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Article

Estimation of In-Situ Heat Capacity and Thermal Diffusivity from Undisturbed Ground Temperature Profile Measured in Ground Heat Exchangers.

Claude Hugo K. Pambou [1,*], Jasmin Raymond [1], Mafalda M. Miranda [1] and Nicolò Giordano [2]

[1] INRS – Institut national de la recherche scientifique, 490 rue de la Couronne, Quebec (QC) G1K 9A9; claude.hugo_koubikana.pambou@ete.inrs.ca (CHKP), jasmin.raymond@inrs.ca (JR), mafalda_alexandra.miranda@inrs.ca (MMM)
[2] Géotherma solutions inc, 13-2528 Avenue de Monceaux, G1T2N7, Québec; nicolo.giordano@geotherma.ca
* Correspondence: claude.hugo_koubikana.pambou@ete.inrs.ca

Abstract: Undisturbed ground temperature (UGT), thermal conductivity (TC) and heat capacity (HC) are essential parameters for the design of borehole heat exchanger (BHE) and borehole thermal energy storage systems. However, field methods to assess the thermal state and properties of the subsurface are costly and time consuming. Moreover, HC is often not evaluated but arbitrarily selected from literature considering the geological materials intercepted by boreholes. Therefore, this work aims at proposing a field heat tracing method to infer the thermal diffusivity (TD) and HC with assumption of natural transient heat conduction in the subsurface. Empirical equations were developed to reproduce a UGT profile measured along a BHE. Experimental coefficients are found with a non-linear least square solver optimization and used to calculate the damping depth and TD. Subsequently, the TD is used to evaluate HC considering TC obtained from a thermal response test (TRT). Results from this proposed heat tracing method were verified and validated against a set of TRT results and oscillatory TRT analysis using a field dual probe concept to infer HC. The example here described highlights the advantages and novelty of this fast and simple field method relying only on a single UGT profile measured before a TRT.

Keywords: heat conduction; thermal properties; geothermal heat pump; damping depth

1. Introduction

Thermal response tests (TRTs) made in borehole heat exchangers (BHEs) are commonly used to infer in-situ thermal conductivity (TC) [1-3]. However, an estimation of the in-situ thermal diffusivity (TD) and heat capacity (HC) is also needed for the analysis of a TRT when applying the infinite line-source equation to reproduce observed temperatures [4]. Unfortunately, HC cannot be accurately evaluated during a TRT [4,5] and core pieces or chip samples can be analyzed in the laboratory to better assess thermal storage properties and reduce uncertainty [4,6]. However, samples are commonly disturbed, and analysis may not be representative of the in-situ conditions. Another common simple practice is to arbitrarily select a literature-based in-situ HC that matches the geological description of materials found in a borehole [7-10]. However, a study carried out by Giordano et al. [11] revealed that typical uncertainty associated to the in-situ TD is about ± 40% when a conventional TRT is analyzed with an approximated HC for common geological materials (1.5 to 3.2 MJ m^{-3} K^{-1}). Therefore, alternative field methods to infer heat storage properties is still need. Oscillatory TRT (OTRT) proposed and discussed by, for instance, Oberdorfer [12], and applied by Giordano et al. [11], have the potential to evaluate the in-situ TD and HC. Although this methodology is an important step taken towards the in-situ evaluation of this thermal property; it still remains complex because of the analysis of the oscillating temperature response and needs more improvement to significantly reduce uncertainty

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(currently on the order of ± 15%). Thus, improving ground thermal properties assessment with simple and efficient methods to infer the in-situ HC, is necessary.

Other alternatives involve the analysis of ground temperature profiles to characterize geological properties [4,11,13-16]. Ground temperature profiles can be acquired with a submersible probe that is lowered into the BHE during or after a TRT[15-16]. These ground temperature profiles can be used to improve the in-situ TC evaluation and horizontal groundwater fluxes estimation [1,13-16]. Moreover, ground temperature profiles measured in the BHE before the TRT have also commonly been used to evaluate the undisturbed ground temperature [10,15-17]. Such equilibrium temperature profiles can be reproduced numerically to extend the conventional in-situ TC assessment of a TRT and to infer the terrestrial heat flow [18,19]. Ground temperature profiles measured in observed wells are also used to evaluate other thermal properties such as in-situ TD [20-24]. A calculated ground temperature profile using such analytical or numerical approaches can be further matched to the observed ground temperature profile and used to evaluate vertical groundwater fluxes and hydraulic conductivity as well as thermal properties of the aquifer [22,25,26]. The method is based on the evaluation of the annual amplitude temperature decay and the annual damping depth during a long-term observation of the ground thermal disturbance diffusion resulting from the annual thermal flux at the ground surface [24,27,28]. Often, one-dimensional semi-analytical to analytical solutions or numerical simulations are used to infer the ground TD with various methods, such as the amplitude ratio, the phase lag, and the harmonic method [10,21-24,27-30]. Despite the potential of these approaches to provide in-situ evaluation of TD, they appear hardly applicable to the design of ground-coupled heat pump systems. The main reason is the time required to continuously measure the ground temperature profiles during several days to a year, in order to record a periodic cycle of heat diffusion in the subsurface [10]. As a matter of fact, field measurements of prefeasibility studies for the design of ground-coupled heat pumps must be conducted within a few days, for instance 2-3 days when considering the heating period of conventional TRT or up to 5 days if the recovery phase of the TRT is included in the analysis [1-4,10,11,16,33]. Recently, Márquez et al. [10] proposed a methodology for the indirect evaluation of the in-situ TD. This approach assumes transient heat conduction in a semi-infinite medium and is based on the evaluation of the minimum and the maximum mean annual ground temperature measured in a shallow borehole and the depth where that mean annual ambient temperature is observed in the ground. In other words, the method proposed by Márquez et al. [10] is based on the assessment of the depth at which the annual ground temperature remains constant throughout the year (i.e., where there are no seasonal variations). That observed value is called the undisturbed ground temperature (T_{UGT}) [34,35]. The results obtained by Márquez et al. [10] were consistent with TD of mean geological materials identified from a reference borehole. However, this approach requires continuous ground temperature measurements during seven days to a year to identify and confirm the depth where T_{UGT} is located. This field approach is time consuming for a ground-coupled heat pump project. Moreover, the result is sensitive to measurement errors since it is based on a single evaluation of T_{UGT} [21,29,36]. An entire temperature profile may provide more information from the BHE (in terms of geology and thermophysical properties of the geological materials) and thus potentially minimize uncertainty [10,15,16].

All the aforementioned difficulties in assessing accurately and quickly the in-situ HC can eventually contribute to increasing errors in the design of geothermal heat pump systems and ultimately impact their installation cost [4,11]. Therefore, evaluating the in-situ HC can be useful for simulating the operation of BHEs used for both ground-coupled heat pump and underground thermal energy storage systems [11]. In fact, Giordano et al. [11] study indicated that the total drilling length of BHEs calculated when designing a ground-coupled heat pump system can be affected by ± 6–7%, which influences the total system cost by 3–4%. This clearly highlights that an accurate evaluation of the in-situ HC can help to better design ground-coupled heat pump projects by accurately targeting their installation cost and, therefore, positively impacting the geothermal heating and cooling market [4,11,37,38].

Thus, bearing in mind the importance of a quick and accurate assessment of in-situ HC, this research study had the objective of developing an alternative heat tracing approach to evaluate this thermal property considering the main guidelines of the TRT [1-11]. This study was carried out within the scope of a TRT performed in a pilot BHE [10,16]. The resulting method relied on the measurement of a single equilibrium temperature profile that is not disturbed by the heat injection of a TRT or drilling of the BHE and can be recorded before the TRT. Analysis of this equilibrium temperature profile using heat tracing principles allowed the evaluation of in-situ TD. Afterwards, HC was calculated based on the in-situ TC evaluated with a TRT. This heat tracing method appears rather novel as it is performed in a short amount of time. Moreover, it uses a single observed temperature profile at equilibrium and a TC assessment obtained from a TRT analyzed with the slope method. The methodology proposed does not need additional borehole or several temperature measurements. Finally, it does not depend on a priori knowledge of the Earth heat flow since it is only based on an empirical approach to reproduce the observed undisturbed ground temperature profile measured in the BHE.

2. Methodology

2.1. Theoretical background

General concepts used in this heat tracing method are described below to provide the basis of the new field approach developed and applied in this study. The observed undisturbed ground temperature value (T_{UGT}; °C) is used in this newly proposed method as a criterion to constraint the analysis, and the damping depth and the curve-fit between observed and calculated undisturbed ground temperature profile in order to infer in-situ TD.

A recognized practice to accurately evaluate T_{UGT} is based on the graphical selection of the depth interval to be used for evaluation of the mean ground temperature [9,16,34,38], discarding near surface data that visually appears to be affected by surface thermal disturbances. That depth at which T_{UGT} is found or at which thermal disturbances from the surface are not perceived is called the depth of zero temperature amplitude (Figure 1) and it defines the boundary between thermocline and the thermostatic zones, where the geothermal gradient can be observed [34].

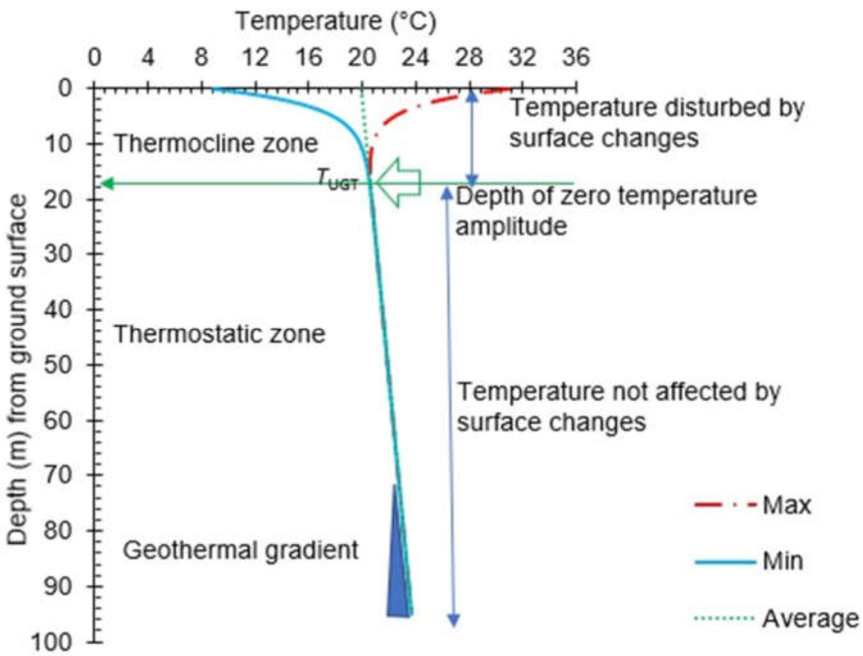

Figure 1. Theoretical ground temperature distribution showing the depth of zero temperature amplitude. The blue triangle indicates the geothermal gradient.

Usually, estimation of the depth of zero temperature amplitude requires monitoring ground temperature profile at different depths on a yearly basis [9,34], which we want to avoid here to fulfill the TRT practice [3, 7, 10,16]. For this new method, the acquisition and analysis of ground temperature observations need to be short enough for the test to be reasonably implemented during prefeasibility studies of ground-coupled heat pumps.

Additionally, analysis of the daily ground temperature distribution during seasonal or yearly observations have revealed a near surface depth from where the initial temperature amplitude is damped in the thermocline zone [20,22,28,34,35]. From that so-called damping depth, the wave of the oscillatory surface temperature begins a linear attenuation with depth in the interval located before the thermostatic zone (Figure 2).

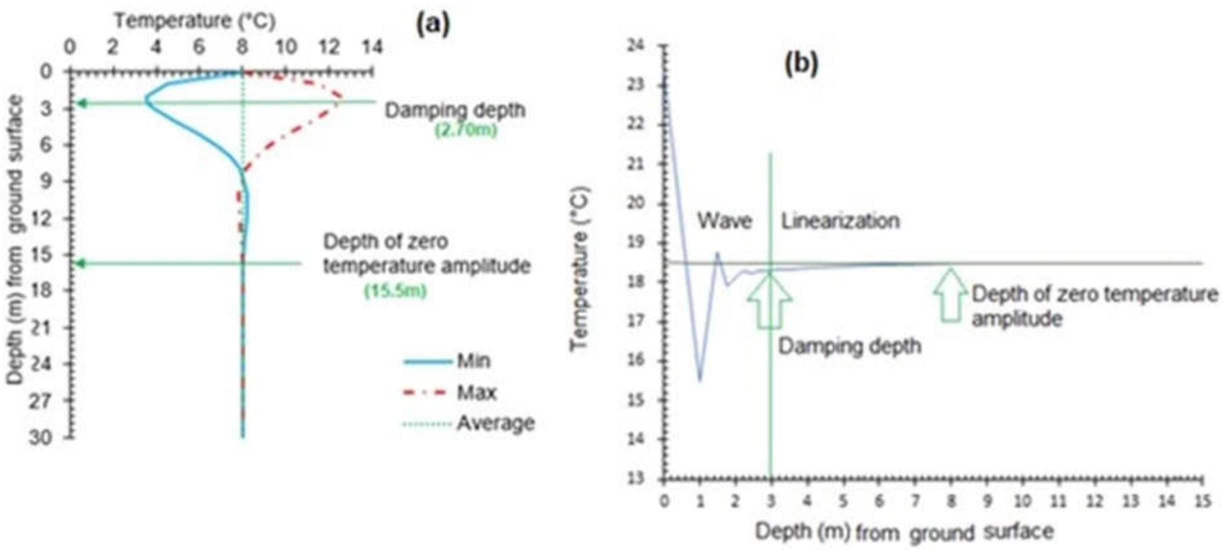

Figure 2. Ground temperature distribution showing the damping depth and the depth of zero temperature amplitude, with (a) annual ground temperature profile span, and (b) components of the daily oscillatory ground temperature influenced by surface temperature variations diffusing in the shallow subsurface.

A practical approximation ratio is used to evaluate the damping depth by considering the depth where the surface temperature amplitude is reduced to e^{-1} (1/2.718 = 0.37) of its initial value [20-36,39-41]. Beyond the approximation ratio approach, several other mathematical equations have been proposed to evaluate the damping depth. Those are based on the sinusoidal propagation of surface temperature changes in the ground, the mean ambient temperature, or the temperature amplitude variation with depth/time [25-36,39-42]. The mathematical formulations are, for instance, the amplitude decay method, the phase lags method, or the inverse slope of a linear regression method [34,35]. Additionally, Taniguchi [20], Stallman and Gold [25,26] and Tong et al. [28] proposed an analytical parameter method to compute damping depth based on its dependence on subsurface thermal properties (TD, TC and HC) and hydraulic properties (porosity and Darcy flux). However, these listed approaches require series ground temperature profiles measurements which is time consuming and less attractive when considering the scope of TRT.

Therefore, a new empirical equation is proposed to compute the damping depth. It relies on empirical coefficients found by least square method with a solver applied to the curve-fit of observed and calculated ground temperature profile.

2.2. Model assumptions and parameter estimation procedure

In this research work, it was assumed that an accurate observed T_{UGT} value can be found by averaging ground temperature profile measured in the thermostatic zone [10,17,34]. Thermal disturbances caused by surface temperature variations propagate by transient heat diffusion in the semi-infinite isotropic and assumed homogeneous subsurface [9,20-34]. The latter implies that the diffusion of surface temperature variations can be described by a sinusoidal function or an exponential form of the one-dimension solution governing heat conduction [9,20-34].

Theoretical and field results have demonstrated that in-situ TD could be evaluate using ground temperature profiles measured in the borehole [9,20-34]. Usually, a general equation of the heat conduction or conduction-advection solution is applied to generate ground temperature profiles that are fitted to the observed ground temperature profiles.

Thus, in this project, a ground temperature profile (T_{obs} (z)) is measured in the BHE before carrying out a TRT. Then, a heat transfer equation can be applied to the observed ground temperature profile, considering TD as an unknown parameter. With this assumption in mind, an empirical equation (Eq. 1) was developed to calculate a normalized ground temperature profile (T_g (z)) of the observed ground temperature (T_{obs} (z)), in which it is possible to evaluate a damping depth (Z_{dd}) in order to infer TD by common analytical equation and the calculated undisturbed ground temperature (C_1) at the depth of zero amplitude temperature.

A trial-and-error approach could be used to retrieve and approximate C_1 and Z_{dd}, but the analysis would be time consuming when considering the scope of TRT. Therefore, a heat transfer equation (Eq. 2) related to the surface temperature variations and a solver optimization (Eq. 3) are suggested as the fastest method to accurately find C_1 and Z_{dd} values. These results are subsequently validated using Eq. (4) and the curve-fit of the observed temperature against normalized depth-temperature profiles (Figure7).

Detailed explanations of each equation used in this proposed heat tracing method are presented in the following subsection.

2.2.1. Calculated undisturbed ground temperature profile

An empirical heat conduction equation (Eq. 1) was developed with the goal of calculating a normalized ground temperature profile at any depth z considering the entire length of the BHE. This proposed equation could be used to approximate the one-dimensional solution of the governing heat conduction equation considering a surface temperature diffusion in the half-infinite medium [9,21,23,40-42]. The proposed equation was described as with an exponential form to normalize each observed ground temperature (T_{obs} (z)), and it is defined as:

$$Tg(z) \cong \frac{C_1}{T_{bot}} \times T_{obs}(z) + 0.24615 \text{x} \, e^{\left[0.001257 - \frac{Z_{dd}}{L_{obs}}\right]} \tag{1}$$

where T_g (°C) is the normalized ground temperature at depth over the entire length of the BHE, C_1 (°C) is the average ground temperature at the depth of zero temperature amplitude, T_{obs} (°C) and T_{bot} (°C) are the observed temperature at any depth and at the bottom of the borehole, respectively, Z_{dd} (m) is the damping depth and L_{obs} (m) is the length of the borehole surveyed.

Each ground temperature value calculated using Eq. (1) is assumed to be a normalized value of the measured ground temperature at each depth over the entire length of the BHE.

Applying the heat balance concept, it is assumed that Z_{dd} and C_1 are integrated parameters of the thermocline zone (Figures 1-2) and the interpolated undisturbed ground temperature at the depth of zero temperature amplitude, when considering one-dimension heat conduction, respectively [19-24,27,28, 32-34]. Therefore, an equation can be used as upper boundary condition to describe the surface temperature variations transferred to the subsurface by oscillatory heat diffusion [28, 33,43-46]. Thus, the calculated ground temperature was defined as sinusoidal function of the heat diffusion:

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$$T_{\text{calc}}(z) \cong C_1 + C_2 \cdot e^{(C_3\text{-}C_4 \cdot z)} \text{SIN} \left[2\pi\text{-} \frac{z}{0.6027315 \cdot C_3 + C_4} \right] \tag{2}$$

where C_1 (°C), C_2 (°C), C_3 (m) and C_4 (m) are experimental coefficients that can be found by using a non-linear solver optimization (Eq. 3) related to the objective function (OF) and defined as:

$$OF = \sum_{1}^{N} \frac{1}{T_{obs}(z)} [T_{obs}(z) - T_{calc}(z)]^2 \tag{3}$$

where *OF* (°C) is the sum of the squared residual computed from the difference between observed and calculated temperature at the same depth. 1 to N is the depth interval distribution covering the total length of the BHE.

The optimization function *OF* is validated when the bias error (*BE*) between C_1 and the T_{UGT}, inferred from the ground temperature profile measured in the BHE, is less than 5%, such that:

$$BE(C_1, T_{UGT}) < 5\% \qquad \text{where } BE \text{ in } \% = [1\text{-}\frac{C_1}{T_{UGT}}] \text{ x } 100 \tag{4}$$

2.2.2. Calculated damping depth

Using the experimental coefficients from Eq. (2), Z_{dd} is computed by a novel proposed field correlation, defined as:

$$Z_{\text{dd}} = 0.6027315 \cdot C_2 + C_3 \tag{5}$$

2.2.3. Calculated subsurface thermal diffusivity

In-situ TD can be inferred using the damping depth method, defined as [10, 22-40]:

$$\alpha_{\text{calc}} \cong \frac{\pi \ (Z_{\text{dd}})^2}{P} \tag{6}$$

where α_{calc} ($m^2\ s^{-1}$) is the calculated effective thermal diffusivity of the subsurface and *P* (s) is the harmonic period for a radial frequency of the sinusoidal thermal penetration in the subsurface and is assumed as a year equal to $P = 31536000s$.

2.2.4. Calculated subsurface volumetric heat capacity

In-situ HC is calculated directly from the analytical thermal diffusivity equation, with respect to the thermal conductivity inferred from a TRT done in the BHE [4,11,47]:

$$HC_{\text{calc}} = \frac{\lambda_{\text{eff}}}{\alpha_{\text{calc}}} \tag{7}$$

where HC_{calc} ($J\ m^{-3}\ K^{-1}$) is the in-situ heat capacity and λ_{eff} ($W\ m^{-1}\ K^{-1}$) is the effective thermal conductivity inferred from the TRT.

2.3. Quality of parameter estimation

Statistical parameter analysis was used to evaluate accuracy and efficiency of the correlation between observed and calculated temperature. Relative error (*RE*) and root mean square error (*RMSE*) were calculated as:

$$RE = [1 - \frac{y_{calc}}{y_{obs}} \times 100], \tag{8}$$

$$RMSE = \left[\frac{1}{N} \sum_{0}^{\infty} \frac{1}{y_{obs}} [y_{obs} - y_{calc}]^2 \right]^2, \tag{9}$$

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where y_{obs} and y_{calc} are the observed and calculated parameters, respectively. N (-) is the total number of observations from the equilibrium temperature profile. RE (%) is an indicator of an overestimated (positive difference) versus an underestimated value (negative difference), while the $RMSE$ (-) indicates the deviation magnitude in the range value.

2.4. Stepwise procedure for parameter assessment

The following stepwise procedure (Figure 3) is suggested to summarize the parameter estimation analysis:

1. Accurately measure an equilibrium temperature profile (T_{obs}(z)) in a BHE and apply proper corrections for the rise of the water level in the U-pipe when using a wired probe as suggested by Pambou et al. [16];
2. Perform a standard TRT and evaluate in-situ TC;
3. Prepare the solver optimization to reproduce the normalized temperature profile (T_g(z)) through Eq. (1) to (5);
4. Match the observed and calculated temperature profile using Eq. (2) and refine the results by minimizing BE (Eq. (4)), which describes the difference between T_{UGT} and C_1;
5. Evaluate the quality of parameter estimation using statistical analyses (Eq. (8) and Eq. (9)) and proceed to the next step when the results are within the best value range and thus considered acceptable by statically analysis (Eq. (8-9));
6. Calculate the damping depth Z_{dd}, in-situ TD and HC (Eq. (5) to Eq. (7)).

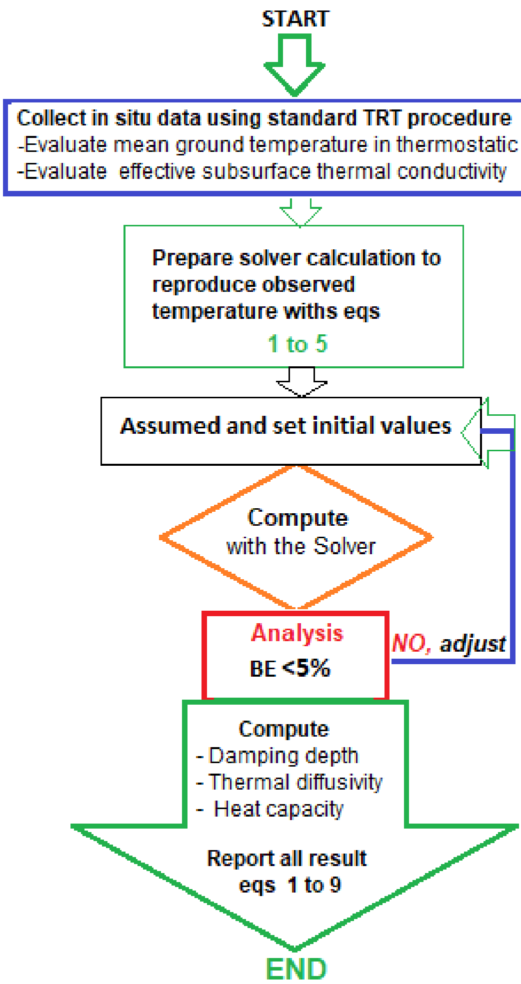

Figure 3. Procedure for assessing the in-situ HC from a temperature profile undisturbed by a TRT and the in-situ TC inferred from the TRT.

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Microsoft Excel spreadsheet and its solver were used in this research work to implement the equations, found the empirical coefficients by optimization, and use the newly proposed method. The validation of the methodology is given in the next subsection.

2.5. Validation of the proposed method

The methodology proposed in this research work was verified and validated by evaluating the in-situ HC at the INRS geothermal experimental site in Quebec City (Figure 4). This geothermal experimental site was chosen for its scientific and technical interest due to the availability of BHEs and observation wells. In fact, several research works have been conducted at this site to improve the design of the BHEs and the methods for characterization of thermal properties [4,11,9,20,21,40-42]. For example, several field measurements were performed with different equipment to accurately assess T_{UGT} [4,10;16] and several types of TRT were carried out in different seasons (fall, winter, summer) to infer TC and borehole thermal resistance [4,10,11,16,33]. Recently, other work of interest was made to evaluate heat flux density [19], subsurface thermostratigraphic log and groundwater flow [16], as well as in-situ HC evaluation [11].

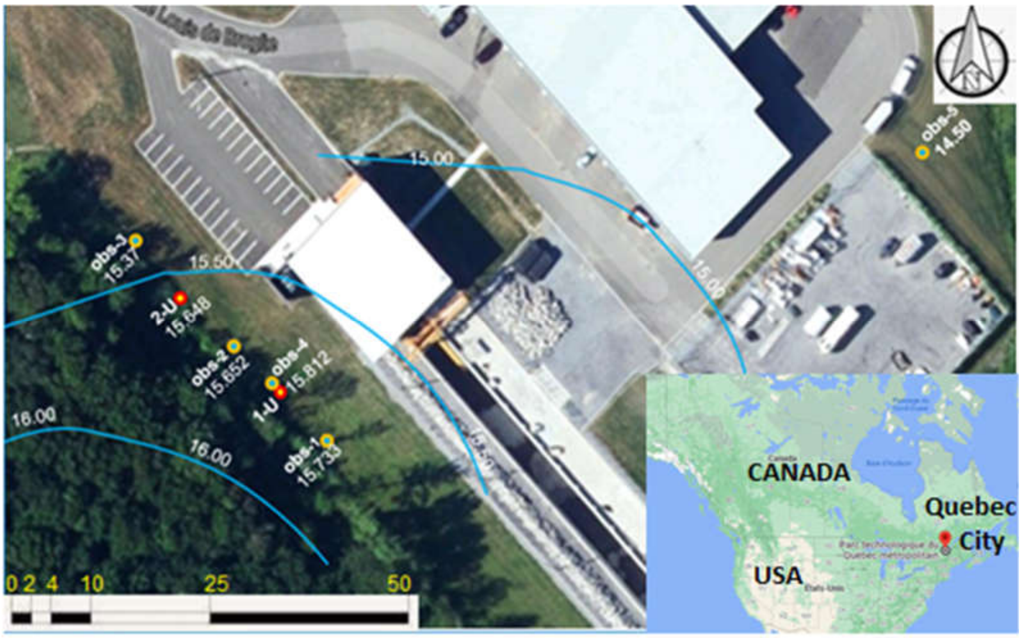

Figure 4. Geothermal experimental site at INRS (Quebec City). Numbers beside boreholes (obs and U) in white and along blue lines indicate elevation of the water table in meter above the sea level and local potentiometric level, respectively [7]. Obs are for open observation wells, while 1-U and 2-U are the borehole heat exchangers.

2.5.1. Borehole heat exchanger and site description

This geothermal experimental site has two BHEs (1-U and 2-U; Figure 4) and five observation wells (obs; Figure 4) that were installed from 2015 to 2020. The single U-pipe BHE used in this study has a diameter of 114 mm (4.5 in) and is grouted with a mix of bentonite and silica sand down to an entire depth of 154 m.

The subsurface described at the site of INRS consists of shale bedrock under an overburden of 10 to 14 m in thickness (see Figure 5, for an example at the location of the 1U-BHE). The shale bedrock is fractured, and groundwater fluxes were inferred in the fractured zones [10,16]. At the site, elevation of the water table varies from 14 to 16 meters above the sea level with northeast flow direction towards the Saint-Charles River.

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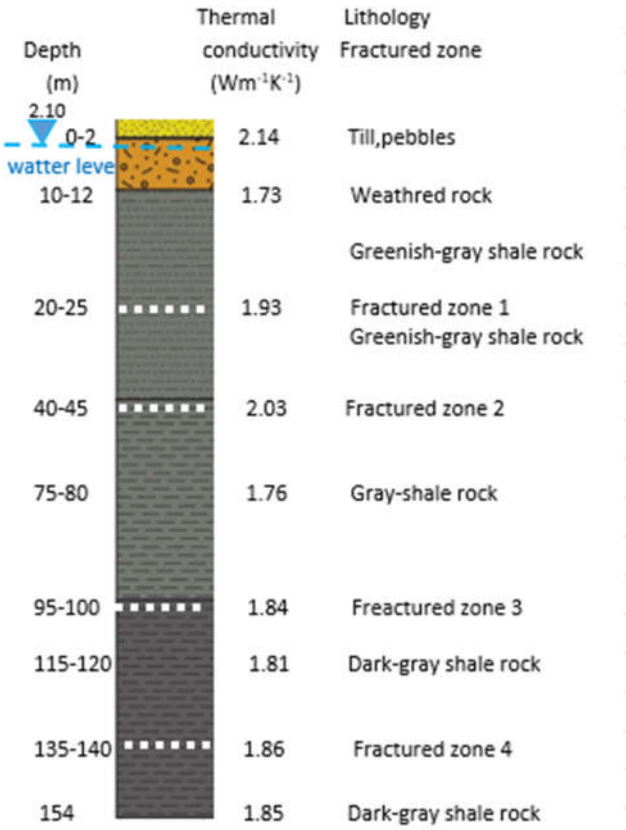

Figure 5. Thermostratigraphic log of the 1U-BHE at INRS experimental site.

2.5.2. Field validation

Assessment of the mean T_{UGT} is required to validate experimental coefficients C_1 to C_4 using the criterion describes in the Eq. (4). Then, a first step involves estimating of the mean T_{UGT} from temperature profiles measured at equilibrium state. The ground temperature profiles were acquired in 2015 and 2016 before the TRTs, respectively [10,16;19]. Two techniques were used for the temperature measurements. One was based on a submersible wired probe using a vertical spatial resolution of 1 m. The second was based on a fiber optic distributed temperature sensing with a spatial resolution of 0.25 m [16;19]. The temperature measurements made with a wired probe were corrected for the rise of the water in the U-pipe of the BHE [16].

In the second step, the coefficients C_3 and C_4 were used to calculate the damping depth Z_{dd} and effective in-situ TD and HC. The bulk TC previously estimated from a conventional TRT performed at this field site [10] was used for the evaluation of HC.

Additionally, the in-situ HC estimated with the approach developed in this work was consecutively compared to the results obtained for the in-situ HC determined by Giordano et al. [11]. The approach developed by these authors to evaluate in-situ HC is briefly described in the following lines to facilitate understanding and comparison.

Giordano et al. [11], at first, evaluated HC following the dual needle probe concept suggested in Raymond [4], using the 1-U BHE and the observation well (obs4; Figure 4). This allowed to independently assess the in-situ HC and validate the OTRT method. The TRT was performed with a heating cable and temperature sensors in both the BHE and the observation well located 1.2 m apart. Temperature sensors were placed in the observation well at vertical distances varying from 2.5 to 5 m. The analysis was performed with the infinite line source equation and results from this test can be assumed as the reliable field assessment of the in-situ HC. As a second step, Giordano et al. [11] performed a sinusoidal heat injection for the OTRT based on Oberdorfer protocol [12]. The oscillatory thermal response was analyzed with equations proposed by Eskilson [44]. In-situ TC was inferred using the infinite line source equation applied to the linear temperature component as in a conventional TRT [2,4,10,16]. Then, in-situ TD was calculated using the amplitude attenuation and the phase lag of the oscillatory component [20-24,27-30]. HC was then evaluated similarly to what was done in this new heating thermal method using Eq. (7).

3. Results

The validity and applicability of the new heat tracing method to assess the in-situ HC are presented and discussed below. A comparison between calculated and observed temperature was carried out as well as between inferred thermal properties using results from various field methods applied at the same experimental site and previous geological characterization [48].

3.1. Empirical parameters estimation

3.1.1. Observed undisturbed ground temperature

Equilibrium ground temperature profiles (T_{obs} (z)) measured in warm and cold seasons were used to accurately analyzed and evaluate the in-situ T_{UTG} (Figure 6). The evaluated T_{UTG} was estimated to vary between 7.90 and 8.01 °C using temperature from the depth interval 15 to 154 m and considering the temperature profiles measured at different times of the year with a vertical spatial resolution of 1 m.

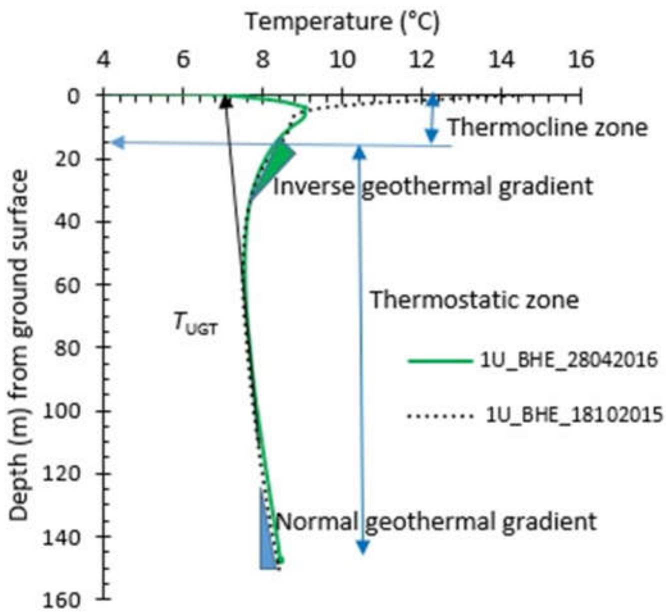

Figure 6. Observed undisturbed ground temperature at INRS experimental site.

These profiles highlight the influence of the seasonal air temperature variations and the heat diffusion within the subsurface at the INRS experimental site. Two zones can be defined from the temperature profiles with analogy to Figures 1 and 2. These two zones are: the upper part which is influenced by the surface conditions (thermocline zone), and the lower part which is not affected by seasonal variations (thermostatic zone) but the geothermal gradient (Figure 6; [19,34,48]). The temperature profiles acquired show an inverted gradient in the upper thermostatic zone (Figure 6). This inverted gradient can be due to recent climate warming [34,45,48,49]. Finally, it can be observed that in the thermostatic zone both the temperature profile from the observation well and from the BHE have the same behavior. These results are in a good agreement with the assumption of temperature diffusion by heat conduction in a homogeneous and isotropic media [49].

3.1.2. Empirical coefficients assessment

The T_{UTG} was evaluated using a single equilibrium temperature profile (T_{obs} (z)) measured in 2015 before a conventional TRT was done (Figures 5 and 6). The calculated T_{UTG}, which is assumed equal to C_1, gave the value 7.96 °C. The absolute difference between measured mean ground temperature (7.90-8.01 °C) and the calculated T_{UTG} (or C_1) ranges between 0.69% and 0.57%. Such results indicate a low bias error (Eq. (4)). Furthermore, these results are used to validate the empirical coefficients C_1 to C_4 found by the solver (Figure 3; Table 1).

Table 1. Experimental coefficients estimated from solver optimization (Eq. (2) to Eq. (4)) applied on the temperature profile measured (T_{obs} (z)) in 2015 at INRS experimental site before a TRT.

Empirical coefficient	Value
C_1 (°C)	7.96
C_2 (°C)	0
C_3 (m)	0.30
C_4 (m)	2.52

The results obtained suggest that calculated C_1 is similar to T_{UTG} evaluated from the measured temperature profile and is in the range of the validation criterion BE< 5%. Moreover, the value C_2 equals to zero suggests that the calculated T_{UTG} (or C_1) is assessed close to the depth of zero temperature amplitude (Figures 1 and 2). Thus, these experimental coefficients C_3 and C_4 can be used for the next step to ultimately evaluate the in-situ HC (Figure 3). The curve-fit between normalized ground temperature profile (T_g (z)) based on Eq. (1) against the measured temperature profile (T_{obs} (z)) at equilibrium state during the TRT [16,39] is plotted in Figure 7.

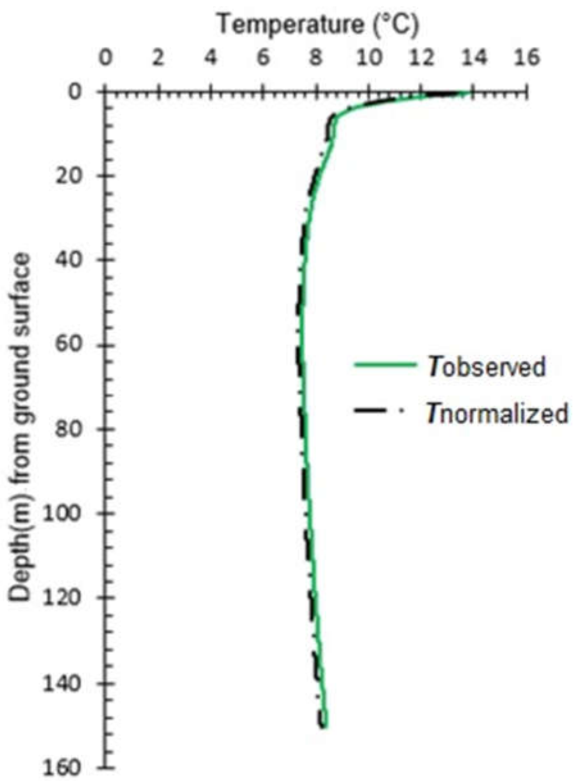

Figure 7. Normalized ($T_{normalized}$) and measured ($T_{observed}$) temperature profiles at INRS experimental site.

3.2. Subsurface thermal diffusivity and volumetric heat capacity

3.2.1. HC estimation with the new empirical method

The value of Z_{dd} (Eq. (3)) was evaluated equal to 2.70 m. The resulting thermal diffusivity (Eq. (6)) was 7.28×10^{-7} m^{-2} s^{-1}. The conventional TRT done on this BHE revealed a bulk TC of about 1.75 W m^{-1} K^{-1} [10]. Thus, the resulting HC (Eq. (7)) is 2.40 MJ m^{-3} K^{-1} (Table 2).

Table 2. In-situ TD and HC estimated (Eq. (2) to Eq. (6)) by applying the new heat tracing method on the temperature profile measured in 2015 at INRS experimental site before a TRT.

Parameter	Value	Description
C_1 (°C)	7.96	Undisturbed ground temperature
Z_{dd} (m)	2.70	Damping depth
α_{calc} (m^{-2} s^{-1})	7.28×10^{-7}	Thermal diffusivity
HC_{calc} (MJ m^{-3} K^{-1})	2.40	Volumetric heat capacity

3.2.2. Comparison of calculated subsurface heat capacity with the dual needle concept

Temperature measurements done down to a depth of about 22 m, in the observation well obs4 (Figure 4) with the heating cable TRT were used to evaluate both in-situ TD and HC [11]. The results, which are thought most accurate among Giordano field method [11], are presented for each submersible temperature sensor inserted at different depths in the BHE and ground layer encountered in the observation well obs4 (Table 3).

Table 3. Subsurface HC inferred with the new empirical method compared to the results of the dual needle concept at INRS experimental site [11].

Depth (m)	TRT with observation well HC (MJ m^{-3} K^{-1})	New empirical approach HC (MJ m^{-3} K^{-1})	Relative difference (%)	Thermo-geological zone
5	2.81	2.4	14.59	Overburden (sediments)
7.5	2.67		10.11	
10	2.81		14.59	
12.5	2.75		12.73	
17	2.27		-5.73	Bedrock (shale)
22	2.48		3.23	
Mean	**2.61**	**2.4**	**|10.16|**	

Field results from dual needle concept were compared with those from this new heat tracing method using Eq. (6) and Eq. (7) to infer the in-situ HC (Table 2 and Table 3). The average absolute discrepancy for the upper layer made of mixed unconsolidated sedimentary deposits and weathered shale (0 to 12.5m) was 13.01% while that for the lower layer made of shale (17 m to 22 m) was 4.48% (Table 3). The average absolute discrepancy considering both layers was 10.16% (Table 3; Figure 5). This difference between field results obtained at the same site using different methods was considered small enough, and therefore this new heat tracing method was confirmed reliable (Table 3).

3.2.3. Comparison of calculated subsurface heat capacity with OTRT method

Results from this new heating tracing method were also compared with results from the OTRT method from Giordano et al. [11] (Table 4). Absolute discrepancy when considering the HC evaluated with the oscillatory resistance method and phase shift method was found to be greater than 26% compared with this new empirical approach (Tables 2 versus 4).

Table 4. Subsurface HC inferred with the new empirical method compared to the results of the OTRT at INRS experimental site [10].

Analysis procedure	OTRT HC	New empirical	Relative

	(MJ m-3 K-1)	approach HC (MJ m-3 K-1)	difference (%)
Thermal recovery period	2.16		-11.11
Oscillatory resistance	1.9	2.4	-26.32
Phase shift	3.56		32.58

The results obtained from the recovery period revealed an underestimated value on the order of 10%; while the difference with the oscillatory resistance analysis and from the phase shift analysis are out of 15%, respectively (Tables 2 versus 4). The differences found in these values suggest that the OTRT may be affected by uncertainties, and it may be useful to use corrected factors to adjust the range of the values when evaluating in-situ HC using the OTRT (Tables 4). The sources for such variability can be caused by, for instance, the HC of the grout filling the BHE [11].

Analysis of the results reveals that the concept used by Giordano et al. [7] is straightforward but the implementation in the field of a sinusoidal heat injection can be complex and need specific analytical expertise, which is not always available.

Despite some sources of uncertainty that needs to be addressed, such as the influence of the backfilling material, the project made by Giordano et al. [7] proposed alternative avenues to improve in situ assessment of subsurface HC and was used as a basis to compare results obtained in this present work.

Finally, these results suggest that the new heat tracing method here developed and discussed below is, at present, more reliable than the OTRT analysis (Tables 2 to 4).

4. Discussion and conclusions

A one-dimensional heat tracing field method was developed and applied to accurately evaluate the undisturbed ground temperature ($T_{UGT} = C_1$) considering the entire length of the ground temperature profile measured into the BHE and the damping depth (Z_{dd}) of the surface changes in the subsurface at the vicinity of the BHE. These values were used to infer the in-situ TD (α_{calc}) and subsequently the in-situ HC (HC_{cal}). This empirical heat tracing method assumes transient heat conduction mechanism of the surface temperature variations diffusing through an isotropic and homogeneous semi-infinite medium (i.e., the subsurface in which an equilibrium temperature profile is measured). This newly proposed method uses least squares and a nonlinear solver optimization to fit the observed temperature profile and to find the experimental coefficients (C_1 to C_4). These parameters are incorporated in the semi-analytical ground temperature sinusoidal function which is assumed to be an upper boundary condition of the heat conduction equation [46,50,51]. This method thus relies on an accurate equilibrium ground temperature profile measured in a BHE before a TRT [10]. The calculated experimental coefficients are used to evaluate a damping depth and an effective TD. The bulk HC of the geological materials is afterwards estimated using a bulk in-situ TC inferred from a conventional TRT.

The in-situ HC evaluated with the newly proposed method at INRS experimental site in Quebec City was successfully compared to that inferred by other field methods (Tables 3 and 4) as a criterion of validation [11,51]. Furthermore, these results were in the range of thermal properties for geological materials of the Quebec-city area [48]. Hence, the obtained results validate the model assumptions and the parameter estimation procedure and, therefore, the stepwise implementation of this new method (Figure 3) can be conducted in the scope of ground-coupled heat pump system design [1,3,4,10,11,19]. Moreover, this method proposes a new damping depth equation which does not rely on the temperature amplitude as the previous methods adopted to evaluate the in-situ TD [20-24,27-30]. In addition, the newly proposed heat tracing method does not rely either on a priori knowledge of the subsurface heat flux or does not require time series of the annual temperature monitoring [9]. This is an advantage compared to previous damping depth methods used for the same purpose [34,35]. Field measurements only require a single temperature profile that can be rapidly collected at before a conventional TRT. This highlights the advantages and novelty of the proposed methodology when compared to other approaches using a time series of ground temperature measurements [20-24,27-30,45,51-53]. Another field benefit is that the new method does not need additionally borehole when compared to the field needle dual method experimented by Giordano et al. [7]. A practical advantage is also related to the mathematical formulation that can be easily implemented and optimized with a built-in solver found in a spreadsheet program. Considering one hour for the field setup and measurements with a wireline temperature probe for a BHE of 154 m depth and a single analysis that should not require more than half an hour for data processing, the method can be qualified as fast when compared against commonly used field methods [2, 4, 7]. The results obtained with this newly proposed heat tracing method depend on experimental coefficients that, in turn, rely on an accurate ground temperature profile measurement that was successfully reproduced at INRS experimental site.

Current practice is to infer the mean ground temperature from the measurements of a ground temperature profile that is acquired before a TRT and by lowering a submersible temperature datalogger in the BHE [16,18]. In some cases, measurements can be done with a 1 m spatial resolution over the length of the BHE that can reach 160 to 200 m. Measurements using a spatial resolution of 5 to 10 m are typically not good enough for this proposed method. Moreover, care should be taken with the field procedure by selecting an accurate temperature probe and by correcting the temperature profile for the water level rise when measured in a U-pipe [16]. For example, the submersible temperature sensor and pressure probe used in this study had a $\pm 2\times10^{-3}$ °C accuracy, $< 5\times10^{-5}$ °C resolution, $\pm 5\times10^{-4}$ dbar accuracy and $< 1\times10^{-5}$ dbar resolution.

As scientific contributions, this study put forward a new damping depth equation and field estimation of TD and HC relying on a single measured equilibrium ground temperature profile. It confirms that ground temperature profiles measured in BHEs is an inexpensive source of data that can be analyzed to obtain more information on the subsurface thermophysical properties [4,9,11,14-23]. These contributions provide advantages for the design of ground-coupled heat pump systems by considering this heat tracing method as a complementary in-situ tool for improving conventional TRTs [2,4].

Nomenclature

*C*1 to *C*4: empirical coefficient
e: exponential
HC: volumetric heat capacity [J m^{-3} K^{-1}]
L: length [m]
N: number of observations
SIN: sine function
T: temperature [°C]
y: assessed parameter
z: depth [m]
Z: damping depth [m]

Greek symbol

α: thermal diffusivity [m^2 s^{-1}]
λ: thermal conductivity for injection period [W m^{-1} K^{-1}]
π: constant (3,14159265358979)

Subscript

calc: calculated
dd: damping depth
eff: effective
g: normalized
obs: observed

bot: bottom

Acronym

HC: volumetric heat capacity
OTRT: oscillatory thermal response test
RE: relative error
RMSE: relative mean square error
TC: thermal conductivity
TD: thermal diffusivity
TRT: thermal response test
UGT: undisturbed ground temperature

Author Contributions: Conceptualization and methodology were developed by Pambou K.C.H. and discussed with Giordano N. and validated by Raymond J. Field investigations were made by Pambou K.C.H. with contribution of Mafalda M. and supervision of Raymond J. All authors have participated for writing—review and editing writing—original draft preparation and formal analysis data curation under supervision of Raymond J. Raymond J. provided funding acquisition and supervised all steps of this work. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science and Engineering Research Council of Canada (NSERC) through a discovery grant of Professor Raymond J. and the APC was funded by the Institut National de la Recherche Scientifique (INRS) of Quebec.

Data Availability Statement: Data supporting reported results can be found by writing to corresponding author: claude.hugo_koubikana.pambou@ete.inrs.ca

Acknowledgments: Colleagues at INRS that further helped with the work are acknowledged. In memory of Maria Isabel Vélez Márquez, who has always had a word and a smile and an availability for those who were at the crossroads of their path. We kindly recognize her contribution, involvement and listening ear during the primary discussions on the problematic of this project and its scientific feasibility.

Conflicts of Interest: "The authors declare no conflict of interest." "The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results".

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