Improving Thermal Efficiency of horizontal ground heat exchangers

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Keywords: environment resources and sustainability, very shallow geothermal systems, thermal conductivity, backfilling material, heat baskets

ABSTRACT

Since heating and cooling demands constitute almost 50% of the final energy demand in Europe, the development of geothermal energy systems and especially very shallow geothermal solutions, reveals a huge potential in providing thermal energy for residential and tertiary buildings, thanks also to its local availability, manageability and flexibility.

ITER Project (Improving Thermal Efficiency of horizontal ground heat exchangers) is a project (http://iter-geo.eu/) funded by European Commission under the Marie Skłodowska Curie Fellowship Programme (Horizon 2014-2020) focused on improving heat transfer efficiency of existing shallow geothermal systems. The overall aim of ITER is to ensure the sustainability of ground coupled heating-cooling systems and especially the horizontal ground heat exchangers systems. Key challenges are

i. to enhance the heat transfer of the ground surrounding the pipes creating thermally enhanced backfilling material (TEBM) suitable for horizontal systems;

ii. to assess the performance and the environmental impacts of new promising technological solutions as helix systems with and without TEBM;

iii. to monitor the results over time through direct measurements and numerical simulation, in order to understand the heat pollution effect in the surrounding environment.

Thermal laboratory measurements and in situ monitoring of existing and duly installed horizontal systems will be provided by close cooperation between host institutions and non-academic partners.

A test site was realized in Eltersdorf, near Erlangen (Germany): 5 Helix horizontal probes (3m length) were installed at a depth of 0.6 m below the ground level and the trenches were filled in with 5 different materials, ranging from natural material as fine sand (0-1 mm) till commercial products, that will be analyzed also in laboratory.

This paper present the preliminary results obtained during the first months of research activity.

1. INTRODUCTION

The performance of very shallow geothermal systems, as horizontal collector systems or special forms, interesting the first 2 m of depth from ground level, is strongly correlated to the kind of sediment with corresponding grain size, the ground temperature and moisture gradient locally available (Dingmann 2008; Bertermann et al 2015).

As well known by literature, the thermal conductivity of soils depends on texture, temperature, mineralogical and water contents (Farouki 1981; Hiraiwa et al 2000; Gonzalez et al 2012; Nikolaev et al 2013). Among these, the soil moisture content and the grain size are considered as the most influencing factors on the performance of the collectors and the ground heat pumps. In fact, if the soil is dry the coefficient of performance (COP), a technical parameter measuring the heat pump efficiency, suddenly decreases. If an increase of the water content is noticed, then the heat transfer exchange between the ground and the device is improved, due to the replacement of air with water in the pore size, favouring the heat transfer continuity in the medium (Farouki 1981; Leong et al 1998).

In general, in the same saturation condition, the sand shows better thermal performance than clay, silty clay and silty loamy material, due to the high thermal behaviour of its main component, quartz. However, well graded soils can retain a greater amount of water, a very important condition if higher thermal conductivities are desired over time (Moya et al 1998; Saxton et al 2006; Smits et al 2010; Tuller and Or 2005). Moreover, the soil water characteristics are affected by soil texture, organic matter content (OM), soil density, the gravel size particles and salinity (Farouki 1981; Saxton et al 2006).

According to the main findings of recently ended ThermoMap EU Project (http://www.thermomap-project.eu/), the grain size distribution (including information about air capacity (ac), field capacity (fc,) dead water content (dwc), water content (wc), bulk density (BD) values) plays a fundamental role for the estimation of the very shallow geothermal potential (vSGP): an improvement of heat conductivity transfer is expected when the soil water content is increased (Bertermann et al 2014; Bertermann et al 2015).

In coarse soil (i.e. sand, fine sand...) characterized by a high air capacity, the thermal conductivity is reduced due to the presence of air (a good heat isolator) in the voids. In saturated conditions, when in the pore system the air is replaced by water, the thermal conductivity values are expected to increase, determining better condition for the transfer of heat in the same sediments. Therefore, an optimal distribution of air capacity and available field capacity, typical of loamy soils, seems to provide the highest thermal conductivity performance over time (Bertermann et al 2014; Bertermann et al 2015).

Then, a small addition of a natural additive (i.e. clay) to a coarse soil (i.e. sand) leads to an increase in the thermal conductivity, thanks both to the pronounced binding effect noticed in nearly anhydrous conditions and to the increase of the sediment field capacity, defined as the value of water content remaining in a unit volume of soil after downward gravity drainage has materially ceased (Farouki 1981; Nikolaev et al 2013).

A key challenge for very shallow geothermal systems is to understand how to enhance the heat transfer of the sediments surrounding the pipes, taking into account the interactions between the soil, the horizontal heat exchangers and the surrounding environment and the daily and seasonal variability of weather conditions, able to modify the moisture and water content in the first ground meters depth.

Trying to answer to these questions, this research focuses on improving heat transfer efficiency of soils creating thermally enhanced backfilling material (TEBM), using natural materials and acting on their ability to preserve a constant thermal behaviour in the long term.

Given the heterogeneity of sedimentary deposits in alluvial plain and the uncertainties related to the estimation of thermal parameters for unconsolidated material affected by thermal use, physical-thermal parameters (i.e. moisture content, bulk density, thermal conductivity...) are determined in laboratory for sand and loamy sand samples under different degree of water content. In addition, preliminary results for the same material collected directly on a field test site located within an urban area are also shown.

2. METHODOLOGY

The laboratory test working plan foresees to analyze the physical-thermal properties of two natural sediments (fine sand material grain size between 0-1 mm; sand material grain size between 0-5 mm), alone and mixed with two additives, under different water content percentages and different consolidation degree. In addition, also a natural sandy clay sediment will be tested in the same way.

The two additives consists respectively of bentonite and clay powder, commercial products readily available on the market. They will be mixed separately to the natural sediment in different percentages (i.e 8% and 15%).

Each mixture is analyzed under different water content (from dry condition till complete saturation) and under different loads (0-1-3-5 tons).

Main parameters determined for sand and each mixtures, both in laboratory and on test field, are:

i. *thermal conductivity* by thermal properties analyzer (KD2Pro apparatus, Decagon Devices, Inc.). The device consists of a handheld controller and a single needle sensor probe (TR-1, 2.4 mm diameter, 10 cm long needle) operating according to the transient line source method (ASTM D5334-08), between the range 0.1-4.0 $Wm^{-1}K^{-1}$, accuracy ±10% from 0.2 to 4.0 $Wm^{-1}K^{-1}$ and ±0.02 $Wm^{-1}K^{-1}$ from 0.1 to 0.2 $Wm^{-1}K^{-1}$ (Decagon Device; Naylor et al 2015);

ii. *moisture content and bulk electrical conductivity* (measured simultaneously) by time domain reflectometry (TDR) device (TRIME IMKO GmBH). The device allows the determination of the soil moisture content, empirically related to the apparent dielectric constant (k_a) of the soil, thanks to the probe TRIME PICO 32. The measurement range of the probe is between 0-100% θ, accuracy not declared, repeatability 0.30% (IMKO Micromodultechnik GmbH (a)-(b); Susha Lekshmi et al 2014);

iii. *electrical resistivity* by using a high precision instrument for determination of soil resistivity (4point light hp earth resistivity meter, Lippmann Geophysikalische Messgeräte). This resistivity meter provides information on induced polarization of soil (accuracy ±0.2%). It measures the phase shift between the current injected into the ground and the voltage seen at the potential electrodes (Lippmann 2012; Leopold et al 2011);

iv. *bulk density* is determined on duly collected sample (for every moisture content step and each load) according to the DIN 52102;

v. *water content* is determined on duly collected sample (for every moisture content step and each load) according to the DIN 18121;

Grain size and mineralogical content analyses for each mixtures are now under processing and are being completed in the next future.

2.1 Eltersdorf test site

In the framework of ITER Project, a test site was set up in Eltersdorf, about 10 km south-west from the Friedrich-Alexander University in Erlangen, Germany (Fig.1).

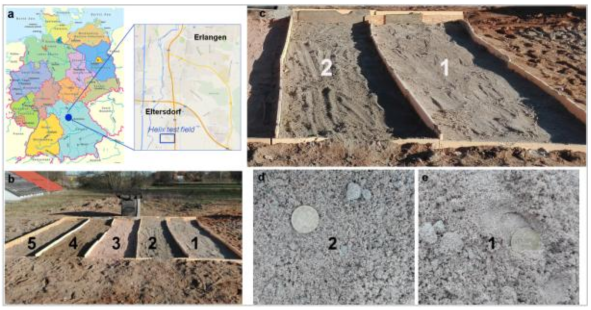

Figure 1: Test site in Eltersdorf, Germany: a) location; b) five sectors filled in with fine sand 0-1 mm (fs0-1mm, 1), fine sand 0-1 mm with 15% bentonite (fsB15, 2), sand 0-5 mm (s0-5mm, 3), sand 0-5 mm + 15% bentonite (sB15, 4), sandy clay (sc, 5); c) focus on sectors (1) and (2); detail of the fine sand (d) and of the mixture between fine sand and bentonite 15% (e)

Five horizontal collectors (3m lenght) made available by the REHAU company, partner of the project, are installed at a depth of 0.6 m below the ground level. Then the trenches were filled in using as backfilling material three natural sediments and two mixtures, that are also being tested in laboratory (Fig.1):

1. fine sand 0-1 mm (fs0-1mm);
2. fine sand 0-1 mm with 15% bentonite (fsB15);
3. sand 0-5 mm (s0-5mm);
4. sand 0-5 mm + 15% bentonite (sB15);
5. sandy clay (sc);

Measurements of thermal conductivity, moisture content and electrical resistivity have been collected monthly since November 2015.

3. RESULTS AND DISCUSSION

Eltersdorf test site

At the time of paper writing, five data acquisition campaigns (16.11.2015; 25.01.2016; 22.02.2016; 05.04.2016; 26.04.2016) were completed at the test site in Eltersdorf and the preliminary results for thermal conductivity and moisture content are here presented (Fig.2).

For each sector under investigation, 3 series of data have been collected by KD2Pro and IMKO. Given that the needle probe of both devices has a length of only 10 cm, the acquired data relate solely to the surface material, more affected by climatic fluctuations. Then, the results presented can be compared with the laboratory data determined for 0 tons load, when available.

In November, the soil mixtures just put in the trenches have not yet undergone the natural compaction due to the weight of the unsaturated sediment. Then the contribution to the heat transfer can be ascribed mainly to the mineralogical composition of the material and the presence of air in the voids.

In January the formation of ice in the ground due to the low air temperatures registered for this month, determines high thermal conductivity values for all mixtures except the sand 0-5mm (s0-5mm). In this last case the sand was so dry from the beginning, not allowing to host pore water converted into ice in the time frame of one month (Fig.2b). However, in the remaining 4 sectors the high λ values are representative of the ice itself more than of the sediments under studying, and they can be neglected in the general analysis of data (Fig.2a).

From February to April, three different trend are visible for thermal conductivity values: (i) the lowest trend (values < 1.3 $Wm^{-1}K^{-1}$) belongs to pure fine sand and pure sand alone; (ii) the highest to sandy clay material ($\lambda > 2.0$ $Wm^{-1}K^{-1}$); (iii) the values in between to the compounds with the addition of 15% bentonite.

The difference in behavior between pure and mixed materials is connected to the moisture content: as visible in Figure 2b, there is a remarkable improvement in the ability to retain water in the pores when bentonite is added to the pure material. In the same climatic conditions, this factor seems greatly contribute to a better performance of the heat exchange within the sediments.

Instead, the sandy clay material shows an intermediate trend for moisture content. However, this condition, combined with the original mineral composition of the sediment, results in the best thermal performance registered on field.

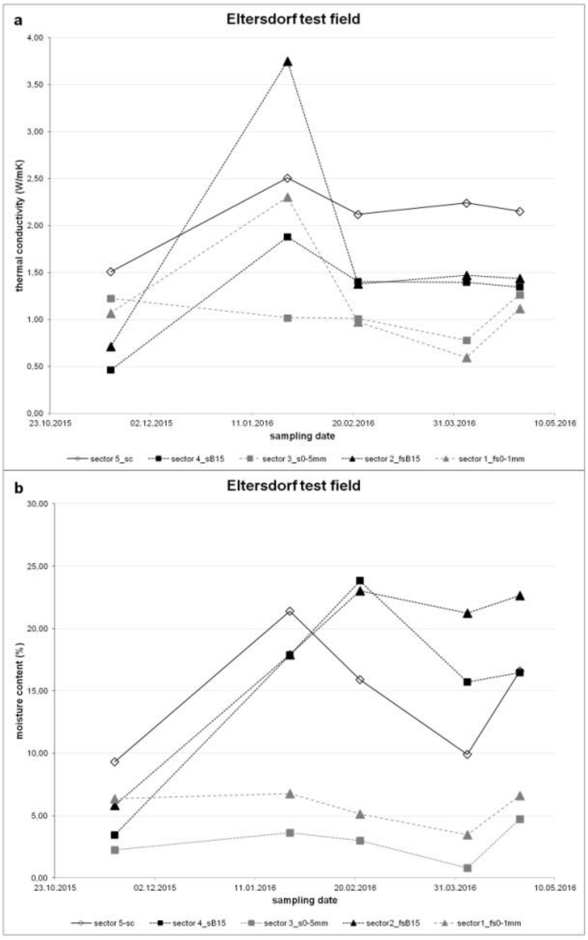

Figure 2: Thermal conductivity (a) and moisture content (b) values collected monthly in Eltersdorf test site, for all the five mixtures used in situ

If only the fine sand mixtures (fs0-1mm and fsB15) are taken into consideration, from February to April, the pure fine sand shows always λ values lower than those of fsB15 (Fig.3). In detail, in the fourth campaign, on a sunny day in the wake of a whole week of good weather condition, the fine sand presented a value of λ=0.595 $Wm^{-1}K^{-1}$, typical of a dry fine sand with a volumetric water content lower than 5% (laboratory data λ=0.724 $Wm^{-1}K^{-1}$ for θ=5.18% at 0t). Instead, the bentonite mixture, subjected to the same environmental conditions, has a value of 1.471 $Wm^{-1}K^{-1}$, that, according to the preliminary laboratory outcomes, is typical of a fine sand with a volumetric water content of about 17% (laboratory data λ=1.480 $Wm^{-1}K^{-1}$ for θ=17.64% at 0t).

Taking into consideration the moisture content acquired by TDR system device, the fsB15 soil shows always a greater ability to retain water than the fine sand alone (Fig.3b). This behavior seems at the base of the better performance of fsB15 registered on the field and is in agreement with the main findings of laboratory measurements registered until now.

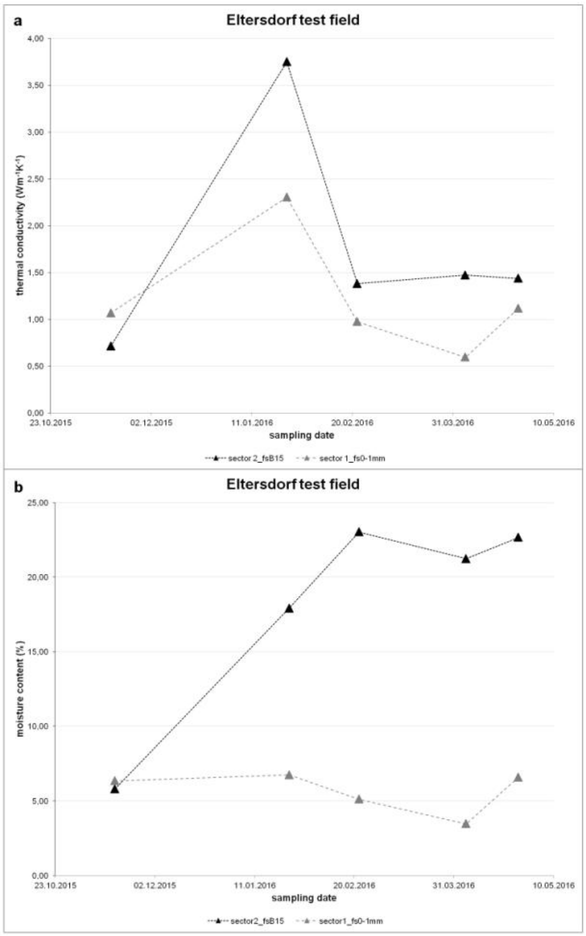

Figure 3: Thermal conductivity (a) and moisture content (b) values collected monthly in Eltersdorf test site, for fine sand 0-1 mm (sector 1) and fine sand with 15% bentonite (sector 2)

4. CONCLUSIONS

The preliminary results of ITER Project, at the forefront of very shallow geothermal research, are encouraging. The analyses performed up to now clearly shows the potential of thermally enhanced backfilling material created using natural components to preserve a constant thermal behaviour in the long term, thanks to their ability to retain water.

In fact, the thermal performance of a fine sand compared to that of soil mixtures with bentonite is strictly related to the environmental conditions:

- if the soils are affected by the same climatic condition, the presence of water in the voids play a fundamental role in enhancing the thermal conductivity. In the Eltersdorf test site, for example, the fine sand 15% bentonite mixture produce the same effects of a fine sand material with a volumetric water content of about 17%, while the behaviour of the fine sand alone in the field is that of a dry material (θ<5%).

In the future, laboratory and test site analyses will continue in order to provide a greater variety of data related to sand material and clay-bentonite mixtures.

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Acknowledgements (optional)

This project has received funding from the European Union’s Framework Programme for Research and Innovation Horizon 2020 (2014-2020) under the Marie Skłodowska-Curie Grant Agreement No.[661396-ITER].