates a permanent system able to inject thermal power to the ground, composed by a 3 kW electric heater and a circulation pump, dissipating heat into the fluid running through the borehole heat exchanger. With this injection equipment a thermal response test was executed, beginning on December 15, 2010 at 11:00 am, and injecting a thermal power average W(injection)=2449±67 W to the shorter U-pipe. The duration of the test was seven days, ending on December 22, 2010 at 10:30 am.

Thermal power injected to the ground, *W(injection)*, was calculated with expression:

$$W(injection) = m_{water} c_{water} \left(t_{in} - t_{out}\right) \quad (1)$$

Where m_{water} is the water mass flow, c_{water} the water heat capacity, t_{in} the inlet water temperature to the BHE and t_{out} the outlet water temperature from the BHE. Water mass flow was measured with Contazara CZ3000 equipment. Water temperatures were measured with PT100 sensors, each sensor previously calibrated by means of a thermal bath FRIGITERM 600038 from PSELECTA®. Water mass flow was kept constant along test execution to a value m_{water}=525±3 l/h. Figure 4 shows the values of thermal power injected to the ground measured every three minutes.

Second U-pipe was used to measure ground temperature profile during and after the test, inserting a calibrated temperature sensor in the pipeline, and measuring the temperature of the ground every meter. In addition, this procedure was used to measure the undisturbed ground temperature. This measurement was done two times, first one the day before the starting of the response test and second one just before switching on the electric heater. In figure 6 these two measurements are shown with labels "*profile 14-DEC; 11:00"*, and "*profile 15-DEC; 11:00"*. Both curves are almost identical, showing that ground temperature profile is in a stationary state. From 7 to 40 m. ground temperatures are quite constant, estimating the undisturbed ground temperature on a value between 20.0 ºC and 20.2 ºC (T_0=20.1±0.1 □C)

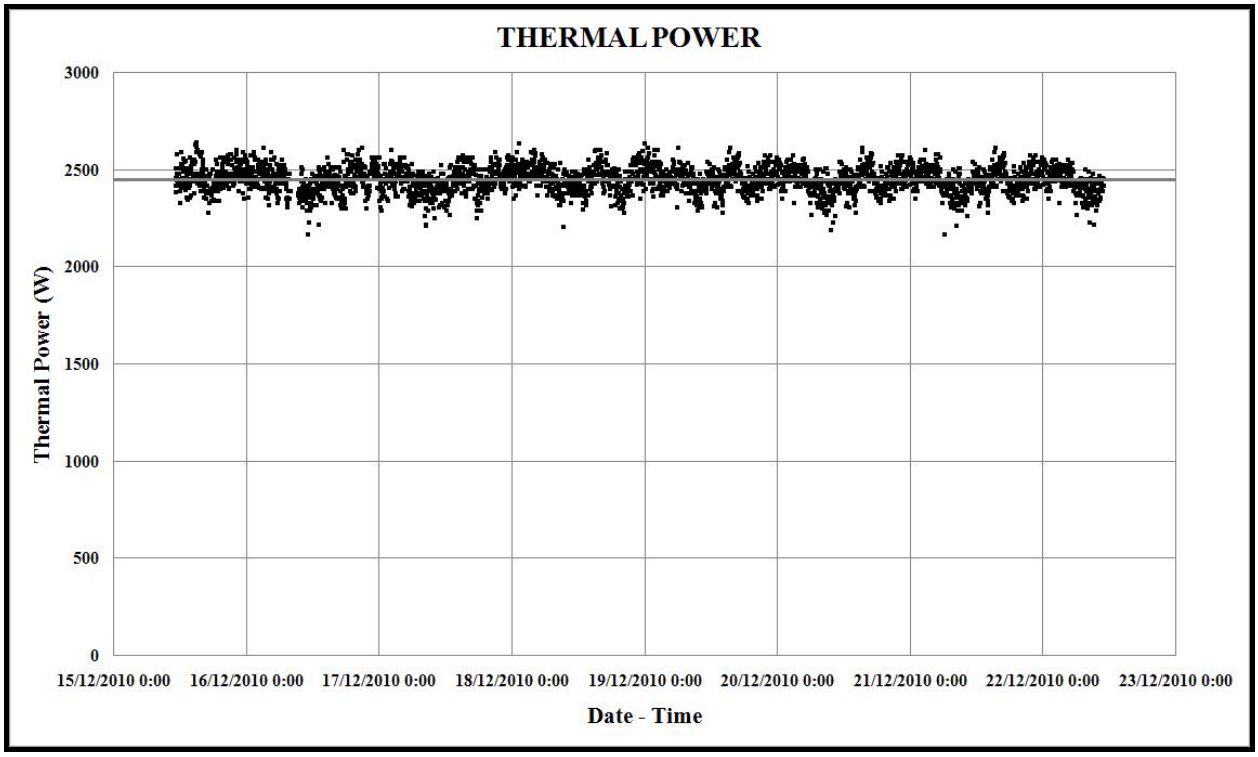

Figure 4: Thermal power injected to the ground is shown as a function of time. Average power injected during the test is 2449 W, represented by the grey horizontal line.

From the measurements of inlet and outlet temperature, taken every three minutes, the average fluid temperature is calculated:

$$T_{ave} = \frac{T_{in} + T_{out}}{2} \tag{2}$$

Standard analysis of thermal response test data compares the average fluid temperature with infinite linear source model prediction, given by expression:

$$T_{ave} = T_0 + R_b Q_Z + \frac{Q_z}{4\pi\lambda}\left(Ln\left(\frac{t}{t_0}\right) - \gamma\right) \tag{3}$$

Where T_{ave} is the average fluid temperature, average of the temperatures at the inlet and outlet of the heat exchanger, T_0 is the undisturbed ground temperature, R_b is the thermal resistance of the underground heat exchange, Q_z it is the thermal average power per unit length transferred to the ground and λ is the effective conductivity of the ground. The number γ is the Euler constant and t_0 is a time constant equal to $r_b^2/4\alpha$, where r_b the radius of the exchanger (80 mm) and α the ground diffusivity.

Rewriting equation (3) as:

$$\begin{aligned} T_{ave} &= T_0 + R_b Q_Z + \frac{Q_z}{4\pi\lambda}\left(Ln\left(\frac{t}{t_0}\right) - \gamma\right) = a + bx \\ a &= T_0 + R_b Q_Z \\ b &= \frac{1}{4\pi\lambda} \\ x &= Q_z\left(Ln\left(\frac{t}{t_0}\right) - \gamma\right) \end{aligned} \tag{4}$$

Is clear that average fluid temperature, T_{ave}, must follow a linear behaviour when plotted against x variable, being the slope of this line inversely proportional to the ground thermal conductivity. Figure 5 shows the plot of T_{ave} against x.This figure shows how the data obtained from this test deviate from the prediction of the infinite line model, showing a gradient that decreases with x variable, which means that ground thermal conductivity increases as test execution advances. A linear fitting using data belonging to first test hours gives an estimate of conductivity λ = 1.9 W/Km, while the same linear fitting using data belonging to the final test hours increases this estimate up to λ = 2.8 W/Km. This value also affects to the estimation of borehole thermal resistance, R_b, as the slope b decreases, the intercept a increases, driving to a estimation of R_b increasing with test duration.

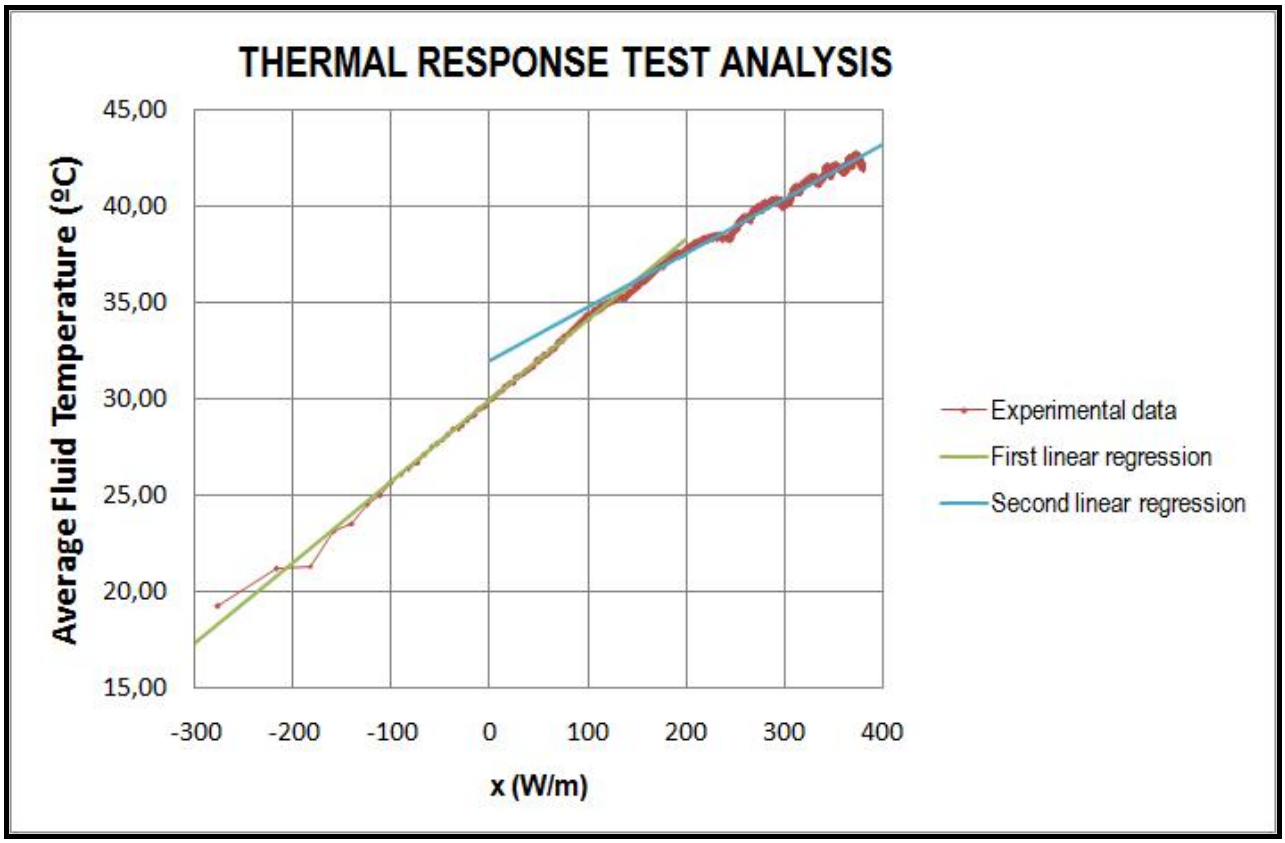

Figure 5: The average fluid temperature is shown as a function of the variable $x = Q_z (\ln(t/t_0)-\gamma)$. Two linear fits are included, one associated with the points of the initial segment, and another associated with the points of the final section.

The observed behaviour is typical of areas affected by the presence of ground water flows: increase of the ground thermal conductivity with the advance of the test caused by the greater heat absorption capacity of the layers affected by presence of groundwater. A measure of the evolution of the ground temperature profile along the test would show layers in which the heat absorption is much higher.

4. EVOLUTION OF THE GROUND TEMPERATURE PROFILE

The measure of the ground temperature profile was carried out by introducing a temperature probe on the U-pipe not used during the test, measuring the temperature every meter up to the BHE depth (40 meters). Figure 6 presents the evolution of the temperature profile during the execution of the Thermal Response Test, showing three zones with higher heat absorption capacity, first one around 10 meters deep, second one around 19 meters and third one around 25 meters. This behaviour can be seen more clearly in the monitoring of the ground to the original situation, shown in Figure 7. Same areas show a faster recovery, clearly indicating the presence of a phenomenon that increases heat dissipation capacity of the ground, attributable to the presence of groundwater. It is also remarkable the time needed by the ground to recovery its initial state, as can be seen in figure 7, 19 days after the test ground temperature profile still shows significant differences with the undisturbed ground temperature profiles of around 2ºC.

5. CONCLUSIONS

Main conclusion of this study is the clear identification of several layers with quite different thermal behaviour and the importance of monitoring the evolution of the ground temperature profile before, during and after a Thermal Response Test, because it generates relevant information about the ground structure and ground thermal response to be considered in the HVAC system design based on geothermal heat pumps.

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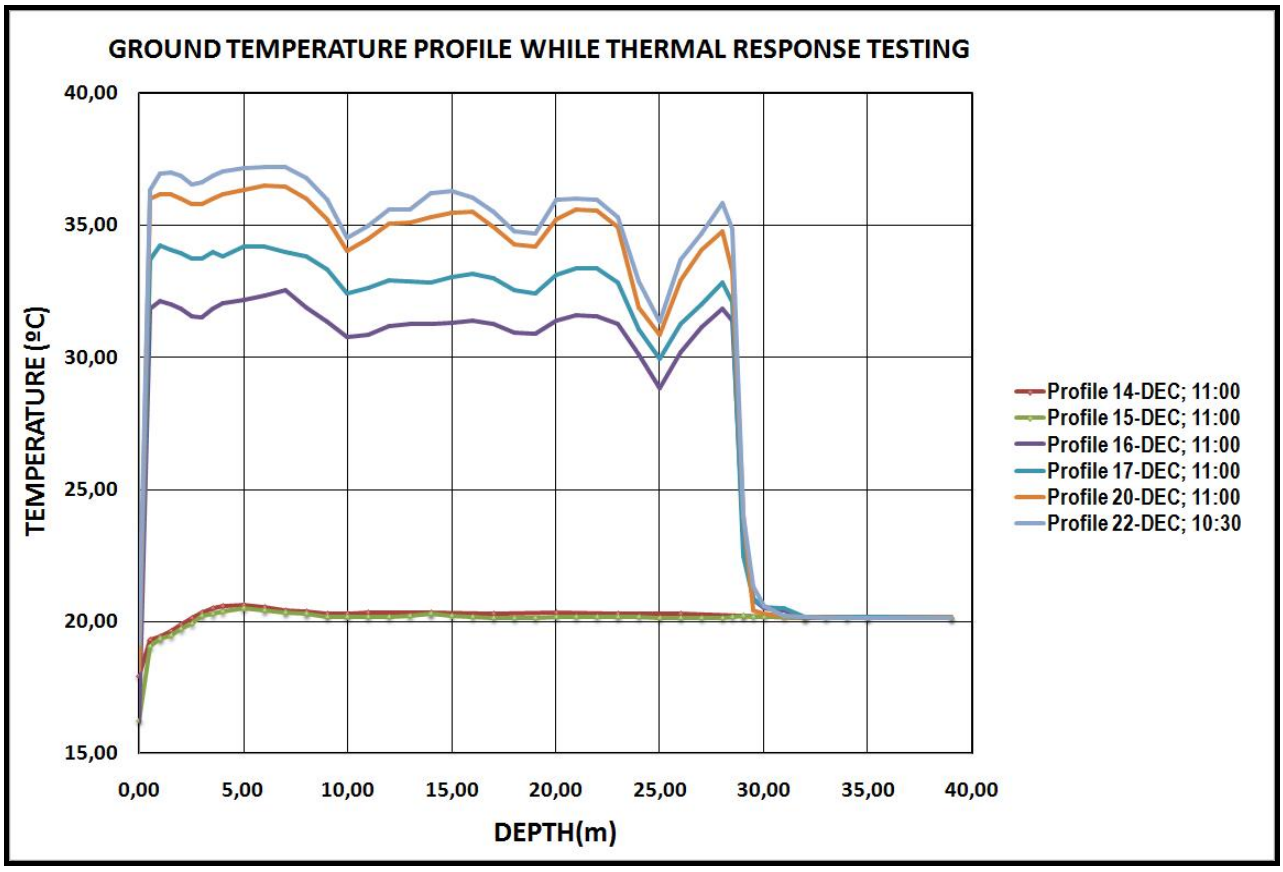

Figure 6: Ground temperature profile while thermal response testing. Data from the day before the start of the test (December 14 at 11 am), just before the test (December 15 at 11am), three measures during implementation (16, 17 and 20 December at 11am) and a final measure at the end of the injection of thermal power to the ground (December 22 at 10:30 am).

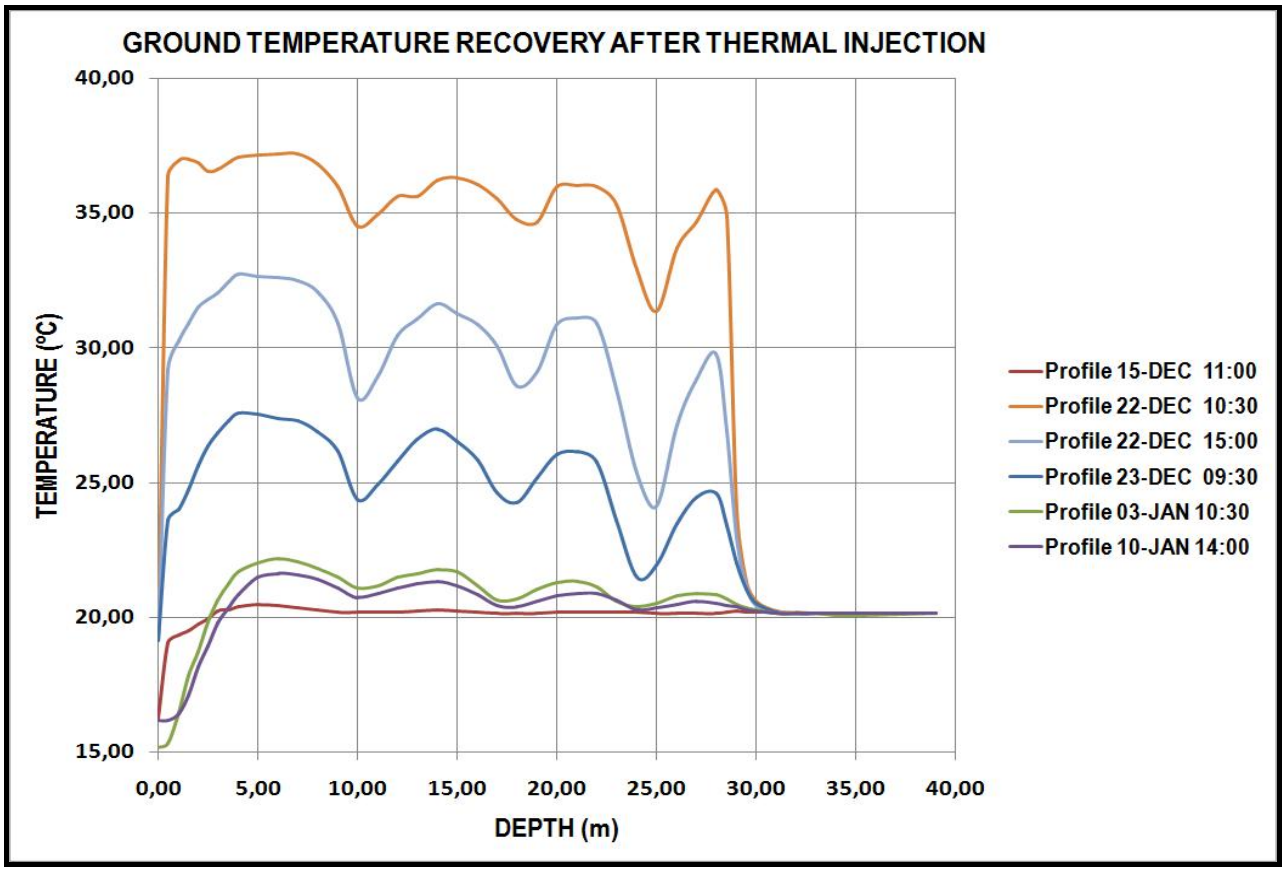

Figure 7: Evolution of the ground temperature profile after completing the heat injection test. Six temperature profiles are presented: just before the test (December 15 at 11am), just after the heat injection (December 22 at 10:30 am), and the remaining four after the end (4 hours and half after, December 22 at 15:00; 23 hours after, December 23 at 9:30; 12 days after, January 3 at 10:30; 19 days after, January 10 at 14:00).

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