LABORATORY SCALE ELECTRICAL RESISTIVITY MEASUREMENTS TO MONITOR THE HEAT PROPAGATION WITHIN POROUS MEDIA FOR LOW ENTHALPY GEOTHERMAL APPLICATIONS

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Introduction. In the context of energy transition, the utilization of the underground as a heat source and a volume for storing the thermal energy has gained increasing importance in recent years. Several kind of low enthalpy geothermal applications were developed and most of them are emerging in various European countries (in particular Northern Europe). Nevertheless, at present no homogenous legislation exists for economical, ecological or political control of these systems. It is common to find different temperature limits for groundwater reinjection and, additionally, various legal constraints for heat transfer (Hähnlein et al., 2011). Within each country it is also not so rare that local governments allow what other administrations forbid. This confusion contribute to obstruct this growing market and does not guarantee a correct design and monitoring of these applications, which are fundamental for a valuable system’s efficiency and safety. The design of these applications is indeed mostly based on literature extracted values of the thermal properties and on numerical simulation of the heat propagation within soils. These assumptions are often inadequate for real applications and they could lead to system’s efficiency problems. According to Leong et al. (1998), coupling of ground data and detailed mathematical model of heat and moisture flow (i.e. numerical simulation) should be the starting point of a reliable design. Conversely there is not still any protocol for a large scale
correct monitoring of these systems besides local temperature measurements carried out in the thermal exchangers themselves.

Basically, two types of geothermal systems use the ground as a heat source - open and closed loop systems. Both open and closed loop systems are generally coupled with electric heat pumps which arise the achieved temperature with a thermodynamic cycle. On the one hand, the open loop systems (aquifer thermal systems) use the shallow groundwater as warm or cold source directly. The groundwater circulates within one or more extraction and injection wells. In summer periods, the groundwater is used to cool down the building and the heat is transferred into the ground, with an increasing groundwater temperature approximately from 6 to 8 °C (Bonte et al., 2011). In winter periods, the groundwater gives the heat necessary to warm up the building, with a consequent cooling effect on the groundwater temperature of approximately 5 to 10 °C being observed (Bonte et al., 2011). On the other hand, the closed loop systems exploit the ground as a heat source. The borehole heat exchangers (BHEs) used by these applications are conductor pipes filled with different heat transfer fluid. The circulating fluid within these pipes extracts the heat from the ground and thereby it influences the ground temperature indirectly. Similarly, other shallow geothermal applications exploit the ground as a storage volume for the thermal energy. These systems are generally called Seasonal Thermal Energy Storage (STES), because they transfer the heat in the ground in the summer periods and they extract it when the heating demand arises, in the cold periods (Xu et al., 2013). The STES systems include several methodologies for storing the heat: for instance the ground is used as storing medium and the connection with the ground is provided by a series of BHEs (Reuss et al., 2006).

In all of the mentioned applications a wide knowledge of the thermal properties of the ground and their influencing factors is needed towards a reliable design, which should be efficient, cost-effective and environmentally sustainable. Moreover, some correct monitoring protocols are required to evaluate the efficiency of the system and prevent environmental problems.

This study aimed at evaluate at laboratory scale the use of non-invasive electrical measurements for the characterization and monitoring of shallow geothermal applications. Electrical measurements could be indeed considered as a time and cost efficient method for the characterization and long-term monitoring of shallow geothermal systems. We have evaluated their potentiality in monitoring groundwater and soil changes under temperature variations by performing laboratory measurements under known boundary conditions in an ad hoc designed thermal box and to analyze the correlation between electrical and thermal properties for different media, taking their influencing parameters into account. This can be viewed as a fundamental calibration step for a further application of the methodology to a real case study.

Theoretical background.

State of the art. So far, there is limited specific knowledge about the long-term effects of unsuitable system design or the effects of groundwater temperature changes and chemical changes within the subsurface and the resulting consequences. A few studies have already measured the thermal effects of geothermal plants within field sites, for instance Huber and Arslan (2012). They also compared their field results with numerical simulations and laboratory measurements with a forced groundwater flow (Arslan and Huber 2013). Nevertheless, these studies do not fill the criteria of being rapid, non-invasive and in-expansive monitoring technologies for efficient applications and environmental protection.

Geophysical methods can conversely provide information over large areas at relatively inexpensive costs compared to other general methods or applications. For example the surface electrical resistivity tomography (ERT) has many practical applications for studying soil properties and processes in the subsurface (Ramirez et al., 1993). In the context of geothermal reservoirs, ERT has already been extensively applied for hydrothermal fluids. For temperatures up to 150 °C, it reveals characteristic specific resistivity values in contrast to their corresponding soil resistivity values. Therefore, with the ERT method, the geothermal
reservoir itself and the flow path can be mapped (e.g. Bruno et al., 2000; Garg et al., 2007). Hermans et al. (2012) demonstrated the ability of ERT to study heat flow and heat storage within a small field experiment in a shallow aquifer. They injected heated water and monitored the electrical values with cross-borehole time-lapse ERT but did not measure the temperature changes. Fragogiannis et al. (2008) also used ERT for monitoring the thermal performance of the ground at the University of Athens with an installed ground-source heat pump system consisting of 12 borehole heat exchangers.

**Electrical resistivity effecting parameters.** The electrical resistivity $\rho$ (or its inverse conductivity $\sigma$) depends on different soil and environmental attributes. Friedman (2005) gave an overview of these parameters and their impact. He stated three categories: 1) parameters describing the bulk soil, such as porosity ($n$), water content ($\theta$) and structure, 2) the time-invariable solid particle quantifiers such as particle shape and orientation, particle-size distribution, wettability or cation exchange capacity (CEC) and 3) fast-changing environmental factors, such as ionic strength, cation composition and temperature. However, these factors do not act separately. For unsaturated soils, porosity ($n$) especially influences the attributes of the second group. So with the main influencing factors of water content and therefore the electrical conductivity of the water/fluid within the soils pores ($\sigma_w$) (Friedman, 2005; Dietrich, 1999), the differentiation of soils as a two-phase system (saturated soils) and as a tri-phase system (unsaturated soils) must be considered.

For the electrical resistivity of soils, as a two-phase systems with negligible matrix conductivity of clay-free porous media, the most important attribute is the conductivity of the fluid within the pores. Therefore, the Archie’s empirical law is the most widely used application:

$$\frac{\rho_a}{\rho_w} = \frac{\sigma_a}{\sigma_w} = \frac{1}{F} = n^m$$  \hspace{1cm} (1)

whereby $\rho_a$ and $\rho_w$ are the resistivities of the mixture and of the saturating water respectively (and $\sigma$ their inverse conductivities), $F$ is a formation factor and $m$ a material-depending exponent (cementation index) of the porosity $n$ (Archie, 1942). Further applications are shown in Friedman (2005) or Sihvola and Kong (1988).

For unsaturated soils as part of a three-phase-system, the $\rho_a$ is a mixture of the soil properties, especially porosity, saturation degree with the fluid composition (ions) and the air content. In this case, Archie’s law can be rewritten as:

$$\rho_a = \frac{\rho_s}{\theta^x}$$  \hspace{1cm} (2)

here, the saturation degree ($\theta$) has to be considered, $\rho_s$ is the resistivity of the solid phase and the coefficient $x$ is the saturation coefficient, that takes different values depending on the saturation level (Dietrich, 1999).

Under laboratory conditions some of the electrical resistivity-influencing soil parameters can be a-priori known (e.g. medium porosity and composition, saturation degree) so that the temperature is the part which can be analyzed to understand the correlation with electrical resistivity. As these are the same influencing parameters for thermal conductivity (Singh and Konchenapalli, 2000; Singh et al., 2001), a general relationship between the electrical ($\rho_E$) and the thermal resistivities ($\rho_T$) can be expected:

$$\log(\rho_E) = C_R \log(\rho_T)$$  \hspace{1cm} (3)

$C_R$ is a multiplier dependent upon the gravel and sand size fraction of the soil (Singh et al., 2001). Different authors (e.g. Singh et al., 2001; Sreedeeup et al., 2005; Fragogiannis et al., 2010) showed this correlation of thermal and electrical conductivities within laboratory measurements for different soils in dependence of the water content.

**Materials and methods.** A common box, sized 1.0 m x 0.4 m x 0.4 m, was prepared for the experimental tests. Within this box, the correlation of the thermal and electrical measurements
can be analyzed for a known porous medium to validate the influences that material characteristics and water content have on them. Within the box, three parts were separated by permeable membranes. For the analyses, the central part, approximately 0.6 m in length, was filled by the porous medium for a thickness of about 0.3 m. In the outer sectors, two PVC pipes were placed surrounded by high porosity material for adjusting the water level and establishing a water flux if needed. In the central sector within the analyzing medium, a thermal resistor, controlled by a thermometer and rheostat to ensure a constant temperature, served as a heat source. Four resistance thermometers (Pt-100) were placed at specified distances from the heat source, while four watermark sensors continuously monitored the soil moisture, assuring a constant water content. A total of more than 50 experiments were carried out. They differ in time of heat up, static or dynamic conditions of water fluxes, number, position, temperature and geometric configuration of the heat sources, position of the T-sensors. During some of these temperature-recording tests, electrical surveys were carried out with different configurations.

Fig. 1 reports the configuration adopted during the tests presented in this paper. The heat source was placed in the center of the box and the T-sensors were aligned, aside of the heat source, along the major axis of the box. For monitoring the electrical resistivity changes in two perpendicular directions, 24 electrodes were placed in a network mode all around the source with a 9 cm spacing. The variation of the apparent resistivity as a function of temperature and time was therefore recorded in different locations. This kind of configuration was useful for checking the heat spreading in a plan view located at about 10 cm depth, which is also the depth of the temperature sensors. The tested porous medium presented in this paper has 91% vol. of sand and 9% vol. of silt, compacted to a porosity of 0.46 and at complete saturation.

Results and discussions. The results of the electrical surveys showed the expected correlation of decreasing electrical resistivity values with the increasing temperature induced by the heat source, the opposite is true after the source’s turn off. The electrical resistivity decreases more slowly with increasing distance from the heat source, as temperature does, and is dependent upon the heat flux within the material.

Fig. 2 shows the comparison between the temperature recorded by each sensor and the apparent resistivity measured close to it. The resistivity changes achieved show an inverse trend with the temperature data. More specifically, a good agreement is clear in the heating period, while a less marked increase in resistivity is noticeable when the source was turned off. The electrical resistivity shows also a slower return to the initial conditions than temperature. As an average, it has been observed that a 10% positive variation in temperature generates a 2.5% negative change in electrical resistivity. Fig. 3 presents the time-lapse sequence of the apparent resistivity during the heating and the cooling period imaged in the plan view.
within the whole central sector. The radial heat propagation is well described by the changes in electrical resistivity, showing an homogeneous radial distribution in the heat up. The more heterogeneously distributed resistivity during the cool down is probably influenced by some evaporation occurred within the medium throughout the test that could have influenced the propagation patterns. This can also partially explain the difference observed with temperature in the cool down period.

The network configuration allowed us to describe the heat propagation in two dimensions around the source. The outcomes highlighted that the heat flows quite homogenously in a radial mode from the source, if no advective flux occurs. The possible differences within the medium, noted in particular in the cooling period, are caused by different water contents due to evaporation phenomenon which influences the local thermal properties. The electrical method was therefore useful to highlight heterogeneous water contents within the medium, key factor in the lab experiments performed for understanding the differences in the heat distribution at different saturation degrees (Comina et al., 2013).

Fig. 2 – Temperature and electrical resistivity differences plotted as a function of time. The lines and the dots show the temperature and resistivity trend respectively. The rounded numbers indicate the steps of the electrical measurements imaged in Fig. 3.

Fig. 3 – Electrical resistivity difference map; plan view 10 cm. deep. The heat source is in the center and each step takes 2 hours. The upper row shows the heating period, while the lower row shows the cool down, after the source was turned off. The position of the heat source and the T-sensors are indicated.
Additionally, the thermal properties of the medium can be achieved by means of the electrical surveys results. Applying Eq. (3), we obtained the thermal resistivities of the medium at each of the 19 steps, starting from the recorded electrical resistivities. We calculated the multiplier $C_R$ with the equations proposed by Sreedeep et al. (2005), founding a value of $C_R = 2.01$. The results, $\rho T$ ranging between 6.56 and 4.56°C m W$^{-1}$, are reported in Tab. 1. The outcomes are rather high for a fine sand but in general accordance with many studies on this topic (Sreedeep et al., 2005; Singh and Konchenapalli, 2000).

**Conclusions.** The first experimental results of this study confirmed the expected correlation of decreasing electrical resistivity with an increasing temperature induced by the heat source. A general negative variation of around 2.5% of resistivity was recorded when a temperature increase of 10% occurs. Moreover, the correlation between electrical and thermal resistivities was tested. Our electrical surveys on the lab device highlighted therefore their potential for monitoring and quantifying the increase in temperature at the respective measuring points and the differences in heat propagation through the medium.

A possible future work that could be carried out includes further testing of different materials under the same conditions, to ensure comparability of the different media and their influencing soil parameters for the thermal and electrical conductivities.

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Further, a numerical simulation of electrical resistivity values for different porous media within the box should be carried out, to evaluate the reliability of frequently-used numerical models for the dimensioning of near surface geothermal systems. Comparisons between the experimental results and the numerical model should be verified. Moreover, the same methodology will also be applied at field scale by performing electrical surveys on a test site of STES system, which is being built at the University Campus of Torino (Grugliasco, TO, Italy). In particular, the network configuration shall be applied with more than 24 electrodes (48 or 72) in order to acquire data for a useful 3D imaging of the subsoil. The periodical geophysical surveys will be coupled with a continuous temperature recording data within the BHEs and the solar panels. A numerical modeling of the site and some direct measurements of the thermal properties will be compared to the geophysical outcomes within a multidisciplinary approach able to achieve reliable and valuable results.

References


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