Assessment of thermal conductivity scanner for the determination of soils thermal conductivities for geothermal applications

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ABSTRACT

Laboratory techniques have been developed for the determination of the ground thermal conductivity. Generally those techniques have been initially designed to be used either with rock (cohesive material) or soil (loose material) specimen, but rarely with both type of geomaterials. This paper investigates the feasibility of the use of the thermal conductivity scanner set-up not only with rock specimen, but also with compacted soils. A methodology for the use of this set-up with soil specimen is defined. The methodology is then validated first through the comparison with other experimental data obtained with a thermal needle probe set-up. Then the validation is extended to the comparison between the experimental data and the predictions from existing models providing the evolution of the thermal conductivity with the water content or the dry density.

1. INTRODUCTION

Shallow geothermal energy is a renewable energy source which is easily and worldwide accessible, versatile, local and inexhaustible. Amongst the different techniques closed-loop Ground Heat Exchange (GHE) systems are the most frequent applications for extracting thermal energy from the shallow subsurface. The efficiency of closed-loop ground-heat exchangers (GHE) depends amongst others on the thermal conductivity of the ground. Geological layers with high thermal conductivity maximize the heat transfer between the ground and GHE.

The ground thermal conductivity used in the design of GHE is generally determined through conventional Thermal Response Test (TRT). During a TRT, a constant heat is injected in the water circulating in the pipe of a GHE. The measurement of the temperature rising in the circulating fluid allows quantifying the ground thermal properties through the analytical line source model. TRTs are very robust, easy to implement and straightforward for interpretation. However, the obtained results provide only an “average” thermal response of the ground without any clue on how and where the heat is dissipated in the ground.

Improved methods have been thus developed to determine the ground heterogeneity, such as the distributed thermal response test (D-TRT). It consists in an improvement of conventional TRT with tracking of the temperature at different depths in the borehole by means of thermo-couples or optic-fibres (Acuña et al., 2009). D-TRT allows determining the local thermal conductivity from the temperature gradient of the fluid through a linearization of the temperature profile in a homogeneous layer. Enhanced thermal response tests (E-TRT) have been then developed and applied in boreholes (Heske et al., 2011). E-TRT uses a copper wire to generate a homogeneous controlled heat flux all along the cable installed in the borehole. Simultaneously, the temperature evolution along the borehole is tracked by means of an optic fibre cable. The technique allows the determination of the local ground thermal conductivity with an exact control of the heat power injected in each geological layer.

Even if all those in-situ techniques provide relevant information for the determination of local ground heterogeneity, there is also an interest to develop laboratory techniques to determine the ground thermal conductivity and to better understand the physical and microstructural mechanisms that lead to high or low thermal conductivity. For shallow geothermal energy applications, such laboratory tests should be achieved on soil cuttings collected during drilling operations.

Vieira et al. (2017) propose an extensive literature review and comparison between traditional and new, in-situ and laboratory techniques to measure and determine the average or local ground thermal conductivity. The existing techniques are generally devoted for compacted soils (thermal needle probe) or for rocks (transient plane source or optimal scanning technique), but rarely for both type of geomaterials.

The objective of this paper is to investigate how the optimal scanning technique, initially imagined and designed for measurements on rocks core or samples, can be extended to the measurements of thermal conductivities on soil samples. This technique is indeed fast (compared to thermal needle probe) and accurate, and there is therefore an interest to use a single set-up for measurements of thermal properties on both soils and rocks. This extension to the soil samples requires the definition of an appropriate methodology for the soil preparation and the test procedure. Next, the results have to be validated. In this paper, the experimental data obtained on a silty soil are first validated through the comparison with other experimental data obtained on the same soil with the thermal needle probe. Then the validation is extended to the comparison with existing (semi-)empirical relationships predicting the thermal conductivity according to various parameters as the density, the water content or the quartz content.

2. EXPERIMENTAL SET-UP

The Thermal Conductivity Scanner (TCS) is a non-contact experimental set-up using optical scanning to determine the thermal conductivity of material samples (Popov et al., 1999). The sample surface is heated by means of a focused heat source. Infrared temperature sensors allow the measurement of the temperature increase at soil surface before and after the passage of the heat source, and then the determination of the thermal conductivity of the materials through the Fourier's heat transfer law. TCS presents the advantage to be fast, robust and straightforward for interpretation. This experimental technique has been initially designed for hard materials (i.e. rock, concrete) because the samples have to be installed on 2 punctual supports and need to be self-supported at the centre. The relative accuracy of the thermal conductivity values is equal to 3%.

In practice, two infrared temperature sensors and a heat source are passed in front of black coated samples at a constant distance and constant velocity (Fig. 1). Measurement can be carried out either for plane or cylindrical surfaces of dry or saturated samples. The measurement may be performed directly on the rough surface (surface roughness of up to 1.0 mm) covered with an optical coating (25–40 µm thick) to minimize the influence of the varying optical reflection coefficient.

In this study the TCS technique has been extended for soft materials as soils (Fig. 2). For that purpose, cuttings from drilling are initially compacted in moulds to produce soil samples with similar densities and water contents as in the subsurface.

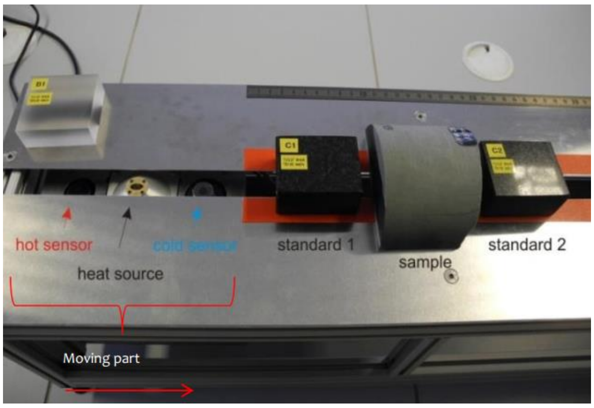

Figure 1: Thermal Conductivity Scanner with rock sample.

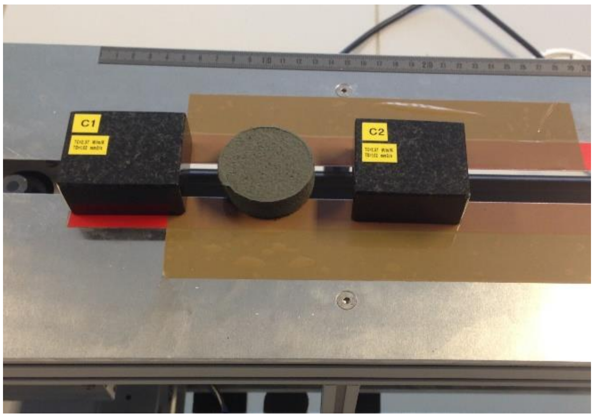

Figure 2: Thermal Conductivity Scanner with compacted soil sample.

3. PREPARATION OF THE SAMPLES

The thermal conductivity scanner can be used with soft soils if compacted soil specimen are prepared. The complexity of the samples preparation is to reproduce similar densities and water contents as in the subsurface, because they are not accurately known. Also, the sample preparation requires spraying of a black coating on one specimen surface. The duration (and in turn the thickness) of the black coating can influence the results. There is therefore an interest to investigate the influence of all those parameters on the ground thermal conductivity. Air-drying of the coating is necessary because the measurement cannot be performed on wet coating. The time between the spray and the measurement is also analysed.

The research has been achieved on a silty soil from Marche-les-Dames, Belgium. The choice of this soil is motivated by the large number of researches already performed in the Laboratory of GeoMechanics at ULB on this soil. The silty soil is made out of 65 % silt and 9 % sand accounting for a quartz content of 70 %.

The standard characteristics for sample preparation are water content of 14.8 %, porosity of 30.4 %, colouring during 2 s, 60 min between colouring and thermal conductivity (TC on graphs) measurements. The sample dimensions are 1.5 cm thick and 5 cm in diameter.

In all the next results, the relative accuracy of the measurements (3%) is represented by error bars.

3.1 Porosity

The porosity of the compacted sample has been tested. Figure 3 highlights the strong influence of the porosity on the thermal conductivity. As expected, denser soil samples exhibit higher thermal conductivity due to better contact between soil grains.

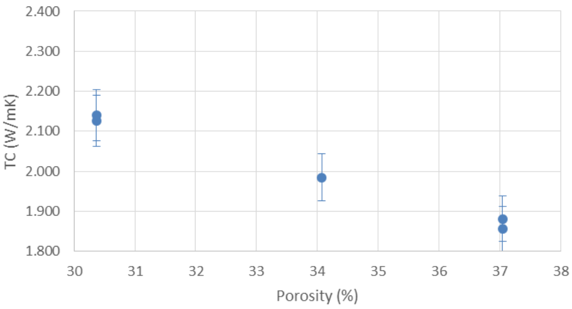

Figure 3: Thermal conductivity (TC) vs. Porosity on MLD silty soil.

3.2 Water content

The water content of the compacted sample has been tested. Figure 4 highlights the influence of the water content on the thermal conductivity. As expected, higher saturation corresponds to higher thermal conductivity due to the high conductivity of the water. Also, a plateau seems to be observed for water content higher than 15%.

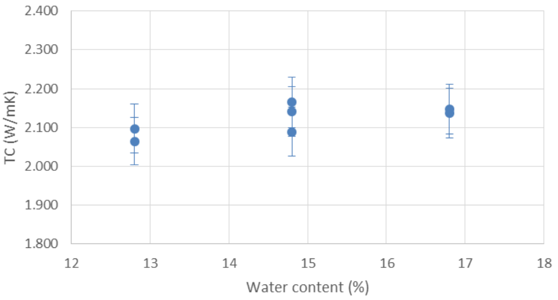

Figure 4: Thermal conductivity (TC) vs. Water content on MLD silty soil.

3.3 Duration of colouring

There is no clear recommendation from the manufacturer on the time of colouring of the sample surface. As illustrated on Figure 5, this parameter influences the thermal conductivity, even if the variation remains limited (and lower than the accuracy of the method). Colouring of 2 seconds has been adopted for the next tests, because the surfaces look generally well coated after 2 seconds of spraying.

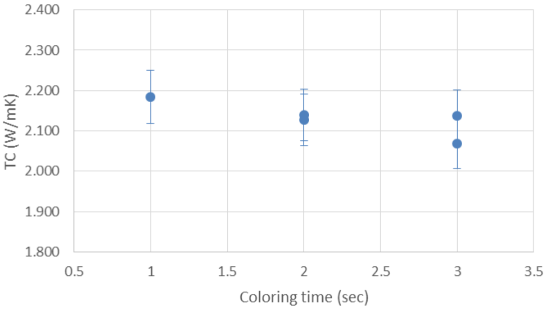

Figure 5: Thermal conductivity (TC) vs. Duration of colouring on MLD silty soil.

3.4 Time between colouring and test

The coating applied on the plane surface has to be dried before the test. The time between colouring and the test can have a strong effect, because specimen are air-dried. That can lead also to change in the sample water content. Figure 6 shows that a plateau is reached after 60 min of drying. This value is adopted for the next tests.

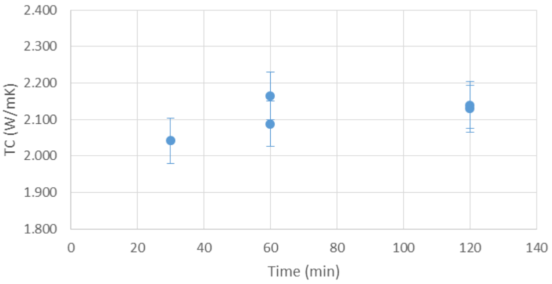

Figure 6: Thermal conductivity (TC) vs. Time between colouring and test on MLD silty soil.

3.5 Definition of a methodology

This tests campaign allows defining a methodology for thermal conductivity measurements by means of the TCS. Colouring during 2 seconds and 60 minutes between colouring and thermal conductivity measurements will be thus considered for future studies. The validation in the next two sections will demonstrate also the relevance of those choices.

4. COMPARISON WITH OTHER LABORATORY TECHNIQUES

Rasson (2013) performed a series of thermal needle probe tests on the same silty soil. He tested also the influence of the water content and the porosity (similarly the dry density) on the thermal conductivity. This research has been achieved in a totally other context (and so with other water contents and dry densities). However it is relevant to compare the experimental data between both studies, even if the comparison if not so straightforward due to different test conditions.

Figure 7 highlights the influence of the dry density on the thermal conductivity. The labels indicate the water contents at which the thermal conductivities have been measured. The results provided by both techniques are relatively similar, even if slightly higher thermal conductivities can be observed with TCS set-up. This comparison highlight the reliability of the thermal conductivity determined by TCS.

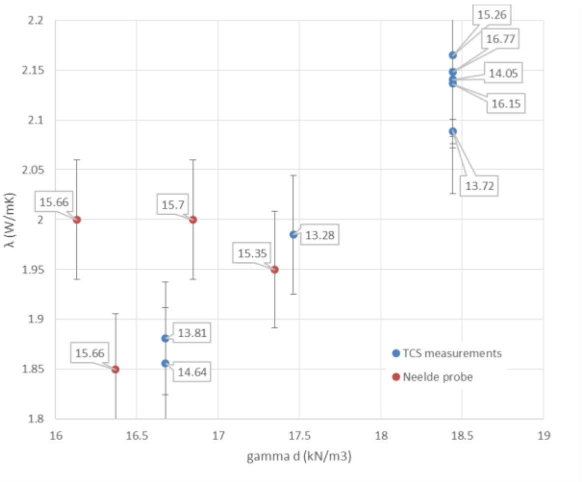

Figure 7: Thermal conductivity vs. Dry density on MLD silty soil. Comparison between thermal conductivities measured with TCS and thermal needle probe. Labels indicate the water content.

5. COMPARISON WITH EXISTING MODELS

Finally it is relevant to compare our experimental data with existing models in the literature predicting the evolution of the thermal conductivity with the water content or the dry density.

For that purpose, a new set of laboratory tests has been performed in order to highlight the influence of a larger range of dry densities for nearly constant water content (=9%). Figure 8 presents the results how those new tests. A clear increase of the thermal conductivity with the dry density if obviously observed.

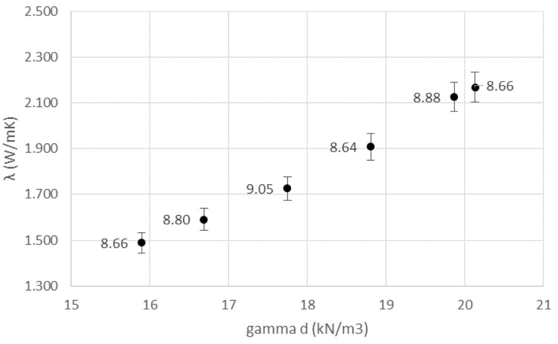

Figure 8: Thermal conductivity vs. Dry density on MLD silty soil. New experimental data for validation through thermal modelling.

Those experimental data will be compared with the prediction of 4 existing models. 3 models have been selected from Rasson's literature review (Rasson, 2013). A more recent additional model is also considered in this section. The four models are presented hereafter. All of them explicitly depend on the degree of saturation S_r that can be calculated from the water content w as:

$$S_r = \frac{w}{\frac{1}{\gamma_d} - \frac{1}{\gamma_s}}$$

where γ_d is the dry density and γ_s is the solid grain density (=2.65 g/cm³ for our silty soil).

Also, the porosity n can be calculated from the dry density γ_d:

$$n = 1 - \frac{\gamma_d}{\gamma_s}$$

5.1 Johansen (1977)

Johansen proposed a semi-empirical model predicting the thermal conductivity as a function of the degree of saturation and the porosity His approach consisted in expressing the conductivity of a moist soil material at a given degree of saturation and porosity by making an interpolation at constant porosity between the conductivity of the soil in a dry and saturated state. He introduced the Kersten number K_e which characterizes the variation of thermal conductivity between the dry and the saturated state at constant porosity. It leads to

$$\lambda = K_e(\lambda_{sat} - \lambda_{dry}) + \lambda_{dry}$$

where λ_{sat} is the thermal conductivity of a saturated soil, λ_{dry} is the thermal conductivity of a dried soil.

$$K_e = \log S_r + 1$$

where Sr is the degree of saturation.

Johansen assumed that the geometric mean equation was a good estimation of the thermal conductivity of saturated soil, as suggested by Hashin and Shtrikman (1961):

$$\lambda_{sat} = \lambda_w^n \lambda_s^{1-n}$$

where λ_w is the thermal conductivity of the water, λ_s the thermal conductivity of the solid grains and n the porosity.

Finally Johansen recommends the following semi-empirical relationship for the thermal conductivity of dry natural soils:

$$\lambda_{dry} = \lambda_{air}^n \frac{n + 6.65(1-n)}{n + 0.053(1-n)}$$

where λ_{air} is the thermal conductivity of the air (=0.024 W/mK).

Figure 9 shows the comparison between our experimental data and the Johansen's model for samples compacted at water contents between 8 and 10%. The best fitting has been obtained for a thermal conductivity of the solid grains λ_s = 4.2 W/mK. This value seems consistent owing to the mineralogical composition of the silty soil, and will be also adopted for the next two models. Figure 9 does not show a good agreement between our data and the Johansen's model.

The slopes for constant water content are indeed not the same. Johansen's model is probably too simplified to be able to reproduce the behaviour of large range of soils, from sand to clay.

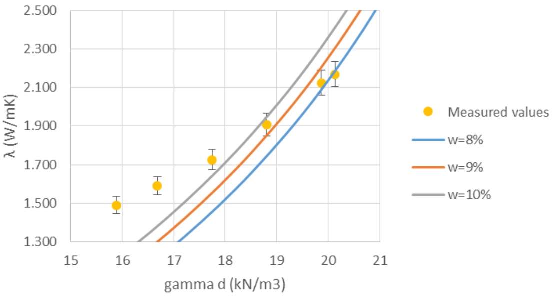

Figure 9: Thermal conductivity vs. Dry density on MLD silty soil. Comparison between TCS data and Johansen model.

5.2 Coté and Konrad (2005)

Coté and Konrad (2005) adopted Johansen's normalized thermal conductivity concept in order to develop a model suitable for all types of soil used as construction material over the whole range of degree of saturation. They noticed that Johansen's empirical equations to determine the normalized thermal conductivity were not valid at low degrees of saturation. They proposed a new generalized equation for the normalized thermal conductivity valid for all soils by introducing the soil-type dependent parameter κ.

$$K_e = \frac{\kappa S_r}{1 + (\kappa - 1)S_r}$$

Based on an extensive study of nearly 500 available experimental results covering crushed rocks, natural gravel, sands, fine-grained soils and peat, Coté and Konrad determined best-fit values for κ. For silty soils, they proposed a value of 1.90. They also reviewed Johansen's equation for dry soils and proposed

$$\lambda_{dry} = \chi 10^{-\eta n}$$

where χ and η are material parameters that take into account the particle shape effect. For silty soils, χ and η are equal to 0.75 and 1.20 respectively.

Figure 10 shows the comparison between our data and Coté and Konrad model (for water contents between 8 and 9 %). Here also, the model fails in reproducing our experimental data. It is also worth to mention that the predictions of Coté and Konrad model seem very similar to the Johansen's model.

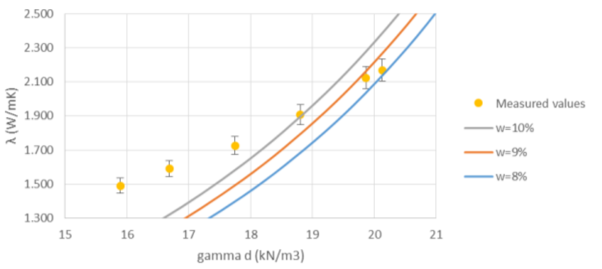

Figure 10: Thermal conductivity vs. Dry density on MLD silty soil. Comparison between TCS data and Coté and Konrad model.

5.3 Lu et al. (2007)

Lu et al. (2007) proposed yet another equation for K_e and λ_{dry} based on their measurement performed on 12 soils

$$K_e = exp\left(\alpha\left(1 - S_r^{\alpha - 1.33}\right)\right)$$

$$\lambda_{dry} = -\Gamma n + \zeta$$

where α, Γ and ζ and empirical parameters. For fine grained soils, $\alpha = 0.27$ whereas values for a and b are 0.56 and 0.51 respectively.

Figure 11 presents the comparison between our experimental data and Lu's model. The agreement is also not perfect, and Lu's model predictions are relatively similar to the two previous models (Fig. 9 and 10).

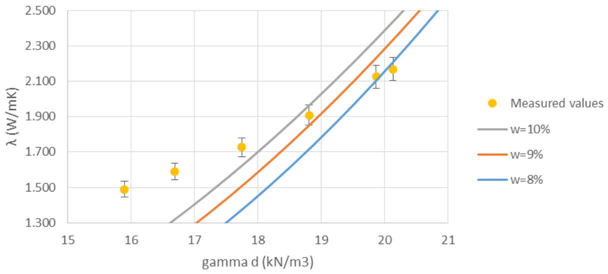

Figure 11: Thermal conductivity vs. Dry density on MLD silty clay soil. Comparison between TCS data and Lu et al. model.

5.4 Nikoosokhan et al. (2015)

More recently, Nikoosokhan et al. (2015) proposed an extension of the previous models, considering soil texture, dry density and water content. In this model, they used also the concept of normalised thermal conductivity. The model considers explicitly the quartz content x_s in the determination of the thermal conductivities of the saturated and dried soil. The Kersten's number K_e is adopted from Coté and Konrad's model. They proposed that the coefficient κ is texture dependent which varies linearly with the quartz content.

$$K_e = \frac{\kappa S_r}{1 + (\kappa - 1)S_r}$$

$$\kappa = e x_s + f$$

$$\lambda_{sat} = a x_s + b\gamma_d$$

$$\lambda_{dry} = c x_s + d\gamma_d$$

where a, b, c, d, e and f are parameters fitted on thermal conductivity values coming from 8 soils from China. They suggest that a is equal to 0.53 W/mK, b to 0.1 Wm²/(K.kN), c to 0.087 W/mK, d to 0.019 Wm²/(K.kN), e to 4.4 and f to 0.4. The quartz content x_s of our silty soil is equal to 70%.

Figure 12 shows the comparison between our experimental data and Nikoosokhan's model. The agreement is here much better, and it highlights the need to consider explicitly the quartz content in a thermal modelling approach.

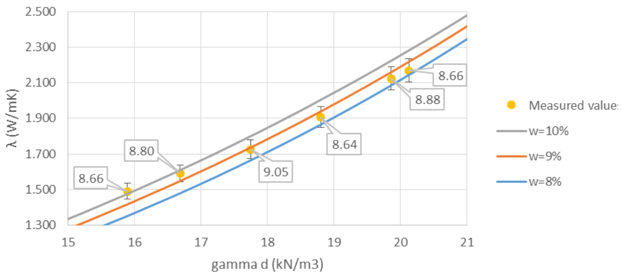

Figure 12: Thermal conductivity vs. Dry density on MLD silty soil. Comparison between TCS data and Nikoosokhan et al. model.

6. CONCLUSIONS

A methodology has been defined for the determination of the thermal conductivity of compacted soil samples by means of the thermal conductivity scanner. This laboratory set-up initially designed for testing rock samples can be also a fast and straightforward technique to determine the thermal conductivity of soils. The comparison with experimental data obtained by means of thermal needle probe and the comparison with existing empirical and analytical models have allowed to validate the methodology.

The next step will be the comparison of local thermal conductivities determined by enhanced thermal response test (e-TRT) and thermal conductivities determined by TCS on cuttings coming from geothermal boreholes.

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