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A review of vertical ground heat exchanger sizing tools including an inter-model comparison

by

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Abstract

This paper attemps to fill a gap in the literature on ground heat exchanger sizing tools which are routinely used but have not been recently compared against each other. First, a comprehensive review of the governing equations of these tools is presented. The tools are then classified into five levels ($L0$ to $L4$) according to their level of complexity from tools based on rules-of-thumb ($L0$) to those using annual hourly simulations ($L4$). Then this study presents a methodology for comparing vertical ground heat exchanger sizing tools. After a review of available tests, four test cases are proposed to cover the full spectrum of conditions from single boreholes to large bore fields with various annual ground thermal imbalances. This is followed by an inter-model comparison of twelve sizing tools including some commercially-available software programs and various forms of the ASHRAE sizing equation. In one of the tests on a single borehole subjected to a one-hour peak load duration, it is shown that the minimum and maximum lengths obtained by the various tools are 39.1 m and 59.7 m. Tools that include short-term effects tend to calculate smaller lengths while longer lengths are predicted by tools that evaluate effective ground thermal resistances using the cylindrical heat source solution. In another test involving a large annual ground imbalance on a 5×5 borehole field, it is shown that results vary from 93.0 m to 128.9 m among the twelve tools. A group of seven tools, including $L2$, $L3$, and $L4$ tools are in good agreement with a minimum of 121.0 m and a maximum of 128.9 m. Two tools have determined lengths that are much lower than the rest of the tools (103.9 and 93.0 m). Clearly, these two tools cannot properly account for borehole thermal interaction caused by large annual imbalanced loads.

Keywords: geothermal energy, sizing tools, vertical ground heat exchangers, inter-model comparison, test cases.

1. Introduction

Ground heat exchanger sizing tools use different calculation procedures to obtain the required bore field length for a given set of ground loads. The last serious attempt to compare these design tools is about two decades old. Since then, tools have been improved and new ones have been introduced. The goal of this paper is to provide an updated inter-model comparison of twelve tools. Aside from this end result, this study classifies the various calculation procedures into five levels based on their complexity. It also provides a rigorous methodology to compare the various tools and proposes test cases for a range of conditions.

A ground source heat pump (GSHP) system equipped with vertical ground heat exchangers (GHE) is depicted in Figure 1. This system is composed of a series of boreholes and heat pumps which provide heating and cooling to a building. The bore field consists of a number of boreholes, N_b, with length H, spaced apart by a distance B and buried at a depth D. The overall length of the bore field, L, is thus equal to $N_b \times H$. Boreholes have a radius r_b and typically contain one or two U-tubes with a thermal conductivity, k_p. In the case of Figure 1, two pipes (one U-tube) with internal and external diameters, $r_{p,i}$ and $r_{p,o}$, are used. They are separated by a distance $2d_p$. The borehole is usually filled with grout with a thermal conductivity, k_{gr} , and a thermal capacity, MCp_{gr}. The ground is characterized by its thermal conductivity, k_g, thermal diffusivity, α_g, and undisturbed temperature, T_g.

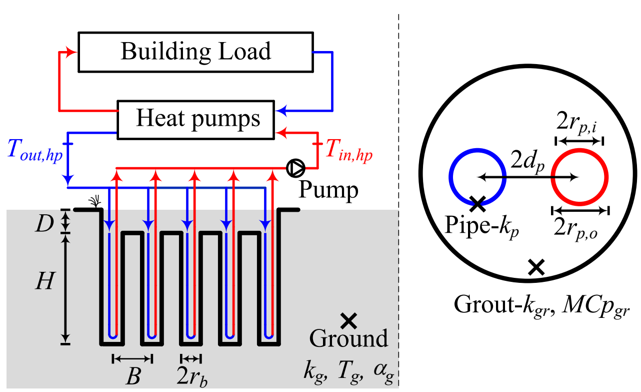

Figure 1: Schematic representation of a ground-source heat pump system (left) and a borehole cross-section with one U-tube (right)

Boreholes are typically connected in parallel. The fluid inlet temperatures and flow rates are usually assumed to be identical for all boreholes. Assuming negligible heat gains/losses in the piping between the boreholes and the heat pumps, the bore field outlet temperature is equal to the heat pump inlet temperature, $T_{in,hp}$, and the heat pump outlet temperature, $T_{out,hp}$, is equal to the bore field inlet temperature. The flow rate in each borehole is equal to $\dot{m}_f/N_b$, where $\dot{m}_f$ is the total bore field flow rate. For commercially available heat pumps, $T_{in,hp}$ can be as low as −7°C in heating and as high as 45°C in cooling. However, designers most often plan their system so that $T_{in,hp} \geq 0$°C in heating and $T_{in,hp} \leq$ 35°C in cooling. These two limiting temperatures will be referred to T_L and T_H, respectively. Unlike HVAC equipment which are typically sized only for peak load conditions, bore field sizing has to account for the thermal history of heat injection/collection into the ground and the period of the year when the system starts to operate [1].

A number of input parameters, listed in Table 1, need to be determined prior to using sizing tools. Building or ground loads are generally determined using separate tools. Inaccurate loads will have an impact on the accuracy of L. For instance, Bernier [2] has shown, for a particular case, that an uncertainty of ± 10% on the peak, monthly and annual ground loads (q_h, q_m, q_y in equation 4 – to be described later) translates into a cumulative uncertainty of ± 8.9% on L. The duration of peak loads has also an influence on L: typical values range from 4 to 6 hours. The next required input parameters are the target heat pump inlet temperature limits, T_H and T_L, that should not be exceeded during the expected lifetime of the system. The user has also to decide on the bore field geometry which is often dictated by the available land area. Cimmino and Bernier [3] have shown that borehole placement within a given rectangular land area is not crucial in terms of total borehole length. An accurate value of the ground thermal conductivity is important to properly size a bore field while the ground thermal diffusivity is less important. Bernier [2] has shown that a ± 10% uncertainty on k_g and α_g lead, respectively, to uncertainties of ± 7.1%, and ± 1.0% on the bore field length for a particular case. An accurate value for the ground temperature is also important and when it's value is close to T_H or T_L, longer boreholes are required. The borehole characteristics need to be carefully selected to optimize the borehole thermal resistance and the overall length. Some sizing tools account for borehole thermal capacity and in these cases, the thermal capacities of the pipes, the fluid and the grout are required. If building loads are used as inputs in sizing tools, heat pump coefficient of performances ($COPs$) in heating and cooling are required to calculate ground loads. The simpler methods will only require COP_H and COP_C at T_L and T_H while more elaborate tools will evaluate COP_H and COP_C as a function of $T_{in,hp}$. The selection of a flow rate has an influence on borehole heat transfer and on the ΔT across the borehole. A high flow rate reduces the borehole thermal resistance and the ΔT but increases pumping power. Low flow rates may lead to laminar flows in the borehole pipes which should be avoided at peak ground load conditions. For sizing purposes, the flow rate is typically around 0.05-1.0 L/s per kW of peak load. The required borehole length is not necessarily obtained at the end of the design period (typically 10 to 20 years). Indeed, Monzó et al. [1] have shown that the maximum length might be required during the first year of operation depending on the starting month of operation.

Table 1: Required input parameters for most sizing tools

Building or ground loads and peak load duration
Target temperature limits for heat pumps (T_L and T_H)
Bore field geometry (number of boreholes and location)
Ground thermal properties (k_g α_g and T_g)
Borehole characteristics (geometry, thermal properties)
Heat pump characteristics (COP_H and COP_C)
Flow rate
Design period
Starting month of operation

Sizing tools take different paths to obtain L with various levels of complexity and accuracy. Spitler and Bernier [4] have identified five such levels ($L0$ to $L4$). Figure 2 presents typical calculation sequences associated with tools in the $L1$ to $L4$ categories. These levels are described in the next section including a presentation of some available sizing tools within each level. This is followed by a literature review on comparisons of bore field sizing tools. Then, a series of test cases are proposed. Finally, these test cases are used in an inter-model comparison of several existing tools.

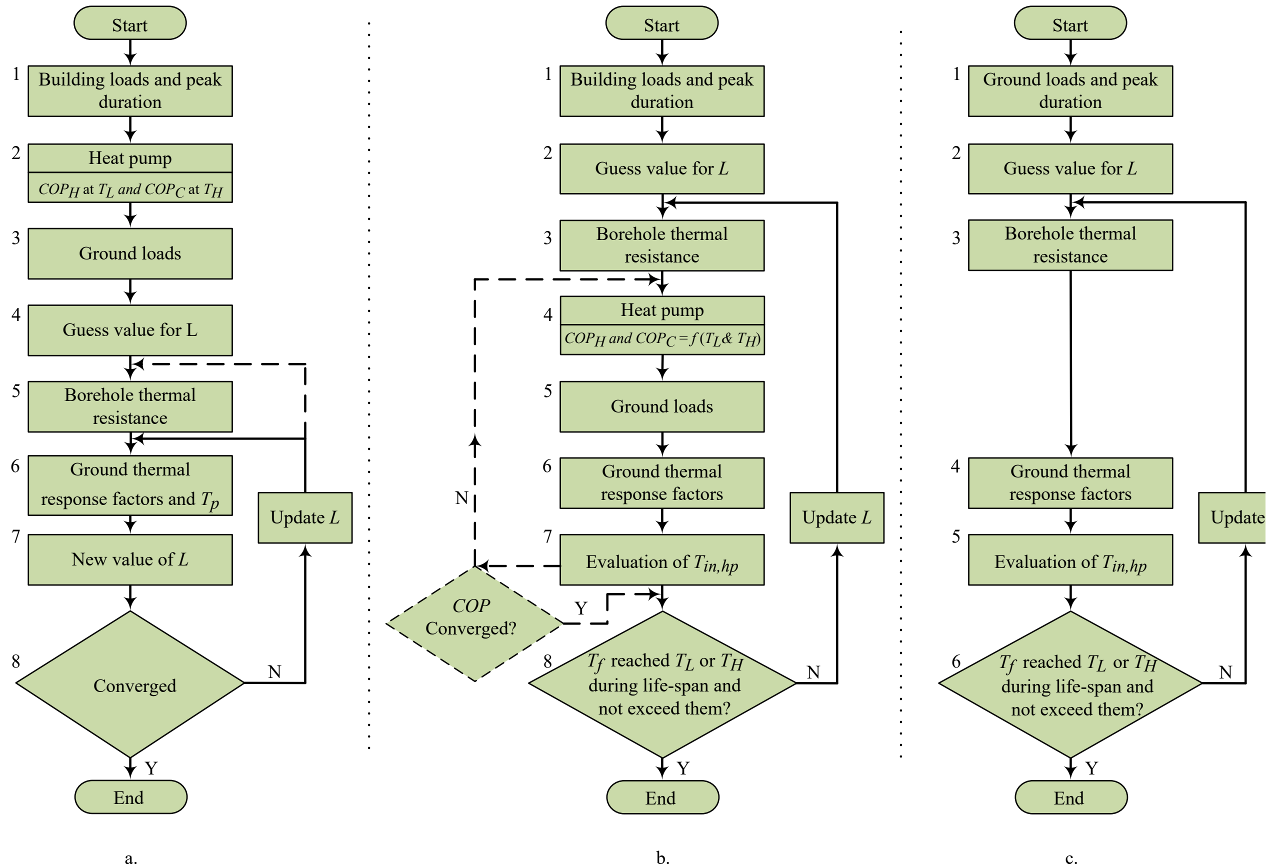

Figure 2: Typical steps required to size a bore field for a) $L1$ and $L2$ methods, b) $L3$ and $L4$ methods with building loads as input, and c) $L3$ and $L4$ methods with ground loads as inputs.

2. Categories of sizing tools

2.1. $L0$ – *Rules-of-thumb*

Level $L0$ tools are simple rules-of-thumb. They typically relate the borehole length to the building peak heating or cooling loads or installed capacity, typically expressed as W/m or ft/ton. Spitler and Bernier [4] mention that $L0$ tools are mostly used for small systems in heating only applications. They are bound to give erroneous results in large systems where borehole-to-borehole thermal interaction, caused by ground thermal imbalance and/or small borehole spacing, is large. Also, they do not consider the borehole thermal resistance. They should only be used as a reality check for more advanced sizing tools.

Excluding $L0$ tools, most sizing methods are derived from Equation 1:

$$L = \frac{\sum_{i=1}^{N} q_i R_i + q_h R_b}{T_m - (T_g + T_p)} \tag{1}$$

where q_i is a ground thermal pulse associated with a certain time period, R_i is the corresponding ground thermal response which takes the form of an effective ground thermal resistance, q_h is the peak ground thermal pulse, R_b is the borehole thermal resistance, T_m is the mean borehole fluid temperature (=$(T_{inHP} + T_{outHP})/2$)), and T_p is a temperature penalty to account for borehole-to-borehole thermal interaction. In some methods, this thermal interaction is included in R_i values and for such methods, T_p = 0. Equation 1 can be used for heating or cooling applications with appropriate signs for ground loads (negative when heat is extracted from the ground).

2.2. $L1$ – *Two pulses –peak heating and cooling loads*

$L1$ methods use two heat pulses which are either the maximum heating and cooling heat pump capacities or the building peak heating and cooling loads. They are somewhat outdated but it is interesting to present them from an historical perspective. $L1$ methods have been described by Bose et al. [5], OSU [6], and Kavanaugh [7]. With reference to Figure 2a, a $L1$ tool would typically go through the six step process starting with the peak building loads or in some cases with the installed heat pump capacity. In step 2, values of COP_H and COP_C are determined based on values of T_L and T_H and used in the determination of the ground loads in step 3. Heat pump compressor power is either added or subtracted from the building to obtain ground loads. Thus, the heat pump COP, which is the ratio of the capacity (heating or cooling) over compressor power, has an impact on bore field sizing. For example, the overall length of a bore field will decrease with an increase of heat pump COP when a bore field is sized in cooling. Conversely, when a bore field is sized for heating conditions, an increase in the COP value will lead to an increase in the bore field length. Rudimentary values, by today's standards, of the borehole thermal resistance and ground thermal response factors are typically evaluated in steps 4 and 6. Finally, L is obtained directly in step 7 and iterations on L are generaly not required. $L1$ tools are perhaps best explained by examining the so-called IGSHPA method which is thoroughly described by Bose et al. [5]. This method follows the sequence presented in Figure 2a except that building loads are replaced by heat pump capacities in step 1. In this method, the lengths in heating (L_H) and cooling (L_C) are determined using Equation 2 with the longest of the two giving the total required borehole length, L. As shown in Equation 2, the heat pump capacities in heating and cooling, Cap_H and Cap_C, are multiplied by a factor involving $COPs$ in heating and cooling (COP_H and COP_C) to obtain peak ground loads in heating and cooling, respectively. These loads are then multiplied by the sum of the pipe (borehole) resistance, R_p, and of the ground thermal response (ground thermal resistance), R_s. This last value is multiplied by the runtime fraction, ($Run_{f,H}$ or $Run_{f,C}$). The denominator of Equation 2.c is the difference between T_g and T_L in heating or between T_H and T_g in cooling.

$$L_H = \frac{Cap_H \dfrac{(COP_H - 1)}{COP_H}\left(R_p + R_s Run_{f,H}\right)}{\left(T_g - T_L\right)} \tag{2.a}$$

$$L_C = \frac{Cap_C \dfrac{(COP_C + 1)}{COP_C}\left(R_p + R_s Run_{f,C}\right)}{COP_C\left(T_H - T_g\right)} \tag{2.b}$$

$$L = \max(L_H, L_C) \tag{2.c}$$

The ground thermal resistance, R_s, is determined using the infinite line source solution. Its value depends on the time period over which the ground load is applied. Also, spatial superposition can be used to account for borehole thermal interaction as discussed by Bose et al. [5]. The pipe resistance, R_p, is the ancestor of the modern borehole thermal resistance. For a U-tube geometry, it is approximated using an equivalent diameter.

Equation 2 is applied for winter and summer design periods. Cap_H and COP_H are evaluated at T_L while Cap_C and COP_C are evaluated at T_H. Accurate values of L are largely dependent on the selection of the design period duration, which influences R_s, and on the estimation of the run time fraction for the heat pumps during that period, ($Run_{f,H}$ or $Run_{f,C}$). Typically, the extent of the design period is of the order of one to three months.

The ground thermal resistances evaluated by this approach are not precise for long-term estimations since the one-dimensional (radial) infinite line source solution does not account for increased heat transfer at the borehole extremities which can be important after several months of operation. These simplifications, as explained by Cane and Forgas [8] and Caneta [9] lead to borehole oversizing.

2.3. *L2 – Three pulse methods*

$L2$ methods use temporal superposition of three successive load pulses to size bore fields. These pulses are: i) peak ground load; ii) average monthly ground load during the month in which the peak load occurs; and iii) the yearly average ground load. With reference to Equation 1, the summation term would then involve three terms. Each of these pulses is applied over a certain time period which typically corresponds to: 4 to 6 hours for the peak load; 30 days for the monthly load; and 10 years for the yearly load. Thus, the lengths L determined with $L2$ methods are the lengths required to reach the temperature limits (T_L or T_H) when the bore field is subjected to 10 years of the yearly average ground load followed by 30 days of the average monthly ground load and finally 4 o 6 hours of the peak ground load.

With reference to Figure 2a, $L2$ methods start either at step 1 or 3. Step 1 involves the determination of three building loads associated with the three thermal pulses, i.e. the peak building loads in heating and cooling and their duration, the monthly averaged building loads in heating and cooling during the peak month and the total annual heating/cooling loads. Then, peak ground loads are obtained in step 3 using the COP_H and COP_C values determined in step 2. Monthly ground loads are evaluated as a fraction (often called the Part-Load Factor – PLF) of the peak loads and the annual average ground load can be calculated using the concept of equivalent full load hours using the peak loads and COP_H and COP_C determined in step 2. Then, three ground thermal response factors (or ground thermal resistances) and T_p are evaluated in step 6. As shown below in the description of some $L2$ tools, these values are determined using either the infinite cylindrical heat source analytical solution or g-functions. If the ground thermal resistances (and T_p) depend on the borehole length then an iterative process is required and ground thermal response factors are re-evaluated until convergence as indicated in Figure 2a. In some methods, the borehole thermal resistance depends also on L, in which case the calculations are reinitiated in step 4 as indicated by the dotted line in Figure 2a. Three $L2$ methods (and their variations) will now be reviewed.

ASHRAE sizing equation

Equation 3 will be referred here as the ASHRAE sizing equation. This equation first appeared in the 1995 ASHRAE Handbook-Applications [10] and in a paper by Kavanaugh [11] and is still used in the latest version [12] of the ASHRAE Handbook-Applications. Earlier versions of these equations were presented by Kavanaugh [7, 13]. Equation 3 can either be used for heating or cooling applications: $T_{in,hp}$ is replaced by T_L or T_H, the design temperature limits in heating and cooling, respectively, and $T_{out,hp}$ is determined from an energy balance on the bore field.

$$L = \frac{q_y R_y + (q_h - W)(R_b + PLF_m R_m + R_h F_{sc})}{T_g - \frac{(T_{in,hp} + T_{out,hp})}{2} - T_p} \tag{3}$$

In Equation 3, the annual, monthly and peak load pulses are given by: i) q_y, the net annual average heat transfer to the ground, ii) $(q_h - W)PLF_m$, the monthly average heat transfer to the ground, and iii) $(q_h - W)$, the peak heat transfer rate to the ground. Note that q_y is a ground load and that q_h is a building load which is converted into a ground load by subtracting the compressor power at peak load, W. PLF_m is the part load factor during the design month and finally F_{sc} is the short circuit heat loss factor in the borehole. This last value, which is typically very close to 1, is tabulated in the ASHRAE handbook [12]. R_y, R_m and R_h are the yearly, monthly and hourly effective ground thermal resistances which are evaluated using the infinite cylindrical source (ICS) analytical solution. With the use of the ICS, the ASHRAE equation is relatively simple to calculate as the ground thermal resistances do not depend on the heat exchanger length and so the result can be determined directly without iterations. However, the use of the ICS implies that borehole-to-borehole thermal interaction is not accounted for. The equation thus needs a correction factor, referred to as a temperature penalty, T_p.

Values of T_p are tabulated in the ASHRAE Handbook [12] for a limited number of bore field configurations and annual ground thermal imbalances (q_y). These values are based on a calculation procedure developed by Kavanaugh and Rafferty [14] which was recently slightly modified [15] to account for heat transfer from the bottom of the bore field. This last method of calculating T_p will be used later in the inter-model comparison. With this method, T_p can be regarded as the increase/decrease of the temperature in the ground volume occupied by the boreholes caused by the annual ground thermal imbalance. This method of calculating T_p has been criticized by a number of authors (e.g. Bernier et al. [16], Fossa [17]) and has been shown to underestimate T_p.

As for the determination of the borehole thermal resistance, R_b, the ASHRAE handbook proposes a table of R_b values for two (one U-tube) and four pipes (two U-tubes) for three grout conductivities, three fluid flow regimes (laminar, transition, and fully turbulent), three U-tubes sizes, and three bore diameters. Various pipe locations within the borehole are also considered. Reported values are calculated using a publicly-available spreadsheet program [18]. The ASHRAE equation has been implemented in a tool called GCHPcalc [11].

Modified and modified+ ASHRAE sizing equation

Bernier [19] suggested to rewrite the ASHRAE sizing equation as follows:

$$L = \frac{q_y R_y + q_m R_m + q_h R_h + q_h R_b}{T_m - \left(T_g + T_p\right)} \tag{4}$$

This will be referred to as the modified ASHRAE sizing equations. In Equation 4, T_m= ($T_{in,hp}$+$T_{out,hp}$)/2, q_m is the monthly average heat transfer to the ground, and q_h is the peak ground load, in contrast with q_h in Equation 3 which is the peak building load. There are three other differences between Equations 3 and 4: the F_{sc} term has been dropped, the borehole thermal resistance is calculated based on the zeroth order expression of the multipole method [20], and T_p is obtained using a correlation based on g-functions [16] which accounts for the three dimensional nature of heat transfer in a bore field. This value of T_p corrects the borehole temperature obtain with the ICS to account for borehole-to-borehole thermal interactions. Since g-functions depend on borehole length, an iterative procedure is required as discussed earlier in conjunction with Figure 2a.

Philippe et al. [21] developed a user-friendly spreadsheet for sizing bore fields based on Equation 4 for three fixed pulses of 10 years, 30 days, and 6 hours. The spreadsheet can perform up to five iterations which is usually sufficient to obtain a converged solution for L. However, there are some limitations associated with this tool. First, the correlated equation for T_p is limited to rectangular bore fields of less than 144 equally-spaced boreholes. Secondly, it is not possible to change the duration of the three heat pulses. Monzó et al. [1] overcame this limitation by implementing a marching solution where Equation 4 is applied month after month with the value of q_y replaced by the ground load averages of the proceeding months. Finally, the value of R_b does not account for the possible thermal short-circuit between the upward and downward legs in the borehole. An improved version of the original spreadsheet of Philipe et al. [21], refered to as the modified+ ASHRAE sizing equation, has been developed. First, the duration of the three pulses are now user-defined. Secondly, values of T_p are not restricted to rectangular geometries and equally-spaced boreholes. They can be evaluated using either the method of Bernier et al. [16] or Fossa's approach [17] which are summrarized in Equations 5 and 6.

$$T_p = \frac{q_y}{2\pi k_g L}\left[g_N(t) - g_1(t)\right] \quad (5)$$

$$T_p = \frac{q_y}{k_g L}\left[\frac{g_N(t)}{2\pi} - G(t)\right] \quad (6)$$

where g_N and g_1 are the g-functions for the entire bore field (composed of N boreholes) and for a single borehole, respectively; G is the ICS solution for one borehole. Finally, the time t at which T_p is evaluated is not restricted to 10 years.

The third improvement included in the modified+ ASHRAE sizing equation is related to the borehole thermal resistance, R_b, which is calculated using the first-order expression of the multipole equation (equation 13 in ref. [20]). Furthermore, these R_b values are corrected to account for possible thermal short-circuiting in the borehole. The corrected values are usually referred to as an effective borehole thermal resistance, R_b^* which can either be based on a constant heat flux or constant temperature boundary condition at the borehole wall (equations 3.67 and 3.68 in ref. [22]). Typically, the average of the two R_b^* values is used and this will be the case in the tools used in the inter-model comparison reported below.

ASHRAE's Alternative method

Ahmadfard and Bernier [23, 24] suggested a further improvement to the modified ASHRAE sizing equation to eliminate the need to evaluate the temperature penalty. The resulting alternative equation is:

$$L = \frac{q_y R_{gy} + q_m R_{gm} + q_h R_{gh} + q_h R_b}{T_m - T_g} \quad (7)$$

This $L2$ method uses g-functions to calculate the three effective ground thermal resistances corresponding to the three ground loads. As g-functions account for borehole thermal interactions, the temperature penalty is no longer needed. However, an iterative calculation procedure is required as g-functions depend on the borehole length. The method can be applied to any bore field configuration as it calculates g-functions dynamically as the solution evolves. Since only three g-function values corresponding to the three heat load periods are required the whole g-functions curve does not need to be evaluated [23, 24]. Recently, Ahmadfard and Bernier [24] introduced the concept of short-term g-function into this equation to account for borehole thermal capacity (fluid, pipe and grout). With this technique, R_{gh} and R_{gm} are based on short-term g-functions. These values are obtained in a way similar to the one used by GLHEPro with the use of an equivalent diameter.

GHX Design Toolbox (in $L2$ mode)

In his book, Chiasson [25] provides access to a spreadsheet-based design tool which can size vertical GHE with either $L2$ or $L3$ approaches. For $L2$ (Figure 2a), hourly peak building loads in heating and cooling as well as their duration are provided by the user along with monthly and yearly load factors and a constant borehole thermal resistance. These values are then used along with constant values of COP_H and COP_C to calculate various ground loads: peak loads in heating and cooling, average monthly heating and cooling loads during the peak months, and annual load. Then, a g-function based approach similar to the one proposed by Ahmadfard and Bernier [23], i.e. Equation 7, is used to obtain L. An iterative procedure on L is required. It takes the form of a single variable optimization, using the golden section search method. The g-functions are calculated using the analytical g-functions obtained by Claesson and Eskilson [26] as the base and the Incomplete Bessel Function (i.e. the Leaky Well Function) for evaluating the borehole-to-borehole thermal interactions. The borehole locations are user-defined and are not limited to rectangular configurations.

2.4. *L3 -Monthly and peak pulses*

Some of the most popular software tools use $L3$ methods which rely on monthly averaged loads and monthly peak loads. The objective of $L3$ methods is to obtain T_m (or T_{inHP}) for a given bore field length (Equation 8). Since the ground thermal response (values of R_i) vary with borehole length, an iterative process is required as shown in Figure 2b.

$$T_m = \frac{T_{inHP} + T_{outHP}}{2} = \frac{\sum_{i=1}^{N} q_i R_i + q_h R_b}{L} + T_g \quad (8)$$

Typically, Equation 8 would be evaluated month by month for the entire design period. For example, Equation 9 would be used to obtain $T_{m,2}$ after the second month of operation:

$$T_{m,2} = \frac{T_{inHP,2} + T_{outHP,2}}{2} = \frac{q_{m,1}R_{m,1} + q_{m,2}R_{m,2} + q_{h,2}R_{h,2} + q_{h,2}R_b}{L} + T_g \tag{9}$$

where $q_{m,1}$ and $q_{m,2}$ are the average ground loads for the first two months, $q_{h,2}$ is the peak ground load of the second month (typically applied at the end of the month), $R_{m,1}$, $R_{m,2}$, and $R_{h,2}$ are the ground thermal responses corresponding to the duration of $q_{m,1}$, $q_{m,2}$, and $q_{h,2}$, respectively.

In theory, $L3$ methods should be more accurate than level $L2$ methods as they follow more closely the time evolution of the loads. The calculation sequence for a typical $L3$ method can be explained using Figures 2b and 2c. Two approaches are typically used: one which starts with building loads and the other with ground loads. In the first approach (Figure 2b), the user typically inputs 48 building loads, i.e. 12 monthly averaged building loads and 12 monthly peak loads for both heating and cooling conditions. These values are assumed to repeat each year for the design period of the system. It is important for the user to carefully select the duration of the peak loads as this has a relatively important influence on the results. The reader is referred to the work of Cullin and Spitler [27] who have formulated a method to determine peak loads and their duration using hourly building load profile.

It should be noted that the calculation process described in this paragraph applies to $L3$ and $L4$ (to be described shortly) methods. Calculations start in step 2 with a first estimate of the borehole length. Then, the borehole thermal resistance (which in some tools depend on L) is evaluated in step 3. Then, COP_H and COP_C are typically evaluated each month (each hour in $L4$ methods) based on values of T_{inHP} prevailing at peak conditions during that month (or during the given hour in $L4$ methods). With known values of $COPs$, ground loads can be evaluated in step 5 followed by the calculation of the ground thermal response factors in step 6. Then, Equation 8 (Equation 1 for $L4$ methods) is applied sequentially from month to month (hour to hour in $L4$ methods) for the expected lifetime of the system to determine T_{inHP} in step 7. If calculated values of T_{inHP} have not converged then the process goes back to step 4 for an update on the COP values. If T_{inHP} has converged then a check is made to verify if the temperature limits (T_L or T_H) have been reached. If not, then the value of L is updated and calculations proceed back to step 3. When the method starts with the ground loads (Figure 2c), the calculation sequence is simpler. The tool sets a guess value for L then evaluates the borehole thermal resistance for this value of L. Ground thermal response factors are calculated in step 4 and Equation 8 (equation 1 for $L4$ methods) is used to evaluate T_{inHP} in step 5. As shown in step 6, if either T_L or T_H has been reached then a converged value of L is obtained, if not, L is updated and the sequence goes back to step 3. Note that if the tools assume that the borehole thermal resistance is independent of L, then iterations go back to step 4 instead of step 3 in both paths (Figures 2b and 2c). If $COPs$ are dependent on the fluid temperature, the ground loads are evaluated iteratively at each time step. The iterative procedure uses an initial guess value for the $COPs$ and iterates until convergence as shown in Figure 2b. Four $L3$ methods will now be described.

NWWA method

The *National Water Well Association* (NWWA) method is a $L3$ method where ground loads are used directly. It has been described by Hart and Couvillion [28]. The NWWA method applies Kelvin's line source model to evaluate ground heat transfer. It takes into account the effects of cyclic on-off operation as well as thermal interferences of adjacent boreholes. As reported by Cane and Forgas [8] the entering heat pump fluid temperature at month k (T_{f_k}) obtained by the NWWA method is evaluated using the following equation:

$$T_{f_k} = \sum_{i=0}^{i=k} \left(\left(\frac{q}{\sum_{j=1}^{layers} \left(\frac{L_j}{(L_M/L_s)_j R_{s_j} + R_p} \right)} \right)_i \Delta RTR_i \right) + \frac{q\ RTR}{2\left(\dot{m}\ SG\ Cp_f\right)} + \Delta T_{g_k} + T_{g_k} \tag{10}$$

The term $q/\sum_{j=1}^{layers}\left(L_j/\left((L_M/L_s)_j R_{s_j} + R_p\right)\right)$ represents the heat transfer between the heat exchanger fluid and the ground, q is the heat exchanged with the ground, L_s is the length of single-pipe heat exchanger and L_M is the length of multiple heat exchangers, L_j is the length of pipe in the jth ground layer, $(L_s/L_M)_j$ is the length multiplier for a multiple system in the jth layer of the ground, R_{s_j} is the ground thermal resistance in the jth ground layer surrounding the borehole, R_p is the pipe thermal resistance, i is any month from the beginning of the period up to month k, RTR_i represents the ratio of run time to the cycle time of month i, ΔRTR_i is the change in run time ratio from one month to the next, $\dot{m}$ is the fluid flow rate in the pipe, SG and Cp_f are the specific gravity and specific heat of the fluid, respectively, T_{g_k} represents the average far field temperature in month k, ΔT_{g_k} is the average seasonal variation of the far field temperature in month k. The obtained fluid temperatures are compared to the user specified lowest and highest entering fluid temperatures. If the difference satisfies the specified convergence criterion, the iterative procedure stops, otherwise, a new heat exchanger length is selected and the procedure is repeated until convergence. The NWWA has been shown to be more precise than the IGSHPA method [9]. However, it does not reach the accuracy that can be achieved with modern techniques.

Quasi-three pulse method with running average

Monzó et al. [1] have proposed a methodology which accounts for monthly loads but that still uses the three-pulse approach of $L2$ methods. The resulting sizing method is shown in Equation 11. In their approach, the length is determined for each month i over the design period. The yearly load and corresponding value of the effective ground thermal resistances (product $q_y\ R_y$ in Equation 4) is replaced by a running average of the loads of the previous months multiplied by the corresponding effective ground thermal resistance ($\overline{q}_{pm,i}R_{pm,i}$). The monthly pulse term in Equation 4 ($q_m\ R_m$) is replaced with the monthly pulse and the corresponding effective ground thermal resistance of the current month ($q_{cm,i}R_{cm}$). The temperature penalty ($T_{p,i}$) is evaluated iteratively for each month using the technique described in Equation 5.

$$L_i = \frac{\overline{q}_{pm,i}R_{pm,i} + q_{cm,i}R_{cm} + q_{h,i}R_h + q_{h,i}R_b}{T_m - \left(T_g + T_{p,i}\right)} \qquad (11)$$

Even though this method uses the three pulse approach of $L2$ methods it is considered here as a quasi $L3$ method because monthly loads are considered.

It is also possible to extend the $L2$ alternative method described earlier to a quasi $L3$ method using the approach proposed by Monzó et al. [1] but using g-functions instead of T_p. The resulting equation is given in Equation 12,:

$$L = \frac{\overline{q}_{pm,i}R_{g,pm,i} + q_{cm,i}R_{g,cm} + q_{h,i}R_{gh} + q_{h,i}R_b}{T_m - T_g} \qquad (12)$$

where the index g has been added to the effective ground thermal resistance to indicate that they are based on g-functions. Finally, much like for the alternative method described earlier, it is possible to account for borehole thermal capacity by evaluating R_{gh} and $R_{g,cm}$ with short-term g-functions.

GHX Design Toolbox (in $L3$ mode)

In addition to the $L2$ approach described earlier, Chiasson's [25] spreadsheet has $L3$ capabilities. The user can either specify 48 monthly values (average building loads and peak loads for heating and cooling) directly or enter the hourly building load values which are then pre-processed to obtain the 48 monthly building loads. The building loads are then converted to ground loads based on the user defined COP values as a function of $T_{in,HP}$. The peak load durations in heating and cooling are also specified by the user. Once these values are entered, the calculation proceeds as shown in Figure 2b. More specifically, Equations 13.a to 13.d are solved for both heating and cooling conditions to obtain L.

$$T_{f,avg} = T_g + \sum_{i=1}^{n} \frac{\left(q_i^{'} - q_{i-1}^{'}\right)}{2\pi k_g} g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}, \frac{B}{H}\right) + q_n^{'} R_b \tag{13.a}$$

$$T_{f,peak} = T_{f,avg} + \frac{q_{rej,peak}}{H.N_b} R_q \tag{13.b}$$

$$R_q = \frac{ln\left(4\alpha t_p / r_b^2\right) - 0.5772}{4\pi k_g} \tag{13.c}$$

$$T_{in,hp,peak} = T_{f,peak} + \frac{q_{rej,peak}}{2\dot{m}C_p} \tag{13.d}$$

where $T_{f,avg}$ and $T_{f,peak}$ are the average and the peak mean fluid temperature in the boreholes and $T_{in,hp,peak}$ is the peak inlet fluid temperature to the heat pumps determined for the nth month of operation, $q_i^{'}$ is the net average ground load per unit borehole length for the ith month, g is the ground thermal response factor (g-function), which is a function t/t_s, r_b/H, and B/H, and t_s is the borehole time scale, and $q_{rej,peak}$ is the net peak ground load. It is obtained by subtracting the average cooling or heating loads from the cooling or heating peak loads. R_q is estimated by an approximation of the infinite line source solution (ILS) and is dependent on the peak load duration. Equations 13.b to 13.d are calculated each month over the expected life time of the system. Then, as shown in Figure 2b, L is updated if convergence has not been reached. It is updated using the golden section search optimization method where the objective function is defined as the square of the error of the calculated and target values of T_L and T_H.

EED

EED (v3.2) is a $L3$ sizing tool which sizes the ground heat exchangers based on either the building or the ground loads [29]. It should be noted that the newest version of EED (v4) can also operate as a $L4$ tool. With EED in $L3$ mode, the sequences presented in Figure 2b or 2c are used. When building loads are specified, constant COP values are used to obtain the ground loads. Thus, the inner iteration loop on T_{inHP} shown in Figure 2b is not used. The duration of peak loads can be set to different values for each month. When ground loads are specified (Figure 2c), heat pump characteristics are not required. The borehole thermal resistance can be entered directly by the user or it can be evaluated within the sizing sequence. The user can choose if borehole short circuiting effects should be accounted or not. EED calculates effective borehole resistances and so iterations go back to step 3 (Figures 2.b and2.c). Ground thermal response factors are derived using pre-calculated g-functions stored in an extensive database with various bore field geometries including boreholes positioned in various configurations (in-line, L- and U-shape, open rectangular or rectangular). EED v4 can approximate irregular borehole patterns with regular ones. The data base of g-functions are for specific values of r_b/H, B/H. During the course of a calculation, if values of r_b/H and B/H do not match these values, then a correction factor [30] is applied to account for different values of r_b/H and the tool interpolates between g-function values for different B/H by keeping the borehole distance spacing constant and changing boreholes depth.

The tool evaluates the average and the peak monthly mean fluid temperatures over the design period of the system and determines the minimum required bore field length which satisfies the heat pump temperature limits as shown in Figures 2b and 2c.

GLHEPro

GLHEPro [31, 32] is a $L3$ sizing tool which uses average and peak monthly heat loads. Note that GLHEPro V.5 can also perform hourly simulations ($L4$ level) for a given bore field length. Much like EED, two paths are possible either with the building loads or directly using ground loads. The heat pump $COPs$ can either be defined as constant or dependent on the inlet fluid temperatures. In this later case, an inner iteration is required, as shown by the dash line in Figure 2b. The calculation methodology for GLHEPro is similar to the one presented in Equations 13.a to 13.d. However, as noted by Cullin and Spitler [27] the evaluation of $T_{f,peak}$ uses R_b in addition to R_q.

$$T_{f,peak} = T_{f,avg} + \frac{q_{rej,peak}}{H.N_b}(R_q + R_b) \tag{14}$$

where $R_q = g\left(t/t_s, r_b/H\right)/\left(2\pi k_g\right)$ which is the effective ground thermal resistance for the peak load duration. R_q is evaluated based on short-term g-functions determined by a technique elaborated by Xu and Spitler [33]. This technique is based on an earlier methodology developed by Yavuzturk et al. [34] and Yavuzturk and Spitler [35]. In effect, this method accounts for thermal capacity (fluid, pipe and grout) inside the borehole.

The method finds the maximum and minimum heat pump inlet fluid temperatures for each month by superimposing the temperature response of the peak loads on the obtained average fluid temperature (Equation 13.d). Then, these maximum and minimum values are compared to the specified temperature limits until convergence. The tool uses 307 pre-calculated g-functions [31] that are stored in a database for various types of bore field. GLHEPro evaluates the effective borehole thermal resistance using 10th order multipole [20].

2.5. $L4$ –Hourly loads

Hourly building or ground loads are used as the starting point in $L4$ methods. Typically, the same hourly loads are used from year to year for the design period. With reference to the general sizing equation (Equation 1), $L4$ methods involve 8760 terms in the summation for each year of calculation. This makes the calculations computationally intensive and most often loads are aggregated to reduce the number of terms in the summation. Aside from the different time scale of the loads, the calculation sequence of $L4$ methods is identical to $L3$ methods and follows the sequence presented earlier depending on whether building (Figure 2b) or ground loads (Figure 2c) are provided.

As indicated above, the newest versions of EED has an option to perform $L4$ calculations. A number of tools can be considered to be quasi $L4$ tools. For instance, GLHEPro V5.0, Energy Plus, eQuest all provide hourly simulations but for a fixed bore field length. It is possible to update "manually" this length until T_L and T_H are reached to get the design length. The Duct ground heat STorage (DST) model, which is part of the TRNSYS package, is not considered to be a ground heat exchanger sizing tool. However, it can predict the hourly fluid temperature evolutions over the expected life of the system. Recently, Ahmadfard et al. [36] have combined the DST model with GenOpt to automate this iterative procedure to make it a $L4$ method. It will now be briefly described.

DST model used a sizing tool In TRNSYS

The Duct ground heat STorage (DST) model has been developed originally by Hellström [37] to simulate seasonal thermal storage of densely packed boreholes configured in an axisymmetric pattern. It is part of the TESS library [38] of TRNSYS [39] and is known as Type 557. The ground thermal response is calculated using a one dimensional analytical model to solve for the ground temperature in the local region and a two-dimensional explicit finite difference model to simulate the ground temperature in the global region.

With the approach suggested by Ahmadfard et al. [36], GenOpt starts the iteration with a guess value for the length. It then calls the DST model and runs a simulation for the expected design period of the system. Next, it analyzes the results and updates the guessed length and runs a new iteration. This iterative procedure continues until the minimum borehole length that satisfies the maximum and minimum fluid temperature limits is obtained. The model can handle both constant and variable $COPs$. In the latter case, the tool has an inner hourly iteration loop (steps 7 to 3 in Figure 2.b). There are two major drawbacks when using the DST model. First, it is only strictly applicable to axisymmetric configurations. Secondly, borehole thermal capacity is not considered and the borehole thermal resistance remains constant throughout a simulation.

3. Literature review of inter-model comparisons

Caneta [9] performed one of the earliest comparative studies where the IGSHPA and NWWA methods were compared to a rule-of-thumb. A real installation composed of three boreholes with an actual total borehole length of 274.3 m is used. The evaluations are based on monthly loads including eight heating months and four cooling months. The resulting borehole lengths obtained from the sizing tools were: 271.7, 330 and 365.8 m for the NWWA, IGSHPA, and rule-of-thumb methods, respectively. This represents differences of 0.94, 20.3, and 33.35 % when compared to the real installation.

Thornton et al. [40] are at the origin of the first serious efforts to compare modern vertical GHE sizing tools. They used one year of site-collected data from a single-family residence at Fort Polk, Louisiana to first calibrate the inputs to the DST model to obtain “best-fit” thermal properties. These inputs are then used to compare one-year design lengths obtained with five commercially-available sizing tools for eight values of T_H and two ground temperatures. The most important spread in the results is obtained when T_H = 29.5°C, where differences of about 83 and 88 % are observed for ground temperature of 16.7°C and 20.6°C, respectively.

Shonder et al. [41] repeated the comparison exercises for residential applications with updated version of the five sizing tools used by Thornton et al. [40] and one new tool. Two sites, in cooling- and heating-dominated applications are examined. The DST model is used as the benchmark and it is first calibrated with site collected data. For the cooling-dominated application, four values of T_H are considered and the GHE length is determined for 1 and 10 years of operation. Results show a much better agreement compared with the previous results of Thornton et al. [40]. For T_H = 35°C, the six sizing tools determined the borehole length within 7% for a one-year operation. However, all six programs seem to undersize the GHE to some extent when compared to the DST model. The ten-year design lengths obtained by four programs vary by about 17% for T_H = 35°C. For the heating-dominated case and for T_L = -1.1°C, the one-year and ten-year design lengths vary by about ±16% and ±15%, respectively.

Shonder et al. [42] compared four GHE sizing tools for a relatively large bore field (12×10) in an elementary school in Lincoln, Nebraska. The authors first used the DST model in TRNSYS as a benchmark and calibrated its inputs with one year of site-collected data. Since this is a heating-dominated application, the four design tools were compared for values of T_L equal to -1.1°C, 1.7°C, and 4.4°C for one and ten year design periods. On average, there is a ±16% difference between the four sizing tools and the DST model. Overall, the GHE lengths differ by an average of ±12% from the TRNSYS benchmark, somewhat less than the ±16% difference for the one-year lengths. The ten-year GHE design lengths are on average, about 7% higher than the one-year lengths, indicating only modest multi-year effects. Indeed the annual ground thermal imbalance is 1.76 kW (in heating mode) which leads to a relatively small temperature penalty, T_p = 0.35 °C. It should also be noted that the DST model is designed to simulate boreholes in an axisymmetric pattern not a rectangular 12×10 geometry. The resulting error from this approximation has not been documented by the authors.

Spitler et al. [43] performed an inter-model comparison of six different simulation tools including the DST model, three g-function based models implemented in EnergyPlus, eQuest, and HVACsim+, and two proprietary models. Two set of data were used: The first set comes from a three-borehole ground heat exchanger at Oklahoma State University, with 15 months of hourly-averaged experimental data. The second set is composed of one-year of hourly ground load data obtained by simulating an office building in Tulsa. A 196 borehole configuration is used in this second case. Results for the first set of data indicate that all models show higher oscillation amplitudes than the experiment, probably indicating that the dampening effect associated with borehole thermal capacity is not properly accounted for in the models. In addition, the authors indicate that the use of hourly time steps that do not correspond to the heat pump on/off cycles, may have causes these differences. The authors cite model assumptions that may not have been encountered in the experiments: uniform undisturbed ground temperature, no ground water flow, no moisture transport in the upper, unsaturated region of the ground, and uniform heat transfer along the borehole length.

For the second test with the 196 borehole configuration, substantial differences in the evaluation of the long-term temperature rise and monthly fluid temperature changes at the heat pump inlet are observed after 20 years of simulated operation. It is speculated that the assumptions used for superposition of individual boreholes, boundary conditions and heat transfer variations along the borehole are the likely causes of discrepancies. Finally, the authors note that user input and post-processing errors should not be ruled out in such a comparison.

Bertagnolio et al. [44] presented test cases for comparing the time evolution of borehole wall temperatures obtained using three analytical solutions (infinite line source (ILS), infinite cylindrical heat source (ICS), and finite line source (FLS), two numerical models (g-functions and DST) and a hybrid model (ICS/Tp/MLAA) based on a combination of the infinite cylindrical heat source, and improved calculation of T_p and a so-called multiple load aggregation algorithm (MLAA). The authors defined two series of test cases for single and multiple boreholes. Synthetic load profiles are used in all cases. They are generated using a relatively simple mathematical function which enables reproducible profiles. The same approach will be used later in the paper for some test cases. For single boreholes, constant heat rejection load, symmetric cyclic heat load, asymmetric heat load (cooling dominated for 20-year) and non-continuous (heating only) heat load are considered. The results show that analytical one-dimensional radial models (ILS, ICS) are in good agreement with three dimensional models for relatively short-simulation periods. However, for longer time periods the results are not as accurate since the axial effects become more significant and only the FLS, g-functions and DST models have good accuracies. Cyclic heat load tests proved to be useful in evaluating the accuracy and the computational performance of different load aggregation algorithms. Results obtained with the asymmetric load revealed that ICS-based models predict borehole wall temperatures within ±1ºC of the DST model.

For multiple boreholes, constant heat rejection and asymmetric loads (cooling dominated for 20-year) are considered. Constant load tests illustrated significant differences among the two numerical and hybrid models. These differences are due to two factors. First, the ICS/Tp/MLAA model cannot account for axial effects and these effects become important over the long term. Secondly, the DST model arranges the boreholes in an axisymmetric configurations which resulted in some error for in-line configurations.

Kurevija et al. [45] compared the ASHRAE sizing equation (Equation 3 – $L2$ method) with $L3$ sizing methods based on g-functions. Two borehole arrangements, 6×7 and 21×2, are considered for a Croatian building. Borehole spacing is varied from 4 to 9 m giving a total of 12 comparisons. Peak and monthly building loads are given as well as the estimated peak duration and the equivalent full load operating hours (to obtain the annual ground loads). The bore field is sized for a 30-year operation. The lengths obtained with the g-function based methods are 8.8% to 10.7% (for the 21×2 configuration) and 10.7 to 19.3% (for the 7×6 configuration) greater than the ones obtained with the ASHRAE sizing equation with the largest differences occurring for small borehole spacing. The authors explain that these discrepancies are due to the fact that the ASHRAE sizing equation uses a simplistic borehole interaction model for predicting the heat buildup in the ground over time.

Cullin et al. [46] used six years of experimentally measured data on a 3×2 ground heat exchanger, located in Valencia, Spain, to compare the sizing results of a simulation-based design tool (GLHEPro) and the classic ASHRAE sizing equation against the known borehole length (50 m). Results indicate that the simulation tool under predicts the required heat exchanger length by 4%, while the ASHRAE sizing equation over predicts it by 103%. A sensitivity study on the input uncertainties revealed that the simulation-based method could under predict the results by about 2 % and over predict them by as much as 12%. However, only 9% of the over prediction obtained with the ASHRAE sizing equation could be attributed to inputs inaccuracies.

Cullin et al. [47] extended their study to compare the design results of a simulation-based tool (GLHEPro) with the ASHRAE equation using experimental data from four systems. In addition to the Valencia case, data from systems located in Stillwater (USA), Atlanta (USA) and Leicester (UK) are used. Results show that the simulation-based tool predicts the actual installed borehole length to within 6% in all cases. Use of the ASHRAE sizing equation results in predicted borehole lengths which are significantly different from the actual lengths. Differences of -21%, +26%, +60%, and +103% are observed (negative/positive values represent undersizing/oversizing, respectively). The authors explained that the load representation and, to a lesser extent, the calculation of the borehole thermal resistance explain much of the differences between the ASHRAE sizing equation and the simulation-based tool. The authors also point out to the inherent uncertainty in reading values from the G-factor chart provided by Kavanaugh and Rafferty [14] which is used to determine the effective ground thermal resistances. As indicated above, the ASHRAE sizing equation has been developed to calculate the required length based on three thermal pulses with durations of 10 years, 30 days, and 6 hours, respectively. The four cases represent measurement periods of six years or less. Therefore, the ground thermal resistance for the 10 year pulse in the ASHRAE sizing equation has to be adapted.

The present authors have also looked at the data for the Valencia case and determined the required borehole length based on their own interpretation of the data. Table 2 summarizes the results of these calculations and a comparison is made with the results provided by Cullin et al. [47]. As shown in Table 2, there are some significant differences in the evaluation of the parameters used in Equation 3.

First, the value of q_a is estimated to be -17.4 kW based on an analysis of the raw data. The PLF_m value of 0.192 is obtained from 2405/(17.4×720), where the value of 2405 kWh is the total heat injected during the 6th month of the third year of operation [47] and 720 is the number of hours in the month of June. Values of R_h, R_m, R_y are also different. In the present case, they are obtained using calculated values of the G-factor based on the solution of the ICS solution provided by Cooper [48] with a borehole radius of 75 mm, a thermal conductivity of 1.6 W/m-K [47], and a ground volumetric heat capacity of 2250 kJ/m^3-K [46]. The values of T_{inhp}/T_{outhp} (30/35.5°C) are taken from the raw data at the peak conditions. The calculated value of -0.27°C for T_p is obtained using the original concentric ring technique proposed by Kavanaugh and Rafferty [14] with a borehole separation distance of 3 m, a period of 3 years, and a borehole length of 61.1 m.

Table 2: Two different set of inputs to be used with the ASHRAE sizing equation for the Valencia case

Parameter	Units	Values used by Cullin et al. [47]	Values used in the present study
q_h	kW	-17.0	-17.4
$q_h \times PLF_m$	kW	-17.0×0.27	-17.4×0.192
q_a	kW	-0.469	-0.469
$R_h/R_m/R_y$	m.K.W^{-1}	0.169/0.244/0.193	0.113/0.217/0.179
R_b	m.K.W^{-1}	0.11	0.11
$t_h/t_m/t_a$	hours/days/years	6/30/3	6/30/3
T_{inhp}/T_{outhp}	°C	27.2/32.7	30/35.5
T_g	°C	19.5	19.5
F_{SC}	-	1.04	1.04
T_p	°C	-0.5	-0.27
L	m	101	61.1

The final calculated length (61.1 m) obtained using the ASHRAE sizing equation with the current set of inputs is much closer to the actual length (50 m) than the results of calculations performed by Cullin et al. [47] using the same ASHRAE sizing equation (100 m) but with a different set of inputs. If the duration of the peak heat load is assumed equal to 3 hours [49], the length obtained by the ASHRAE equation goes down to 56.8 m. These discrepancies show the importance of human interpretation of the raw data on the final results. This is one reason why all loads are pre-treated in the inter-model comparison so that all tools have the same inputs. Li et al. [50] have also used the four cases introduced by Cullin et al. [47] to validate their methodology which is based on a reformulation of the ASHRAE sizing equation. For the Valencia case presented in Table 2, they obtain a length of 77 m. Finally, as mentioned by Spitler [51], these four cases have reasonably balanced annual heat extraction and rejection loads with no significant long-term heat build-up or draw-down. Therefore, these data sets are not necessarily suited to check long-term effects.

4. Proposed test cases

One of the goals of this work is to propose a set of test cases that could be used to compare vertical GHE sizing tools against each other. With reference to the BESTEST terminology [52, 53] for building simulation software tools, three types of sizing test cases can be defined for comparisons: 1- simple analytical test cases, 2- comparative test cases and 3- real/experimental cases. Analytical test cases can only be applied for the simplest conditions (e.g. single borehole with constant load). Good long-term experimental data suitable for comparative testing could not be found in the literature. Therefore, only comparative test cases are examined in this work.

Differences in the required bore field length calculated by sizing tools can be the result of input errors or modeling differences. Input errors may be the results of human errors (e.g. different users may enter different ground thermal conductivities) or differences of interpretation for the raw data (e.g. different user may select different peak load duration or may convert building loads to ground loads differently). In an effort to avoid input errors, all test cases reported here are performed using a common set of data entered in each software by the same user and checked by another. Differences in results are thus presumed to be mainly due to the use of different modeling approaches or coding errors.

It should be noted that a spreadsheet containing all the loads and input data accompanies this paper so that other users can test other sizing tools with the same data. This spreadsheet also includes the test results of the inter-model comparison presented below. With reference to the general sizing equation (Equation 1), sizing tools will differ in the way they calculate the values of the ground thermal response, R_i, including in some cases the value of T_p, and the borehole thermal resistance, R_b. Also, software tools from the same level will handle the summation term (in Equation 1) differently. In order to separate problems linked to the evaluation of R_b from the rest of the calculation methodologies, most of the test cases are solved with imposed values of R_b.

There are many data sets in the literature that could be used for inter-model comparative testing. A total of four data sets have been selected for the present study, each addressing a specific difficulty. A summary table of other data sets found in the literature is provided in Appendix A. The four data sets include: i) a synthetic perfectly balanced hourly load profile; ii) the monthly and peak load data provided by Shonder et al. [42] for a school in Lincoln, Nebraska; iii) the set of monthly and peak load values presented by Monzó et al. [1]; iv) the hourly load profile used by Bernier [19] for a simulated building in Atlanta.

4.1. Input parameters

Table 3 shows the input parameters used for all test cases. Some tools need specific parameters that are not required by other tools. These parameters are listed at the bottom of Table 3.

Table 3: Input parameters for the four test cases

Parameter	Test 1 Synthetic balanced load	Test 2 Shonder et al. (2000)[42]	Test 3 Monzó et al. (2016)[1]	Test 4 Bernier (2006)[19]	units
N_b	1	12×10	7×7	5×5	------
B	6	6	5	8	m
D	4	3	2.5	4	m
r_b	75	54	75	75	mm
$r_{p,i}$, $r_{p,o}$	16.7, 13.7	16.7, 13.7	16.7, 13	16.7, 13	mm
$2d_p$	75	47.1	75	83	mm
$\dot{m}_f$	0.443 (ground load) 0.559 (building load)	29	33.1	10.34	$kg.s^{-1}$
ρ_f	1052	1026	1026	1026	$kg.m^{-3}$
Cp_f	3795	4019	4019	4019	$J.kg^{-1}.K^{-1}$
μ_f	0.0052	0.00337	0.00337	0.00337	$kg.m^{-1}.s^{-1}$
k_f	0.480	0.468	0.468	0.468	$W.m^{-1}.K^{-1}$
$c_{p,g}$	2073.6	2877	2592	2052	$kJ.m^{-3}.K^{-1}$
α_g	0.075	0.068	0.075	0.08	$m^2.day^{-1}$
k_g	1.8	2.25	2.25	1.9	$W.m^{-1}.K^{-1}$
k_{gr}	1.4	1.73	1.73	0.69	$W.m^{-1}.K^{-1}$
k_p	0.43	0.45	0.4	0.4	$W.m^{-1}.K^{-1}$
T_g	17.5	12.41	10	15	°C
T_L	0	4.4	0	0	°C
T_H	35	35	35	38	°C
R_b	0.13	0.113	0.1	0.2	$m.K.W^{-1}$
t	10	10	10	20	years
COP_C	3.825 (building load)	3.643	------	3.86	------
COP_H	3.49 (building load)	4.09	------	4.03	------
When required by some tools, the following parameters are used: F_{sc}=1.04 q''_g = 0 W/m2 (geothermal heat flux) MCp_{gr} = 3900 $kJ.m^{-3}.K^{-1}$ (grout volumetric heat capacity) MCp_p = 1540 $kJ.m^{-3}.K^{-1}$ (pipe volumetric heat capacity) R_c = 0 $m.K.W^{-1}$ (contact resistance) h_{conv} = 1000 $W.m^{-2}.K^{-1}$ (Internal convection coefficient in pipes)					

4.2. Test 1 -Synthetic balanced load – one borehole

The first test case uses a synthetically generated balanced load profile either as a ground load or as a building load. For this test, it is assumed that the load is handled by just one borehole. The sizing tools are compared on their ability to predict the length of a single borehole when the borehole-to-borehole thermal interference is inexistent. Thus, T_p= 0 since q_y is zero (Equations 5 and 6).The balanced load is generated based on the methodology proposed by Bernier et al. [54] using the following parameters: A=2000, B=2190, C=80, D=2, E=0.01, F=0 and G=0.95. The resulting sine profile with daily and weekly variations is shown in Figure 3a (a positive value represent a heating load). Figure 3b represents the cumulative energy of this load over the year. It can be seen that the cumulative energy is zero at the end of the year. This means, for example, that when the load is used as a ground load, the cumulative annual amount of energy injected/retrieved from the ground is zero.

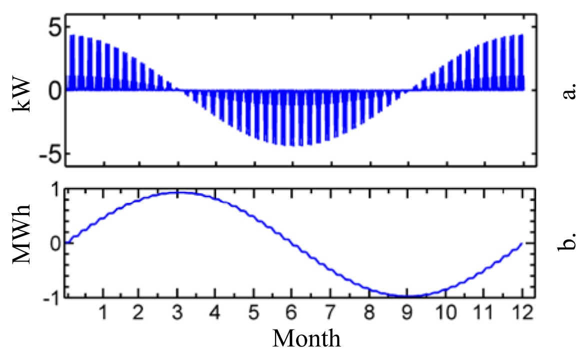

Figure 3: a) Hourly loads for the synthetic profile; b) Cumulative energy exchange resulting from the hourly loads.

In the inter-model comparison of $L4$ methods, this hourly load profile is used either directly as a ground load (Test 1a) or as a building load (Test 1b). Monthly and peak values is extracted from hourly values for use with $L3$ methods (Table 4). The three loads used for $L2$ methods have also been determined and are presented in Table 5. When the input load is a building load (Test 1b), it is converted to a ground load using Equations 15.a and 15.b where $T_{in,HP}$ is in °C [44]. When constant heating and cooling $COPs$ are assumed, COP_H and COP_C are evaluated at T_L (0 °C) and T_H (35°C) giving COP values of 3.49 and 3.825 in heating and cooling, respectively. For $L4$ tools that use a variable COP, Equations 15.a and 15.b are used with the current value of T_{inHP} during a given time step.

$$COP_H = 3.49 + 0.061 \times T_{inHP} \quad (15.a)$$

$$COP_C = 7.92 - 0.117 \times T_{inHP} \quad (15.b)$$

The nominal flow rate is assumed to be 0.1 kg/s per kW of peak load to ensure turbulent flow. Since the peak ground loads in Tests 1a and 1b are 4.428 and 5.586 kW, respectively, the corresponding flow rates are 0.443 and 0.559 kg/s. The borehole is sized for a 10-year design period.

Table 4: Monthly average and peak ground loads to be used with $L3$ methods (all loads are in kW)

Month	Test 1				Test 2			Test 3		Test 4	
	1a-ground		1b-building								
	q_m	q_h	q_m	q_h	q_m	q_h	Peak duration (h)	q_m	q_h	q_m	q_h
1	0.604	4.401	0.431	0.000	100.003	395.127	11	105.374	238.670	7.938	-35.770
2	0.492	3.707	0.351	0.000	77.624	375.484	5	91.741	214.170	3.784	-53.548
3	0.202	2.208	0.144	0.000	37.794	374.729	2	55.245	181.170	-8.085	-83.086
4	-0.168	-2.002	-0.212	-2.525	9.705	200.208	3	0.051	107.330	-21.107	-93.549
5	-0.430	-3.605	-0.543	-4.548	-35.161	108.792	1	-65.165	80.420	-35.048	-120.782
6	-0.685	-4.387	-0.864	-5.533	-81.056	50.619	1	-122.411	0.000	-43.666	-130.893
7	-0.648	-4.428	-0.818	-5.586	-105.101	46.841	1	-150.538	0.000	-46.983	-139.731
8	-0.478	-3.726	-0.603	-4.701	-108.986	33.998	1	-103.258	0.000	-44.389	-131.761
9	-0.186	-2.137	-0.235	-2.695	-36.244	63.462	6	-51.053	57.080	-34.678	-111.780
10	0.160	1.968	0.114	-0.009	-2.861	239.494	1	4.382	111.500	-18.686	-97.338
11	0.478	3.746	0.341	0.000	59.615	243.271	2	50.366	150.670	-2.983	-52.843
12	0.680	4.427	0.485	0.000	111.392	281.802	4	92.720	198.000	5.853	-34.284

Table 5: Synthesis of the data for each Test used in $L2$ methods (negative values indicate that cooling conditions determine the required length)

	Test 1		Test 2	Test 3	Test 4
	1a-ground	1b-building			
	kW	kW	kW	kW	kW
q_h	-4.428	-5.586	---	-139.731	---
q_m	-0.648	-0.818	---	-46.983	---
q_a	-0.001	-0.120	---	-19.968	---
q_h	4.427	---	395.127	---	238.670
q_m	0.680	---	100.003	---	105.374
q_a	-0.001	---	1.763	---	-7.712

Data presented in Tables 4 and 5 need some further explanations. First, data are presented sequentially starting with January as month #1 which is also the starting month of operation. The monthly loads are the average of all hourly loads including the peak load during a given month. The monthly peak load is found by searching for the maximum monthly load. Thus, taking the first month of the synthetic load as an example, the average monthly load is 0.604 kW and the peak load is 4.401 kW. The duration of the peak loads is assumed to be 6 hours in $L2$ and $L3$ methods. It is not necessary to assume peak load duration in $L4$ methods as the calculation methods follow the hourly loads. In some test cases, the peak load durations are reduced to 1 hour or, in the case of Test 2, the actual peak durations are used (see Table 4). Some tools require the monthly loads to be entered as cumulative energy values. In this example, the monthly energy load for January would then be 0.604×31×24 = 449.376 kWh. In $L3$ methods, the monthly peak is typically superimposed at the end of the month. Again, using the synthetic load profile as an example, and referring back to Equation 9, $T_{m,2}$ (mean fluid temperature in the borehole at the end of February) is calculated using $q_{m,1}$= 0.604 kW, $q_{m,2}$=0.492 kW, and $q_{h,2}$=3.707 kW with corresponding durations of 31 days, 28 days minus 6 hours (in some models 28 days), and 6 hours.

It should be noted that only the dominant loads that lead to longer lengths are reported in Table 5 which explains why either heating or cooling loads are presented.

4.3. Test 2 – Shonder's test – 120 boreholes

Shonder et al. [42] used the data from an elementary school located in Lincoln, Nebraska to perform an inter-model comparison. Since this comparison is almost two decades old, it was felt that it needed to be revisited with the current state of sizing tools. This test case concerns an installation with a 12×10 borehole field. Boreholes are 73 m deep and are spaced 6 m apart. Table 4 presents the loads obtained from the data reported by Shonder et al. [42]. In their article, Shonder et al. [42] provide peak building loads but not peak ground loads. They do provide a table of COP values as a function of T_{inHP} which was used here to convert building loads to ground loads. Heating and cooling $COPs$ of 4.09 and 3.643, for T_L = 4.44 °C and T_H = 35 °C are assumed here but other COP values may have been used by Shonder et al. [42]. The monthly peak load durations are assumed equal to the measured values reported by these authors (see Table 4). Peak load durations of 6 hours are also considered in the comparison. In addition, the shank spacing and pipe thermal conductivity are assumed to be 47.1 mm and 0.45 W.m^{-1}.K^{-1}, respectively. The properties of the heat transfer fluid (propylene glycol, 22%) are evaluated at 10 °C. As was done by Shonder et al. [42], the bore field is sized for the heating case. Test 2 is not particularly severe in terms of borehole-to-borehole thermal interference since there is a relatively small annual ground thermal imbalance (1.76 kW). The monthly and peak loads reported in Table 4 are used to generate hourly loads as shown in Figure 4 with a 6 hour peak duration.

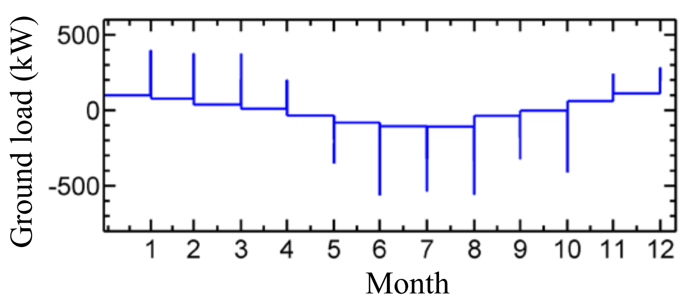

Figure 4: Hourly ground loads generated from monthly and peak loads for $L4$ methods used in Test 2

4.4. Test 3 – Required length during the first year

Monzó et al. [1] proposed a methodology, presented earlier (Equation 13), which accounts for monthly loads but that still uses the three-pulse approach of $L2$ methods. Their methodology was tested using an hourly, cooling dominated, ground load profile which will be used as a test case in the present study. The profile, shown in Figure 5, was analysed to obtain monthly averaged and monthly peak values (Table 4) and the three load pulses (Table 5). This profile is interesting in that the required length occurs in the first year of operation. Thus, as will be shown in the results section, methods that do not calculate the required length in the first year, will lead to inaccurate results. The monthly peak heat loads are defined as the maximum heating and cooling loads of each month and their durations are assumed to be 6 hours. In order to simplify calculations, Monzó et al. [1] assumed that every month had an equal duration of 30.42 days. However, in this work the monthly ground loads are evaluated based on the exact number of days for each month.

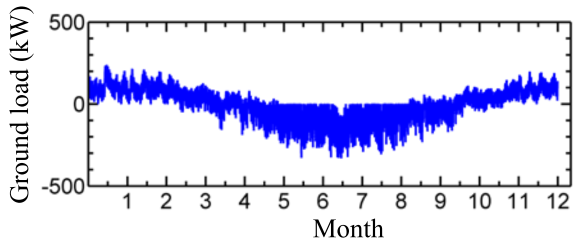

Figure 5: Hourly ground load profile for Test 3

4.5. Test 4 – High annual ground load imbalance

Test 4 has a relatively high annual ground load imbalance. Building loads for this case are generated using TRNSYS based on a building that is part of the TESS library [55]. Figure 6 shows the hourly building load profile. The building has an area of 1486 m^2 and is assumed to be located in Atlanta. Bernier [19] has shown that this profile has an annual ground load imbalance which leads to relatively high values of T_p of the order of +7.0 °C after a 20 year period. Thus, this profile should provide a good test to evaluate the long-term borehole thermal interference effects of the various tools. Using constant COP values of 4.03 and 3.86 in heating and cooling, respectively, monthly average ground loads and monthly peak ground loads are evaluated (Table 4). Finally, the monthly pulses required for $L3$ methods and the three pulses required for $L2$ methods are presented in Tables 4 and 5.

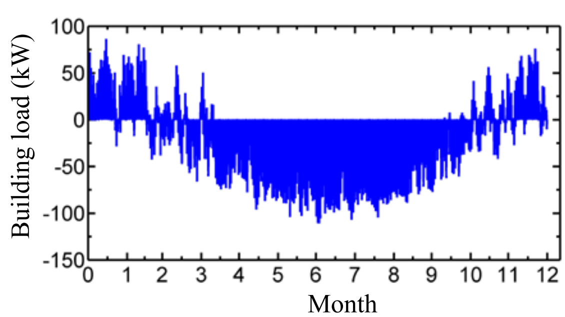

Figure 6: Hourly building loads considered for Test 4

4.6. Results of the inter-model comparison

The four test cases are used in an inter-model comparison of twelve different sizing tools covering the range from $L2$ to $L4$ methods. These sizing tools are listed in Table 6 with their main characteristics. The results of the four test cases are presented graphically in Figure 7 while exact lengths are presented in appendix B. It should be noted that some tools can not be used for particular tests. Tool B could not be used for Test 1a (with a one hour peak duration), Test 2 and Test 4, because it has fixed pulse durations. Also, tool L with an hourly varying COP is only used for Test 1b.

Table 6: Sizing tools used in the inter-model comparison

Identifying letter	Tool	Main characteristics	Level
A	Classic ASHRAE sizing equation	- Based on Equation 3 - Ground thermal resistance evaluated using the ICS - T_p evaluated using the modified concentric ring technique [15] - First-order multipole for the effective borehole thermal resistance	$L2$
B	Modified ASHRAE sizing equation	- EXCEL tool of Philippe et al. [21] is used (Equation 4) - Ground thermal resistance evaluated using the ICS - Rectangular geometries - Fixed pulse durations - Zeroth order multipole for borehole thermal resistance	$L2$
C	Modified + ASHRAE sizing equation-B	- Based on Equation 4 - Ground thermal resistance evaluated using the ICS - T_p evaluated with Equation 5 (Bernier's approach) - User defined pulse durations - Not restricted to rectangular geometries - First-order multipole for the effective borehole thermal resistance	$L2$
D	Modified + ASHRAE sizing equation-F	- Same as C expect that T_p is evaluated with Equation 6 (Fossa's approach)	$L2$
E (E_{st})	Alternative method	- Based on Equation 7 - Ground thermal resistance evaluated using g-functions - User defined pulse durations - Not restricted to rectangular geometries - First-order multipole for the effective borehole thermal resistance - A modified version, (E_{st}), accounts for short-term effects	$L2$
F	GHX design tool box	- Based on Equation 7 - Ground thermal resistance evaluated using g-functions - User defined pulse durations - Not restricted to rectangular geometries - First-order multipole for the effective borehole thermal resistance	$L2$
G	Quasi $L3$ method – Equation 13	- Based on Equation 11 - Effective ground thermal resistances are calculated using the ICS - User defined pulse durations - Not restricted to rectangular geometries - First-order multipole for the effective borehole thermal resistance	$L3$
H (H_{st})	Quasi $L3$ method - Equation 14	- Based on Equation 12 - Effective ground thermal resistances are calculated using g-functions - User defined pulse durations - Not restricted to rectangular geometries - First-order multipole for the effective borehole thermal resistance - A modified version, (H_{st}), accounts for short-term effects	$L3$
I	EED – monthly (v.4.17)	- g-function based method - Pre-defined geometries are used - Effective borehole thermal resistance based on 10 multipoles	$L3$
J	GLHEpro (v 5.0)	- g-function based method - Pre-defined geometries - Effective borehole thermal resistance based on 10 multipoles - Accounts for short-term effects using short-term g-functions	$L3$
K	EED – hourly (v.4.17)	- g-function based method - Pre-defined geometries - Effective borehole thermal resistance based on 10 multipoles	$L4$
L	DST	- Numerical/Analytical model - Strictly valid for axisymmetric geometries - First-order multipole for the effective borehole thermal resistance	$L4$

Test 1a. Synthetic balanced ground load – one borehole

As shown in Figure 7, three variations of Test 1a are reported. In the first two sets, the peak load durations are assumed equal to 6 hours and the borehole thermal resistance is evaluated either internally by the tool or is entered as a constant value (=0.13 m.K.W^{-1}) in all tools. In the third set, the peak load duration is assumed to be one hour and the results are evaluated with the same borehole thermal resistance (=0.13 m.K.W^{-1}) for all sizing tools.

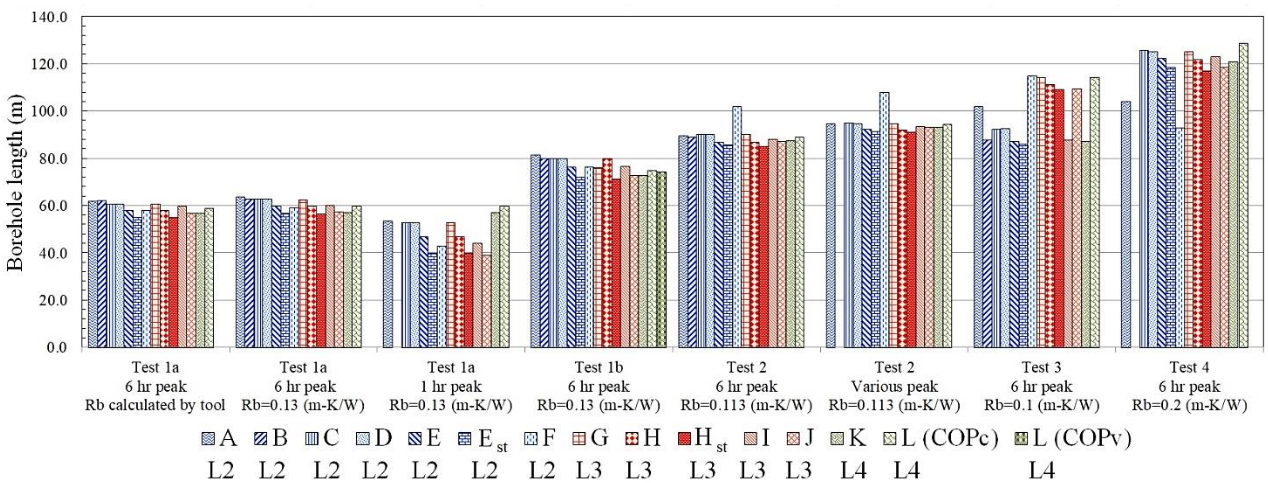

Figure 7: Inter-model comparison of twelve sizing tools for four test cases.

An analysis of the first two sets in Test 1a reveals that the results obtained by the various sizing tools are in a relatively good agreement. The minimum and maximum lengths in the first set are 54.8 and 62.1 m, respectively. These lengths are 6.6% below and 5.9% above the mean value. Tools E_{st} ($L2$), H_{st} ($L3$), J ($L3$), K ($L4$) and L ($L4$) give results that are lower than the mean. This is most likely due to the fact that E_{st}, H_{st} and J account for short-term effects (i.e. borehole thermal capacity) and that $L4$ tools use hourly values, not a 6-hour peak duration. For $L2$ methods, tool B has a higher predicted length because the value of R_b calculated by the tool is higher than other $L2$ tools. The borehole thermal resistances evaluated by the tools vary from 0.120 to 0.127 m.K.W^{-1}, a 5.8% difference, as reported in Table B-1. When the same value of R_b (=0.13 m.K.W^{-1}) is used for all tools (second set of cases for Test 1a), the minimum and maximum lengths are 56.5 m (5.8% below the average) and 63.7 m (6.2% above the average), respectively. It can be seen that using an identical borehole thermal resistance for all tools reduces the differences marginally by about 0.5 %. The differences among sizing tools in the evaluation of R_b experienced for Test 1a is typical of what was encountered for all test cases. In other words, no apparent flaw was detected among tools in the evaluation of R_b. Therefore, the remainder of the inter-model comparison will be performed for identical values of R_b for every sizing tool. The reader is referred to the spreadsheet which contains the values of R_b obtained by the various tools for every test case. Aside from short term effects and the differences in the value of R_b, it is difficult to pinpoint other reasons that could explain the differences for this second set for Test 1a. One modeling difference that might have an impact is the use of the ICS for the evaluation of the ground thermal resistance in some of the tools (A, B, C, D, and G) which implies that axial heat transfer effects are not accounted.

The third block of results for Test 1a is obtained using a peak duration of one hour. As shown in Figure 7, the required length decreases and the relative difference among results increases. The minimum and maximum lengths are 39.1 m (19.1% below the mean) and 59.7 m (23.5% above the mean). The main reason for these significant differences is related to the short term effects (borehole thermal capacity). This was already observed above for the 6 hour peak duration. However, the impact is much greater when the peak duration is only one hour as shown with results obtained with tools E_{st} ($L2$), H_{st} ($L3$) and J ($L3$) which have the smallest lengths. If tools E and E_{st}, which are identical except for the inclusion of short term effects in E_{st}, are compared, they show a difference of about 14.7%. The magnitude of this difference depends on the magnitude of q_h. For example, if the value of q_h is doubled and halved (everything else remaining the same) the differences in required lengths between tools E and E_{st} increases to 18% and decreases to 9.9%, respectively.

Test 1b. Synthetic balanced building load – one borehole

The synthetic load is used as a building load in Test 1b. This test is mainly used to detect if $L3$ tools are using heating and cooling $COPs$ correctly to evaluate ground loads and to test the impact of an hourly varying COP on the results of $L4$ tools. The calculated lengths are also higher than the ones evaluated for Test 1a because of larger ground loads. Test 1b is solved by considering one borehole, a six hour peak duration, R_b =0.13 m.K.W^{-1} and a 10-year design period. As shown in Figure 7, the length varies from 71.3 m to 81.3 m, 6.5% below and 6.6% above the average, respectively. Similar to Test 1a, tools E_{st}, H_{st} and J have determined the smallest lengths as they account for the short term effects. Tools K and L have also determined small lengths; however, this is mainly due to the fact that they use hourly-based loads. The lengths determined by tool L with constant or variable COPs have about a 0.8 % difference. So it appears from this test that the use of constant COP values evaluated at T_L and T_H is more than adequate to predict the required length.

Test 2. Elementary school in Lincoln, Nebraska – 120 boreholes

Test 2 examines the differences among the various tools for a large bore field (12 ×10). It is based on the original comparison of Shonder et al. [42]. Sizing is performed for heating for a 10 year design period with identical borehole thermal resistances (= 0.113 m.K.W^{-1}) first by assuming a peak load duration equal to six hours and then by using the original peak load durations provided by Shonder et al. [42] which are presented in Table 4.

As shown in Figure 7 for the case in which the peak duration is assumed to be six hours, the results vary from 85.1 m to 102.0 m which are, respectively, 4.5% below and 14.5% above the mean value. The results calculated using the original peak durations vary from 91.1 m to 108.0 m, i.e. 3.6% below and 14.3% above the mean. In both cases, tools E_{st} and F have calculated the minimum and maximum lengths, respectively. The length calculated by tool F is about 12 meters higher than the next higher value. After examination of the results, it was found that the g-functions evaluated by this program are not sufficiently accurate. By ignoring the results of program F, the results vary from 85.1 m to 90.2 m when the peak load duration is considered to be six hours and they vary from 91.1 m to 94.9 m when the original peak load durations are assumed for each month. In their original paper, Shonder et al. [42] obtained lengths ranging from 65.6 m to 87.3 m. As mentioned earlier, it is not clear what values of $COPs$ they used to convert building loads to ground loads which might explain the observed differences. Nonetheless, it appears that current tools are in closer agreement than in the original comparison of Shonder et al. [42]. However, the ground load imbalance is not severe so any deficiency in the borehole thermal interference calculation in a tool would not have a significant impact on the results. Test 4 will tackle the issue of a large ground load thermal imbalance. Results for tools C and D do not have a significant difference. Recall that these tools only differ in the way they calculate T_p (Equations 5 or 6). This behavior can be seen in the other test cases for multiple boreholes. Overall, the difference observed between tools C and D is less than 1% for all test cases.

Test 3. Length required in the first year– 49 boreholes

Test 3 involves the sizing of a 49 borehole field over a 10 year period with a constant value of R_b (= 0.1 m.K.W^{-1}) and a six hour peak duration. Tthe design period is selected to be 10 years and the goal is to see if the sizing tools can adapt to the fact that the maximum required length occurs during the first year of operation.

As shown in Figure 7, the required length varies from 85.9 m to 115 m for Test 3. These values are 13.9% below and 15.3% above the mean. This test shows that $L2$ sizing tools underestimate the required length when the maximum length is required in the first year. Tool A appears to give better results that other $L2$ tools, however the result is due to an underestimation of the temperature penalty (+1.18 °C, while the T_p evaluated by other tools is about +2.24 °C). Thus, two effects (wrong T_p and inability to size during the first year) tend to somewhat compensate each other for Tool A. The same can be said about tool F which appears to give good results but the inaccurate g-function determination mentioned earlier has a tendency to compensate for other factors. Surprisingly, tools I and K, which are $L3$ and $L4$ tools (thus not constrained by the 10 year period) calculate lengths below the average.

Test 4. Large annual ground load imbalance– 25 boreholes

Test 4 is based on the loads used by Bernier [19]. The required length is calculated for a 20 year design period for a 5×5 borehole field and a borehole thermal resistance of 0.2 m.K.W^{-1}. As mentioned earlier, the annual load is highly imbalanced and peak load conditions occur in cooling. As shown in Figure 7, results vary from 93.0 m to 128.9 m which represents values that are, respectively, 21.7% below and 8.5% above the mean. Three different group of results can be seen. First, results from tools C ($L2$), D($L2$), E($L2$), G($L3$), H ($L3$), I($L3$), K($L4$), L(($L4$) are in good agreement with a minimum of 121.0 m and a maximum of 128.9 m, thus a maximum difference of 6%. This tends to indicate that even though $L2$ methods appear to be less sophisticated that $L4$ methods, they give similar results. The second group of tools account for short-term effects, i.e. tools $\mathrm{E_{st}}$ ($L2$), $\mathrm{H_{st}}$ ($L3$), and J ($L3$). The agreement among these tools is excellent with calculated lengths of 118.4 m, 117.0 m, and 118.5 m, respectively. Finally, tools A ($L2$) and F ($L2$) have determined lengths that are much lower than the rest of the tools (103.9 m and 93.0 m). These values are, respectively, 13 and 24 m lower than next lowest result (117 m). Clearly, these two tools cannot properly account for borehole thermal interaction caused by large annual imbalanced loads.

4.7. Sensitivity analysis

In this section, a sensitivity analysis is performed on Test 4 to check the variation of five parameters: peak load magnitude, q_h, thermal conductivity, k_g, borehole spacing, B, ground temperature, T_g, and the total number of boreholes, N_b. In this analysis, parameters are varied one at a time, and the new lengths are compared with the original Test 4 results for each tool. Results are shown in Figures 8.a to 8.e where relative differences from the original Test 4 results are shown. Each curve in these Figures is composed of three points including the pivot points representing results obtained for the original Test 4. It should be mentioned that results for tool B are not presented because it is unable to calculate a 20-year design period. In addition, it is not possible to change the peak load magnitude for $L4$ tools (since the loads are hourly based) and, therefore, they are not included in the analysis of the peak load variation (Figure 8.a).

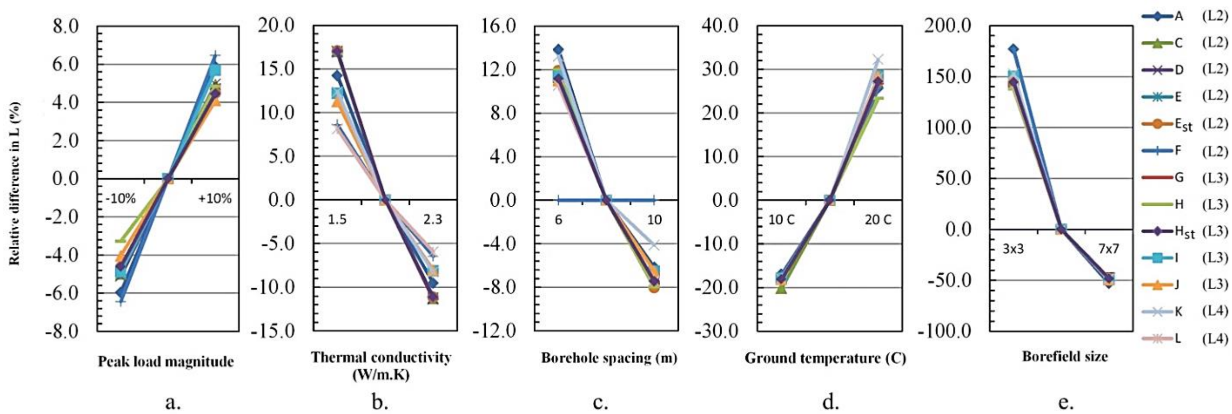

Figure 8: Sensitivity analysis for five parameters compared to the original Test 4 results obtained by each tool.

In Figure 8.a, the value of q_h has been varied by ± 10%. As shown, some tools are more sensitive to peak load variations. For example, tool F predicts variations of - 6.5% and +6.5%, while tools G or H show variations about half as important (- 3.3% and +4.8%). In Figure 8.b, the original thermal conductivity, 1.9 W.m^{-1}.K^{-1} is varied upward and downward by ± 0.4 W.m^{-1}.K^{-1}. Here again, the slopes are different and tools react differently to a change in thermal conductivity. $L2$ tools are more sensitive to the thermal conductivity variation and they vary on average by +17.0% and -11.3%.Tools F and L predict lower variations. The results for tool F vary by +8.6% and -6.5 % and tool A vary by +14.2% and -9.5 % and the ones evaluated by tool L vary by +8.1% and -5.9 %. In Figure 8.c, the borehole spacing is varied by ± 2 m. All tools exhibit a similar trend except tools A, F, K. First, tool F shows no variations with borehole spacing which seems to indicate a problem with the tool. Tool A shows a higher relative difference than other tools when borehole spacing is reduced to 6 m but has approximately the same relative difference compared to the other tools when borehole spacing is 10 m. This tends to corroborate the fact that tool A cannot accurately predict borehole thermal interference which increases as borehole spacing decreases. Tool K behaves much like tool A when the borehole spacing is 6 m and shows a smaller relative difference than all the other tools when borehole spacing is 10 m. In Figure 8.d, the original ground temperature of 15 ºC is varied by ± 5 ºC. This has the effect of decreasing/increasing the denominator in Equation 1 and thereby increasing/decreasing the borehole length. There are also secondary effects occurring here. Indeed, a borehole length variation has an impact on the effective ground thermal resistances and also on the value of T_p which are both length dependent. For the case where the ground temperature is reduced to 10 ºC (from 15 ºC), tools show about the same variations in length (-17.0 % to -18.2 % with an average of -17.9 %).With a ground temperature of 20 ºC (thus reducing the magnitude of the denominator), tools show different variations, from 23.3% to 32.2% with an average of 27.2%. Finally, the original 5×5 borehole field is changed to 3×3 and 7×7 configurations. All tools show approximately the same relative variations when the 7×7 configuration is examined. However, when borehole thermal interference becomes important for the 3×3 configuration, tools A (+177.0 %) and F (+177.4 %) show a marked difference when compared to the average of all tools (+145.5%).

5. Conclusion

The present study provides a general methodology for comparing vertical ground heat exchanger sizing tools. In the first part of the paper, sizing tools are categorized into five levels ($L0$ to $L4$) with increasing complexities: rules-of-thumb ($L0$), one-pulse ($L1$), three-pulse ($L2$), monthly-based ($L3$), and finally hourly-based annual simulations tools ($L4$). The calculation methodologies involved in $L1$ to $L4$ methods are presented in details and summarized schematically (see Figure 2). Descriptions of some of the available tools are given. Then, the literature on comparative testing of sizing tools is reviewed. The most important study to date remains the work of Shonder et al. [42] but it is almost two decades old and is revisited here with current sizing tools.

The second part of the paper presents the four test cases selected for the inter-model comparison. Test 1 uses a synthetically-generated balanced ground/building load for a single borehole for a 10-year design period; Test 2 revisits the Shonder et al. [42] comparison which consists of a 12×10 borehole field for a heating dominated load; Test 3 involves a 7×7 geometry with a load profile which lead to a maximum required length in the first year of operation; Test 4 involves sizing of a 5×5 configuration with a high annual ground load imbalance for a 20-year design period. A total of twelve different sizing tools (described in Table 6), some of them commercially-available, are then compared against each other. A summary of the comparison is presented in Figure 7. These tools cover the $L2$ to $L4$ range with three of them including short-term effects (i.e. borehole thermal capacity). A spreadsheet has been constructed to archive the various loads of each test and report the results obtained with the various tools. A link is provided at the end of the paper to get access to this spreadsheet.

Test 1 is actually composed of four sub-tests. In the first sub-test, the borehole thermal resistance, R_b, is evaluated by each tool and the peak duration is set at six hours. Results indicate a difference of 5.8% in the evaluation of R_b among all tools. This difference is typical for all the tests considered in this study and the reminders of the tests are performed assuming the same value of R_b for all tools. When the same value of R_b (=0.13 m.K.W^{-1}) is used for all tools, the minimum and maximum lengths are 56.5 m (5.8% below the average) and 63.7 m (6.2% above the average), respectively. Tools that include short-term effects tend to calculate smaller lengths while longer lengths are predicted by tools that evaluate effective ground thermal resistances using the cylindrical heat source solution which neglects axial heat transfer in boreholes. When the peak duration is reduced to one hour, short-term effects are much more important and results indicate that minimum and maximum lengths are 39.1 m (19.1% below the mean) and 59.7 m (23.5% above the mean). The fourth sub-test reveals that tools can correctly convert building loads to ground loads. Furthermore, it appears that using a constant value of COP evaluated at the design heat pump inlet temperature, T_L and T_H , to convert building loads to ground loads gives essentially the same results as the length obtained using a variable COP.

For Test 2, and using the peak durations provided by Shonder et al. [42], the results vary from 91.1 m to 108.0 m, i.e. 3.6% below and 14.3% above the mean. The upper limit of 108.0 m is reduced to 94.9 m when the results of one of the tools are excluded. When compared to the original comparison of Shonder et al. [42], it appears that current tools are in closer agreement. However, this test is not severe with a relatively small annual ground load imbalance.

For Test 3, the required length varies from 85.9 m to 115 m. These values are 13.9% below and 15.3% above the mean. It is shown that all of the $L2$ tools as well as one $L3$ and one $L4$ tool were unable to detect that the maximum required length is needed in the first year.

In Test 4, the cooling dominated load used by Bernier [19] is applied to check if the sizing models can account accurately for the thermal interactions between the boreholes when the annual ground load is relatively highly imbalanced. The calculated lengths vary from 93.0 m to 128.9 m which represents values that are, respectively, 21.7% below and 8.5% above the mean. One group of tools, which includes $L2$, $L3$ and $L4$ tools, shows a relatively good agreement with minimum and maximum values of 121.0 and 128.9 m., a 6% difference. This tends to indicate that even though $L2$ methods (three-pulse method) appear to be less sophisticated that $L4$ methods (hourly simulations), they give similar results if used with the correct set of inputs. A second group of tools that account for short-term effects show excellent agreement with calculated lengths of 118.4 m, 117.0 m, and 118.5 m, respectively. Finally, two tools have determined lengths that are much lower than the rest of the tools (103.9 m and 93.0 m). Clearly, these two tools cannot properly account for borehole thermal interaction caused by a large annual ground load imbalance.

In the final part of the paper, a sensitivity analysis is performed on Test 4. The main conclusion of this sensitivity analysis is that tools vary differently to a change in parameters. For example, when the peak load magnitude is varied by ± 10%, some tools predict length variations of + 6.5% and -6.5%, while other tools predict variations about half as important.

This work provides a set of test cases that can be used to compare other software tools against the ones used in the present study with the ultimate goal of improving the reliability of design methods for sizing vertical ground heat exchangers.

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6. Nomenclature and Acronyms

Capital letters

B = distance between the boreholes (m)

Cp_f = specific heat capacity of the circulating fluid (kJ.kg^{-1}K^{-1})

Cp_{gr}= specific heat capacity of the backfilling material (kJ.kg^{-1}K^{-1})

Cp_p= specific heat capacity of the pipe (kJ.kg^{-1}K^{-1})

Cap_H, Cap_C= heat pump capacities in heating and cooling (kW)

COP_H, COP_C= heat pump coefficient of performances in heating and cooling (---)

D = distance between the ground surface and the top of boreholes (m)

F_{sc}= short circuit heat loss factor in the borehole (---)

G= thermal response factors calculated by the infinite cylindrical source model (---)

H = borehole depth (m)

L = total overall length of boreholes (m)

$L0$, $L1$, $L2$, $L3$, $L4$ = classification of sizing models (---)_

L_s, L_M, L_j= length of single and multiple heat exchangers and the length of pipe in the jth ground layer (m)

M = mass (kg)

N_b = total number of boreholes (---)

N_U = number of U tubes in each borehole (---)

PLF_m= part load factor during the design month (---)

R_b = thermal resistance of the boreholes without thermal short-circuiting (m.K.W^{-1})

R_b^* = effective thermal resistance of the boreholes (m.K.W^{-1})

R_c = contact thermal resistance (m.K.W^{-1})

R_p= pipe thermal resistance (m.K.W^{-1})

R_q = ground thermal resistance caused by the peak load (m.K.W^{-1})

$R_{s\,j}$= ground thermal resistance related to the jth ground layer surrounding the borehole (m.K.W^{-1})

R_y, R_m, R_h= yearly, monthly and hourly peak load ground thermal responses (m.K.W^{-1})

RTR_i= ratio of run time to the cycle time of month i (---)

$Run_{f,H}$, $Run_{f,C}$= heating and cooling runtime fractions (---)

SG = specific gravity of the fluid (---)

T_H = maximum inlet fluid temperature to the heat pump (°C)

T_L = minimum inlet fluid temperature to the heat pump (°C)

$T_{f,avg,}$ T_m = mean fluid temperature in the borehole (°C)

$T_{f,peak}$ = peak fluid temperature in the borehole (°C)

T_g, $T_{g\,k}$= initial temperature of the ground and the average ground temperature in month k (°C)

$T_{in,hp}$ = inlet fluid temperature of the heat pump (°C)

$T_{out,hp}$ = outlet fluid temperature of the heat pump (°C)

T_P = Temperature penalty (°C)

W= compressor power at peak load condition (kW)

Small letters

d_p = half of the center-to-center spacing between the legs of a U-tube (mm)

g_N, g_1= thermal response factors evaluated for N and 1 boreholes by the finite line source method (---)

h_{conv}= internal convection coefficient in pipes (W.m^{-2}K^{-1})

k_f = fluid thermal conductivity (W.m^{-1}K^{-1})

k_g = soil thermal conductivity (W.m^{-1}K^{-1})

k_{gr} = thermal conductivity of the backfilling material (W.m^{-1}K^{-1})

k_p = pipe thermal conductivity (W.m^{-1}K^{-1})

$\dot{m}_f$ = flow rate of the circulating fluid (kg.s^{-1})

q''_g = geothermal heat flux (W.m^{-2})

q_y (q_a), q_m, q_h= yearly, monthly and hourly building or ground loads (kW)

$q_{rej,peak}$= net peak ground load (kW)

r_b = borehole radius (mm)

$r_{p,i}$ = inner radius of U-pipe legs (mm)

$r_{p,o}$ = outer radius of U-pipe legs (mm)

t_y, t_m, t_h = duration of yearly, monthly and hourly peak load pulses (h)

Greek letters

α_g = soil thermal diffusivity (m^2.day^{-1})

ρ_f = density of the heat carrier fluid (kg.m^{-3})

μ_f = viscosity of the heat carrier fluid (Kg.m^{-1}s^{-1})

Acronyms

ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers

DST = Duct ground heat STorage

FLS = Finite Line heat Source

GSHP = ground source heat pump systems

GHE or GHX = ground heat exchangers

HVAC = Heating, ventilation, and air conditioning

ICS = Infinite Cylindrical heat Source

IGSHPA = International Ground Source Heat Pump Association

ILS = Infinite Line heat Source

MLAA = Multiple Load Aggregation Algorithm

NWA = National Water Well Association

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Appendix A

Table A-1 presents test cases found in the literature and used for validation of different sizing tools.

Table A-1: Sizing test cases found in the literature

<table>
<tr><th>Level</th><th>Reference</th><th>Main caracteristic</th><th>Bore field</th><th>Solved by</th></tr>
<tr><td>L1</td><td>Sanaye, and Niroomand [56]</td><td>Synthetic problem</td><td>Single borehole</td><td>Modified version of IGSHPA method</td></tr>
<tr><td colspan="5">The model is modified to account for the thermal short-circuit and the convection effects. The method is applied to a synthetic example and then the results are compared with the ones evaluated by the IGSHPA and ASHRAE methods and the recommendations presented by Kavanaugh and Calvert [57]. The results had respectively 1.01, 3.9 % and 7.51 % difference.</td></tr>
<tr><td>L2</td><td>Kavanaugh [11]</td><td>An office building in Birmingham</td><td>5×6</td><td>GchpCalc, developed based on Eq. 3</td></tr>
<tr><td colspan="5">Designed for 10 years. Load pulses are calculated using a design day in cooling and the annual equivalent full load hours of each zone. Constant COPs are applied. The equivalent diameter concept is used to calculate the borehole thermal resistance. Solved with and without ground water movements. Some design alternatives for minimizing costs are also examined.</td></tr>
<tr><td>L2</td><td>Italian standard UNI 11466 [58]</td><td>A residential and an office buidlings</td><td>3 and 15 boreholes</td><td>ASHRAE equation (Eq. 3)</td></tr>
<tr><td colspan="5">Designed for 10 years. Uses monthly average building loads, annual heating and cooling equivalent full hours, part load factors, constant COPs. The maximum heating and cooling power of the system are used as peak loads.</td></tr>
<tr><td>L2 and L3</td><td>Staiti and Adriana [59]</td><td>A residential and an office buidlings</td><td>Single borehole and various rectangular patterns from 1×5 to 4×5</td><td>ASHRAE classical equation and GLHEpro</td></tr>
<tr><td colspan="5">Designed for 10 years, The authors applied two sizing models to the two sizing problems introduced in Italian standard and checked the effects of various design alternatives such as the two temperature limits of the heat pumps, borehole spacing and the thermal conductivity of the ground. Compared to GLHEPRO, the results show that the ASHRAE sizing equation over estimates the boreholes length up by up to 27%.</td></tr>
<tr><td>L2</td><td>Bernier [60]</td><td>Building loads evaluated by a synthetic equation</td><td>-----</td><td>Modified ASHRAE equation</td></tr>
<tr><td colspan="5">Designed for 10 years. Building loads are converted to ground loads using a constant COP. It is suggested to calculate ground loads using hourly simulations instead of a design day load. It is also suggested to use the real borehole diameter instead of the equivalent U-tube diameter. In the modified ASHRAE equation, the part load factor (PLF) is eliminated, the bore field configuration or borehole spacing is not specified and a value is just assumed for the temperature penalty.</td></tr>
<tr><td>L2</td><td>Lamarche [61]</td><td>Cooling dominated building</td><td>Single borehole</td><td>Alternative method (Eq. 7)</td></tr>
<tr><td colspan="5">It is showed that the effect of short time g-functions appears both in R_{gm} and R_{gh}. For the term $q_h(R_{gh} + R_b)$ in numerator of Eq. 7, three alternatives are suggested and by each one the problem is solved and the final results are compared.
Designed for 10 years. The problem is introduced to show the impact of short-term effects on the overall length. The sizing problem introduced by Philippe [21] is used with some modifications. It is showed that by neglecting the thermal capacity of the boreholes the length is oversized.</td></tr>
<tr><td>L2</td><td>Li et al. [50]</td><td>Four cases introduced by Cullin et al. [47]</td><td>1×3, 2×3, 2×6 and 7×8</td><td>An iterative alternative model based on the ASHRAE equation</td></tr>
<tr><td colspan="5">Level 3, Designed for various numbers of years, It is shown that results evaluated by the proposed method are shorter (Due to using short time effects) and in three cases closer to the actual lengths compared to the values determined by Cullin et al. [47] by using ASHRAE equation.</td></tr>
<tr><td>L2</td><td>Fossa and Rolando [62,63 64], Fossa [65]</td><td>Cooling and heating cases</td><td>Various arrangements</td><td>Modified ASHRAE equation (Eq. 4) with correlated temperature penalties</td></tr>
<tr><td colspan="5">In these papers, a series of correlated equations are developed and modified for evaluation of the temperature penalty required in ASHRAE equation.</td></tr>
<tr><td>L3</td><td>Bank [66]</td><td>Synthetic problem</td><td>3×5</td><td>EED</td></tr>
<tr><td colspan="5">The test case is not solved as a sizing problem. It is introduced to show the effects of various design parameters as the average and peak heat loads, balanced or unbalanced loads, boreholes configuration and boreholes spacing. It is first solved based on the heating loads and next based on both heating and cooling loads. The system is sized for one and twenty five years and as the system has a small net annual ground load the results do not vary significantly.</td></tr>
<tr><td>L3</td><td>Hellstrom and Sanner [67], Hellström et al. [68] and Sanner [69]</td><td>Various synthetic problems</td><td>-----</td><td>EED</td></tr>
<tr><td colspan="5">These papers introduce the functionality of different versions of the EED.</td></tr>
<tr><td>L3</td><td>Spitler [32]</td><td>A two floor office in Ottawa divided into seven zones</td><td>5×9</td><td>GLHEPRO</td></tr>
<tr><td colspan="5">Designed for 12 years. Building loads are converted to ground loads using a correlation for the COP which depends on the inlet temperature. Ground loads are relatively balanced. The relatively small difference between T_g and T_L caused the boreholes length to be sensitive to T_L.</td></tr>
<tr><td>L3</td><td>Sutton et al. [70]</td><td>An elementary school located in Lincoln, Nebraska</td><td>12×10</td><td>Multilayer bore field design algorithm (MLBDA)</td></tr>
<tr><td colspan="5">The model is based on Hellström's duct storage model [71] but can be applied to a series of geological layers.</td></tr>
</table>

<table>
<tr><td colspan="5">Level 3. Designed for 10 years. Problem based on the work of Shonder et al. [42] except that two heating and cooling scenarios are defined for the building, Ground loads are applied, The peak heat loads are assumed to occur on the 21st of each month and their duration is assumed to be 8 hours. For the heating dominated case, the model is compared against five sizing tools including the DST model but for the cooling case only the DST model is used for comparisons.</td></tr>
<tr><td>L3</td><td>Ping et al. [72]</td><td>Commercial building in the city of Shandong in China</td><td>-----</td><td>GEOSTAR</td></tr>
<tr><td colspan="5">The sizing program uses the finite line source and a quasi-three dimensional models for the heat transfer inside and outside of the boreholes, the quasi-3d model accounts for the fluid temperature variation along the boreholes depth and the thermal interaction between the boreholes legs.
The sizing problem is related to a real GSHP installation. Two values are reported for the cooling and heating peak loads but the peak durations are not reported. Borehole configuration is not mentioned. The system is sized for 20 years and the effects of certain parameters as the ground and grout thermal conductivities, borehole spacing, shank distance and annual load imbalance load are examined. More details about the GEOSTAR program are provided by Cui et al. [73].</td></tr>
<tr><td>L4</td><td>Lamarche et al. [74]</td><td>Residential building in Montreal</td><td>2×2</td><td>Hourly load simulation design model (HLSD)</td></tr>
<tr><td colspan="5">The HLSD model simulates the thermal response of the hourly loads with the use of inverse Laplace transform of the g-functions instead of using load aggregation. The method can take into account the short time effects and can accept variable COPs and determine iteratively the ground loads at each hourly step.
Designed for 10 years using building loads. The problem is also solved using DST, EED and GS2000. GS2000 is a level three sizing model which uses cylindrical and line source models. For HLSD and DST models hourly loads and for EED and GS2000 monthly average and peak heat loads are used. The ground heat loads are evaluated iteratively based on the COP values provided by TRNSYS and HLSD models. For EED and GS2000, they are evaluated based on the average COP values. The borehole thermal resistance evaluated by the DST was used in EED and HLSD simulations. For GS2000, it is not possible to enter the borehole thermal resistance as an input. Some parameters are also missing: i.e. B, $C_{p,g}$, R_b , $\dot{m}$ and peak durations.</td></tr>
<tr><td>L4</td><td>Capozza et al. [75, 76]</td><td>Heating dominated office in Padova and a cooling dominated office near Milan</td><td>16 boreholes in a semi L-shape pattern, 51 boreholes in a semi rectangular pattern</td><td>CARM model and ASHRAE equation (Eq. 3)</td></tr>
<tr><td colspan="5">CARM is a thermal capacity and resistances model; it is not a sizing model. However, it determines the entering fluid temperature of the heat pumps on hourly basis. The authors used their CARM method to model two real cases and also check the effects of possible modifications such as increasing the number of boreholes or the use of hybrid systems. The ASHRAE equation is used to size the boreholes and then the obtained lengths are compared with real boreholes lengths.
Designed for 10 years. Building loads are used with constant COPs. In both problems the peak loads and their durations are not reported. For the 51 borehole case, only the monthly average loads were available. The temperature penalty required in ASHRAE sizing equation is obtained by the model suggested by Capozza et al. [77]. For the 16 borehole case, the ASHRAE equation underestimated the result by 4% while for the other case it oversized the boreholes by 41.5%. The authors explain this difference due to inaccuracy of the ground loads.</td></tr>
</table>

Appendix B

Table B-1: Results presented in Figure 7 in addition to the mean and individual differences from the mean

Scenario:	Sizing model	A	B	C	D	E	E_{st}	F	G	H	H_{st}	I	J	K	L COPc	L COPv	mean
Level		L2	L2	L2	L2	L2	L2	L2	L3	L3	L3	L3	L3	L4	L4	L4	
Test 1-a, 6 hr peak -R_b calculated by tool	L (m)	61.7	62.1	60.7	60.7	57.8	54.8	58.0	60.7	57.8	54.8	59.8	56.7	56.8	58.7	----	58.6
	Dif. %	5.2	5.9	3.5	3.5	-1.4	-6.6	-1.1	3.5	-1.4	-6.6	2.0	-3.4	-3.1	0.1	----	
	Rb (m-K/W)	0.122	0.127	0.122	0.122	0.122	0.122	0.126	0.12	0.12	0.12	0.127	0.127	0.127	0.125	----	0.123
Test 1-a, 6 hr peak -R_b=0.13 (m-K/W)	L (m)	63.7	62.7	62.7	62.7	59.8	56.6	59.0	62.6	59.7	56.5	60.0	57.3	57.0	59.7	----	60.0
	Dif. %	6.2	4.5	4.5	4.5	-0.3	-5.7	-1.7	4.3	-0.5	-5.8	0.0	-4.5	-5.0	-0.5	----	
Test 1-a, 1 hr peak -R_b=0.13 (m-K/W)	L (m)	53.4	----	52.8	52.8	46.9	40.0	43.0	52.7	46.8	39.9	44.1	39.1	57.0	59.7	----	48.3
	Dif. %	10.5	----	9.3	9.3	-2.9	-17.2	-11.0	9.1	-3.2	-17.4	-8.7	-19.1	18.0	23.5	----	
Test 1-b, 6 hr peak -R_b=0.13 (m-K/W)	L (m)	81.3	80.0	80.0	79.9	76.2	72.1	76.2	75.9	80.0	71.3	76.7	72.6	72.6	74.8	74.2	76.3
	Dif. %	6.6	4.9	4.9	4.8	-0.1	-5.5	-0.1	-0.5	4.9	-6.5	0.6	-4.7	-4.8	-1.9	-2.7	
Test 2, 6 hr peak -R_b=0.113 (m-K/W)	L (m)	89.7	89.1	90.2	90.2	86.9	85.5	102.0	90.1	86.7	85.1	88.0	87.2	87.3	88.9	----	89.1
	Dif. %	0.7	0.0	1.3	1.3	-2.4	-4.0	14.5	1.2	-2.7	-4.5	-1.2	-2.1	-2.0	-0.2	----	
Test 2, various peak -R_b=0.113 (m-K/W)	L (m)	94.6	----	94.9	94.8	92.2	91.4	108.0	94.7	92.1	91.1	93.6	93.2	93.2	94.5	----	94.5
	Dif. %	0.1	----	0.4	0.3	-2.4	-3.3	14.3	0.2	-2.5	-3.6	-0.9	-1.3	-1.4	0	----	
Test 3, 6 hr peak -R_b=0.1 (m-K/W)	L (m)	101.9	87.9	92.4	92.6	87.2	85.9	115.0	114.2	111.1	109.0	87.8	109.6	87.2	114.4	----	99.7
	Dif. %	2.2	-11.9	-7.3	-7.1	-12.6	-13.9	15.3	14.5	11.4	9.3	-12.0	9.9	-12.6	14.7	----	
Test 4, 6 hr peak -R_b=0.2 (m-K/W)	L (m)	103.9	----	125.8	125.1	122.5	118.4	93.0	125.1	121.7	117.0	123.0	118.5	121.0	128.9	----	118.8
	Dif. %	-12.5	----	5.9	5.3	3.1	-0.3	-21.7	5.3	2.5	-1.5	3.6	-0.2	1.9	8.5	----	