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Ultrasonic equipment aimed to detect grouting homogeneity in geothermal heat exchangers

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ABSTRACT

The purpose of this study is to assess homogeneity and integrity of cementing grout in vertical borehole heat exchangers used for geothermal heat pumps using an ultrasonic non-destructive test. The used testing equipment, TUC (Ultrasonic Test to certificate grouting Continuity), is based on an ultrasonic system able to generate and record wave propagation from the inside of heat exchangers to the surrounding (cementation and soil, possibly). Differences in signal characteristics of the recorded waves along the pipe can indirectly provide useful information to evaluate the successful realization of the well cementation in terms of vertical homogeneity and continuity. Both laboratory and field tests have been evaluated and are hereafter presented to verify tests effectiveness and discuss eventual limitation of the proposed approach.

1. INTRODUCTION

Geothermal heat pumps are getting more and more common in Italy and all around the world.

Vertical ground heat exchangers used for this purpose typically consist of high-density polyethylene (HDPE) U-tube pipes (or double U), with common diameters range from 19 mm to 38 mm (Fig. 1), inserted in deep boreholes. The well drillings have typical diameters from 76 mm to 127 mm and their depth ranges usually from 80 m to 250 m. The Borehole Heat Exchangers (BHEs) are accordingly closely spaced in the borehole. A grout mixture is typically pumped into the borehole to fill the gap between the U-tube and the borehole walls. The main purpose of the cementation is to improve the heat transfer between soil and plastic pipes by providing a better contact surface between them, and also to create a seal around the U-tubes against migration of potential contaminants into groundwater systems.

As for all relatively new techniques and devices that works under the earth surface there is a general apprehension mainly due to two questions:

a) Is it working?

Figure 1. Example of vertical ground loop heat exchangers made by high-density polyethylene U-tube pipes; common diameters range from 19 mm to 38 mm.

b) Is it a possible source of pollution or interconnection for water tables?

Thermal response tests can answer the first question. This tests are able to integrate the underground thermal properties along the entire length of a BHE, including groundwater and backfilling material, providing the so called effective thermal conductivity (e.g. in Gehlin, 2002; Sanner et al., 2005; Esen and Inalli, 2009). Laboratory measurements alone may lead to different values since they cannot correctly account for groundwater flow and water-filled cracks and pores (Gunn et al., 2005). Moreover, productivity may be overlooked when an interaction occurs between the BHEs of a geothermal fields, decreasing the final yield.

The second question is still an open problem. Actually, the only assurance that the PVC pipes are completely insulated from the ground (and from the aquifers) is given by the blowing up of the backfilling material, pumped up from the bottom of the drilling.

However both these open questions highlight the importance of a correct cementation procedure (a review of cementing techniques, equipment and materials can be found in Hole, 2008) that represent the most critical component of the drilling process to the integrity and longevity of geothermal exchangers.

Hence, the need of an indirect technique to ensure the cementation conditions of BHEs, led us to the development of an ultrasonic-based methodology, which has been tested in laboratory and on the field showing good potentiality to detect discontinuities and flaws in the cementing grout. The adopted measuring technique is an adaptation of common investigation techniques adopted in the field of Civil Engineering for testing the integrity of foundations piles (e.g Amir, 2002; Amir et al., 2004; Homuth et al., 2013). Given this similarity several specific steps have been however undertaken in order to execute the tests inside BHE. Particularly the reduced dimensions of pipes required on proper construction of sonotrodes. Similarly interpretation techniques based on the amplitude of received waves have been adopted and calibrated to the specific working environment.

In this paper results from laboratory and field tests are summarized and a discussion on further developments is presented.

2. THE INSTRUMENTATION

The testing system, called TUC (Ultrasonic Test to certificate grouting Continuity), includes a generator, an ultrasonic transmitter (sonotrode) with a matched receiver and an acquisition system (Comina et al, 2010; Guglielmetti et al, 2011). Testing is executed by lowering transmitter and receiver probes, arranged one on top of each other at a fixed constant distance (15 cm), at the bottom of the investigated vertical exchanger and then scanning the pipes when the ultrasonic system is retrieved (fig. 2 and 3).

The records of signal characteristics yield an assessment of concrete quality and continuity. The system is based on the emission of a train of square waves, at close constant time intervals (1 sec). In this way, since the acquisition takes place lifting the instrumentation from the bottom to the surface at a constant known velocity and the time interval between the ultrasonic emissions is also known, we can refer each measurement to its depth of acquisition.

The sonotrode transforms the electrical input in a mechanical wave which travels - respectively - through the fluid filling the pipe, the pipe material, the surrounding grout and eventually the bordering ground. Then, the receiver collects the refracted wave and transmits these data to a data logger at the surface which records them on a digital support. In order to introduce sonotrode in the reduced dimensions of BHE pipes on proper instrumentation has been constructed (fig. 4).

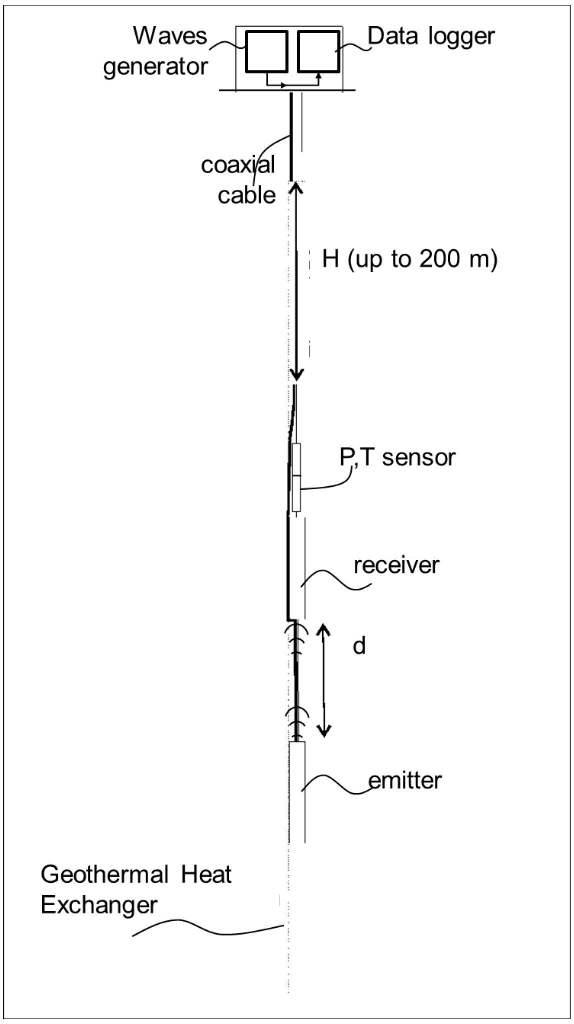

Figure 3 – Sketch of the TUC in action.

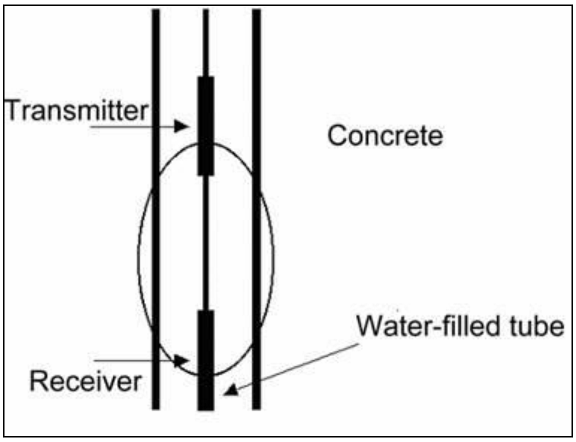

Figure. 3 – Zoom on the instruments disposition during acquisition.

The investigation radius is a direct function of the frequency of the emitted wave (increasing investigated volume with a decrease in the emitted frequency) and of the relative velocities in the different crossed material.

(a)

(b)

Fig. 4 – Particular of the sonotrode (a), built at this purpose by Sirius electrics, and of the generator/receiver (Pundit lab by Proceq from Pasi srl).

Preliminary laboratory tests allowed us to obtain the best results, in terms of transmitted wave amplitude and cleanness of the first arrival time, using probes with a nominal frequency centred around 20 kHz (also 35-Hz and 50-kHz devices were tested). At the same time of the ultrasonic recording, the temperature of the fluid and the hydrostatic pressure are also acquired: in this way the temperature of the soil/grout and the depth at which the measures are referred can be traced back for processing and interpretation.

The operator gets a set of recorded signals at regular intervals (time/space) from which it is possible to extract:

- the arrival time of the input wave at the receiver in order to calculate the mean ultrasonic velocity in the surrounding media, which is directly related to the physical and mechanical properties of the investigated materials;

- the spectral amplitude with related attenuation, by a simple computation of the cumulative spectral content of the Fourier spectra around the central frequency peak of the transmitted wave. As for velocity, the spectral amplitude is proportional to the physical and mechanical properties of the material. Passing from materials with good mechanical properties to other with worse characteristics cause a decrease in the spectral amplitude.

The acquisition procedure is simple and the processing scheme can be easily automatized. Results of on proper laboratory and field tests are reported in the following to discuss the potentiality of the technique and the advantage of amplitude versus travel time determinations.

3. LABORATORY TESTS

In laboratory, we built three simplified reproduction of geothermal probes within plastic cylinders (Fig. 5a, h=40 cm and Ø=30 cm).

Short portions of geothermal probes (Fig. 5b, h=50 cm, Ø=32 mm) were placed in the centre of each cylinder after waterproofing their bases.

Figure 5. Materials used for laboratory test simulations: plastic cylindrical containers (a) and short segments of HDPE geothermal probes (b).

The surroundings of each probe were then filled using three different materials (fig. 6):

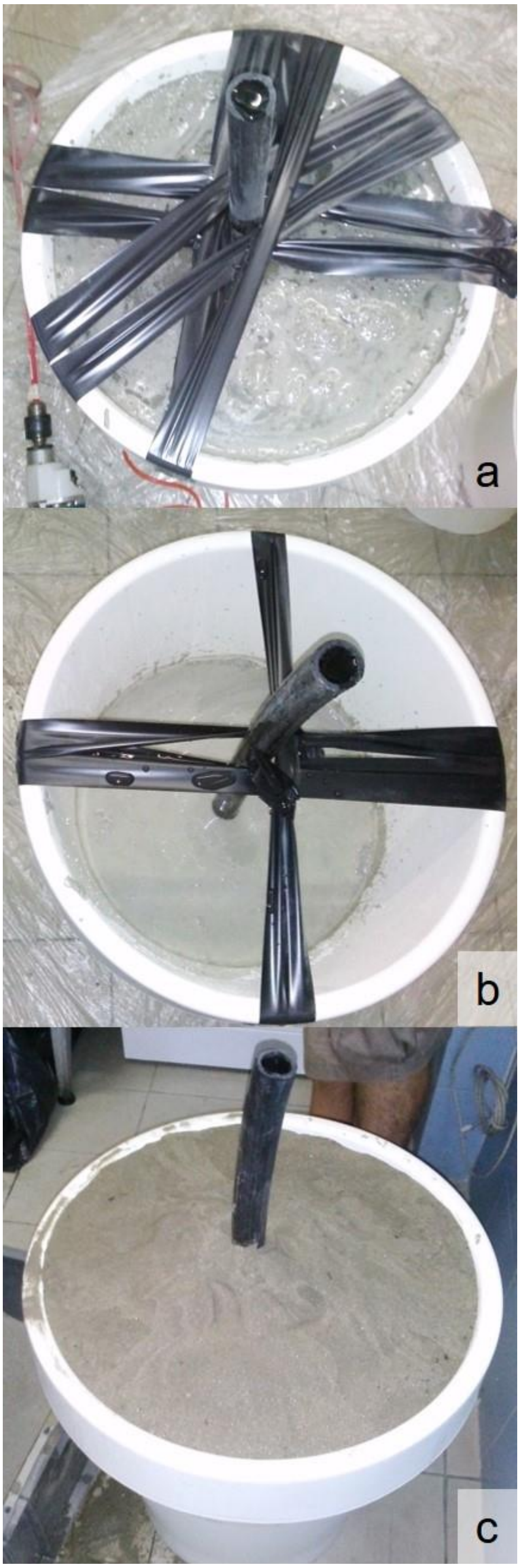

Figure 6. The three laboratory probes under construction with different filling materials: classical cement (a), geothermal cement (b) and mixture of sand and gravel (c).

i) classical cement (32,5R – Fig. 6a),

ii) geothermal cement (Fig. 6b),

iii) heterogeneous mixture of sand and gravel (Fig. 6c).

The final height of the filling within the cylinders was around 30 cm for classical cement, 20 cm for geothermal cement and 40 cm for sand and gravel.

Measurements with TUC instrumentation were repeated from July 2015 (one week after the construction) to October 2015, in order to allow the complete cement hardening to take place and evaluate eventual differences that can be observable during hardening.

Amplitude and velocity of the recorded ultrasonic waves are generally stable over time on each laboratory probe. The ultrasonic velocity on the cylinder with sand and gravel didn't exhibit changes over time, while a weak increase in the values was found in the two cemented probes, probably linked to the progressive grout hardening. Generally travel times determination from the recorded traces has revealed to be very difficult due to the low resolution in determining a correct first break in recorded traces while moving the transducers along the piles. Therefore in the following attention is focused on the cumulative spectral amplitude extracted from the traces. Further additional tests on the maintenance of the system calibration with time will allow a better time-dependent analysis of the results. At this first stage, we prefer to partially disregard the temporal evolution of the data and focus only to the differences between the propagation response of the three filling materials.

In Figure 7, a comparative summary of the test carried out on lab cylinders is shown in terms of recorded cumulative spectral amplitude.

The three filling materials showed a different response to the propagation of ultrasonic waves. In classical cement (Fig. 7a), substantially higher spectral amplitudes are observed in the recorded traces, which can be explained as a result of its better mechanical properties. A variability within the cementation is also noted with a probable stiffer cemented layer between 0.2 and 0.3 m depth. In more than two months from the construction of the geothermal pilot probes (Fig. 7b), the geothermal grouting shows spectral amplitude values comparable to or even lower than the mixture of sand and gravel (Fig. 7c).

The mean resulting curves for each material are reported and compared in Figure 8. These measurements proved the sensitivity of the methods in the distinction of different types of material, basing on the assumption that with better mechanical properties of the pipe surrounding the resulting amplitude values are higher.

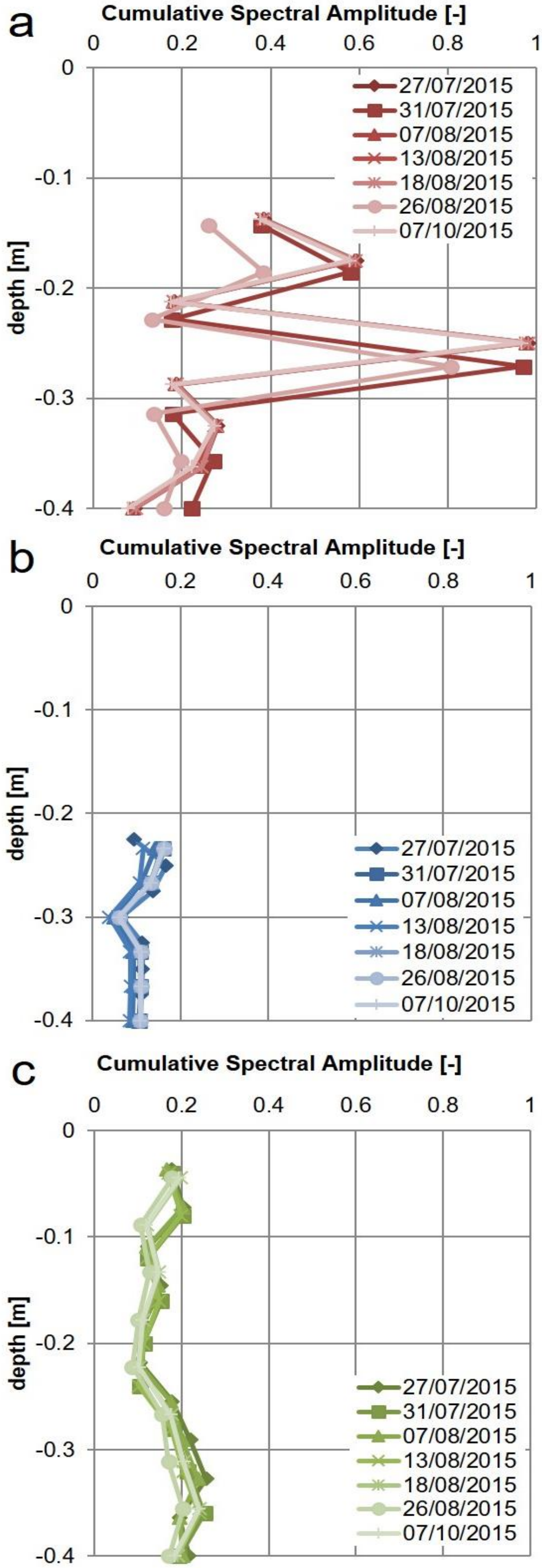

Figure 7. Computed cumulative spectral amplitude for classical cement (a), geothermal cement (b) and mixture of sand and gravel (c).

Additional experiments were also performed to test the vertical sensitivity of the method, in order to recognize different type of material/cementation along the same column (Fig 9). In particular, the cylinder with the geothermal cement bottom filling (h=20 cm) was refilled with fine sand in the upper par, in order to test the ability of the instrument to detect the lithological change along the survey column.

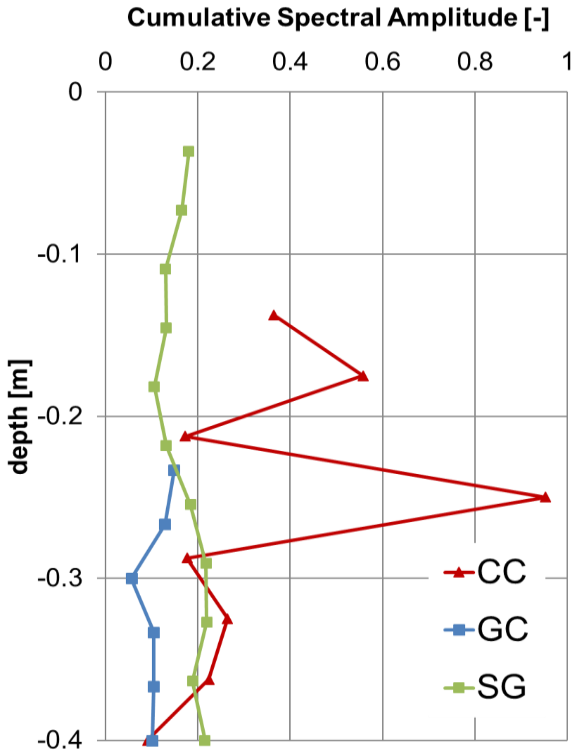

Figure 8. Mean curves for the three filling materials: classical cement (CC), geothermal cement (GC) and mixture of sand and gravel (SG).

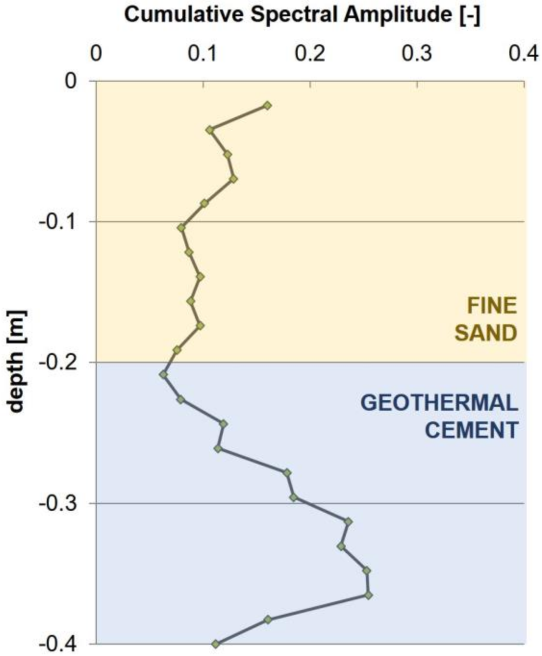

Figure 9. Spectral amplitude for the geothermal grouting cylinder (h=20 cm) refilled with additional 20 cm of sand and gravel.

From the spectral amplitude plot, it is clear that passing from fine sands to the geothermal cement, the values increase, reaching a maximum of about 0.25, characteristic of this cementing material. The minimum in the spectral amplitude is found at the interface between the two different filling materials. This test confirmed the capability of the ultrasonic system to identify differences and discontinuities in the materials surrounding the geothermal probes.

4. FIELD TEST

On the field, two drillings (h=7 m) were realized and equipped with HDPE geothermal U-probes close to the edge of a quarry cliff, in order to enable the digging of the material after the testing and to perform a visual inspection of the status of probes, the cementation continuity and the surrounding geology. Only one of the two test probes was cemented, while the other one was refilled using the same sandy-gravel deposits of the quarry.

According to laboratory tests, also on-site measurements were carried out in different dates to ensure the repeatability of the measurements (4/09/2015 – green data in Fig. 10 - and 25/09/2015 – blue data in Fig. 10). Obtained results are quite stable over time.

Tests carried out on the cementless geothermal probe results in constant amplitude values with depth (Fig. 10b). On the contrary, the cemented probe showed higher amplitude values down to about 4 m depth, while at greater depths values are lowered to an amplitude similar to the one measured along the non-cemented probe (Fig. 10a). This apparently unjustified sudden decrease in the spectral amplitude was directly verified on the field when the column was dug up at the end of the second TUC tests (Fig. 11).

From a visual inspection of the exhumed column, the probe cementation showed optimal characteristics down to 4.10 m depth, confirming the higher values of the recorded spectral amplitude. Beyond this depth, the drilling bumped into a compact naturally cemented layer (conglomerate) with big pebbles and boulders. In this stratigraphic horizon the injection of the cementing material was not continuous and homogeneous as for the upper part of the column, empty spaces between the pebbles and constrictions of the cemented pillar were directly visible (Fig. 12).

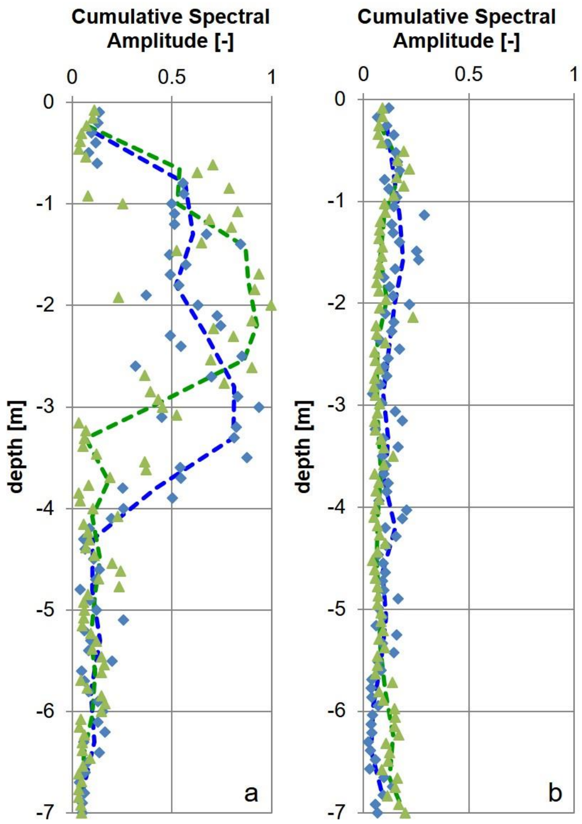

Figure 10. Data from geothermal grouting probes (a) and cementless probes (b): green data refer to the test of 4/09/2015, the blue ones are for the test of 25/09/2015. Points show raw measurements at each depth; lines represent the interpolated results.

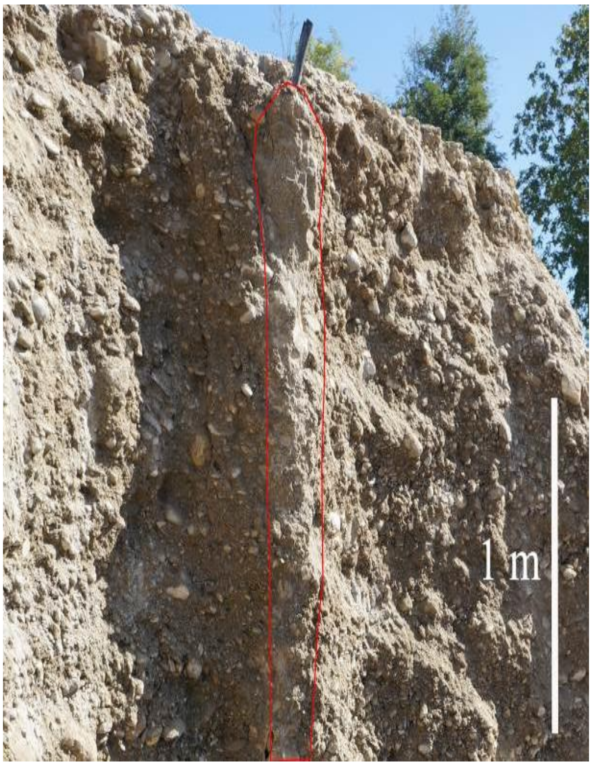

Figure 11: The cemented geothermal probe progressively brought to light during the excavation procedure.

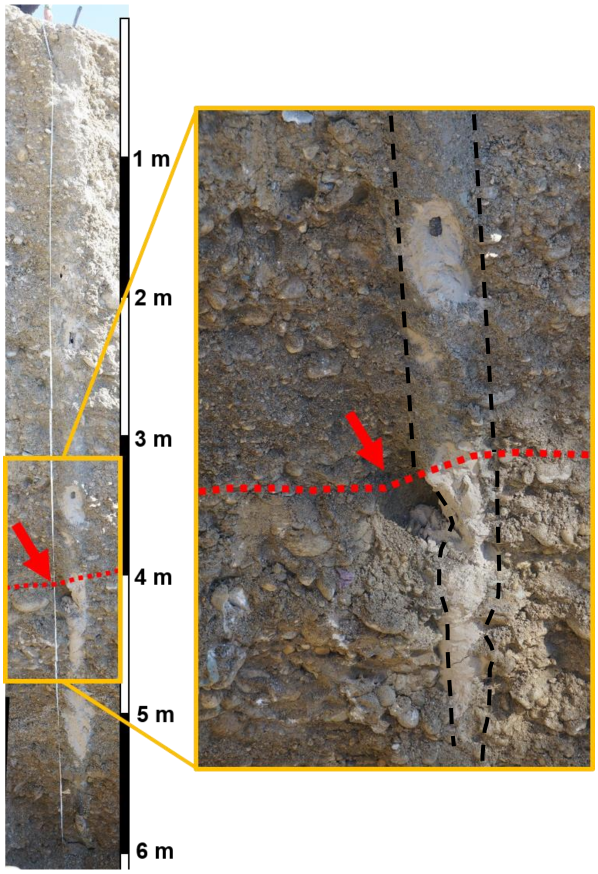

Figure 12: Stratigraphic detail of the cemented geothermal probe. The red dashed line marks the interface between sandy gravels and the more compact conglomeratic layer with coarser grain size. The red arrows and the dashed black lines highlight the presence of empty spaces and discontinuities in the cementation below -4.10 m from the surface.

5. DISCUSSION

The purpose of this study was to provide an inspection system and a corresponding acquisition and data processing procedure to investigate small-diameter pipelines surrounded by cementation, acquiring information in a complete and automatic manner.

From this analysis, we have tried to demonstrate type/quality of information inferred from ultrasonic investigation and the related technical potentialities and limitations. The ultrasonic technique has therefore revealed a valid and applicable tool for the detection of discontinuities and flaws in grouting, both in laboratory and on-site tests, highlighting clear changes in the cumulative spectral amplitude of ultrasonic signals passing thought zones with a different degree of cementation. From these first tests, the technique does not seem to be able to follow the phenomenon of maturation and hardening of cement. As told before, further additional tests on the maintenance of the system calibration with time will allow a better sound time-dependent analysis of the results. At this first stage, we preferred to partially disregard the temporal evolution of the data and focus only to the differences between the propagation response of the three filling materials with measurements carried out at the same time.

Nevertheless, information about the cement hardening could be potentially provided by monitoring the temperature inside the geothermal cemented probe. Two temperature probes were installed inside the probe, respectively at -3 m and -6 m from the ground surface, from the date of drilling to the last TUC test (Fig. 13). While surficial recorded temperatures (-3 m from ground surface) seems to be affected by air temperature fluctuations, the deepest temperature data (-6 m) showed little affection by external air temperature, with a gradual increase of temperature in the two months of monitoring (1.5 °C), in clear contrast to the external climate affecting the upper part of the hole.

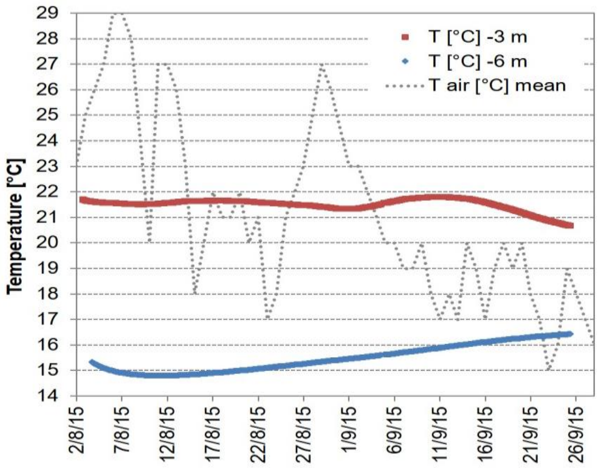

Figure 13. Temperature monitoring inside the geothermal cemented probe at, respectively, -3 m (in red) and -6 m (in blue) form the surface. The daily mean air temperature is reported with the black dashed line.

6. CONCLUSION

At the end of this feasibility research, the preliminary project allowed the identification of the technical characteristics of the equipment and acquisition parameters to be used. The quality of the chosen ceramic sensors and their flexibility in application have provided important information on the characteristics of the wave train emitted and received.

The execution of different tests (both in laboratory and on field) was crucial to identify which peculiar feature of the recorded ultrasonic signals has to be analyzed to infer cementation continuity and homogeneity (wave spectral amplitude around the emitted frequency peak) and to verify the actual reliability of the system.

The TUC technique has revealed valid and applicable for the detection of discontinuities and flaws in the cementation, highlighting changes in the propagation of the ultrasonic signal passing through zones with different cementation features.

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