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On the applicability of the moving line source theory to thermal response test under groundwater flow: considerations from real case studies

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Abstract

The classical methodology to perform and analyze thermal response test (TRT) is unsuccessful when advection contributes to heat transfer in the ground, due to the presence of a groundwater flow. In this study, the applicability, the advantages, and the limitations of the moving line source model to interpret TRT data are discussed. Two real TRT case studies from the Italian Alpine area are reported and analyzed, with both the standard infinite line source approach and the moving line source one. It is shown that the inverse heat transfer problem is ill-posed, leading to multiple solutions. However, besides minimization of the error between measurements and modeling, physical considerations help to discriminate among solutions the most plausible ones. In this regard, the MLS approach proves to be effective in the advection-dominated case. The original time criterion proposed here to disregard initial data from the fitting, based on a resistance–capacitance model of the borehole embedded in a groundwater flow, is validated in terms of convergence of the solution. In turn, in the case when advection and conduction are competitive, the MLS approach results more sensitive to ground thermal conductivity than to Darcy velocity. Although in this case a limited impact of the uncertainty in the groundwater velocity on the boreholes sizing is expected, future studies should focus on the development of a successful TRT methodology for this condition.

Keywords: Thermal response test, Moving line source, Ground, Thermal conductivity, Groundwater, Darcy velocity, Inverse problem, Ground-source heat pump

Background

Thermal response test (TRT) is a well-known experimental procedure allowing to derive in situ fundamental thermal–physical properties of the ground and of the borehole. Since its first developments in the mid-90s, it has spread rapidly, being now available in about 40 countries worldwide (Nordell 2011; Spitler and Gehlin 2015). Typically, it consists in forcing a thermal-carrier fluid at constant flow rate in a test borehole and in regulating the fluid inlet temperature in order to inject into the ground (or extract from it) a constant heat rate for 2–3 days. By choosing a physical model describing the TRT and by solving the associated inverse heat transfer problem, the average ground thermal conductivity, the borehole thermal resistance, and the ground undisturbed temperature can be assessed. Such parameters are the essential inputs for the design of ground heat exchangers (Zhang et al. 2014).

Different analytical models for interpreting the TRT data are available (Philippe et al. 2009), namely the infinite line source (ILS), the infinite cylindrical source (ICS), the finite line source (FLS), where the ILS is the most frequently adopted, due to its simplicity. Besides analytical models, numerical models can be used, requiring more modeling and computational effort, but offering the possibility to analyze heterogeneous geological conditions, groundwater flow, or non-conventional TRT procedures (Signorelli et al. 2007; Raymond et al. 2011).

When ground layers are saturated and significant groundwater flow occurs, the standard interpretation of the TRT, based on the assumption of pure conduction in the ground, fails and it becomes impossible to derive the ground thermal conductivity (Witte 2001; Sanner et al. 2013). Indeed, when groundwater flow is present, heat transfer in the ground occurs not only by conduction but also by advection. Consequently, in order to properly design boreholes operating in the presence of groundwater flow, Darcy velocity should be known, besides ground thermal conductivity. To this purpose, some authors (Wagner et al. 2013) recently proposed to adopt another analytical model, i.e., the Moving Line Source (MLS) to interpret groundwater-influenced TRTs and to derive both ground thermal conductivity and groundwater flow Darcy velocity. The MLS problem was firstly presented and discussed by Chiasson et al. (2000) and by Diao et al. (2004). By applying the MLS model to the results of several numerically simulated TRTs, Wagner et al. (2013) show that the true value of the Darcy velocity is generally underestimated. They attribute the discrepancy mainly to the difference between the hydraulic conductivity of the grouting material, which is almost null, and the aquifer. Therefore, they calculate, by numerical simulations, a correction factor to be applied to the velocity value derived from TRT fitting in order to obtain the true velocity. Such correction factor is derived for fitting thermal conductivity in the range of 1.5–4.5 W/(m K) and for fitting Darcy velocity up to 1 m/day. Finally, Wagner et al. (2013) apply their approach to three real TRTs. For the conduction-dominated case study, they conclude that the MLS approach does not provide any advantage, since although the thermal conductivity is estimated in a very narrow range, the Darcy velocity cannot be derived accurately. For the advection-dominated case study, they find several pairs of thermal conductivity and Darcy velocity values, negatively correlated, and conclude that in such conditions the MLS approach can only be used to derive a plausible range for the hydro-geological and thermal–physical properties of the ground. Finally, in the case where conduction and advection compete, the authors show that the possible pairs lie within a 10% range and thus the MLS approach provides a good estimate of the ground parameters.

In a subsequent study, Wagner et al. (2014) apply the MLS model to interpret both large-scale tank and field TRT experiments. They demonstrate that the test can also be used for hydro-geological characterization of the subsoil, since in both cases the evaluations of both experiments resulted in similar hydraulic conductivity ranges as determined by standard hydraulic investigation methods such as pumping tests and sieve analysis. It has to be pointed out that, since in the mentioned study the authors are not interested to use the TRT to determine the ground thermal conductivity, single parameter fits are carried out.

Chiasson and O'Connell (2011) adopt a parameter estimation technique to a TRT affected by significant groundwater flow and compare three different analytical solutions, namely the MLS, the one based on the groundwater g-function (Claesson and Hellstrom 2000), and a mass transport solution adapted by the authors using a mass-heat transport analogy, that can account for thermal dispersion phenomena. They find that only the mass-heat transport analogy yields a favorable comparison to field test data, while the other solutions do not produce a realistic comparison, implying that thermal dispersion is an important parameter, at least in situations with relatively high groundwater velocities. They also discuss the parameter estimation procedure remarking that multiple local minima are observed and recommending realistic constraints of the parameters for this kind of optimization. The role of thermal dispersion is also highlighted in a sensitivity analysis by Wagner et al. (2012), showing that disregarding dispersion can lead to overestimate the effective thermal conductivity by a factor up to 190%.

A completely different approach to TRT in the presence of a groundwater flow is recently proposed by Rouleau and Gosselin (2016), whose conceptual TRT is designed explicitly to derive information on groundwater flow velocity and direction. The authors propose to place a heating cable in the borehole before backfilling with grout and to place some temperature probes in different horizontal positions at the borehole wall. They assess the performance of the methodology by numerical simulations and find that it is more sensitive to ground thermal conductivity than to groundwater velocity.

Therefore, further efforts are necessary to identify the best methodology to perform and/or to analyze TRT data when groundwater flow is relevant. This study aims to investigate the applicability, the advantages, and the limitations of the MLS approach to TRT analysis. Since a criterion to assess the time from the TRT start since when the MLS model can be applied is lacking, an original time criterion is here proposed, based on physical considerations. The paper reports and deeply analyzes two case studies regarding TRTs performed in the Italian Alpine region. In each case, the ILS and the MLS approaches are applied and compared. The issue of the non-uniqueness of the solutions, namely the existence of several possible pairs of thermal conductivity and Darcy velocity values, is addressed in practice through physical considerations. Finally on the basis of a previous study by the authors (Angelotti et al. 2014), the impact of the uncertainty in the Darcy velocity is discussed, in terms of variation in the expected borehole energy performance.

Methods

The TRTs reported and discussed in this paper were performed by means of the mobile equipment GEOGert 2.0. The apparatus is equipped with three electrical resistances allowing to obtain a maximum thermal power of 8 kW. The monitoring module comprises three PT 100 thermal probes to measure inlet and outlet fluid temperatures and the ambient air temperature, and an electromagnetic flowmeter for measuring the mass flow rate. The minimum sampling time is 2 s.

The TRT data were interpreted firstly with the ILS model and then with the MLS model. The relevant equations for each model and the corresponding fitting methodology are outlined in the following.

Infinite line source analysis

According to the ILS model (Carslaw and Jaeger 1954), an infinite line source with a constant heat rate per unit length q in an infinite medium produces a temperature increase depending on the radial distance and on time as follows:

$$T(r,t) - T_0 = \frac{q}{4\pi\lambda} E_i\left[\frac{r^2}{4\alpha t}\right] = \frac{q}{4\pi\lambda}\int_{\frac{r^2}{4\alpha t}}^{\infty} \frac{e^{-u}}{u} du, \tag{1}$$

where T_0 is the undisturbed medium temperature, λ and α are the medium thermal conductivity and thermal diffusivity, respectively, and E_i is the exponential integral function. If the following condition is satisfied:

$$\frac{\alpha \cdot t}{r^2} > 5 \quad \text{i.e. } t > t_{\text{min,ILS}} = 5\frac{r^2}{\alpha}, \tag{2}$$

it is possible to introduce a logarithmic approximation of the E_i function leading to a maximum 10% error. In a recent review by Li and Lai (2015), thermal responses in the ground calculated by different analytical models are compared in a time scale perspective. Among the models, the composite-medium line source model is taken into account. In such model, the medium is divided into two regions: the grout properties are assigned to the cylinder with $r = r_b$ where the source is located, and the ground properties are given to the annular region with $r > r_{bh}$, so that the heat capacity of the grouting material is properly considered. The authors show that in the short time range ($t < 5t_{bh} = 5\frac{r_{bh}^2}{\alpha_{bh}}$) the conventional responses are markedly different from that yielded by the composite-medium model, but there is a medium range interval where all the responses are in reasonable agreement. Therefore, Eq. (2) with $r = r_{bh}$, originally representing the condition for a mathematical approximation, can also be physically interpreted as the condition for reaching a sort of steady state in the borehole volume.

If Eq. (2) is satisfied, Eq. (1) becomes

$$T(r,t) - T_0 \cong \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right]. \tag{3}$$

Equation (3) can be used to evaluate the temperature increase at the borehole wall. Then the mean thermal-carrier fluid temperature T_{mf} is obtained by means of a simple thermal resistance network:

$$T_{\text{mf}}(t) = T(r_{\text{bh}}, t) + q \cdot R_{\text{bh}} \cong T_0 + q \cdot R_{\text{bh}} + \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right], \tag{4}$$

where R_{bh} is the borehole thermal resistance. Therefore, a linear regression of the experimental trend of T_{mf} versus $\ln(t)$ provides the ground thermal conductivity and the borehole thermal resistance, given that the undisturbed ground temperature T_0 is measured at the TRT beginning at null thermal power injection.

Moving line source analysis

According to the MLS model (Diao et al. 2004), an infinite line source with a constant heat rate per unit length q in an infinite porous medium crossed by a fluid flow with Darcy velocity v_d in the x direction produces a temperature increase depending on polar coordinates (r, φ) and on time t as follows:

$$T(r,\varphi,t) - T_0 = \frac{q}{4\pi\lambda}\exp\left(\frac{Ur\cos\varphi}{2\alpha}\right)\int_0^{r^2/(4\alpha t)} \frac{1}{\eta}\exp\left\{-\frac{1}{\eta} - \frac{U^2r^2\eta}{16\alpha^2}\right\}\mathrm{d}\eta, \tag{5}$$

where $U = v_{df}c_f/(\rho_m c_m)$ is the effective fluid velocity. Equation (5) allows to calculate an average temperature increase at the borehole wall, and then the same thermal network analogy used in Eq. (4) allows to calculate the mean temperature of the thermal-carrier fluid versus time:

$$T_{\mathrm{mf}}(t) = \frac{1}{2\pi}\int_0^{2\pi} T(r_{\mathrm{bh}},\varphi,t)\mathrm{d}\varphi + q \cdot R_{\mathrm{bh}}. \tag{6}$$

In order to apply the MLS model to TRT data, Eq. (6) was implemented in a Matlab code. The root mean squared error (RMSE) between MLS model and experimental data was defined as

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left[T_{\mathrm{mf,MLS}}(t_i) - T_{\mathrm{mf,meas}}(t_i)\right]^2}{N}}. \tag{7}$$

By means of the *fminsearch* function, a minimization algorithm based on the derivative-free method, the minimum of the RMSE was searched, adopting λ, v_d, and R_{bh} as fitting parameters.

To the best of the authors' knowledge, a simple time criterion analogous to Eq. (2) for ILS fitting, to disregard data related to initial times when the heat transfer mainly involves the borehole volume, is lacking. Therefore, a method is here proposed to identify the minimum time for MLS model validity. A lumped capacitance approach is applied to the borehole volume, treated as a homogeneous cylinder filled with grouting. Since the grouting hydraulic conductivity is negligible, groundwater flows horizontally outside the borehole that is modeled as a cylinder in cross-flow cooled by forced convection occurring in the surrounding porous medium. The following energy balance equation for the borehole can thus be written:

$$\begin{cases} C_{\mathrm{bh}}\frac{\mathrm{d}T_{\mathrm{bh}}}{\mathrm{d}t} = qH - hS(T_{\mathrm{bh}} - T_0) \\ T_{\mathrm{bh}}(t=0) = T_0 \end{cases}, \tag{8}$$

where C_{bh} is the borehole thermal capacitance, T_{bh} is the borehole temperature, T_0 is the groundwater temperature equal to the undisturbed ground temperature, q is the heat rate per unit borehole length injected during TRT, H is the borehole depth, and h is the average convective coefficient on the cylinder surface S. The average convective coefficient h is calculated with reference to the correlation for a cylinder in cross-flow embedded in a porous medium where a Darcy flow is present (Bejan 1995):

$$Nu_D = \frac{hD}{\lambda} = 1.015 Pe_D^{1/2}, \tag{9}$$

where D is the borehole diameter and λ is water thermal conductivity. Péclet number is calculated from the Darcy velocity as

$$Pe_D = \frac{\rho_f c_f v_d D}{\lambda}. \tag{10}$$

The solution to Eq. (8) shows that T_{bh} varies exponentially with time (Eq. (11)) and allows to identify a characteristic time τ (Eq. (12)):

$$T_{bh}(t) = T_0 + \frac{qH}{hS}\left(1 - e^{-t/\tau}\right) \underset{t\to\infty}{\to} T_0 + \frac{qH}{hS} = T_{bh,\infty} \tag{11}$$

$$\tau = \frac{C_{bh}}{hS} = \frac{\rho_{gr} c_{gr} V}{hS} = \frac{\rho_{gr} c_{gr} r_{bh}}{2h}, \tag{12}$$

where ρ_{gr} and c_{gr} are the grouting density and specific heat capacitance, respectively. When $t = 5\tau$, $(T_{bh} - T_0) = 0.993\left(T_{bh,\infty} - T_0\right)$, namely the borehole volume has almost reached the asymptotic temperature. Therefore, the following condition is proposed for applying MLS analysis to TRT data:

$$t > t_{min,MLS} = 5\tau = \frac{5\rho_{gr} c_{gr} r_{bh}}{2h}. \tag{13}$$

In order to evaluate the condition expressed in (13), a first estimate of the convective coefficient is required. Starting from a first guess of the thermal conductivity and of the Darcy velocity in situ, Péclet number can be calculated and then h can be derived through Eq. (9). Once the MLS fitting has provided the two parameters, it can be used iteratively to calculate $t_{min,MLS}$.

Results and discussion

Clavière case study

The TRT case studies relevant parameters are listed under "List of symbols." The first case analyzed refers to Clavière, in West Piemonte, at 1760 m a.s.l. In situ drilling revealed the presence of dolostones with fine granulometry and saccharoids in large banks with shallow clayish interpositions up to 150 m from the ground surface, laying on a level of compact crystalline limestone from 150 m up to the borehole bottom at 170 m. Perforations identified three levels of aquifers, namely at 2, 22, and 150 m, and in general a relevant groundwater flow (Delmastro 2014). Starting from this stratigraphic information and considering reference thermal–physical properties of rocks and soil (UNI 11466 2012), the average thermal conductivity and thermal diffusivity on site were estimated as 2.7 W/(m K) and $1.17 \cdot 10^{-6}$ m^2/s, respectively (Table 1).

Table 1 Description of the TRT case studies

Location	Claviére (TO) (Delmastro 2014)	Gardolo (TN) (Zille 2013)
Hydro-geology	Dolostones with shallow clayish interpositions (0–150 m), compact crystalline limestone (150–170 m), aquifers levels at 2, 22, and 150 m	Dry gravel, saturated gravel, sand, and silt with saturated gravel (0–71.5 m), calcareous bedrock (71.5–115 m), aquifer level at 30 ÷ 32 m
Test BHE	Double U pipe, $\Phi_{ext}=40$ mm, $D=152$ mm, $H=170$ m, Termoplast Plus grouting ($\lambda_{gr}=2.0$ W/(m K))	Double U pipe, $\Phi_{ext}=32$ mm, $D=130$ mm, $H=115$ m, Termoplast Plus grouting ($\lambda_{gr}=2.0$ W/(m K))
Undisturbed ground temperature T_0	9.8 °C	13.1 °C
Expected ground properties	$\lambda=2.7$ W/(m K)	$\lambda=2.23$ W/(m K)
	$a=1.17\cdot10^{-6}$ m²/s	$a=9.37\cdot10^{-7}$ m²/s

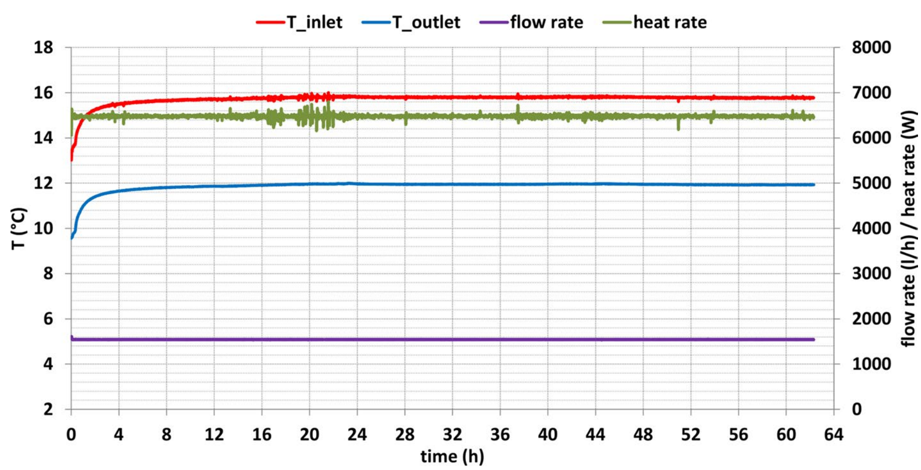

Fig. 1 Clavière case study: TRT results (fluid inlet and outlet temperatures, fluid flow rate, and heat rate)

The undisturbed ground temperature was assessed by flow circulation in the test double U pipe at null heat injection, resulting in $T_0=9.8$ °C. During the TRT, an average thermal power equal to (6479 ± 35) W or (38.1 ± 0.2) W/m was injected. The TRT lasted 62 h, although after the first 20 h the fluid inlet and outlet temperatures almost reached steady state, as Fig. 1 clearly shows. It has to be noted that a steady-state condition does not agree with the ILS model (Eq. 1), while it is predicted by the MLS model (Eq. 5). This outcome is the consequence of the high hydraulic load present at the base of the Chaberton massif, made up of metamorphosed carbonate rocks, where Clavière stands. Although such a rapid time evolution is not frequent, similar cases can be found in Wagner et al. (2013) for the so-called Pannike case (steady state reached in less than 1 day) and in Chiasson and O'Connell (2011) for the referred to Site B case (steady state reached in about 4 h).

In order to adopt the ILS analysis, Eq. (2) was applied, leading to disregard data acquired in the first 6.7 h. Then Eq. (4) was used to interpolate data in the interval $t_{min,ILS}<t<t_{end}$, with t_{end} increasing up to the TRT duration. The resulting ground thermal conductivity as a function of t_{end} is shown in Fig. 2 together with the expected value from literature for comparison. It is clear that thermal conductivity from ILS

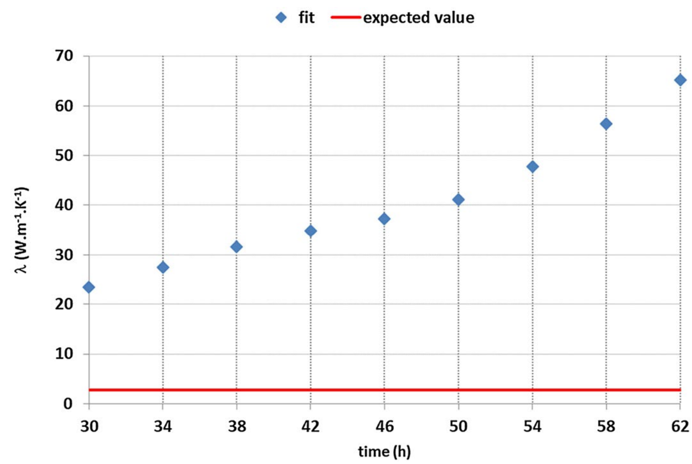

Fig. 2 Clavière case study: thermal conductivity from ILS fit versus t_{end}, compared with expected value

Table 2 MLS analysis: initial values for the parameter estimation technique

Case study	Clavière	Gardolo
λ (W/m/K)	1.5–2.0–2.5–3.0–3.5–4.0	1.5–2.0–2.5–3.0–3.5
v_d (m/s)	10^{-7}–10^{-6}–10^{-5}–10^{-4}–10^{-3}	10^{-8}–10^{-7}–10^{-6}–10^{-5}–10^{-4}
R_{bh} (m K/W)	0.06–0.08–0.10–0.11	0.06–0.09–0.12–0.15

interpolation dramatically increases with the evaluation time and no stable estimate can be derived, in agreement with Witte (2001). In turn, borehole thermal resistance from fit converges to $R_{bh} = 0.106$ m K/W.

In order to adopt MLS analysis, consisting in a parameter estimation for minimizing the RMSE, a matrix of initial values for λ, v_d, and R_{bh} was created, by combining 6 values for λ, 5 values for v_d, and 4 values for R_{bh} (Table 2). 120 combinations of initial values of the parameters were then obtained. The thermal conductivity range was chosen by taking into account literature values for the detected kind of geological formations (UNI 11466 2012); a very large range up to 10^{-3} m/s was chosen for groundwater velocity since a large flow was expected, while the range for the borehole thermal resistance is compatible with double U pipes and a good thermal conductivity grout (Delmastro 2011).

By assuming a first guess value for v_d equal to 10^{-5} m/s, $P\acute{e} = 2.3$ was achieved and the minimum time for the validity of the MLS model was firstly estimated as $t_{min,MLS} = 5.7\ h \cong 6$ h (Eq. 13). As expected for an ill-posed inverse problem, the parameter estimation resulted in several solutions (λ, v_d, R_{bh}), reported in Figs. 3, 4, and 5 as a function of the RMSE. According to these outcomes, ground thermal conductivity lies in the range of 0.01–52.57 W/(m K) (Fig. 3), Darcy velocity in the range of $6.2 \cdot 10^{-10}$–$1.0 \cdot 10^{-3}$ m/s (Fig. 4), and borehole thermal resistance in the range of 0.101–0.107 m K/W (Fig. 5). Only the borehole thermal resistance range is thus narrow, a conclusion similar to the findings in Wagner et al. (2013), while thermal conductivity and groundwater velocity ranges are very large. The best-fit solution, shown in Fig. 6, corresponds to the minimum RMSE equal to 0.019 °C and results in

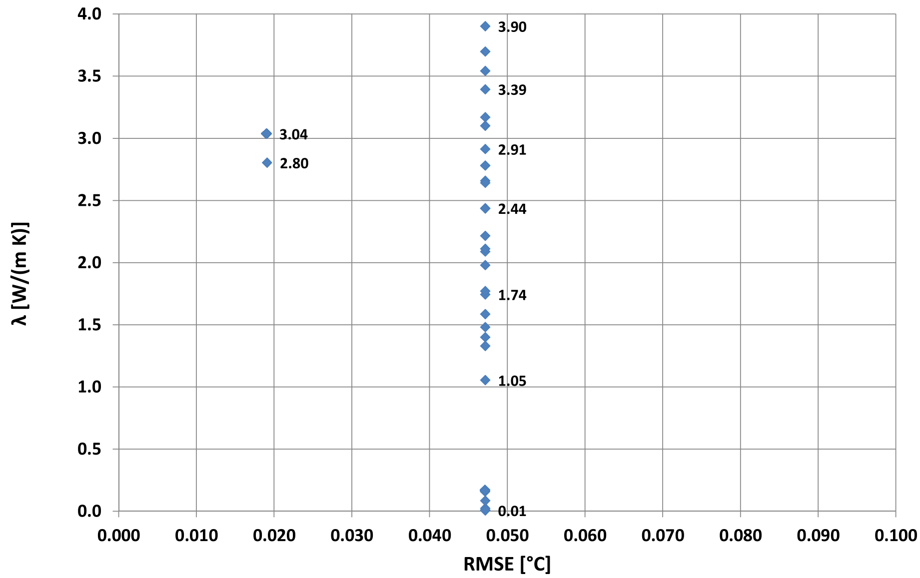

Fig. 3 Clavière case study: thermal conductivity from MLS fit versus RMSE (the point (0.034 °C, 52.56 W/(m K) is not shown for better readability of the graph)

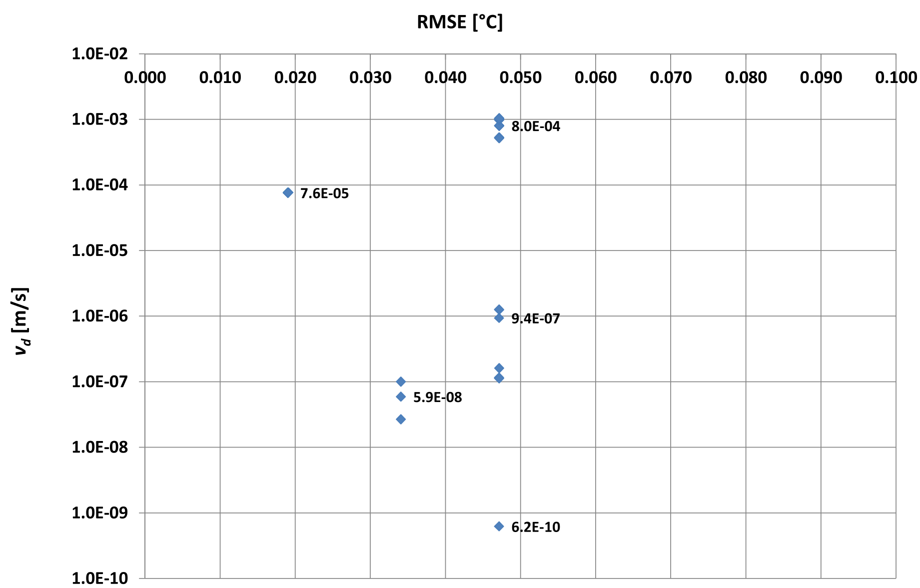

Fig. 4 Clavière case study: Darcy velocity from MLS fit versus RMSE

$\lambda = 3.04$ W/(m K), $v_D = \pm 7.6 \cdot 10^{-5}$ m/s, and $R_{bh} = 0.101$ m K/W. We consider that the two solutions differing only for the sign of the Darcy velocity can be collapsed into a single one, since the MLS model cannot discriminate between the two flow directions. In this regard, such collapsed solution is also the most recurrent one, occurring 75 times out of 120 (63%). Besides, there are some solutions corresponding to a thermal conductivity equal to 52.57 W/(m K), which is clearly physically meaningless, although the RMSE results in 0.034 °C. Such solutions have then to be disregarded

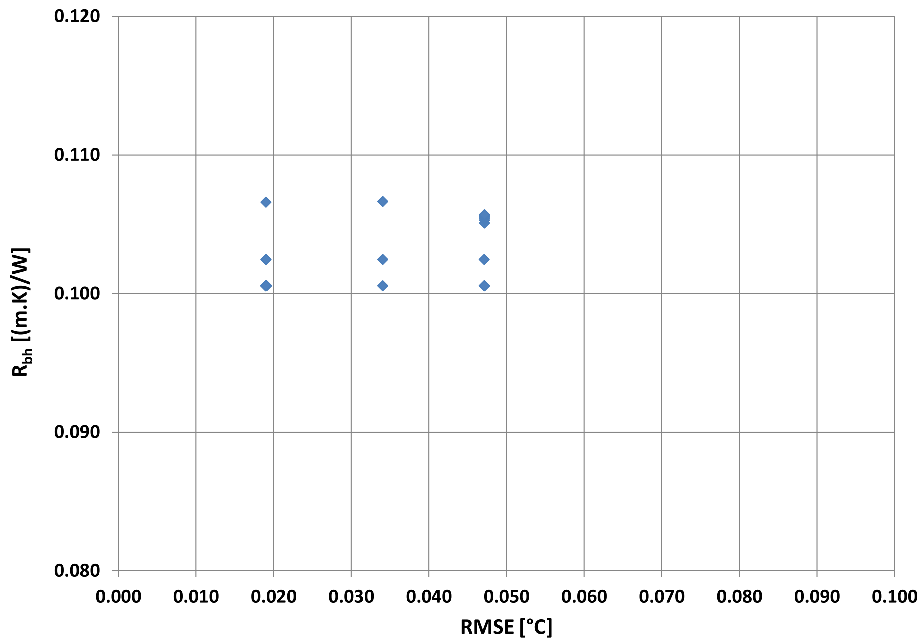

Fig. 5 Clavière case study: borehole thermal resistance from MLS fit versus RMSE

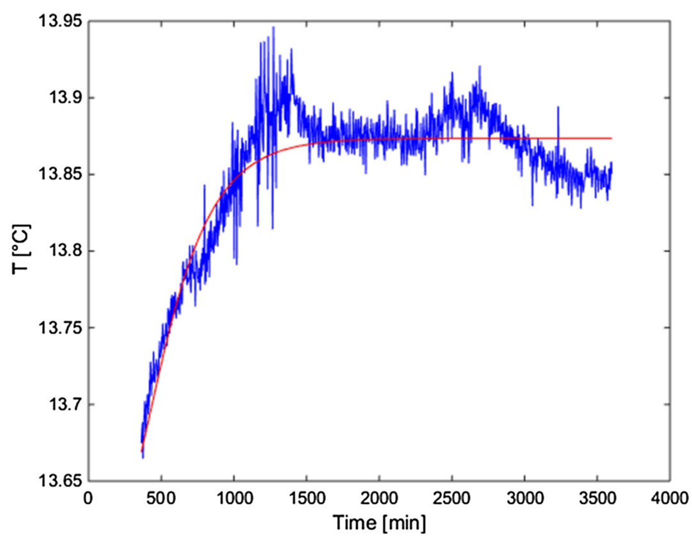

Fig. 6 Clavière case study: experimental mean fluid temperature profile and best-fit MLS solution disregarding the first 6 h

more on the basis of the physical constraints rather than on the basis of the low RMSE. Another group of solutions leads to thermal conductivities below 0.5 W/(m K), which is once again physically meaningless. Finally, there are several solutions that correspond to plausible values for thermal conductivity and Darcy velocity, but result in a less accurate fit. In this case, the poorer quality of such fits can be assessed more by visual inspection than on the basis of the RMSE only (0.043 °C), which is only modestly larger than the best-fit solution one.

By adopting the best-fit Darcy velocity equal to $7.6 \cdot 10^{-5}$ m/s and the best-fit thermal conductivity 3.04 W/(m K) in Eq. (13), the minimum time for data fitting is recalculated and updated to 2.3 h. In order to validate the initial time criterion for the application of the MLS model proposed in this study, the parameter estimation of the MLS solution is then repeated by varying the initial time data, from a minimum of 20 min to a maximum of 6 h. The average RMSE of the solutions and the best-fit solutions RMSE are then reported as a function of the initial time in Fig. 7: it can actually be noticed that disregarding at least the first 2 h allows to significantly improve the accuracy of the fit and that the RMSE rapidly reaches a stable value. At the same time, it is found that the fitting parameters of the best-fit solution reach stable values as the initial time for data interpolation reaches 3/4 h. Therefore in Clavière case, the proposed initial time criterion can be considered satisfactory.

It has to be mentioned that in this case the correction term proposed by Wagner et al. (2013) cannot be applied since the fitting Darcy velocity 6.6 m/day is beyond the range considered by the authors, suggesting that a broader range is worthy of investigation. Yet, on the basis of their work, it can be argued that the true Darcy velocity in this case may be more than 10 times higher than the fitting one.

Gardolo case study

The second case study was performed in Gardolo, in Trentino Alto Adige region. The borehole field 115 m deep is located nearby the Avisio river, and the ground is composed by alluvial deposits up to 71.5 m from the surface over a calcareous bedrock (Zille 2013). The detailed stratigraphy detected on site allowed to estimate (UNI 11466 2012) the average thermal conductivity and the average thermal diffusivity as 2.23 W/(m K) and

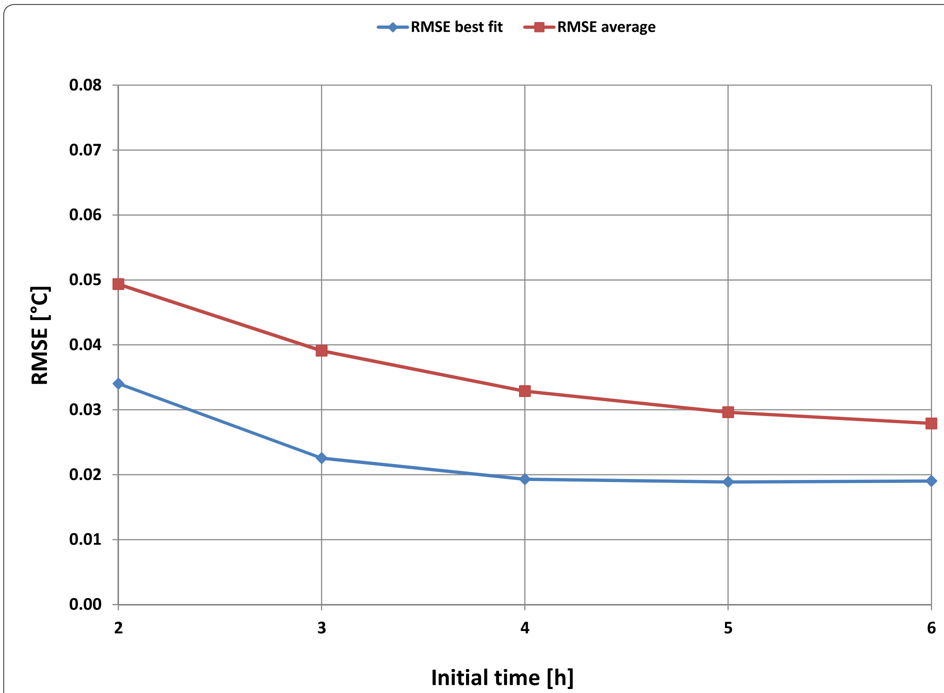

Fig. 7 Clavière case study: RMSE of the MLS fit solutions versus initial time of the data interpolation

$9.34{\cdot}10^{-7}$ m^2/s, respectively (Table 1). The undisturbed ground temperature was found to be $T_0 = 13.7$ °C. The TRT lasted 58 h, with an average thermal power injection equal to (6599 ± 48) W or (57.4 ± 0.4) W/m (Fig. 8).

The minimum time criterion expressed in Eq. (2) results in $t_{\mathrm{min,ILS}} = 5.7$ h. Contrary to the previous case study, the analysis by means of the ILS model results in an almost stable thermal conductivity estimate equal to 3.81 W/(m K) (Fig. 9). Such value, however, is much higher than the expected one and out of range for the kind of soils and rocks detected on site. From the borehole thermal resistance perspective, the fit converges to 0.074 m K/W, lying in the range of possible values for double U pipes in a borehole backfilled with thermally enhanced grout according to Delmastro (2011).

MLS analysis is performed as for the Clavière case. Initial values for the fitting parameters have been chosen according to reference values from literature for this kind of hydro-geological conditions and borehole configuration (Table 2). By taking into account hydro-geological conditions on site, a first guess of the Darcy velocity results in $5{\cdot}10^{-6}$ m/s. The minimum time criterion provides $t_{\mathrm{min,MLS}} = 5.6$ h as the initial time for data evaluation. The RMSE minimization results, as for Clavière case, in multiple solutions. The sensitivity of the average RMSE and of the best-fit RMSE to the initial time is reported in Fig. 10. In this case, disregarding the first 6 h data, as suggested by the proposed criterion, is not sufficient to reach a stable RMSE, which is rather achieved after about 10 h. It can be noticed also that the RMSE alone in this case is not sufficient to discriminate among the multiple solutions, since the best-fit RMSE is only slightly smaller than the average RMSE.

The multiple solutions achieved with $t_{\mathrm{min}} = 10$ h are then reported in Figs. 11, 12, and 13 as a function of the RMSE. From the thermal conductivity point of view (Fig. 11), there are only 2 possible values, namely 0.6 and 2.18 W/(m K), to which minimization converges 45 and 55% of the times, respectively. The lowest conductivity, i.e., 0.6 W/

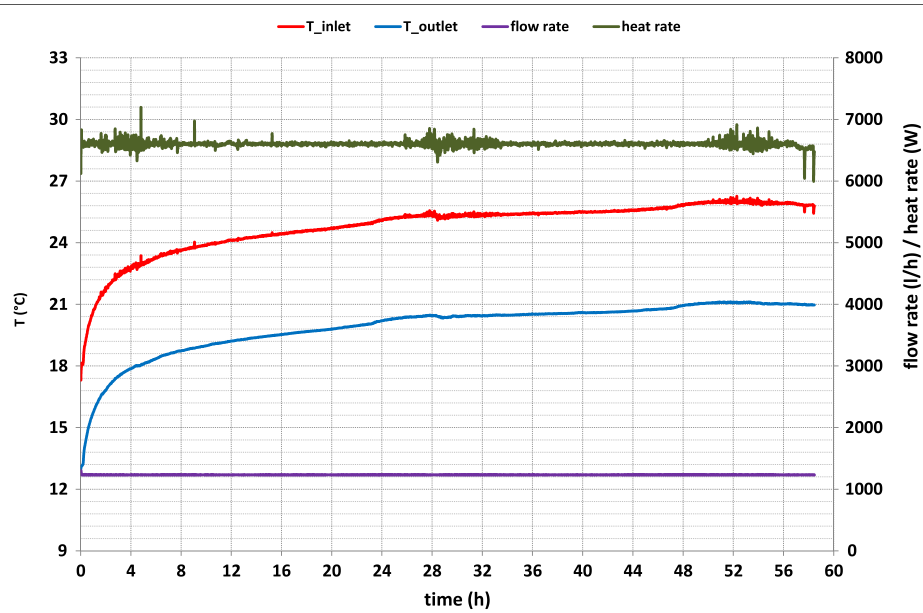

Fig. 8 Gardolo case study: TRT results (fluid inlet and outlet temperatures, fluid flow rate, and heat rate)

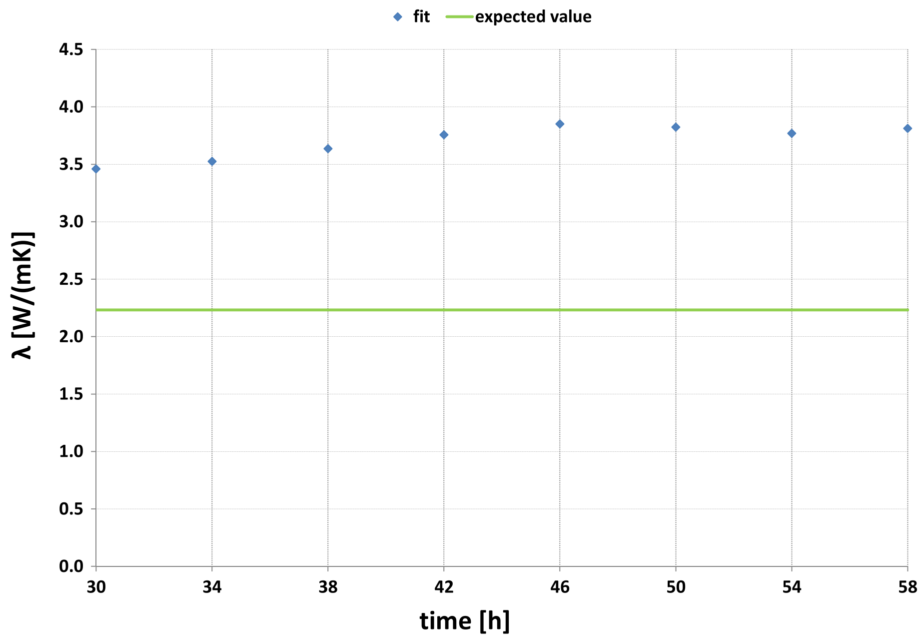

Fig. 9 Gardolo case study: thermal conductivity estimate from ILS fit versus evaluation time, compared with expected value

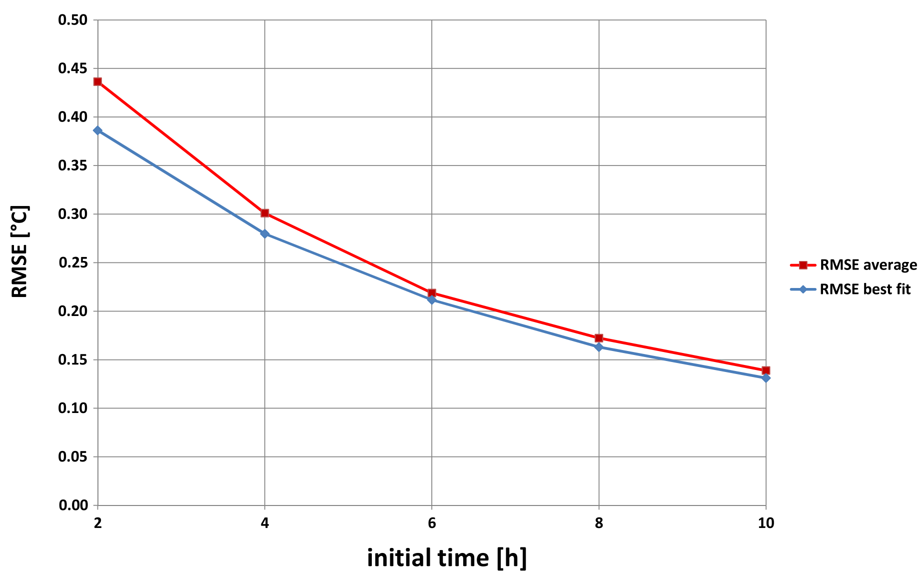

Fig. 10 Gardolo case study: RMSE of the MLS fit solutions versus initial time of the data interpolation

(m K) solution corresponds to the absolute minimum RMSE (best fit), for which Darcy velocity is $v_d = 2.1 \cdot 10^{-5}$ m/s and borehole resistance is $R_{\text{bh}} = 0.152$ m K/W. But such solution is clearly not acceptable from a physical point of view, because the thermal conductivity is too low for this kind of ground and in general for any kind of soil and rock.

The second thermal conductivity value (2.18 W/(m K)) corresponds to a group of solutions with the same borehole thermal resistance (0.149 m K/W), but a large range of flow

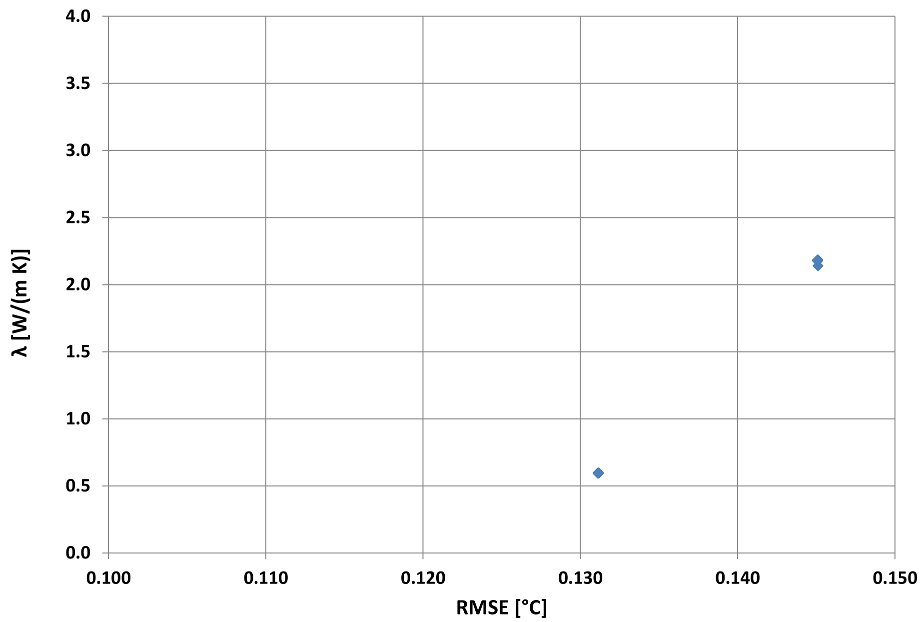

Fig. 11 Gardolo case study: thermal conductivity from MLS fit versus RMSE

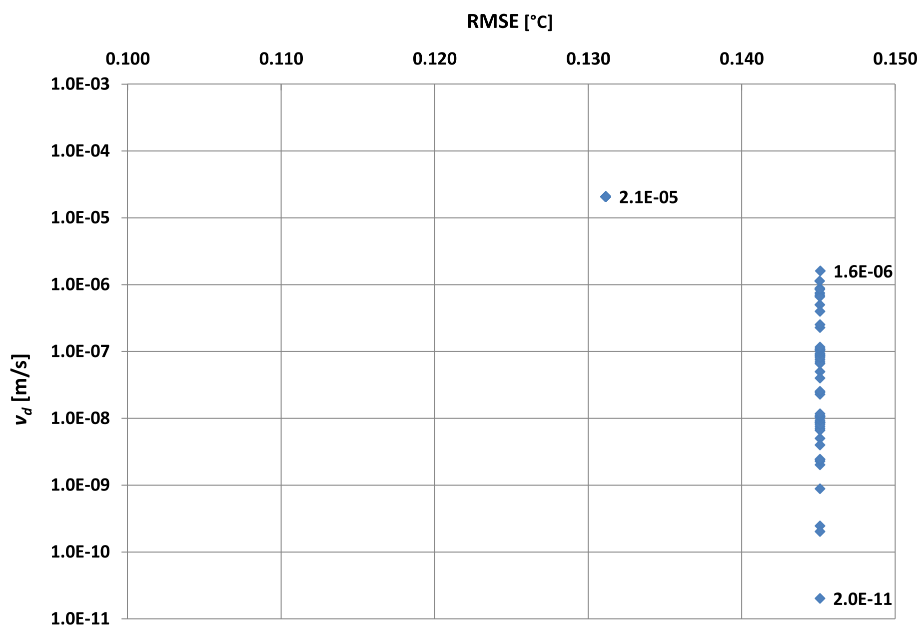

Fig. 12 Gardolo case study: Darcy velocity from MLS fit versus RMSE

velocities, namely $2{\cdot}10^{-11}$–$1.1{\cdot}10^{-6}$ m/s. Actually this group of solutions results in a thermal conductivity quite close to the expected value, but the estimate of the groundwater flow velocity is not unique. Although this output can be overwhelming, it has to be noticed that the highest Darcy velocity taken from this family of solutions Péclet number, calculated by taking the borehole radius as the characteristic length, is about 0.1. According to the study by Angelotti et al. (2014), reporting also similar results from literature, when $P\acute{e} = 0.1$

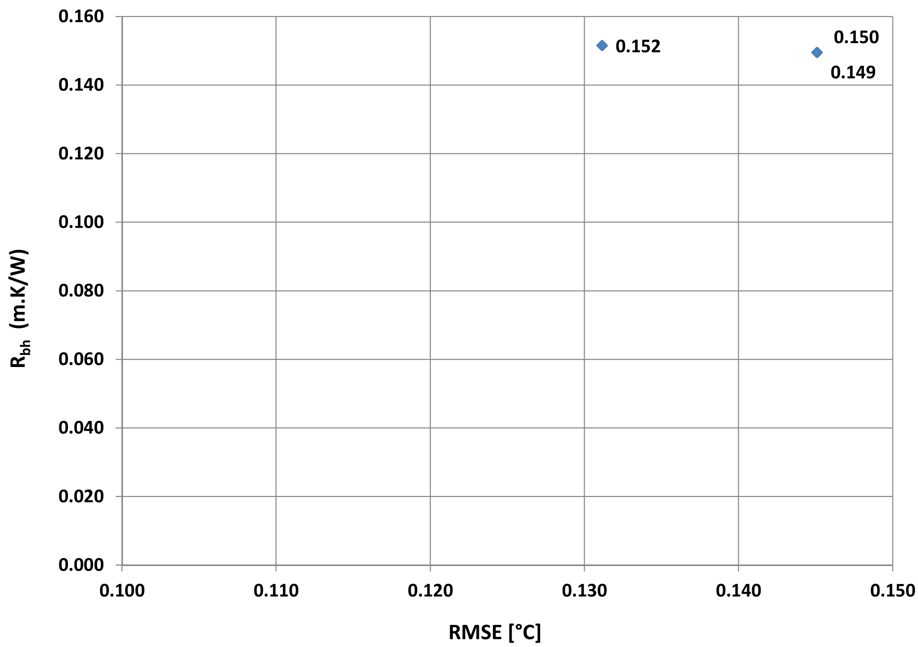

Fig. 13 Gardolo case study: R_{bh} from MLS fit versus RMSE

groundwater influence on the borehole annual energy performance is limited to a maximum of 20%. Therefore, it can be argued that an inaccurate estimation of the Darcy velocity in this range does not affect significantly the borehole heat exchanger design, although further studies are necessary to clarify this issue.

Limitations

The real groundwater velocity and the real ground thermal conductivity for the two analyzed TRT are actually unknown. Therefore, the considerations on the applicability of the MLS analysis to the case studies analyzed in this paper cannot be based on the capability of such model to estimate ground and groundwater properties correctly. Indeed performing quantitative hydro-geological investigations in situ like pumping tests (Wagner et al. 2014) is an expensive procedure, often requiring the drilling of more than one test borehole. The average ground thermal conductivity in situ can in principle be derived from laboratory measurements of homogeneous portions of the core sample extracted. However, especially in case of non-consolidated soils, preserving the sample density and humidity content in laboratory is not straightforward. In turn, a comprehensive validation of the MLS approach to TRT analysis can only come from laboratory tests. To this purpose, the authors are developing a physical model at reduced scale to study TRT procedure and interpretation in the presence of groundwater flow, under controlled and parametric conditions, namely ground composition, Darcy velocity, and source heat rate.

Conclusions

The analysis of the two real TRT cases presented in this paper clearly shows that finding both the ground thermal conductivity and the groundwater flow velocity from the time profile of the thermal-carrier fluid temperature measured in the standard TRT is an ill-posed inverse problem leading to multiple solutions. In turn, the determination of the borehole thermal resistance appears less critical, since multiple solutions lie in a very narrow range. To overcome the problem of multiple solutions, further efforts are necessary to develop new TRT procedures, where more quantities are monitored in order to determine a well-posed inverse problem. To this extent, the conceptual test recently proposed by Rouleau and Gosselin (2016) represents an interesting suggestion.

When applying the MLS approach, in order to discriminate among multiple (λ, ν_{d}) solutions, looking for the absolute minimum RMSE solution proves to be effective in the advection-dominated case (Clavière), but not when advection is small yet not irrelevant (Gardolo case). Physical considerations, given by the general knowledge of the hydrogeological conditions in situ, can lead to identify the most plausible solution, possibly not the best-fit one. In case conduction and advection compete, the MLS approach is not successful in determining the Darcy velocity, for which only a large range can be identified. According to literature, this advection regime may have a modest impact on the long-term energy performance of borehole heat exchangers. At the same time in this case, the standard ILS approach converges to an effective thermal conductivity, whose value larger than expected possibly includes the effects of groundwater. Further investigations are then necessary to understand if using such effective thermal conductivity for ground heat exchanger design leads to acceptable sizing.

Finally, the minimum time criterion developed in this study, although based on a simplified resistance–capacitance analogy for the borehole volume, proves to be effective in providing a basis for identifying the time since when the MLS model can be applied.

List of symbols

Latin symbols

C: heat capacity (J/K); *c*: heat capacity per unit mass (J/(kg K)); *D*: diameter (m); E_i: exponential integral function; *H*: borehole depth (m); *h*: convective coefficient (W/(m^2 K)); ILS: infinite line source; MLS: moving line source; *Nu*: Nusselt number (–); *Pé*: Péclet number (–); *Pr*: Prandtl number (–); *q*: heat rate per unit length (W/m); *R*: thermal resistance (m K/W); *r*: radius (m); *Re*: Reynolds number (–); RMSE: Root Mean Squared Error (°C); *S*: surface (m^2); *T*: temperature (°C); *t*: time (s); TRT: thermal response test; *U*: effective velocity (m/s); *v*: velocity (m/s).

Greek symbols

α: thermal diffusivity (m^2/s); γ: Euler constant (–); φ: polar coordinate (rad); ρ: density (kg/m^3); λ: thermal conductivity (W/(m K)); μ: dynamic viscosity (kg/(m s)); τ: characteristic time (s).

Subscripts

bh: borehole; *d*: Darcy; end: final; f: fluid; gr: grout; m: medium; min: minimum.

Authors' contributions

AA designed the study, developed the methodology, supervised the analysis, and drafted the manuscript. FL performed the analyses and interpreted the results. AZ provided the case studies and performed the geological analyses. All authors read and approved the final manuscript.

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The authors declare that they have no competing interests.

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