THERMAL RECOVERY TEST FOR DETERMINING THE THERMAL CONDUCTIVITY OF THE SOIL

by

Marija M. VASILEV*[*] *and Miloš J. BANJAC

Department of Thermomechanics, Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia

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This paper presents a new in-situ experimental procedure for determining a thermal conductivity of soil, as one of the thermophysical properties necessary for dimensioning vertical buried heat exchangers of geothermal heat pumps. The proposed method, called the thermal recovery test, is based on the assumption that there is a direct analogy between the hydrodynamic process of filling (recovery) the well with water from a porous aquifer after its partial or complete discharging and the process of establishment of thermal equilibrium in an infinite medium previously disturbed by a line heat sink (source). Apart from presentation the theoretical background of these two phenomena, the display of the identical theoretical logarithmic character of the change of hydrostatic pressure and soil temperature, description of the experimental procedure, the experimental results of three performed experiments are also presented. Additionally, results for the experimentally obtained values of the thermal conductivity of the soil are compared with those obtained from the thermal response test, and the advantages and drawbacks of the new thermal recovery test method are analyzed.

Key words*: thermal conductivity of soil, vertical buried heat exchangers, thermal response test, thermal recovery test*

Introduction

Non-renewable fuels like coal, oil and gas have the most significant role in driving worldwide climate shifts, responsible for more than 75% of total global GHG emissions and nearly 90% of CO_2 emissions [1]. The most common and simplest ways to achieve a reduction of CO_2 emissions are by reducing energy consumption or producing energy without CO_2 emissions (involves systems that utilize RES such as hydropower, wind, solar, geothermal energy, and biomass). Among these, geothermal energy holds significant potential. When it comes to low temperature petrol or hydro geothermal energy, ground source heat pumps (GSHP) play a vital role in utilizing that energy for heating and cooling applications. The GSHP system is a comprehensive technology for heating and cooling applications by using low-grade energy stored in soil [2], and it is gradually promoted [3].

Because of the principles of its operation, GSHP extract additional energy from the ground, enabling it to deliver several times more heat than the consumed electric energy. In the

[*]Corresponding author, e-mail: mvasilev@mas.bg.ac.rs

case that these devices operate using electric energy produced from renewable sources and without additional CO_2 emissions, they can also be considered a type of CO_2 absorption systems.

The GSHP system mainly consists of refrigerant, water-antifreeze and water circuit [4]. In the heat pump, fig. 1, refrigerant circulates in a closed loop for safety reasons [6]. In order to harness the geothermal potential of the ground, vertical borehole heat exchanger (VBHE) are designed. The VBHE comprises one or a series of vertical boreholes drilled into the ground, typically reaching depths of approximately 100 m to 150 m [7]. Through these vertically arranged pipes a mixture of water and antifreeze flows [6] and enables the heat transfer between the surrounding soil and refrigerant to cause its evaporation. On the other side, in the heat pump, the refrigerant condenses by transferring heat to a third working fluid-water, which is heated and flows through heat exchangers located in rooms that need to be heated (heat consumers).

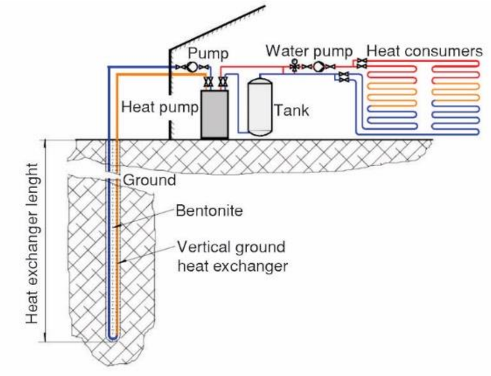

Figure 1. Scheme of a heating system with a geothermal heat pump and a vertically buried heat exchanger [5]

Although the working principle of heat pumps is fully understood and can be described by energy balance equations [4], the performance of geothermal boreholes, which can be represented as linear heat sources/sinks, are insufficiently researched and require simulations and databases.

To ensure adequate performance and energy efficiency of the VBHE within a GSHP system during its design phase, it is necessary to have available data of the thermal properties of the soil (such as density, specific heat capacity, and especially effective thermal conductivity), as well as hydrogeological characteristics of the area, groundwater temperature, *etc*. [8].

Obtaining precise measurements of effective thermal conductivity of soil can be challenging due to uncertainties related to the soil composition, moisture content, groundwater-flows, air volume fraction [9], grain size, bulk density, *etc*. [10]. These factors affect a value of thermal conductivity of the soil and are often not fully known or adequately represented in available data.

In order to overcome these problems, the well-known thermal response test (TRT) is widely used today to determine the required thermophysical data of soil [11] despite some shortcomings. This test originated from the analytical solution of the problem of a line heat source in an infinite medium, as well as the analogy with the hydraulic potential of the soil and Thiem test [12], used to determine the transmissivity of an aquifer [13].

Building upon the idea of an analogy between the thermal and hydraulic potentials of the soil [5], *i.e*. an analogy between the hydrostatic pressure field of groundwater during the non-stationary pumping of water from a well and the temperature field formed in the ground during the non-stationary extraction of its internal energy using a vertically buried heat exchanger, it was assumed that it is possible to define and carry out another type of the test for the non-stationary process of soil regeneration that occurs after the completion of its thermal depletion. By analogy with Theis recovery test [12, 14], used to determine the transmissivity of the aquifer by observing its spontaneous charging after a period of previous discharging, it was assumed that by monitoring the rate of soil recovery after its thermal loads, suitable analogous relationships could be established. In other words, by analogy, a new method for determining the thermal conductivity of the soil could be established – the thermal recovery test.

Theoretical background

Pumping test and recovery test

The use of wells as sources of drinking water or technical water dates back to the very beginnings of human civilization, and the experimental procedures for determining transmissivity – such as line hydraulic sinks, represent well-established and familiar methods. Among the numerous methods for determining capacity of well (or transmissivity of aquifer), probably the most common ones are the so-called pumping test and recovery test.

In the first method (pumping test), the transmissivity of the aquifer is determined by pumping water from the well at a constant rate and observing the decline in water level within the well. If the pumping rate is sufficiently high, due to the limited inflow of water from the surrounding porous soil, the water level in the well will decrease. Since the inflow of water into the well depends on hydrostatic pressure, this phenomenon can be described by the equations of motion of fluids in porous media (continuity equation), expressed by the hydrostatic pressure in the differential form. That equation actually represents Fourier's differential equation in terms of hydrostatic pressure, which in the case of 2-D radial flow in polar co-ordinates becomes [15]:

$$\frac{\partial^2 p}{\partial r^2}+\frac{1}{r}\frac{\partial^2 p}{\partial r^2}=\frac{\mu C_t}{k}\frac{\partial p}{\partial t} \tag{1}$$

where k is the permeability, μ – the fluid viscosity, and C_t – the total compressibility coefficient.

For practical purposes, in eq. (1), instead of pressure figures piezometric level during pumping, h, or drawdown of piezometric level, s, *i.e.* a difference between the piezometric level prior to pumping and piezometric level during pumping, fig. 2, so eq. (1) becomes:

$$\frac{\partial^2 h}{\partial r^2}+\frac{1}{r}\frac{\partial^2 h}{\partial r^2}=\frac{S}{Kb}\frac{\partial h}{\partial t} \tag{2}$$

that is:

$$\frac{\partial^2 s}{\partial r^2}+\frac{1}{r}\frac{\partial^2 s}{\partial r^2}=\frac{S}{Kb}\frac{\partial s}{\partial t} \tag{3}$$

where S is the dimensionless storativity, K – the hydraulic conductivity, and b – the thickness of aquifer layer. A product Kb actually represents a transmissivity of the aquifer [16], while the relationship between hydraulic conductivity and permeability is $K = (k\rho g)/\mu$ [17].

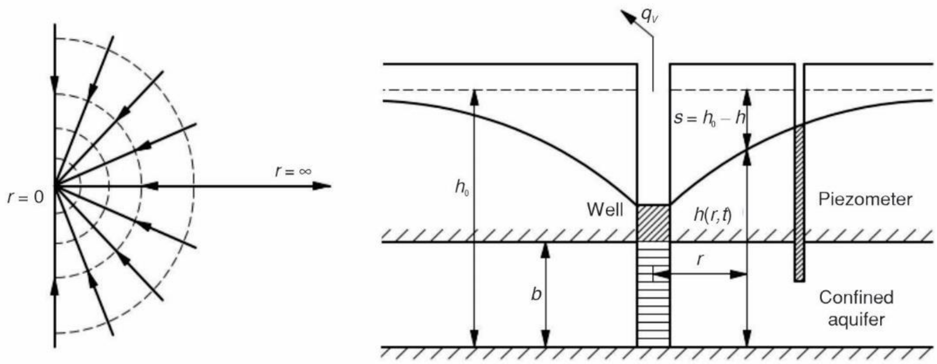

Figure 2. Display of a test pumping of water from a well with the thickness of the aquifer layer, *b* [17]

Starting from the previous equation of motion, eq. (3), Theis [14] derived the equation for unsteady flow for the previously described case of pumping water from a well:

$$s(r,t) = h_0 - h(r,t) = \frac{q_V}{4\pi Kb}\int_u^{\infty}\frac{\exp(-u)}{u}\mathrm{d}u = \frac{q_V}{4\pi Kb}W(u) \tag{4}$$

where q_V is the constant well discharge or well-pumping rate and $W(u)$ – the integral of an exponential function, *i.e.* well function of Theis [14], the solution of which can be represented as a sum of infinite order:

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2\cdot 2!} + \frac{u^3}{3\cdot 3!} - \frac{u^4}{4\cdot 4!} + \ldots \tag{5}$$

where u is:

$$u = \frac{r^2 S}{4Kbt} \tag{6}$$

where r is the distance from the axis of the well and t – the pumping time.

For small values of u ($u < 0.01$), the drawdown can be approximated as [13]:

$$s(r,t) = \frac{q_V}{4\pi Kb}\left(-0.5772 - \ln\frac{r^2 S}{4Kbt}\right) \tag{7}$$

If the pumping rate, q_V, is known, as well as the drawdown, s, in hydraulic head in a confined aquifer at any distance, r, from a well at any time, t, after the start of pumping, it is possible to determine the transmissivity of the aquifer, Kb, [13].

The second most commonly used test for determining the transmissivity of the aquifer (or capacity of well) is the so-called recovery test. The recovery test involves monitoring the rate of water level rise in the well – rate of residual drawdown, from which water has been partially or completely evacuated before. This process is known as the recovery phase of the well, fig. 3. Because of that recovery test can be perform immediately after the termination of the pumping test.

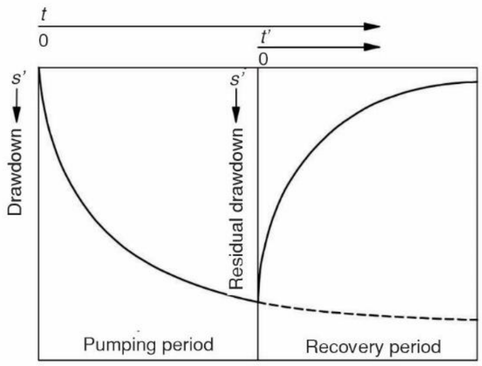

Figure 3. Change of the drawdown of water during the pumping and the recovery period [13]

It is important to notice that residual drawdown data are more reliable than pumping test data due to constant rate of water level rise in the well. The recovery test analysis follows the principle of superposition, assuming that the well is recharging at the same rate as discharging.

Starting from the same eq. (3), Theis [14] derived the expression:

$$s' = \frac{q_V}{4\pi Kb}\left[W(u) - W(u')\right] \tag{8}$$

where s' is residual drawdown and u', similarly as u, is given by:

$$u' = \frac{r^2 S'}{4Kbt'} \tag{9}$$

A time measured from the start of the recovery period is marked with t', and storativity during recovery is marked with S'.

Assuming that $S = S'$ = constant and Kb = constant with the condition that u and u' are sufficiently small (lower than 0.01), eq. (8) can be approximated by [13]:

$$s' = \frac{2.3 q_V}{4\pi Kb} \log \frac{t}{t'} \tag{10}$$

Finally, it follows from the last equation, eq. (10), that the transmissivity of the aquifer, Kb, can be determined if the pumping rate, q_V, and residual drawdown are known, s' [13].

Thermal response test

The TRT has now become widely accepted and almost a standard experimental test for determining the effective thermal conductivity of the soil. This experimental method originated from the analogy with pumping test, an established hydrogeological method used for decades to determine transmissivity of the aquifer. The possibility of establishing this analogy is based on the similarity between the behavior of hydrostatic pressure in a porous homogeneous aquifer and the thermal energy in a homogeneous and isotropic solid body. Consequently, the behavior of these two different physical quantities can be described by the same Fourier's differential equation [15].

The Fourier's differential equation for heat conduction in polar co-ordinates in the 2-D case is given by:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial^2 T}{\partial r^2} = \frac{1}{a}\frac{\partial T}{\partial t} \tag{11}$$

where T is the temperature of the soil and a – the thermal diffusivity.

Using the analogy between thermal potential and hydraulic potential of the soil and the solution of equations for motion of fluids in porous media, eq. (7), the solution for heat conduction equation, eq. (11), for distribution of temperature in an infinite, homogeneous, isotropic medium with a line source that generates heat at a constant intensity can be expressed as [8]:

$$T(r,t) = T_0 + \frac{\varphi_l}{4\pi\lambda}\left(-0.5772 - \ln\frac{r^2}{4at}\right) \tag{12}$$

where T_0 is the undisturbed temperature of the soil, φ_l – the heat rate per unit length, λ – the thermal conductivity of the soil and the time condition $t \geq 5r^2/a$ is considered. If the eq. (12) is presented in a semi logarithmic coordinate system ($\ln t - T$), the change of soil temperature in the axis of symmetry would represent a straight line. Based on that feature, determined conductivity of the soil is possible with the determination of the slope of this line. At the same time, it is necessary to know thermal diffusivity of soil, which is one of the disadvantages of this method.

Thermal recovery test

Upon completion of the TRT, *i.e.* after stop soil heating, due to heat conduction process, soil temperature will decrease, *i.e.* it will tend to return to its original state. That process is named the thermal recovery of the soil. This process is analogous to the prosses of rise in water levels in a well after its previous pumping (rate of residual drawdown). Considering the existence of similarities in hydrodynamic and in thermal phenomena, as well as the already established analogy between pumping test and TRT, it has been concluded that new experimental method for determining the thermal conductivity of the soil, named the thermal recovery test, can be defined.

Additionally, during data processing on changes in soil temperature during and after the TRT, performed in the yard of the Faculty of Mechanical Engineering, University of Belgrade [5, 9], it was observed that the change in soil temperature after completion of the TRT process has the same character as changes in the water level in the well during the recovery period of the recovery test, fig. 4. This observation further raised hopes that a new type of test can be defined to determine the thermal conductivity of soil.

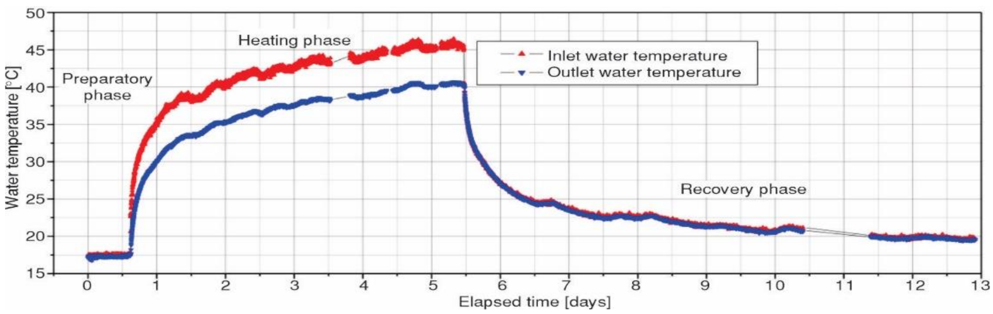

Figure 4. Change of the water temperature at the entrance to the buried heat exchanger and the exit from it during the preparatory, heating and recovery phases [5, 9]

Taking into account all the aforementioned, it follows that the solution of eq. (10) can be written in the form:

$$T'(t') = T_0 + \frac{2.3\varphi_l}{4\pi\lambda}\log\frac{t}{t'} \tag{13}$$

where T' is the temperature of the soil on radius, r, in the recovery period (*i.e*. the arithmetic mean of the inlet and outlet water temperature).

By introducing constant, k_1, as:

$$k_1 = \frac{2.3\varphi_l}{4\pi\lambda} \tag{14}$$

the eq. (13) can be written as:

$$T'(t') = T_0 + k_1\log\frac{t}{t'} \tag{15}$$

Based on the form of the eq. (15), it can be again concluded that if it is presented in a semi logarithmic coordinate system, [$\log(t/t') - T'(t')$], it would represent a straight line and with the determination of the slope of this line is possible to determine conductivity of the soil:

$$\lambda = \frac{2.3\varphi_l}{4\pi k_1} \tag{16}$$

Table 1 was created in order to make it easier to remark analogies between hydrodynamic processes in a porous aquifer and thermal processes in an half infinite medium.

Table 1. Analogical comparison between hydraulic and thermal flow

Hydrodynamic processes in a porous aquifer	Thermal processes in a half infinite medium
Process	
Flow of water	Heat conduction
Analogous laws	
Darcy's law $q_V = -\frac{k}{\mu} A \frac{\partial p}{\partial x}$	Fourier's law $\Phi = -\lambda A \frac{\partial T}{\partial x}$
Analogous tests	
Pumping test	TRT
Recovery test	Thermal recovery test
Fourier's differential equation	
in terms of piezometric level s $\Delta^2 s = \frac{S}{Kb} \frac{\partial s}{\partial t}$	in terms of temperature of soil T $\Delta^2 T = \frac{\rho c_p}{\lambda} \frac{\partial T}{\partial t}$
in polar co-ordinates $\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{S}{Kb}\frac{\partial s}{\partial t}$	in polar co-ordinates $\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{\rho c_p}{\lambda}\frac{\partial T}{\partial t}$
Solution to equation Fourier's differential equation	
$s(r,t) = \frac{q_V}{4\pi Kb}\int_0^t \frac{\mathrm{e}^{-\frac{r^2 S}{4Kbt}}}{t}\mathrm{d}t$	$T(r,t) = T_0 + \frac{\varphi_l}{4\pi\lambda}\int_0^t \frac{\mathrm{e}^{-\frac{r^2}{4\alpha t}}}{t}\mathrm{d}t = T_0 + \frac{\varphi_l}{4\pi\lambda}W(u)$
Solution to pumping test $s(r,t) = \frac{q_V}{4\pi Kb}\left(-0.5772 - \ln\frac{r^2 S}{4\pi Kb}\right)$	Solution to TRT $T(r,t) = T_0 + \frac{\varphi_l}{4\pi\lambda}\left(-0.5772 - \ln\frac{r^2}{4at}\right)$

Experimental procedure and results

Description of the experimental installation

The experimental installation for performing the thermal recovery test shown in fig. 5 is identical to the installation for performing the TRT. It consists of a vertical heat exchanger, 60 m long, buried in a vertical, 16.5 cm diameter borehole (subsequently filled with bentonite), electric boiler, water pump, ultrasonic volumetric flow meter and thermometers.

Water was used as the working fluid. The water-flow was provided by Grundfos UP-Basic 25-4 water pumps. Termomont's electric boiler ETK(E)-9, with a heating capacity of 4.5 kW, was used to heat the water. Danfoss ultrasonic heat meter – SONOMETER TM 1000 equipped with temperature sensors was used as the only measuring equipment for measuring and recording data.

Measuring procedure

The whole experiment was carried out in the laboratory and above the vertical heat exchanger buried in borehole located in the backyard of the Faculty of Mechanical Engineering, University of Belgrade. A necessary preparatory phase for the execution of the thermal recovery test is the process of heating the soil. During the soil heating phase, the rate of heat generation from the heat source was determined and the average heat flow value of 4489 kW was recorded.

Since the soil heating procedure is identical to that used to perform the TRT, this preparatory soil heating phase was used to collect the data necessary to perform a control TRT. The detailed description of the measuring procedure of TRT is given in [5, 9]. After that preparatory phase, the thermal recovery test can be executed. At this thermal recovery test phase, the electric heater is turned off and the water driven by the pump continues to flow through the heat exchanger, changing its temperature in accordance with the change in temperature of soil.

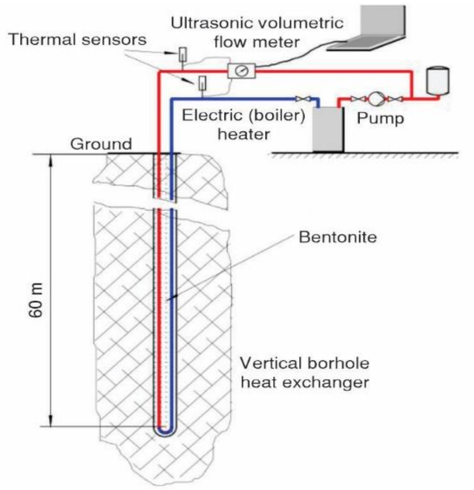

Figure 5. Scheme of experimental installation for determining the thermal conductivity of the soil by thermal response [5, 9] and by thermal recovery test

In order to obtain data about the change of the temperature of the line heat source during the both the soil heating phase and thermal recovery test phase water temperatures at the entrance to the VBHE (incoming fluid temperature, $T_{\rm in}$) and at the exit from it (outgoing fluid temperature, $T_{\rm out}$) were measured and recorded.

The data were recorded every two minutes. These temperature values were used to determine the average water temperature as their arithmetic mean.

To check the reproducibility of the experiment measurements for TRT and thermal recovery test were executed three times with one month time break. The first measurement lasted for three days, the second for seven days, and the third for nine days.

The climate of the location where the experiment was conducted is a humid continental.

Results and discussion

The arithmetic mean of two temperature values measured at the inlet and outlet of the VBHE represents the average water temperature used for data analysis. The average water temperature is presented on a semi-logarithmic diagram on the ordinate, while the ratio, t/t', is represented on the abscissa on a logarithmic scale. A linear fit of the experimental data was achieved using software Origin Pro 8.5, whereby the part of the experimental data from the beginning of the process was excluded in accordance with condition $u' < 0.1$ (*i.e.* $t' > 2.5r^2/a$) [13]. For the purposes of TRT, it was assumed that the thermal diffusivity of the soil, is $a = 10\cdot10^{-7}$ m^2/s [18, 19], which was experimentally found to be made of wet clay, density, $\rho = 1980$ kg/m^3, fig. 6.

The results for the TRT for the first experiment, according to [9] and three thermal recovery tests are shown in the fig. 7(a)-7(d). Based on the slope of the straight line, k_1, obtained by the linear fitting in the software Origin Pro 8.5 and eq. (16), the values of the thermal conductivity of the soil were determined for all three cases. These results and results for the thermal conductivity obtained from the heating phase – TRT, according to [9] are presented in tab. 2. It is obvious that the obtained values of the thermal conductivity of wet clay correspond to the values obtained in laboratory conditions, which, depending on the humidity, are in the range 1.04-1.56 $Wm^{-1}K^{-1}$ [20], 1.44-1.70 $Wm^{-1}K^{-1}$ [21], 0.15-1.8 $Wm^{-1}K^{-1}$ (clay, dry to moist) [22].

Based on the obtained results, it also can be concluded that values of thermal conductivity for all three experiments of the thermal recovery test are close and differ by less than 1%, indicating that this method can provide increased accuracy compared to the TRT, whose values differ by about 3.6%. Also, it can be noticed that values of the thermal conductivity obtained from the thermal recovery test are on average about 2.55% lower than those obtained by the TRT.

Figure 6. The process of drilling a vertical borehole in the yard of the Faculty of Mechanical Engineering

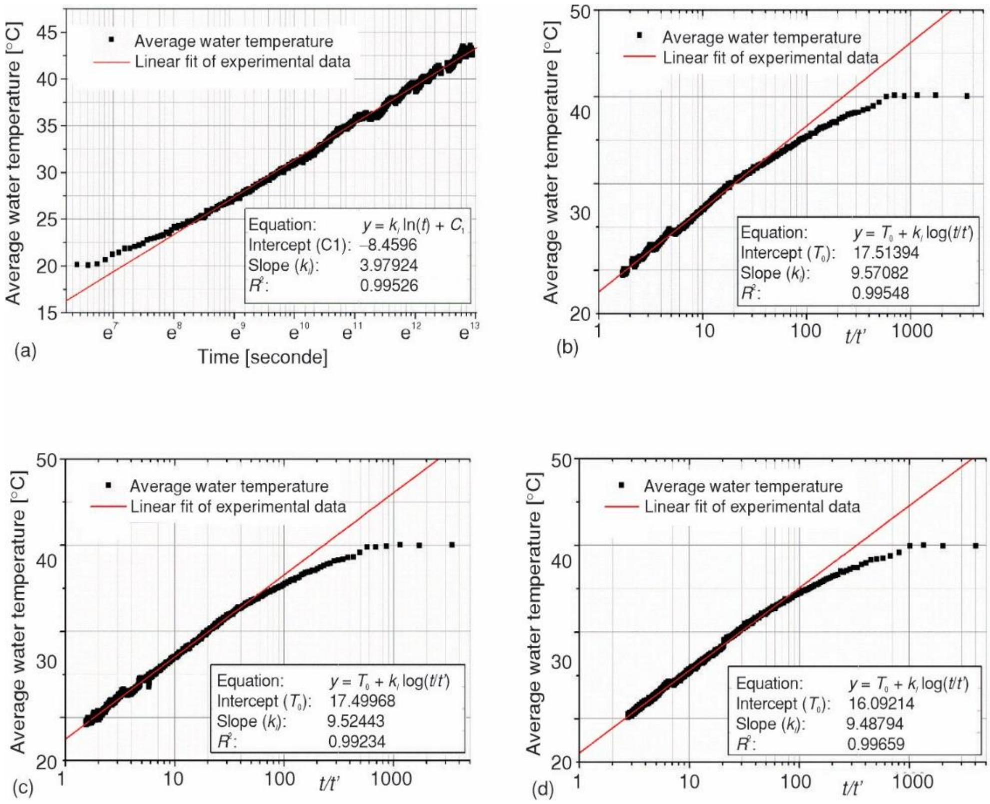

Figure 7. Change in the average water temperature in VBHE and determination of the slope of the straight line, *i.e.* the thermal conductivity of the soil; (a) during the heating phase – measurement No. 1, (b) during the recovery phase – measurement No. 1, (c) during the recovery phase – measurement No. 2, and (d) during the recovery phase – measurement No. 3

Table 2. Experimentally obtained values of the thermal conductivity of the soil (wet clay, density 1980 kgm^{-3}) in the same borehole in three different thermal recovery and TRT

Number of measurements	λ [Wm^{-1}K^{-1}]	
	Thermal Recovery Test	TRT
1	1.431	1.496
2	1.438	1.442
3	1.443	1.488

Conclusions

In order to properly design vertically buried heat exchangers in the ground, as part of geothermal heat pump systems, it is necessary to have data about the thermal properties of the soil, among which thermal conductivity of the soil is the most important. The widely accepted in-situ method for determining this variable is the TRT. To overcome the shortcomings of this experimental method, such as inaccuracies caused by disturbances due to fluctuations in the public electricity grid, which is the usual power supply mode during the TRT, as well as the influence of the outdoor air temperature and necessity to in advance predict value of the thermal diffusivity of the soil, a new in-situ experimental procedure for determining a thermal conductivity of soil is proposed and presented. The proposed method, called the thermal recovery test, is based on the assumption that there is a direct analogy between the hydrodynamic process of filling (recovery) the well with water from a porous aquifer after its partial or complete discharging and the process of establishment of thermal equilibrium in an infinite medium previously disturbed by a line heat sink (source).

In order to check the correctness of these assumptions and the quality of this newly proposed test, its validity and accuracy was checked experimentally. Based on the experimentally obtained data, it was noticed that values of thermal conductivity for all three experiments of the thermal recovery test have good match with the measured values of thermal conductivity of clay in laboratory conditions. Also, they are close and differ by less than 1%, indicating that this method can provide increased accuracy compared to the TRT, whose values differ by about 3,6%. Finally, it was noticed that values of the thermal conductivity obtained from the thermal recovery test are on average about 2.55% lower than those obtained by the TRT. Based on that, it appears that the thermal recovery test could demonstrate higher accuracy and enhanced reliability in comparison to the TRT. Some of the shortcomings of this test could be the significantly longer time required for its performance, and therefore additional financial expenses.

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Nomenclature

a – thermal diffusivity [m^{2}s^{-1}]
b – thickness of the aquifer layer [m]
C_t – total compressibility coefficient [Pa^{-1}]
g – gravitational constant [ms^{-2}]
h – piezometric level [m]
h_0 – piezometric level before start of pumping [m]
K – hydraulic conductivity [ms^{-1}]
k – permeability [m^2]
p – hydrostatic pressure [Pa]
q_V – constant well discharge or well-pumping rate, *i.e.* volumetric flow rate [m^{3}s^{-1}]
r – radial co-ordinate, *i.e.* distance from the axis of the well [m]
S – storativity [–]
S' – storativity during recovery [–]

s – drawdown [m]
s' – residual drawdown [m]
T – temperature of the soil, *i.e.* arithmetic mean of the inlet and outlet water temperature – heat injection period [K]
T' – temperature of the soil, *i.e.* arithmetic mean of the inlet and outlet water temperature – recovery period [K]
T_0 – undisturbed temperature of the soil, before heat injection [K]
t – time [s]
t' – time measured from the start of the recovery period [s]

Greek simbols

φ_l – heat rate per unit length, (= Φ/l) [Wm^{-1}]
λ – thermal conductivity of the soil [$Wm^{-1}K^{-1}$]
μ – fluid viscosity [Pa·s]
ρ – density [kgm^{-3}]

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