Evaluation of the oversizing and computational speed of different open-source borefield sizing methods

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Abstract

This paper compares different borefield sizing methodologies in both oversizing and computational speed. Three different sizing methodologies are considered: a three-pulse, a monthly based and an hourly based method. In this study, these three methodologies are used to size the borefields for three types of buildings: an auditorium, an office, and a swimming pool. Each of these buildings was previously simulated and the resulting heating and cooling demand obtained by these simulations are used as input for the sizing methods. The time needed to size the borefields of all three buildings is compared and the resulting borefield sizes are compared among each other and with a dynamic simulation using the borefield model accessible from the open-source modelica component library IDEAS. Results show that the three pulse and monthly based methods are at least an order of magnitude faster than the hourly based method. However, these methods lead to a larger overestimation of the borefield length compared to the hourly based method. To increase the economic feasibility of geothermal borefields, oversizing needs to be avoided. All calculations and methods are available in the open-source tool: GHEtool.

Highlights

• Different sizing methods were compared in both speed and accuracy.
• All sizing methods show an oversizing due to neglecting the internal borehole dynamics.
• The three-pulse and monthly based sizing methods are at least an order of magnitude faster than the hourly based method. However, these methods lead to a larger overestimation of the borefield length compared to the hourly based method.
• The estimation of the peak duration is important for a borefield that’s limited in the first year of operation.
• When the borefield is limited in the last year of operation, the use of simplified methods is safe.

Introduction

In literature, there is a variety of sizing methodologies for borefields available. Ahmadfard (2018) made an exhaustive list of all available methodologies at that time and listed them into four main categories, ranging from simple rules of thumb (L0 methods) to complicated methods (L4 methods) used, for example, in dynamic simulations.

With exception of the rules of thumb methods, which presuppose a linear relationship between the peak demand and the borefield size, all methods take into account the thermal interaction with the ground and the other boreholes in the field. In order to calculate the ground response in the long term, Eskilson (1987) came up with the idea of g-functions: a normalised temperature response of the borehole wall for a unit heat load as a function of time, like shown in Figure 1. These g-functions are unique for each borefield configuration and can easily be calculated using the the Python package pygfunction (Cimmino and Cook, 2022).

Using these g-functions, the borehole wall temperature $T_b$ at time $t_n$ can be calculated by means of temporal superposition of discrete loads $\dot{Q}_i$ (Cimmino, 2019):

$$
T_b(t_n) = T_g - \frac{1}{2\pi k_s L} \sum_{i=1}^{N} (\dot{Q}_i - \dot{Q}_{i-1}) g(\frac{t_n - t_{i-1}}{t_n - t_i}) \quad (1)
$$

with $T_g$ the undisturbed ground temperature, $L$ the total borefield length\textsuperscript{1}, $k_s$ the ground thermal conductivity, $\dot{Q}_i$ the thermal loads, and $g$ the g-function.

\textsuperscript{1}This equals the borehole depth multiplied by the number of boreholes.
and \( t_i \) the thermal load and time at instance \( i \). Using the borehole equivalent thermal resistance \( R_p^b \), which takes into account all thermal interactions inside the borehole, this \( T_b(t) \) can be converted to an average fluid temperature \( T_f(t) \) (Cimmino, 2019):

\[
T_f(t) = T_b(t) + \hat{Q}_{p,t} R_p^b \tag{2}
\]

with \( \hat{Q}_{p,t} \) the thermal peak load at time \( t \). Equation 2 can also be written as a matrix multiplication and combined with Equation 1 this results in Equation 3 (Coninx and De Nies, 2022).

\[
T_f(t_n) = T_g + \hat{Q}_p(t_n) R_p^b + \frac{1}{2\pi k_s L} \begin{bmatrix} g(t_1) - g(t_{n-1}) & \cdots & \cdots & g(t_n) - g(t_{n-1}) \end{bmatrix} \tag{3}
\]

Given this \( T_f \), the required borehole length can be calculated iteratively by using

\[
L = \max \left\{ \frac{\max(T_f) - T_g}{\min(T_f) - T_g} \right\} \cdot L_{\text{prev}} \tag{4}
\]

where \( T_{\text{max}} \) and \( T_{\text{min}} \) are respectively the maximum and minimum temperature boundaries of average fluid temperature the borefield.

**Three sizing methodologies**

**Three-pulse method (L2-method)**

The three-pulse method originates from the ASHRAE sizing equation (Equation 5) and does not need the detailed fluid temperature profile calculation of Equation 2.

\[
L = \sum_{i=1}^{N} \frac{\hat{Q}_i R_t + \hat{Q}_p R_p^b}{T_m - (T_g + T_p)} \tag{5}
\]

were \( \hat{Q}_i \)'s are the thermal loads, \( R_t \) their corresponding thermal resistances, \( \hat{Q}_p \) the thermal pulse related to the peak load, \( T_m \) the temperature limit (either the \( T_{\text{min}} \) or \( T_{\text{max}} \)) and \( T_p \) a temperature penalty (Ahmadfard and Bernier, 2018).

The temperature penalty in Equation 5 was used initially to account for the borehole-to-borehole interactions (Ahmadfard and Bernier, 2018). Since the \( g \)-functions, as defined by Eskilson (1987), take into account these borehole-to-borehole interactions, the use of a temperature penalty can be avoided in Equation 5. Therefore, the thermal resistances in Equation 5 are defined as follows (Ahmadfard and Bernier, 2018):

\[
R_t = \frac{g(t_f) - g(t_f - i)}{2\pi k_s} \tag{6}
\]

with \( t_i \) a reference time larger than \( i \).

For the three-pulse method, the summation in Equation 5 has three terms and can be rewritten as

\[
L = \frac{\hat{Q}_y R_y + \hat{Q}_m R_m + \hat{Q}_t R_t + \hat{Q}_p R_p^b}{T_m - T_g} \tag{7}
\]

in which \( \hat{Q}_i \) is the yearly imbalance\(^2\), \( \hat{Q}_p \) the peak thermal load and \( \hat{Q}_m \) the average load in the peak month. The thermal resistances in Equation 7 are calculated as

\[
R_y = \frac{[g(t_f) - g(t_f - t_i)]/(2\pi k_s)}{(2\pi k_s)} \tag{8}
\]

\[
R_m = \frac{[g(t_f - t_1) - g(t_f - t_2)]/(2\pi k_s)}{(2\pi k_s)} \tag{9}
\]

\[
R_t = \frac{g(t_f - t_2)/(2\pi k_s)}{(2\pi k_s)} \tag{10}
\]

in which \( t_f = t_i + t_m + t_h, t_1 = t_2 + t_2 = t_f + t_m \) and \( t_f \) is the long-term time horizon (e.g. 20 years), \( t_m \) the time of one month (730 hours) and \( t_h \) the duration of the peak (Ahmadfard and Bernier, 2018).

Peere et al. (2021) noted that this sizing only takes into account the last year of operation and proposed a new, hybrid L2 sizing methodology that also takes into account the first year of operation. This is done by redefining the different time intervals in Equation 8. For more information, the reader is referred to (Peere et al., 2021).

**Monthly sizing method (L3-method)**

For the monthly sizing method, two thermal pulses are considered for each month: one with a duration of 730 hours (related to the average monthly load) and one pulse for the monthly peak load. These pulses are used in Equations 3 and 4 (the \( \hat{Q}_i \)’s are set to be the average monthly loads and the \( \hat{Q}_p \) the peak loads) to iteratively calculate the required borehole depth.

**Hourly sizing method (L4-method)**

For the hourly sizing methodology, the same principle as for the monthly sizing method is followed, although now hourly thermal pulses are used, leading to 8760 thermal pulses in a year. Using again Equation 3 (where now \( \hat{Q}_p = \hat{Q}_t \)) and Equation 4 the required depth can be calculated iteratively.

**Complexity and implementation**

In Table 1 the number of terms in the summation of Equations 3 and 5 is given for the three different sizing methodologies for a simulation period of 20 years.

<table>
<thead>
<tr>
<th>Method</th>
<th>Number of pulses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-pulse method</td>
<td>3</td>
</tr>
<tr>
<td>Monthly method</td>
<td>480</td>
</tr>
<tr>
<td>Hourly method</td>
<td>175,200</td>
</tr>
</tbody>
</table>

Using the insight of Peere et al. (2021) that only the first and the last year are relevant for the sizing of a borefield, this number of terms in the summation can be reduced to

\(^2\)Imbalance is defined as the difference in heating and cooling load, leading to an ever increasing or decreasing ground temperature.
respectively 48 for the monthly method and 17,500 for the hourly method.

For the monthly and hourly sizing further optimisation is possible. Looking at Equation 3 the dot product can be written as a convolution, using

\[
(Q \ast g')[n] = \sum_{m=1}^{M} Q[m] \cdot g'[n - m] \tag{11}
\]

where \(g'[i] = g(t_{i+1}) - g(t_i)\) This implementation has been shown to give the fastest computation times (Coninx and De Nies, 2022).

All methods described above are implemented in the open-source sizing tool GHEtool (Peere and Blanke, 2022).

**Approach**

In order to assess the accuracy and speed of the aforementioned sizing methodologies, borefields are sized for three different buildings: an auditorium, an office building and a swimming pool. Peere et al. (2021) found that every borefield is either limited in the first year of operation or the last year of operation, by either the maximum or minimum average fluid temperature. This gives four different categories of borefield, i.e. four quadrants as shown in Figure 2. These three specific cases where chosen such that 3 out of the 4 borefield quadrants are covered in this paper\(^3\). These three buildings were simulated previously in IESVE and their resulting heating and cooling demand profiles were exported using an hourly resolution. The yearly heating and cooling loads are given in Table 2 and the peak heating and cooling loads are given in Table 3.

For the three buildings, a borefield size is calculated using the three aforementioned methodologies. The sizing as-

\(^3\)Please note that the quadrant where the borefield is limited in the first year of operation in peak heating does exist in theory, but does not occur in practise.

\(^4\)HTF: Heat Transfer Fluid, MFR: Mass Flow Rate

For the three buildings, a borefield size is calculated using the three aforementioned methodologies. The sizing as-
to be constant over the depth of the borefield and equal
to the average of the actual undisturbed ground temper-
arture (starting from 10°C at the surface, an increase of
0.02°C/m is assumed), which is in correspondence with
the implementation in GHETool. The difference in results
between the dynamically simulated average fluid temper-
ature and the temperature limits of the borefield (also an
average fluid temperature) is a measure for the potential
to reduce the total borefield length, thus an indication for
the degree of oversizing. This is assessed together with
the time needed for sizing, using the 3 methods.

Results

The calculated borefield lengths can be found in Table 6
and their respective calculation times in Table 7. From
Table 6 it is clear that the three-pulse (L2) and the monthly
(L3) methods give more or less the same sizing results
(within 2% of each other) whilst the calculation time of the
L2 method is on average 37% smaller.

When comparing the results of the L2 and L3 methods to
the hourly sizing method (L4), a large difference is visible
in the resultant sizing of the auditorium (30% difference),
where the other sizes are more or less in line. This is due
to the fact that the auditorium is limited in the first year
of operation and that the peak duration estimation of 6
hours was wrong in this case (cf. infra). The computa-
tional time for the hourly method, on the other hand, is
one (sometimes even two) orders of magnitude higher.

Table 6: Calculated borefield lengths for the different
methods

<table>
<thead>
<tr>
<th>Sizing</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditorium</td>
<td>2.718 m</td>
<td>2.724 m</td>
<td>2.026 m</td>
</tr>
<tr>
<td>Office</td>
<td>11.080 m</td>
<td>11.290 m</td>
<td>10.700 m</td>
</tr>
<tr>
<td>Swimming pool</td>
<td>95.430 m</td>
<td>93.660 m</td>
<td>93.510 m</td>
</tr>
</tbody>
</table>

Table 7: Computational time for the different methods

<table>
<thead>
<tr>
<th>Sizing</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditorium</td>
<td>216 ms</td>
<td>224 ms</td>
<td>8.720 ms</td>
</tr>
<tr>
<td>Office</td>
<td>96 ms</td>
<td>178 ms</td>
<td>5.340 ms</td>
</tr>
<tr>
<td>Swimming pool</td>
<td>83 ms</td>
<td>212 ms</td>
<td>4.960 ms</td>
</tr>
</tbody>
</table>

In order to verify whether or not the sizing is correct (i.e.
the fluid temperature does not cross its limits), the temper-
ature extremes of the dynamically simulated temperatures
are compared with the temperature limits (see Table 4) for
all three cases and all three sizing methods. The result of
this comparison is presented in Table 8.

Table 8: Temperature extremes as observed in dynamic
simulations using the borehole length calculated in L2,
L3 and L4 method.

<table>
<thead>
<tr>
<th>Sizing</th>
<th>Tmax</th>
<th>Rel. Diff</th>
<th>Tmin</th>
<th>Rel. Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditorium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>14.91</td>
<td>12.3%</td>
<td>7.92</td>
<td>163.9%</td>
</tr>
<tr>
<td>L3</td>
<td>14.91</td>
<td>12.3%</td>
<td>7.93</td>
<td>164.2%</td>
</tr>
<tr>
<td>L4</td>
<td>15.32</td>
<td>9.9%</td>
<td>6.67</td>
<td>122.18%</td>
</tr>
<tr>
<td>Office</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>16.07</td>
<td>5.46%</td>
<td>8.95</td>
<td>198.3%</td>
</tr>
<tr>
<td>L3</td>
<td>16.01</td>
<td>5.8%</td>
<td>9.00</td>
<td>199.9%</td>
</tr>
<tr>
<td>L4</td>
<td>16.18</td>
<td>4.8%</td>
<td>8.86</td>
<td>195.36%</td>
</tr>
<tr>
<td>Swimming pool</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>13.03</td>
<td>23.4%</td>
<td>3.60</td>
<td>20.02%</td>
</tr>
<tr>
<td>L3</td>
<td>12.97</td>
<td>23.7%</td>
<td>3.39</td>
<td>13.0%</td>
</tr>
<tr>
<td>L4</td>
<td>12.95</td>
<td>23.8%</td>
<td>3.33</td>
<td>11.12%</td>
</tr>
</tbody>
</table>

As can be seen in Table 8 all sizing methodologies lead to
an oversized borefield. Even in the case of the auditorium,
where the hourly sizing method gave a significant smaller
borefield length, the temperature is nowhere near its lim-
its. This can be explained by the fact that all these siz-
ing methodologies work with an equivalent borehole ther-
mal resistance $R_b$ which is a steady state assumption (La-
ferrière et al., 2020). According to Eskilson (1987), such
steady-state assumption is only valid for times larger than
$5T_2^*/\alpha_s$ (where $\alpha_s$ is the ground thermal diffusivity),
which for the values in Table 4 is around 6.25 hours, which is
larger than the time resolution of the simulation.

In Figure 4, we zoom in on the average temperature pro-
file of the auditorium which is calculated using Equation
3 and compared to the simulated temperature profile. It is
clear that the temperature difference is more pronounced
during peaks, which can be explained by this underlying
steady-state assumption. In future work, adapting the siz-
ing methodologies to take into account this dynamic be-
haviour, can be of great importance to avoid oversizing
and thus improve the economic feasibility of geothermal borefields.

Table 9: Sensitivity of the sizing methods to the peak duration for first and last year limited borefields.

<table>
<thead>
<tr>
<th>Peak duration</th>
<th>Auditorium</th>
<th>Swimming Pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 h</td>
<td>79.4 m</td>
<td>314.7 m</td>
</tr>
<tr>
<td>2 h</td>
<td>96.2 m</td>
<td>316.0 m</td>
</tr>
<tr>
<td>3 h</td>
<td>108.7 m</td>
<td>316.8 m</td>
</tr>
<tr>
<td>4 h</td>
<td>119.0 m</td>
<td>317.3 m</td>
</tr>
<tr>
<td>5 h</td>
<td>128.2 m</td>
<td>317.8 m</td>
</tr>
<tr>
<td>6 h</td>
<td>135.9 m</td>
<td>318.1 m</td>
</tr>
<tr>
<td>7 h</td>
<td>144.6 m</td>
<td>318.5 m</td>
</tr>
<tr>
<td>8 h</td>
<td>152.0 m</td>
<td>318.8 m</td>
</tr>
</tbody>
</table>

In Table 9 the peak duration is varied for the L2 sizing method for both the swimming pool and the auditorium. It is clear that this can have a substantial impact on the borefield size, as illustrated for the auditorium, which is limited in the first year of operation. When choosing a peak duration between 2 and 3 hours, 101.3 m (as sized by the hourly method, see Table 6) can be obtained. Choosing the right peak duration a priori is not a trivial task and further research is needed to find a correlation between the correct peak duration for these simplified sizing methods and the load-duration curve of the ground load, which needs to be an input that is available. It is safer therefore to use the hourly sizing method when a borefield is limited in the first year of operation. For a limitation in the last year of operation, on the other hand, good estimation of the peak duration (which is needed for these simplified methods) is of great importance. Further research is needed to find an accurate peak duration estimation based on the load-duration curve (when this is available). In these cases, it is safer to use an hourly sizing method to avoid a large overestimation of the borefield length and thus also unnecessary additional investment costs.

Conclusion

In this paper, three different sizing methodologies for borefields were compared for three different cases (an auditorium, an office and a swimming pool). It was found that all methodologies lead to an overestimation of the required borefield depth, since these methodologies do not include dynamic effects and assume a steady-state behaviour of the borehole internals. Furthermore, it was found that the simplified three-pulse and monthly sizing method (L2 and L3 methods) were at least one order of magnitude faster than the hourly sizing methodology. When the borefield is limited in the last year of operation, it is safe to use these simplified methods since their results are very close to that of the hourly sizing method and they are faster. When the borefield is limited in the first year of operation, on the other hand, good estimation of the peak duration (which is needed for these simplified methods) is of great importance. Further research is needed to find an accurate peak duration estimation based on the load-duration curve (when this is available). In these cases, it is safer to use an hourly sizing method to avoid a large overestimation of the borefield length and thus also unnecessary additional investment costs.

Acknowledgement

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Nomenclature

\( \alpha \) thermal diffusivity of the ground \([m^2/s]\]
\( g(t) \) g-function at time \( t \) \([/]
\( k_s \) Thermal ground conductivity \([W/mK]\]
\( L \) Total length of the borefield \([m]\)
\( t_s \) Characteristic time of the borefield \([s]\)
\( t_r \) A reference time \([s]\)
\( T_b \) Borehole wall temperature \([K]\)
\( T_f \) Average temperature of the fluid \([K]\)
\( T_g \) The undisturbed ground temperature \([K]\)
\( T_m \) Temperature limit (minimum or maximum) \([K]\)
\( T_{max} \) Maximum temperature limit \([K]\)
\( T_{min} \) Minimum temperature limit \([K]\)
\( T_P \) Temperature penalty \([K]\)
\( r_b \) Borehole radius \([m]\)
\( R_s \) Equivalent borehole resistance \([mK/W]\)
\( R_i \) Thermal resistance for pulse \( i \) \([mK/W]\)
\( Q_i \) Thermal load at time \( i \) \([kW]\)
\( Q_m \) Thermal load in the peak month \([kW]\)
\( Q_{p,i} \) Thermal peak load at time \( i \) \([kW]\)
\( Q_g \) Thermal load related to the imbalance \([kW]\)

References


Figure 4: The average fluid temperature profile for the auditorium zoomed in.


