Thermal plume dispersion induced by shallow geothermal applications: the case study of Villaverla (Italy)

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ABSTRACT

Among the shallow geothermal applications, the opportunity to detect the thermal plume dispersion induced by a borehole heat exchanger (BHE) coupled with a ground source heat pump in an unconfined aquifer can provide crucial data for environmental purposes. The interpretation of these data could lead to useful information to (1) accurately simulate transport model; (2) to acquire aquifer properties data and (3) to evaluate the environmental impact at local scale.

This paper aims to provide the results of a geophysical methodology developed in order to characterize and to detect the spatial and temporal distribution of the temperature on the ground. Moreover, the presented heat transfer test could be applied also in other applications instead of classical aquifer tracers tests, in order to (1) minimize the environmental impact of tracers, (2) reduce overall costs and (3) improve the aquifer properties evaluation.

With the aim of identify the ground thermal footprint dispersion over time, in the described test the authors combined a fiber optic Distributed Temperature Sensing device, an Electrical Resistivity Tomography, a temperature logs and a thermal properties device. A modified Thermal Response Test device (TRT) trigged the underground heat transfer. The test site area is located in the Villaverla area, in the North Eastern Venetian Plain (Italy). The experimental measurements have been then compared with FEM modelling simulation outcomes, in order to verify the coupling of thermo-geophysical model and simulation output. Finally, the FEM model can be used for aquifer pollution/contamination prediction and management.

1. THEORETICAL BACKGROUND

Since environmental studies are becoming more relevant for a sustainable life, groundwater and hydrogeological analysis are playing a significant role.

Consequently, scientists adopt new and more comprehensive approaches for the environmental management by groundwater characterization and modelling (Konig and Weiss, 2009).

In order to achieve the aquifer parametrization, solute tracers could extensively provide a very great support in that sense; nevertheless, solute tracers could not widely deal to the environmental requirements (Leibundgut, 2009). More recently, heat is also used as tracer, since it is quite simple both providing the energy source and detecting the groundwater temperature (Anderson, 2005). Indeed, the latest developments in field equipment to measure groundwater temperature, including fiber-optic Distributed Temperature Sensors (DTS), shows that there may be a wide scope of unexplored applications where heat can be used to both understand and constrain groundwater issues (Fujii et al., 2009; Bakker et al., 2015).

Many authors highlighted the analogies between the groundwater solute transport mathematical solutions and the groundwater heat transport ones so far (Reed and Reddell, 1980; Anderson, 2005; Banks, 2007; Irvine et al., 2015). The one dimension advection diffusion equation - which defines the way the solute concentration is moved into an aquifer - is homologues to the heat conduction-convection one dimension equation of the temperature variation of heat, according to steady state equilibrium between the porous medium temperatures and pore fluids

(Domenico and Schwartz, 1998). So, the mathematical and physical analysis may be used a comparable way. Therefore, hydrogeologists got used to apply heat transfer through aquifers as tracer, instead of the traditional methods (Anderson, 2005).

The advantage of heat as tool for tracer tests is evident, because it is not necessary pour any solutions or potential pollutants substance into the aquifer.

2. FIELD TEST

The field test is located in the alluvial plain of Northern Italy, where the phreatic level is close to the topographic surface (from few decimetres to few meters), North to the city of Vicenza (figure 1).

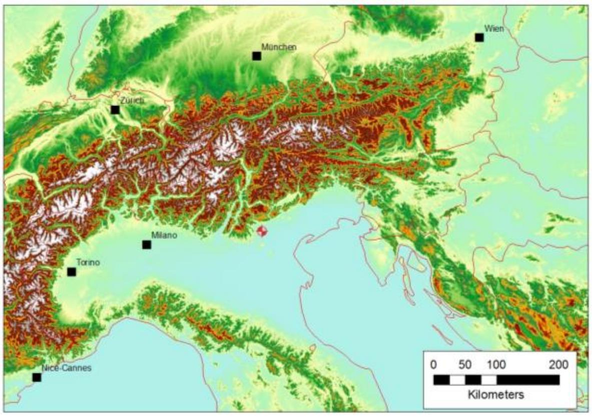

Figure 1: the test field (red cross circle) is located in Northern Italy, in the plain by the Pre-Alps mountain system (Villaverla, Vicenza; Italy).

From the hydrogeological point of view, there are mostly unconsolidated gravel and sandy sediments which host a phreatic aquifer system, although there are several non-continuous thin clayey and silty layers. Downstream a multilayer confined system takes place.

The field test is located in the transition zone in between the unconfined aquifer systems and the multilayer aquifer systems, where groundwaters outcrops as complex plain spring, as figure 2 shows (Cultrera et al., 2011).

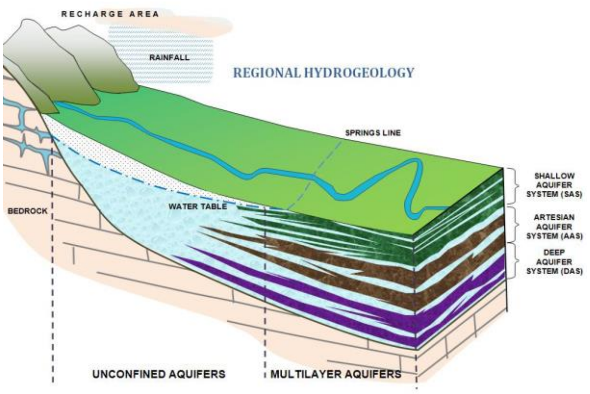

Figure 2: sketch of Venetian aquifer systems; the spring line ("Fontanili") represents a transition zone from the high plain (unconfined aquifer system) to the low plain (multilayer aquifers) (Cultrera et al., 2011).

The test has been carried out using a very shallow borehole, which is 5.0 m depth and involves several different layers, as figure 3 highlights. The thickness of each layer changes from minimum 30 cm up to 200 cm, as figure 3 shows.

The inner diameter is 3" (76.2 mm) and the borehole screen section takes place from 2.0 m from the ground level. The phreatic level fluctuates from couple of meters up few decimetres from the ground level, according to the season and the recharge processes by precipitations.

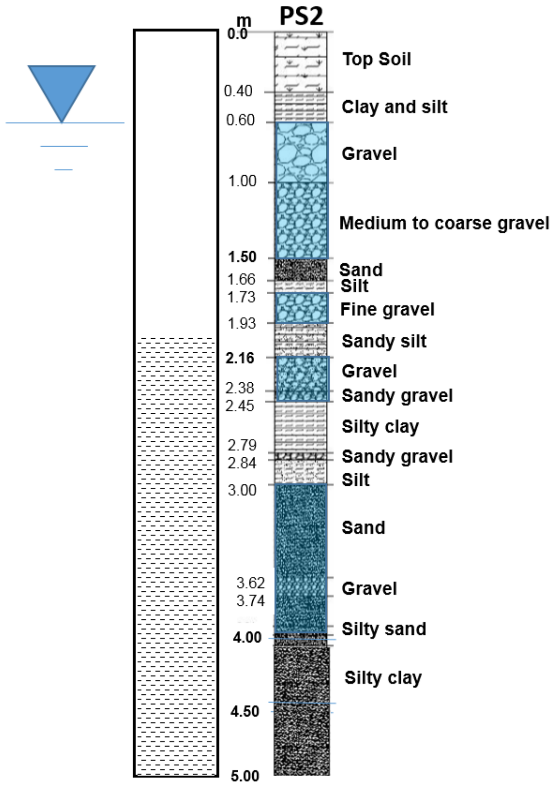

Figure 3: unconsolidated sediments stratigraphy and well completion in PS2 Villaverla borehole.

The Villaverla area has been studied for long time, since there are several wells drilled by the local water authority in order to exploit the groundwater at depth (over 100m) for drinking purposes (De Seta, 2015; Arato et al., 2015; Monego et al., 2010; Capellari, 2007).

Therefore several hydrogeological parameters were already available and a comparison among different geophysical and hydrogeological survey investigations is feasible (Monego et al., 2010; Monego, 2009; Arato et al., 2015; De Seta, 2015; Capellari, 2007).

METHODS

The field tests lasted over 5 days in November 2014, when the air temperature was close to 9°C as average and the phreatic level was close to the ground level.

First, the DTS optical fiber was deployed in the PS2 borehole, linked to a single U-shape copper tube, which was connected to the Thermal Response Test device (TRT) (Raymond et al., 2011; Signorelli et al., 2007). This TRT device provides the power to the PS2 borehole, according to the user inputs. In this case, the input was constant for the first period and then it increased in order to obtain a clear thermal footprint in the aquifers (figure 4). Water is used as carrier fluid in single U-shape copper tube inserted in PS2.

The optical fiber and the TDS unit recorded the temperature logs during the TRT tests, as figure 4 shows. An external thermometer recorded the air temperature as well.

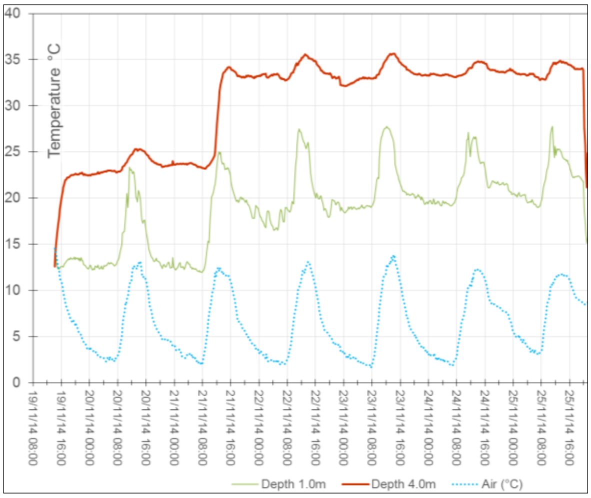

Figure 4: temperatures recorded at the site, at 1.0m and 4m deep (continuous lines) and at ground level (air temperature, dot line).

Meantime, Electrical Resistivity Tromography (ERT) from the surface detected the changes of electrical properties due to the increasing of groundwater temperature (Hermans et al., 2014). The measurements was performed thorough the borehole (PS2) by an array configuration of two orthogonal sections.

Finally, a needle probe of a portable device for direct measurement allowed the definition of thermal properties of unconsolidated sediments (ISOMET), such effusivity, thermal conductivity, diffusivity and thermal resistance. The interpolations of these thermal parameters lead to the heat capacity as result.

3. RESULTS AND DISCUSSION

The ERT surveys highlighted slight temperature changes around the PS2 borehole, as figure 5 shows (Arato et al., 2015).

The analysis of the resistivity changes allows the attempt of the thermal footprint definition and characterization in the aquifers (figure 5), along the two investigated directions.

The hydrogeological, geophysical, geothermal and temperature data have been then used in order to build up a numerical model which couples the equations of state of heat transfer and the fluid flow, using the numerical code FeFLOW (Trefry and Muffels, 2007; Diersch, 2014; H.-J.G. Diersch et al., 2010).

In order to properly modelling the TRT and the single U-shape copper tube, the Borehole Heat Exchanger (BHE) tool has been applied, adjusting the different input parameters to the study case (Al-Khoury and Bonnier, 2006; Al-Khoury et al., 2005; H.J.G. Diersch et al., 2010).

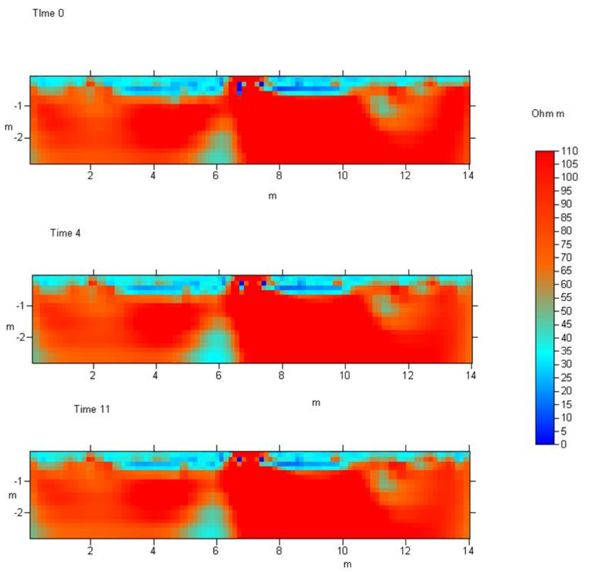

Figure 5: ERT outcomes at different timing. Time 0: before any TRT heat input; time 4: while heating up the PS2 borehole; time 11: after the TRT.

The numerical model was calibrated with the recorded data (figure 6). In order to achieve the best fitting outcomes, the trial and error method was used, after the sensitivity analysis of the main groundwater flow and heat transfer parameters (Anderson and Woessner, 2002).

Comparing the estimated temperature with the simulated ones, the model may be exploited as a reliable tool for the environmental management and analysis.

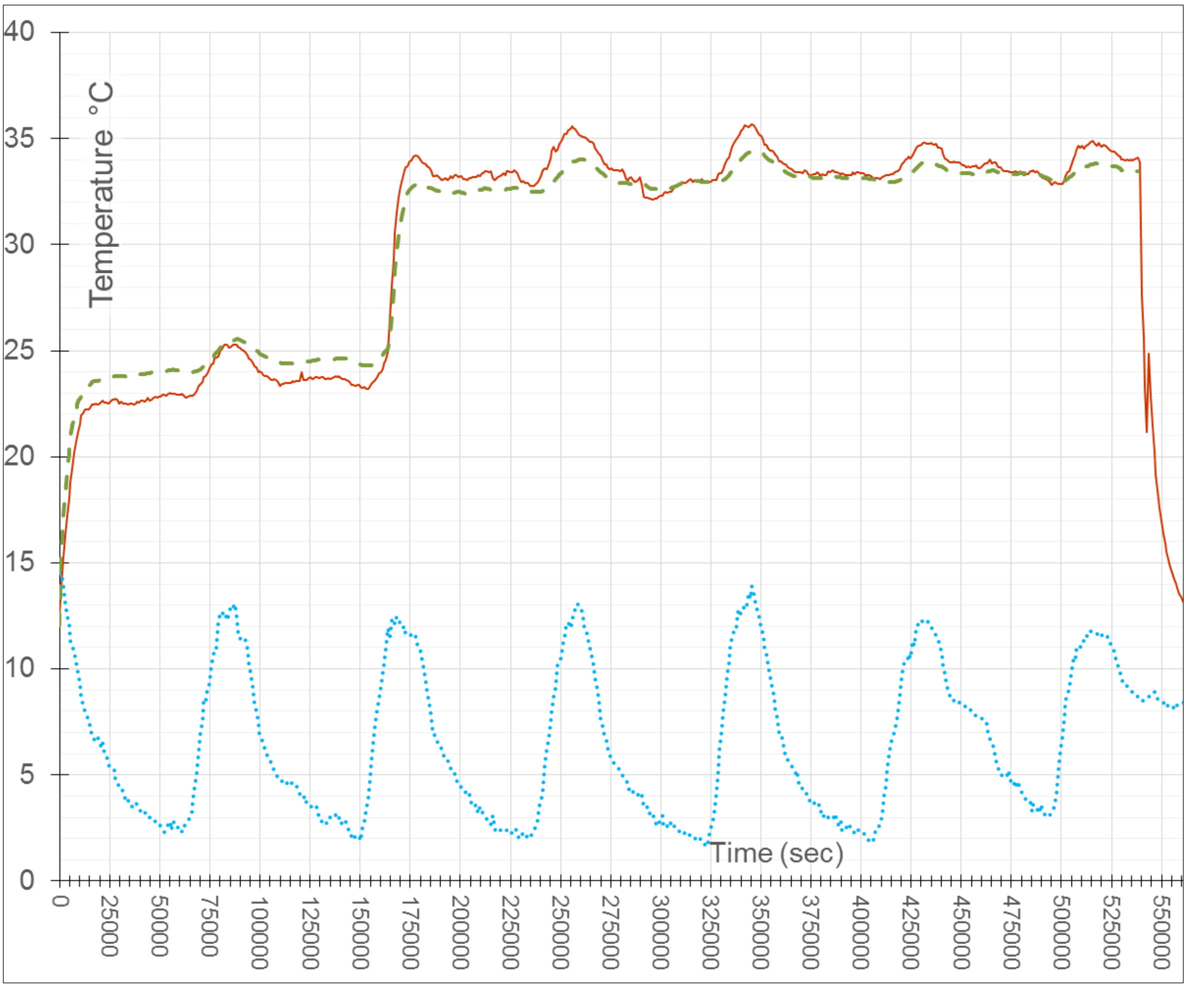

Figure 6: calibrated model. Comparison between measured temperature at 4.0m deep (red continuous line) and the calculated ones (dashed green line); dot blue line provides the temperature at ground level.

CONCLUSIONS

The described experimental application combines multiple and multidisciplinary methods such as Thermal Response Tests, Electrical Resistivity Tomography, and Distribute Temperature Sensing. Underground thermal measurements and the available data set has been exploited in order to build up a numerical model where all parameters are used to best fitting the simulated values to the measured ones.

The model may then be exploited for environmental assessments, groundwater resources management, pollution distribution, heat transfer and heat exchange purposes.

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