Geophysical monitoring for shallow geothermal applications - Two Italian case histories

Geophysical Monitoring for Shallow Geothermal Applications, two Italian case hystories.

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ABSTRACT

In the context of shallow geothermal applications, geophysics can be applied as design and monitoring tool. In the last decades mainly electrical resistivity measurements have been adopted both for the characterization and to image spatial and temporal distribution of temperature within the ground. This paper is therefore focusing on the use of electrical resistivity in this context with a devoted look to Italians state of art. A brief literature review of thermal characteristics influencing the resistivity value and example applications of Electric Resistivity Tomography (ERT) data is reported. Two example case histories, in very different hydrogeological contexts, in northern Italy are also briefly commented.

INTRODUCTION

Electrically derived parameters have many practical applications to study soil properties and processes in the subsurface and more generally to investigate hydrogeological and environmental conditions particularly with respect to their temperature dependence. A linear relation between temperature and electrical conductivity (inverse of resistivity) is known under few tens of degrees °C (Sen and Goode, 1992; Hayashi, 2004). Around 25°C the following equation was proposed:

$$\sigma_T / \sigma_{25} = m \cdot (T - 25) + 1 \qquad [1]$$

where σ_T is the electrical conductivity of the porous medium at temperature T [°C] and m [°C^{-1}] is the fractional change in electrical conductivity. A range of 0.018 °C^{-1} and 0.025 °C^{-1} for m has been indicated by several authors (Arps, 1953; Dachnov, 1962; Sen and Goode, 1992; Revil et al., 1998; Hayashi, 2004; Hayley et al., 2007; Hermans et al., 2012, 2015 varying according to the type of fluid and sediments.

Given this, ERT has been extensively applied in the context of geothermal reservoirs in order to highlight the presence of hydrothermal fluids (T > 90°C). Conversely, only few experiments have been carried out in the context of low enthalpy geothermal applications (T < 90°C). Benderitter and Tabbagh (1982) applied surface ERT to monitor the injection of heated water in a shallow confined aquifer. Ramirez et al. (1993) and LaBrecque et al. (1996) adopted cross-borehole time-lapse ERT to image temperature anomaly related to remediation processes. Frakgogiannis et al. (2008) applied resistivity method to monitor the thermal performance of the ground at the University of Athens with an installed ground coupled heat pump (GCHP) system consisting of 12 borehole heat exchangers (BHEs). Firmbach et al. (2013a) tested ERT as monitoring tool of heat flows in porous media at different saturation degrees at laboratory scale and they compared experimental results with numerical predictions (Firmbach et al., 2013b). Giordano et al. (2013) and Cardarelli et al. (2014) moreover tried to estimate the medium thermal resistivity by means of the relation proposed by Singh et al. (2001) and modified by Sreedeep et al. (2005). Closed-loop (Giordano et al., 2015) and open-loop (Hermans et al., 2012; 2015) heat storage applications were monitored by ERT surveys within small field experiments in shallow aquifers. Some of these applications involved a quantitative evaluation of the thermal anomaly. Nevertheless, Robert et al. (2013) under laboratory conditions highlighted problems of ERT-derived temperatures owing to temperature-related chemical reactions occurring within porous media, both on fluid and solid phases. They observed a divergence between the resistivity and temperature curves related to the increasing solubility of some minerals and the increasing fluid conductivity with increasing temperature.

All of the above mentioned papers have therefore demonstrated the potentiality of using electric resistivity as a monitoring tool. However, further tests are required to obtain a robust and reliable correlation between these parameters and temperature. These relationships demonstrated to be quite consistent if based on laboratory data, but they often suffer from increased uncertainty when transferred to the field scale. It is therefore important to underline the relevance of multilevel approaches for reliable characterization linking laboratory and field tests. In the following, two example applications of resistivity surveys aimed at characterizing and monitoring ground temperature changes for shallow geothermal systems in northern Italy are presented.

CASE 1

The first test site is located in northeastern Italy, approximately 15 km north from the city of Vicenza, in the middle Venetian plain (**Fig. 1a**). From a hydrogeological point of view the alluvial sediments of the Venetian plain identifies three different zones (**Fig. 1c**): (i) *the upstream zone*, close to the Prealps, hosting an unconfined aquifer within gravel and sandy gravel material; (ii) *the downstream zone*, towards the Adriatic Sea, characterized by a multi-layered confined or semi-confined aquifer system that insists on sandy - clayey material; (iii) the *transition zone*, marked by an extreme heterogeneity of sediments, varying from coarse gravel to clay in short distances, that allow groundwater to intersects the topographic surface emerging in the so called *resurgence belt* (De Luca et al., 2014; Minelli et al., 2002).

In detail, the Villaverla area is a natural reserve of about 15.000 m^2, located in the *transition zone*, that belongs to the municipal water supplier for Padova (Hera-AcegaAps). The ground in the upper 10 m is characterized by high heterogeneity, with gravels and sands interbedded with silty and clayey layers. The water table is very shallow, approximately 1 m below the ground surface, with a fairly regular northeast-southwest slope, an average groundwater velocity estimated between 1 and 2.25 m/day and head fluctuations strongly correlated with rainfall (Monego et al., 2010; Cappellari et al., 2007). The depth of the piezometers used in this study ranges from 3.0 to 5.0 m below ground level (b.g.l.).

Main aim of the research is to detect the dispersion of thermal plume in the unconfined aquifer induced by borehole heat exchanger (BHE) coupled with ground source heat pump (GSHP), here induced by a modified thermal response test – TRT (Gehlin, 2002). Monitoring the physical parameters of the aquifer by means of geophysical methods such as Fyber Optic Distributed Temperature Sensing device – DTS (Lane et al., 2008), Electrical Resistivity Tomography – ERT (Hermans et al., 2012) together with temperature logs (Wisian et al., 1998) and thermal properties analyzer (VDI4640 2010; Clauser, 2011a; Clauser, 2011b) allow detecting the ground thermal footprint dispersion over time. The field work lasted ten days, from 18/11/2015 to 28/11/2015 and consisted in:

- heating the underground with a modified TRT to create thermal stress, consisting in closed loop U tubes inserted into the water well, tubes where hot water flows as heat carrier fluid;
- DTS measurements to monitor continuously (every 15 minutes) the temperature variation into the water heat injection well (PS2, **Fig. 1b**);
- ERT multitemporal (time slice) measurements to determine electrical resistivity variation in the underground related to the induced thermal stress;
- temperature log measurements to monitor the thermal plume in monitoring wells upstream (PS1, **Fig. 1b**) and downstream (GP6, **Fig. 1b**) of the injection well.

The thermal anomaly was induced by the TRT system in the selected well, characterized by a depth of 4.5 m and a width of 3 inches (about 75 mm). A U-shaped copper tube hosting the heat transfer fluid (water, in this case) was inserted into the well to heat the groundwater. The modified TRT started on November 19 2014, and began to gradually heat the groundwater up to temperatures of almost 50°C. The thermal stress lasted continuously and uninterruptedly for six days, after which the gradual restoration of the initial groundwater conditions was obtained. Fixing the DTS to the copper tube allows to detect in time the temperature of the surrounding groundwater with a spacing of 0.5 m and a temperature resolution of 0.01°C with a sampling frequency of 15 minutes, in order to obtain 96 measurements per day at different depths. Once switched off the TRT, the data acquisition has been limited only to daylight hours, according to the operator presence.

Considering the temperature variation over time at fixed depth below the ground level (i.e 0.0-1.5-2.0-4.0 m), it is possible to recognize two distinct effects. On the one hand, the influence of air temperature excursion is easily recognizable in the first unsaturated 1.5 meters of depth. On the other, the heating induced by the TRT is easily recognizable. In this timeframe (TRT switched on and switched off) a kind of temperature plateau (30-35°C) is created, beginning few days after heat injection and ending abruptly with a rapid fall at the interruption of the heat supply. It must be noticed that the GRT power from 1.5 kW to 3 kW is gained after about one day of operation.

The aim of this test was the time-lapse monitoring of the dependence of induced temperature increasing on electrical behavior of a shallow gravel aquifer. The experiment was designed to last few days focusing on the proximity of the injection borehole (PS2) even if the aquifer presents high hydraulic advection. Two geoelectrical sections were realized keeping injection borehole in the middle: the first profile (L1, see **Fig. 1b**) consisting of 48 micro stainless steel electrodes installed with 0.25 m spacing for a total array length of 11.75 m; the second profile (L2, see **Fig. 1b**) being made of 24 micro stainless steel electrodes installed with 0.30 m spacing for a total array length of 6.90 m. The ERT device was a Syscal pro georesistivimeter with a dipole-dipole skip 0 scheme collecting both direct and reciprocal measurements, and Profiler code was used for the inversion (Binley, accessed October 2014). **Fig. 1d** shows the resistivity ratio (%) respect to background conditions after 4 days of heating. As it can be seen a small decrease of 3-4 % in terms of resistivity value is observable in the proximity of the TRT borehole. Temperature log profiles carried out in wells located upstream and downstream to the observation point show that the thermal affected zone (TAZ) is confined in the surrounding of the measurement station, supporting the ERT outcomes.

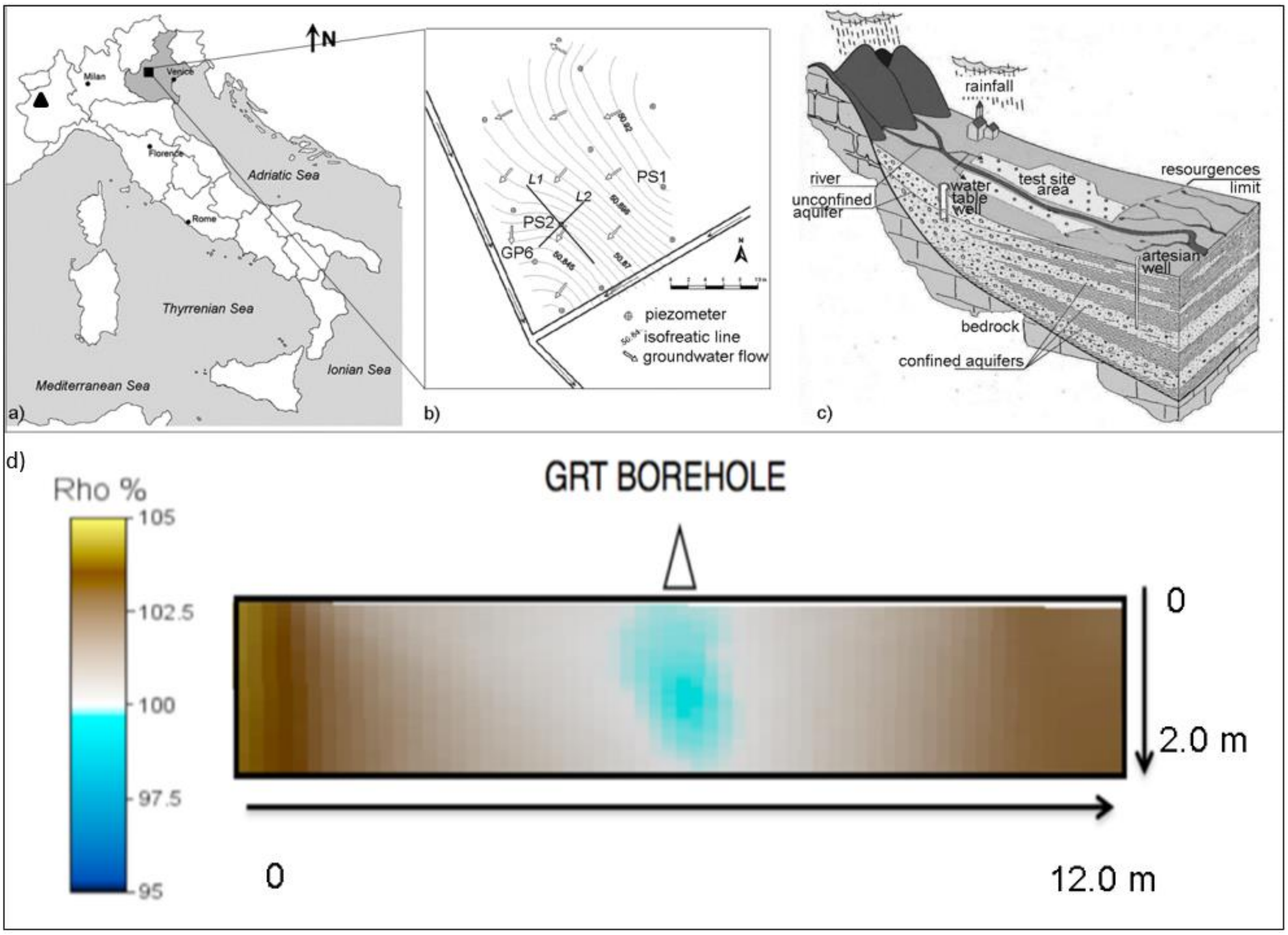

Figure 1: a) b) and c) location of the test site in the Veneto region, northeast Italy (modified from Cappellari et al 2007) and d) results of ERT difference (%) respect to background conditions after 4 days of heating. In a) the location of the second test site in the Piemonte region is also reported (black triangle).

CASE 2

The second test site (**Fig. 1a**) is conversely situated in the north-western portion of the Pianura Padana in the municipality of Grugliasco (Torino). A field scale Borehole Thermal Energy Storage (BTES) was built up in order to test the ability of the alluvial deposits of the north-western Po Plain to collect the thermal energy produced by solar thermal collectors. The drilling activity performed in the area showed 30 m of gravels and sands, sometimes with local decimetric layers of compacted gravelly sands. On the strength of the available data, the water table is thought to stand 35-40 m below the ground level. The underground part of the system stores the heat by means four 27 m deep BHEs. The arrangement consists of a double-U piped borehole placed in the center of an equilateral triangle (2 m side), and other 3 single-U piped BHEs located to the triangle’s vertexes. A 33 m deep monitoring hole was moreover located 2 m away from the double-U heat exchanger. Two solar thermal panels were placed on the roof of a near building and they collect the solar energy with a total net surface of 5.0 m^2 and an inclination of approximately 10°. A total of 20 RTD 4wire Pt100 (measurement range -50 – 180°C, accuracy 5%) were placed every 5 m down-hole in 3 of the 4 BHEs and in the monitoring hole. In addition, 10 temperature sensors of the same type were placed throughout the circuit and on the thermal panels.

Electrical surveys were carried out in order to afford a time-lapse spatial monitoring of the heat injection provided by the plant during the warm season. The aim of evaluating the TAZ of the underground from electrical resistivity measurements is not an easy task in the presented test site. First the system is operating in the partly saturated zone so that possible complex variations in resistivity can be evidenced with increasing temperature (e.g. de-saturation); secondly only a reduced operative space is available for the surveys, lastly several man-made structures are present (entry ways and buildings foundations) which could affect the quality of data. Both 2-D and 3-D ERT time-lapse data have been acquired at the site during a day of heating of the plant. A Wenner-Schlumberger survey was carried out along a 72-electrode profile (at 1 m spacing), while a non-standard Dipole-Dipole array was used to acquire 3-D data over the 72 electrode grid (at 3 m spacing). Raw data have been measured with a Syscal R1 georesistivimeter. Data globally have good quality, with standard deviation on the measured resistance in the range between 0.1 and 5 %. Provided apparent resistivity values were ranging between 50 and 250 Ωm, with some outliers (both low and high resistivity) in correspondence of the entry ways, which behaved anomalously with respect to the surrounding soil. These outliers, such as measurement errors, and anomalous high and low apparent resistivity values, were filtered out before the inversion process.

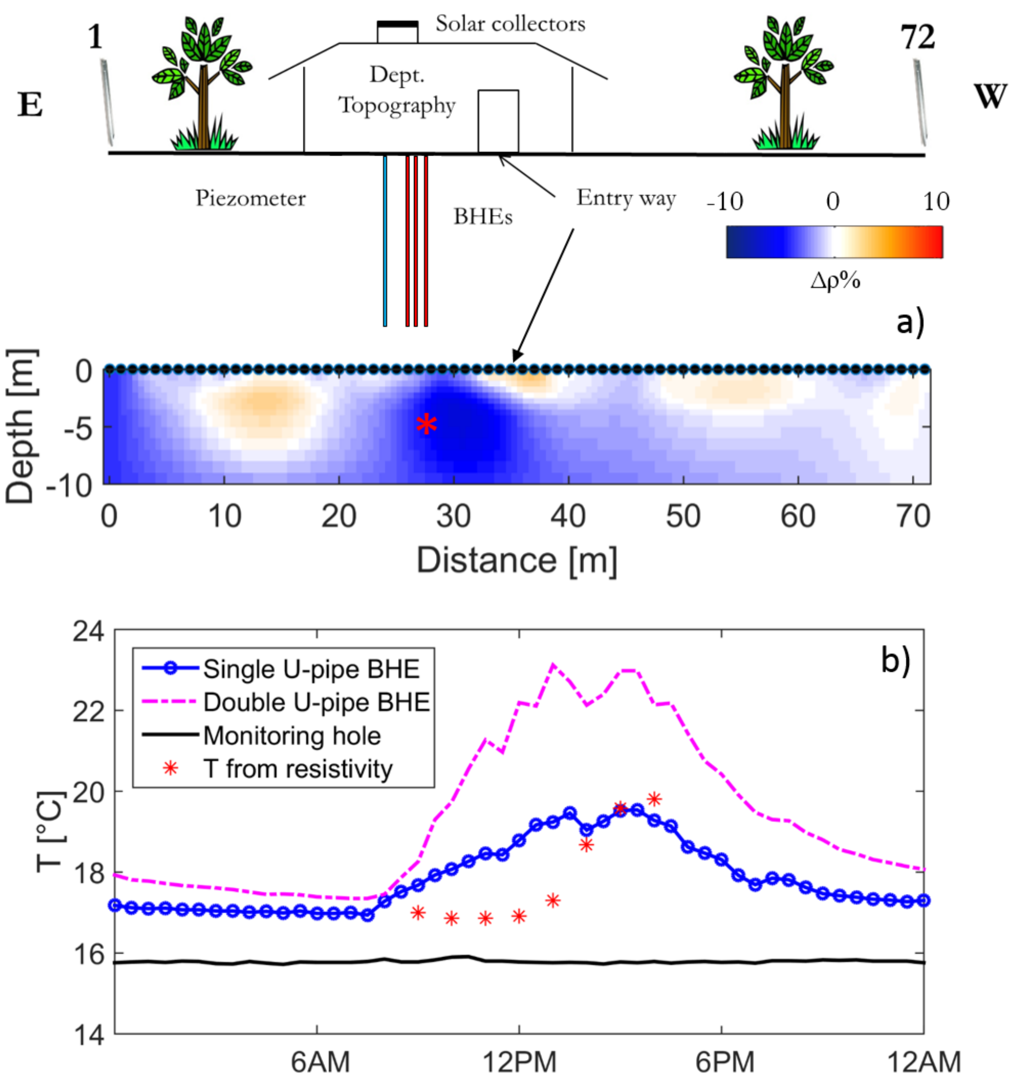

Figure 2 – a) difference resistivity of 4 PM time step with respect to background values and b) comparison between BHE sensors' recordings and ERT-derived temperature. Red star in a) indicates the position of the resistivity values adopted for temperature calculations in b).

The 2D time-lapse data were inverted with the R2 code (Binley, Lancaster University) using the difference inversion algorithm (LaBrecque and Yang, 2001). Supposing the data error to follow a gaussian distribution and smooth changes in the resistivity distribution a least square method was adopted. The starting model of time-lapse inversions of the subsequent time steps was the model resulting from the inversion of background data, thus providing a good starting point for the minimization process. An example of the results that can be obtained during the monitoring of a single heating day (25/07/2015) is reported in this paper. The inversion results (**Fig. 2a**) are showed as the difference between background values and the time step at peak of injection (4 PM). Moreover a comparison between temperature sensors' recordings and resistivity-derived temperature is showed (**Fig. 2b**). The 3-D results are presented in Arato et al. (2015).

The resistivity decrease (in the order of 5-10%) in correspondence of the BHE pipes is compatible with the measured increase in temperature values (2-5°C). ERT-derived temperature shows a 4h delay with respect to sensors' recordings. This is related to the time necessary to heat to pass through the BHE pipes and to start influencing the ground. Unfortunately, because of space limitations, the surveys could not provide a completely satisfactory depth of investigation.

CONCLUSIONS

The results here presented confirmed that ERT surveys can be adopted as monitoring tool for shallow geothermal applications. When the systems are placed below the groundwater table the ERT work well and valid quantitative results can be achieved (Case 1). In presence of unsaturated deposits the long term resistivity monitoring is more difficult, owing to the variation related to other factors rather than temperature (e.g. water content), but a qualitative evaluation of TAZ extension is however reliable (Case 2). Both cases demonstrated that a short-medium testing time gives the best results in monitoring because it is possible to lower the influence of other factors on electric resistivity.

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