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An open library of g-functions for 34,321 configurations

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ABSTRACT

Thermal response functions, known as g-functions, are commonly used in ground heat exchanger design tools and whole building energy simulation programs to simulate the ground heat exchanger performance. Calculation of g-functions can be quite computationally time-consuming, particularly as the number of boreholes gets large. However, once the g-function is computed, the actual simulation time can be quite short, particularly if a hybrid time-step (Cullin and Spitler 2011) approach is used. Because of this, pre-computed g-function libraries are commonly used in design tools and building simulation tools. This paper describes development of a new, publicly available library containing g-functions for 34,321 borehole field configurations; for each configuration, g-functions are provided for 5 depths to allow interpolation between different borehole-to-height ratios. The available configurations include configurations in standard shapes: lines, rectangles, open rectangles, L-shapes, and U-shapes. It also includes new configurations: C-shapes, lopsided-U-shapes, and zoned rectangles, which are rectangular configurations with different interior and perimeter spacing of the boreholes

INTRODUCTION

Thermal response functions, known as g-functions, are commonly used in ground heat exchanger design tools and whole building energy simulation programs to simulate the ground heat exchanger performance. G-functions were originally developed by Prof. Johan Claesson and his graduate students at the University of Lund in Sweden (Claesson and Eskilson 1988, Eskilson 1987, Hellström 1991). g-Functions are unique to a specific borehole field configuration (geometry, e.g., 5 rows of 10 boreholes spaced 5m apart) and borehole depth.

Calculation of g-functions can be quite computationally time-consuming, particularly as the number of boreholes gets large. However, once the g-function is computed, the actual simulation time can be quite short, particularly if a hybrid time-step (Cullin and Spitler 2011) approach is used. Because of this, pre-computed g-function libraries are commonly used in design tools and building simulation tools. In practice, the g-functions are pre-calculated for specific configurations; for each configuration, multiple depths are pre-computed for interpolation purposes. Then, a design tool can iteratively try different configurations and adjust the depth to find the correctly sized ground heat exchanger. Furthermore, the g-functions scale with several non-dimensional parameters that allow wider application than the specific horizontal spacing and depths used in the pre-calculation.

Currently available libraries, implemented in eQUEST (Liu and Hellström 2006), GLHEPRO (Spitler 2000), and EED (BLOCON 2015) have less than 1000 possible configurations and are proprietary. This paper describes development of a new, publicly available library containing g-functions for 34,321 configurations; for each configuration, g-functions are provided for 5 depths. Calculation of the library was made possible by a new tool, cpgfunction (Cook and Spitler

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2021) and thousands of computing hours on the Oklahoma State University High Performance Computing Center (OSUHPCC) cluster. The available configurations include configurations in standard shapes: lines, rectangles, open rectangles, L-shapes, and U-shapes. It also includes new configurations: C-shapes, lopsided-U-shapes, and zoned rectangles, which are rectangular configurations with different interior and perimeter spacing of the boreholes. An example showing the advantage of the zoned rectangular configuration is presented below.

With recent developments in calculation of g-functions (Prieto and Cimmino 2021) that allow calculation of g-functions in a few seconds, even for fields that have hundreds of boreholes, it might be argued that libraries are not needed. Yet, there are applications in automated design and large parametric studies with multiple buildings and numerous locations where the difference between a few seconds and milliseconds is quite important. Furthermore, the Prieto and Cimmino (2021) equivalent borehole model is implemented in Python with extensive use of libraries and is not readily reducible to a DLL[1] that could be used with a compiled program that is readily installable by practicing engineers.

The library is available at the US DOE Geothermal Data Repository: https://doi.org/10.15121/1811518. Fuller explanation of how to use the library is given in the report by Spitler et al. (2021), available at the same link.

METHODOLOGY

This section briefly describes the procedure used to calculate the g-functions. The g-functions are calculated with a tool that is called "cpgfunction" (Cook and Spitler 2021). It is based on the finite line source methodology developed by Cimmino (2018a, 2018b) for an open-source tool written in Python, called pygfunction. Cpgfunction is written in C++. Cpgfunction was developed to reduce memory consumption, which can be quite high for large numbers of boreholes, exceeding 96 GB in many cases. For calculating large numbers of g-functions, as was done here, the memory requirements can become critical when running on a cluster. Keeping the memory requirements below 96 GB allowed full use of the most common compute nodes on the Oklahoma State University High Performance Computing Cluster (OSUHPCC 2020). The time requirement is also improved for most cases, but for large numbers of regularly spaced boreholes, the computation times are similar. For further information on cpgfunction, see Cook and Spitler (2021).

The g-functions are calculated with the "Uniform borehole wall temperature" (UBHWT) boundary condition. That is, the heat input at each segment is adjusted to give uniform (but time-varying) temperatures at the borehole walls. This is the method commonly used to develop other g-function libraries and has been used to size ground heat exchangers for commercial systems for the last 30 years. A burial depth of 2 m is chosen to be representative of US practice.

Arguably, the "Uniform inlet fluid temperature" (UIFT) conditions are more physically realistic, since the boreholes of ground heat exchangers are generally plumbed in parallel, and all receive approximately the same inlet fluid temperature at any time. However, the g-functions calculated with the UIFT condition will be slightly different than those calculated with the UBHWT condition, and they have a dependence on the local borehole thermal resistance and the mass flow rate of the fluid. The g-functions also depend on the number of segments used – like most numerical analyses, increasing the number of cells or volumes increases the accuracy, with diminishing returns. A grid-independency analysis using typical values of borehole thermal resistance and mass flow rate was performed using the UIFT boundary condition. Results for the UBHWT boundary condition were compared to those obtained with the UIFT boundary condition and it was found that a smaller number of segments with the UBHWT boundary condition could closely approximate the g-functions calculated with the UIFT boundary condition, using typical borehole thermal resistances and mass flow rates. This investigation yielded the number of segments summarized in Table 1. These values were used to calculate

[1] The lead author would be happy to be proved wrong on this point. A publicly available open-source but compiled to DLL g-function calculation tool would be quite useful to bridge the gap between research and practice.

the library g-functions and this method is referred to as the "adaptive discretization scheme."

Table 1. Adaptive discretization scheme (NBH= Number of boreholes; BH=borehole)

Depth (m)	Range (NBH)	Segment Length (m)	Number of segments/BH
24	All	8	3
48	All	12	4
96	All	12	8
192	NBH < 120 BH	16	12
192	NBH $\geq$ 120 BH	12	16
384	NBH < 220 BH	16	24
384	NBH $\geq$ 220 BH	12	32

The library presented here represents weeks of computation time on the OSU High Performance Computing Cluster (OSU HPCC), and it would not have been feasible to develop such a library without access to this or a similar resource. Additionally, the memory consumed for computing converged UIFT g-functions would not have been feasible, even with access to the OSU HPCC. The 8-9x memory reduction of Cpgfunction (Cook and Spitler 2021) combined with the adaptive discretization scheme resulted in a near 80x memory reduction. This resulted in an ability to run a significant majority of the calculations on nodes that contained less memory, of which there are nearly 14x as many nodes available on the OSU HPCC.

RESULTS – THE LIBRARY

The library contains configurations previously available – rectangles, open rectangles, L-shapes, and U-shapes - though these configurations are considerably expanded from previously available libraries with larger numbers of boreholes, and, in some cases, up to 3 perimeter rows. The line cases and single borehole case are contained within the rectangle cases. Several of these cases are shown in Figure 1.

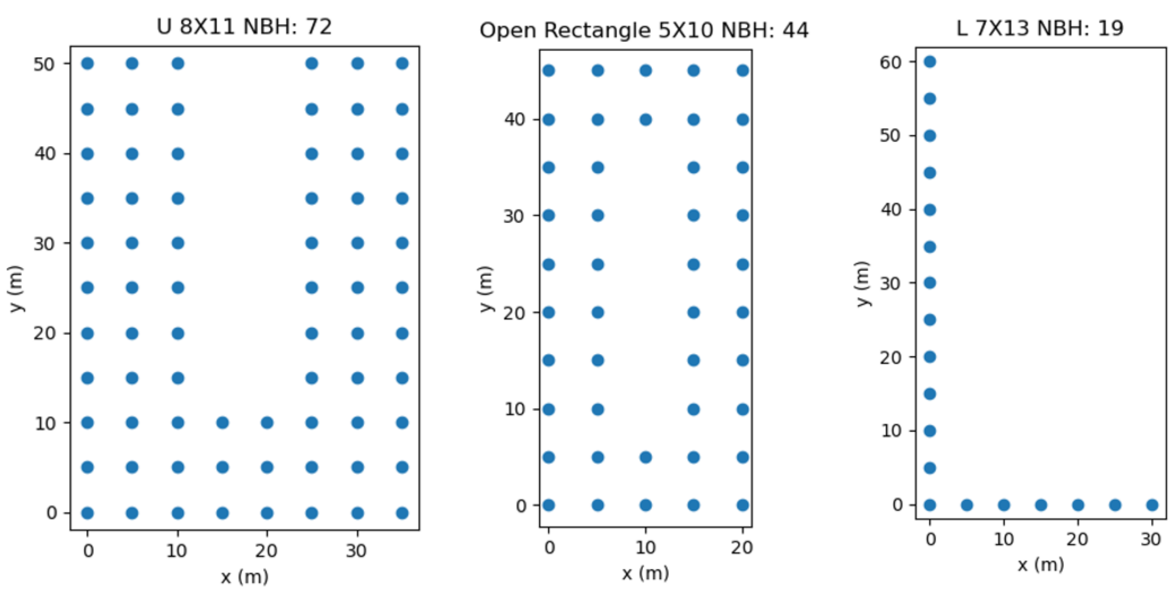

Figure 1 Configurations with 3,2,1 perimeter borehole rows

The new library provides several new configurations. The zoned rectangle configuration (Spitler, et al. 2020) was inspired by the fact that, for large rectangular borehole fields coupled to systems with significant heat imbalance, the perimeter boreholes are more effective in either dissipating heat or extracting heat than the interior boreholes, which can become thermally saturated with time. Spitler et al. (2020) illustrate this for a case with 9x16 boreholes, dominated by heat rejection. The zoned rectangles have a perimeter zone and an interior zone, with the perimeter zone having smaller borehole spacing than the interior zone. In all cases calculated for the library, the perimeter zone contains a single perimeter row of boreholes, and the interior zone contains all interior boreholes.

In addition to the zoned rectangles, two additional shapes, the C-shape and Lopsided U (LopU) shapes, are new library configurations intended to support automated searching for an optimal borehole configuration within a rectangularly-constrained land area. The C-shape is equivalent to an open rectangle, but with some perimeter boreholes removed from one side of the rectangle. The LopU-shape is equivalent to a U, but with some perimeter boreholes removed. The new configurations are illustrated in Figure 2.

The C-shape and LopU-shape support the automated design search by helping to provide a continuous unimodal domain, where moving from one configuration to the next with increased number of boreholes will always reduce the amount by which the design temperatures are exceeded. Within a design tool, where the building may take any size, having a continuous unimodal domain that goes from, say, a 32x32 rectangle down to a single borehole allows for a working design to be identified in any case. So, for example, starting with the maximum number of boreholes, the domain might be something like 32x32 rectangle →-a zoned rectangle with 124 perimeter boreholes and 870 interior boreholes →…[2]→ zoned rectangle with 124 perimeter boreholes and 1 interior borehole → open rectangle with 124 boreholes → C-shape with 123 boreholes →…→ C-shape with 95 boreholes → U-shape with 94 boreholes →LopU with 93 boreholes→…→ LopU with 63 boreholes → L-shape with 62 boreholes→…→L-shape with 31 boreholes → line with 30 boreholes →…→ single borehole. Table 2 lists all the borehole field configurations currently available in the expanded g-function library (Spitler et al. 2021).

Each g-function is represented by 27 pairs of $ln(t/t_s), g$ values, with $3.003 \geq ln\left(\frac{t}{t_s}\right) \geq -8.5$. The thermal properties and depth affect the value of the time scale, t_s, but generally this would cover times between 12 hours and a day at the low end, and hundreds of years at the high end. At the low end, short time-step g-functions (Xu and Spitler 2006) would generally be added in order to use the g-function for simulations.

Accessing the library g-functions is described in the library guide (Spitler, et al. 2021) and an example Python source code is included. For general design use, the g-functions for specific configurations are calculated with set spacings between boreholes and five different borehole depths. Non-dimensional scaling parameters are used to interpolate between the g-functions for the same configuration but with different depths, as described in the library guide.

VALIDATION

The tool used to calculate the library g-functions, cpgfunction, was shown (Cook and Spitler 2021) to give nearly an exact match to pygfunction (Cimmino 2018) with g-functions having less than 0.1% RMSE difference. Results from either tool depend on the boundary scheme, the number of segments, and matching the geometry of the borehole field.

[2] Here, the ellipsis represents a systematic reduction in rows and columns in such a way that at each step either an interior row or column would be eliminated, and then the row or column spacing is adjusted to have uniform interior spacing in each direction, though the spacing between rows and columns may vary slightly. The decision to eliminate a row or column is decided in favor of whichever elimination will maintain the most equal row spacing and column spacing. In general, this systematic reduction tends to alternately eliminate rows or columns.

For purposes of comparison, design depths were computed for three prototypical buildings (hotel, office, and school) in three locations (Atlanta, Chicago, Minneapolis) using GHEDT (Cook 2021) with the new library g-functions and with g-functions calculated with the equivalent borehole method (EBM) (Prieto and Cimmino 2021). The EBM g-functions were calculated with eight non-uniform segments as described by Cook (2021). The resulting design depths for the two different g-function calculation procedures, as shown in Fig. 3, have a maximum difference of 1.8% for the nine cases. These differences are considerably less than other uncertainties in the design, such as the future building loads and should therefore be adequate for design purposes.

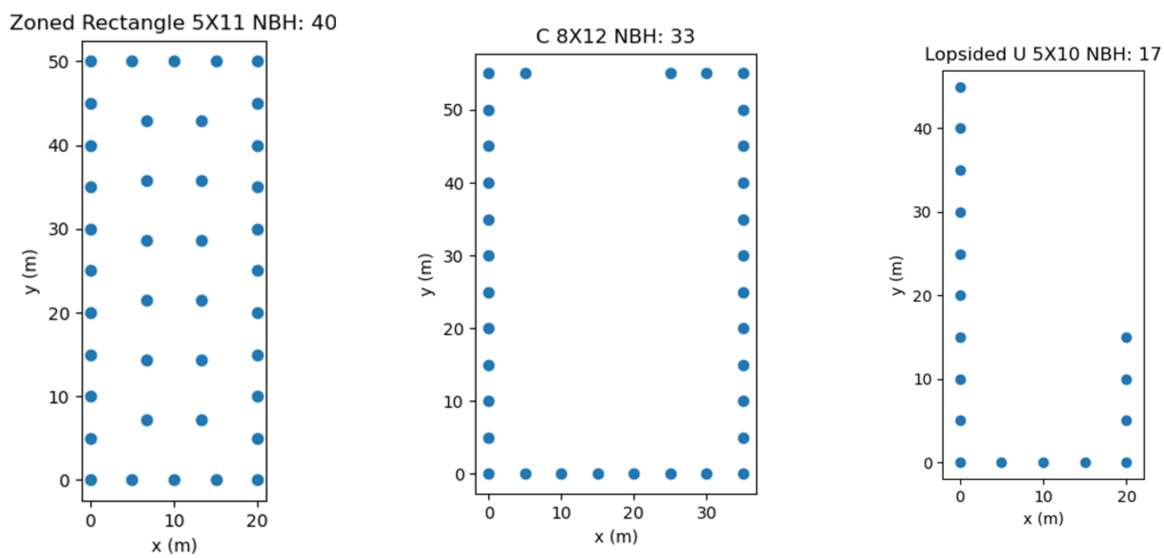

Figure 2 New configurations

Table 2. Library contents overview

Configuration Name	Number of configurations	Notes
Rectangle	1,651	Up to 1024 boreholes
Zoned Rectangle	12,615	
Open Rectangle	2,332	Up to 3 perimeter rows
C-shape	4,525	
L-shape	495	
U-shape	3, 248	
Lopsided U-shape (LopU)	9,455	

EXAMPLE – ZONED RECTANGLE

As an example, a GSHP system serving a 5-story hospital building in Atlanta (Fig. 4) is considered. The 241,310 ft^2 (22,428 m^2) building is simulated with a DOE prototype (USDOE 2022) hospital building model, with the original HVAC system replaced by a distributed GSHP system. As shown in Fig. 4, the hospital requires cooling and heat rejection year-round and therefore represents an extreme case for ground heat exchanger design. An early version of the GHEDT design tool (Cook 2021) was used to select specific configurations and determine the required borehole depth for two configuration types: (1) conventional rectangular array with fixed uniform bore spacing, termed the "square or near square" design routine in Spitler and Cook (2020); (2) constrained within a given land area that matches the "square or near square" land area, but with smaller bore spacing in the perimeter and larger bore spacing in the center zone of the borehole field ("Zoned rectangle" design) (Spitler and Cook 2021). In addition to the borehole field layout, various maximum bore depths are also investigated. Details of the GHE design are given by Spitler et al. (2021).

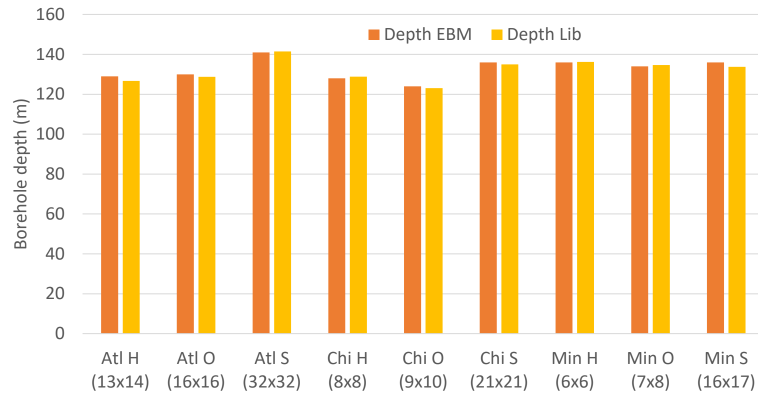

Figure 3 Comparison of borehole depths sized with GHEDT using g-functions from the library and g-functions computed with the EBM for three buildings (H=hospital; O=office; S=school) at three locations

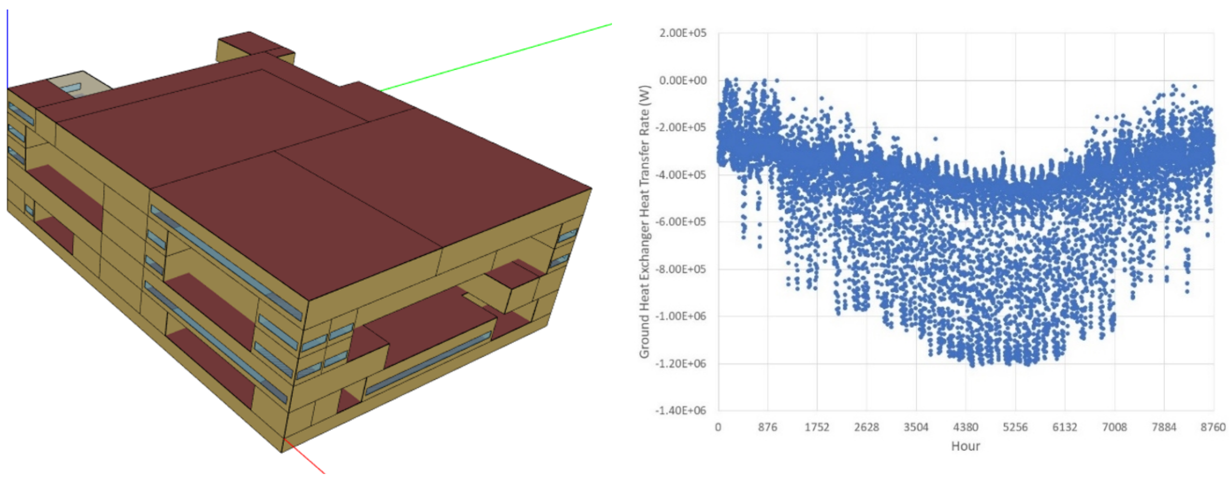

Figure 4 Hospital building (left) with hourly thermal loads imposed on the GHE (right)

Ground heat exchanger designs resulting from the different configuration types are listed in Table 3 and the total bore length of each design is graphically presented in Figure 5. For the same land area (42,630 m^2) needed for a conventional rectangular design, using the "Zoned rectangle configuration" and 119 m individual bore depth, the total bore length is reduced by 37% compared with the conventional rectangular design. The two design configurations are shown in Figure 6. With the conventional borehole field configuration, the total bore length is only reduced by 3% if the maximum bore depth is increased from 90 m to 95 m without changing bore spacing. However, with the "Zoned rectangle configuration" and a 95 m maximum bore depth (MBD), the total bore length is reduced by 21% compared with the baseline. The zoned rectangle configuration takes advantage of the fact that in a large configuration with significant heat imbalance, the perimeter boreholes are more effective in dissipating heat than the boreholes in the center zone (Spitler et al. 2020).

Table 3. Example results

Configuration type and depth constraint	NBH	Spacing	Depth (m)	Configuration	Total bore length (m)	Change (%)
Square or near-square w/ 90 m max. depth	930	7	87.2	Rec 31X30	81,096	-
Square or near-square w/ 95 m max. depth	841	7	94	Rec 29X29	79,054	-3%
Zoned w/ 95 m max. depth	678		94.9	Zoned 27X26 (576 interior BH)	64,342	-21%
Zoned w/ 100 m max. depth	608		98.9	Zoned 27X26 (506 interior BH)	60,131	-26%
Zoned w/ 120 m max. depth	426		119.3	Zoned 27X26 (324 interior BH)	50,822	-37%

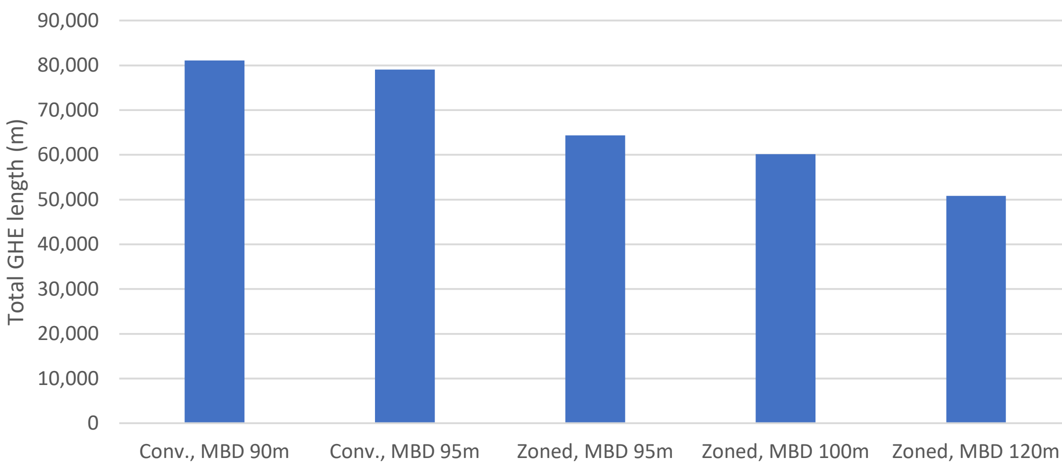

Figure 5 Total borehole length for two configuration types and different maximum borehole depths (MBD)

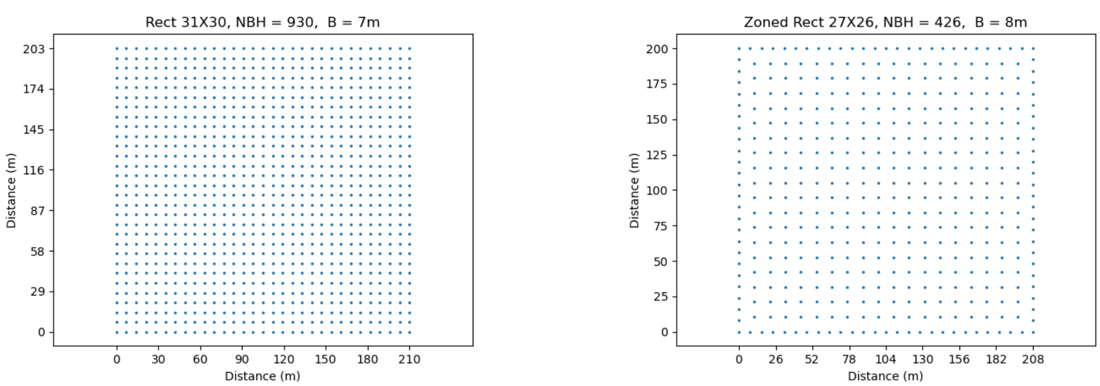

Figure 6 Base case (left) and zoned rectangle with37% less total borehole length

CONCLUSIONS

This paper has presented a new publicly available library of g-functions for use in design of ground heat exchangers and energy analysis of ground-source heat pump systems. Despite recent developments in fast calculation of g-functions, there are still several applications where library look-up of g-functions will be preferred over on-the-fly calculations. The library contains new configurations not previously available, and, in total, about 35 times as many configurations as previously available proprietary libraries. The availability of this new library will aid in design of efficient ground-source heat pump systems. One of the new configurations, the zoned rectangle, with smaller perimeter borehole spacing than interior spacing, was shown to be advantageous for a cooling-dominated Atlanta hospital, allowing significantly less drilling while using the same land area.

ACKNOWLEDGMENTS

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