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Sensitivity analysis of design parameters in RowWise borehole layout for ground heat exchangers

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Abstract

Ground source heat pump systems offer a promising pathway toward energy-efficient building heating and cooling. The performance and cost-effectiveness of these systems heavily depend on the design of the ground heat exchanger (GHE), particularly the spatial placement of boreholes used in large commercial buildings. Among various borefield layout strategies, the RowWise approach generates and optimizes borehole configurations within irregular polygonal land boundaries, providing land-use efficiency and installation flexibility. While multiple geometric design parameters constrain the RowWise layout, their influence on the system thermal performance and total drilling requirements remains unclear. Thus, this study presents a sensitivity analysis of key design parameters influencing the RowWise layout of vertical borehole GHEs, including the perimeter spacing ratio, borehole spacing, borehole field rotation angle, and borehole length. GHEDesigner and Ray Tune are employed to generate and assess different RowWise configurations. A series of parametric simulations was conducted to quantify the impact of each parameter on geometric distribution, economic cost, and computational speed. The results provide critical insights into the sensitivity and relative importance of different design parameters of RowWise method, offering practical guidance for designers aiming to optimize GHE layouts by balancing thermal efficiency, land constraints, and economic feasibility.

Keywords: sensitivity analysis; RowWise; borehole layout; ground heat exchanger; ground source heat pump

1. Introduction

Ground source heat pump (GSHP) systems have emerged as a highly efficient and sustainable solution for reducing energy consumption in building heating and cooling. By leveraging the relatively stable underground temperature as a heat source or sink, GSHPs can achieve significantly higher energy efficiency compared to conventional HVAC systems [1]. As intense effort is made towards energy efficiency in the built environment, GSHP technology presents a compelling alternative for achieving long-term energy savings and environmental benefits. At the heart of the GSHP system lies the ground heat exchanger (GHE), which facilitates thermal exchange between the building and the ground [2]. The performance and cost-effectiveness of a GSHP system are highly dependent on the design of its GHE.

The configuration of the GHE for large commercial buildings typically involves arrays of vertical boreholes. The specific arrangement of these boreholes is a critical design choice that determines the number of boreholes required, the thermal interaction between boreholes, and the overall heat transfer efficiency [3]. A well-designed borefield for GHEs ensures sufficient thermal capacity while striking a balance between drilling cost, land use, and thermal interference between boreholes [4]. Various borefield layout schemes have been

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developed to organize boreholes within a given site boundary. Among them, the RowWise scheme [5] is a layout generation strategy that positions boreholes in parallel rows, allowing for coupled optimization of row spacing and rotation to maximize land utilization. It offers advantages in modularity and installation flexibility, especially for irregular polygonal and constrained land areas.

Given the complexity of GHE borehole design decisions, screening tools are often used in the early planning stage to explore feasible layout options and guide detailed system design [6,7]. However, the RowWise scheme remains underexplored in existing studies and tool development, as most existing studies focus on more traditional grid-based or uniformly spaced layouts [8–10]. Therefore, before fully integrating the RowWise scheme into the screening tools, it is essential to understand how its design parameters influence the final layout and system performance. To address this gap, this study conducts a systematic parametric analysis using an integrated framework and combines GHEDesigner [11] and Ray Tune [12]. GHEDesigner is a Python package for designing GHE used with GSHP, which can synthesize borehole fields that are tailored to specific property boundaries. Ray Tune is a Python library for scalable hyperparameter tuning, which facilitates the multi-trial execution of the parametric study. The objective is to evaluate the sensitivity, interaction, and computational efficiency of key RowWise design parameters. The findings aim to help identify critical factors influencing the design feasibility and efficiency, inform the development of more robust layout algorithms, and ultimately support the practical implementation of RowWise configurations in the GSHP design workflow.

2. Methodology

The workflow of this study is illustrated in Figure 1. First, the building case to be investigated is modelled using EnergyPlus, incorporating critical information, such as the envelope specification, operation schedule, and system configurations. The location of the building and the corresponding weather data are also essential to determine the thermal profile of the case. Since the installation of GHEs requires sufficient land area surrounding the building, the geometric information of the available borefield and restricted areas (referred to as "no-go zones") is extracted from the site layout. Furthermore, the required GHE heat extraction rate is determined using a GHE sizing tool that integrates building load simulation with borefield performance modelling. The tool evaluates hourly thermal loads from the building model, selects feasible borehole layouts within land constraints, computes ground thermal response using g-functions [13,14], and iteratively determines the number, spacing, and depth of boreholes needed to maintain acceptable fluid temperatures. The simulations utilize standard g-function response factors developed by Claesson and Eskilson [15–17]. The model accounts for end-effects by computing conduction into the subsurface, applies an adiabatic ground surface boundary condition, and computes the effects of borehole-to-borehole interactions over time. The model assumes uniform subsurface conditions for the ground temperature and subsurface thermal properties, which are treated as "effective properties" that may account in part for several other phenomena, such as geothermal gradients and ground water advective effects, which are not explicitly modelled. This work builds upon the framework established in [18], where a comprehensive description of the sizing methodology and workflow can be found.

GHEDesigner [11], a tool to automate the design of GHEs, lies at the core of this study. It is available as a Python package and offers various geometric schemes along with their associated design parameters. Specifically, the RowWise layout design in the GHEDesigner is governed by four different types of parameters, which are borehole spacing, borefield rotation, borehole length, and the step size for rotation angle search. Specifically, the borefield rotation refers to the rotation angle of the row grid relative to the horizontal, searched and selected to ensure all boreholes are contained within the polygonal land area.

Overall, GHEDesigner takes the geometric information, GHE load profile, and parameter values sampled from the search space as input. After performing an exhaustive search across possible configurations, the results matrix, comprising borefield layout, total drilling depth, and computational time, is analysed to evaluate parameter sensitivity and computational efficiency.

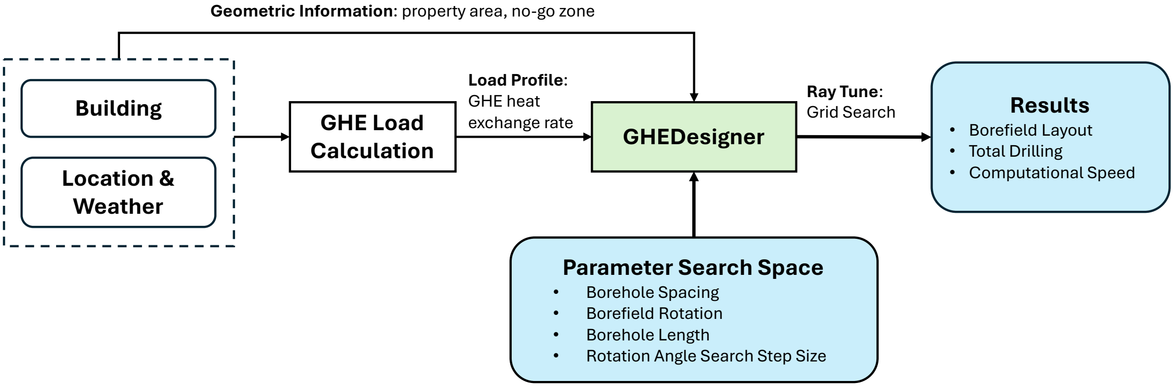


Figure 1. Schematic of the workflow.

2.1. Case Study

The case study was conducted for a commercial building located in Atlanta, Georgia, which has a warm and humid climate classified as ASHRAE climate zone 3A [19]. This climate is characterized by long cooling seasons and relatively mild winters, leading to a cooling-dominant thermal load profile throughout the year [20]. As shown in Figure 2a, the hourly heat transfer rate between the GHE and the surrounding soil reveals this seasonal pattern. For most of the year, the GHE rejects heat to the ground, as indicated by negative heat transfer rate values.

The geometric layout of the case is shown in Figure 2b, where the green area indicates the property boundary available for GHE installation and the red region is the no-go zone, which means no borehole will be placed within it. Both areas are defined by a list of ordered (x, y) coordinates forming a closed polygon. And the available borefield is obtained by subtracting the geometric intersections between the property area and the no-go zone.

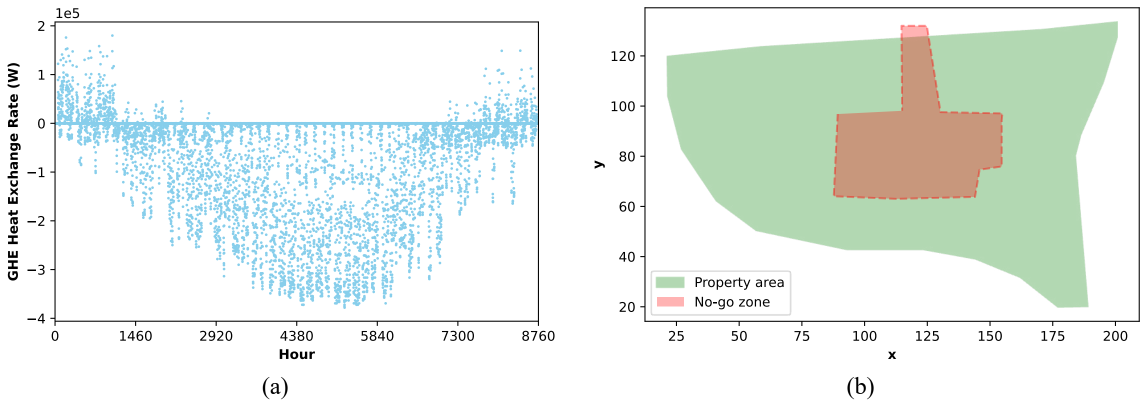


Figure 2 (a) Load profile of the investigated building. (b) Geometric information of available land for placing the boreholes.

2.2. Parameter Search Space

The parameters used in the design of RowWise borehole placement can be categorized into four types [11]:

1. Borehole Spacing

Three parameters are used to constrain the spacing between boreholes, which are perimeter spacing ratio, smallest minimum spacing, and largest minimum spacing. The perimeter spacing ratio (s_{per}) is the ratio between the spacing between the boreholes placed along the borefield perimeter and the spacing between boreholes within the borefield. This controls the density of borehole placement along the perimeter of the available land. Specifically, a smaller s_{per} corresponds to a denser arrangement of boreholes along the perimeter relative to the interior, while a larger s_{per} results in a sparser distribution, which reduces thermal interference but may underutilize the available boundary length.

The minimum borehole spacing plays an important role in GHE design. When the spacing is too small, the heat interference between adjacent GHEs will downgrade the system efficiency. The smallest minimum spacing (s_{min}) controls the minimum distances between the adjacent GHEs and cannot be violated by GHEDesigner during layout generation. In practice, GHEDesigner uses this parameter to trim the search space and speed up the search. In contrast, the largest minimum spacing (s_{max}) defines the upper end of the spacing range that RowWise evaluates. Rather than acting as a hard physical limit, it provides guidance on what spacings are reasonable to check. Because it determines the size of the smallest borefield, choosing a value that is too small may trigger the borehole removal algorithm of GHEDesigner. The borehole removal algorithm [5] is an automated cleanup step that deletes interior boreholes that fall too close to the property boundary or a no-go zone. Although necessary for maintaining geometric feasibility, it does not optimize the resulting layout and the intended layout can degrade, as the boreholes will not be repositioned once removed. Therefore, it is essential to avoid choosing s_{max} values that are small enough to trigger the removal process. On the other hand, a large value of s_{max} may place boreholes scarcely in the available land area and thus does not fully utilize the available land. So, s_{max} is an important design parameter for sizing GHE.

2. **Borefield Rotation**

One of the key advantages of RowWise layout is its flexibility in borehole placement, which can be expressed through the rotation of the borefield in irregular polygonal fields. By exploring different orientations within the available land, the designer can find a borehole configuration that minimizes total drilling length while still satisfying all geometric and practical constraints. The rotation of the field is controlled by two parameters: minimum rotation angle (r_{min}) and maximum rotation angle (r_{max}).

3. **Borehole Length**

The active length of each borehole represents a critical trade-off between thermal performance and economic feasibility. A longer borehole enhances the heat exchange capacity, allowing the system to meet higher thermal demands. Consequently, fewer boreholes are required, which in turn reduces thermal interference. However, it also increases the drilling depth and installation costs, as well as potential technical challenges associated with drilling deeper boreholes. Additionally, excessive length can lead to significant thermal short-circuiting between U-pipe legs, which can reduce the overall efficiency. Conversely, if the borehole length is too short, additional boreholes are required to satisfy the same thermal load, which may not be feasible given the limited land area available for installation. Therefore, it is critical to find the optimal design that satisfies the building's thermal requirements while minimizing the total drilling cost. The length is constrained by a lower bound (l_{min}) and an upper bound (l_{max}).

4. **Rotation Search Step**

The rotation search step (r_{step}) defines the discrete interval for iterating through potential borefield rotation angles. A smaller step size yields a higher resolution in design exploration but results in a corresponding increase in computational time.

The search space for the parameters mentioned above is listed in Table 1. The baseline values and the search range are defined with references to existing studies [21–24]. During parametric analysis, only one parameter is varied at a time, while all others are fixed at their baseline values to isolate its effect. The value lists for the parameters are generated within their corresponding range using either an equal percentage or equal interval method between adjacent values. Specifically, the perimeter spacing ratio employs a two-way fixed percentage to find values. Two-way fixed percentage formulates the value list by starting from the baseline and generating values by increasing 10% at each step until reaching the upper bound of the search range. In the opposite direction, it decreases by 10% per step until reaching the lower bound.

Table 1 Search space for the RowWise layout parameters.

Parameter	Unit	Baseline	Range	Values
s_{per}	-	0.7	(0.5, 1.5)	0.51, 0.57, 0.63, 0.7, 0.77, 0.85, 0.93, 1.02, 1.13, 1.24, 1.36
s_{min}	m	4	/	fixed at 4
s_{max}	m	10	[5, 20]	5.0, 5.7, 6.6, 7.6, 8.7, 10.0, 11.5, 13.2, 15.2, 17.4, 20.0
r_{min}	°	-5	[-90, 80]	-90.0, -68.75, -47.5, -26.25, -5.0, 16.25, 37.5, 58.75, 80.0
r_{max}	°	90	/	fixed at 90
l_{min}	m	50	[50, 70]	50.0, 51.9, 53.9, 55.9, 58.1, 60.3, 62.6, 65.0, 67.4, 70.0
l_{max}	m	150	[90, 150]	90.0, 95.3, 100.8, 106.7, 112.9, 119.5, 126.5, 133.9, 141.7, 150.0
r_{step}	°	1	[0.1, 20]	0.1, 2.31, 4.52, 6.73, 8.94, 11.16, 13.37, 15.58, 17.79, 20.0

2.3. Evaluation Metrics

For a systematic exploration of the governing parameters, Ray Tune [12], a hyperparameter tuning tool, is used to perform a grid search. The tool takes as input the search space defined in Table 1, executes all the cases, and collects the results. Subsequently, visualization and sensitivity analysis are performed based on the collected results. To evaluate the borefield layout, parametric sensitivity, and computational speed, the following metrics are used.

1. **Borefield Layout**
   - number of boreholes (-): number of boreholes placed on the borefield to satisfy the thermal load
   - borehole spacing (m): the spacing between boreholes
   - rotation angle (°): the rotation angle of the rows of boreholes
   - active borehole length (m): the active length of each borehole
2. **Total Drilling**
   - total drilling (m): number of boreholes (-) × active borehole length (m)
3. **Computational Speed**
   - computational time (s): total computation time of a design case

It is worth noting that among all the evaluation metrics, total drilling is assigned the highest priority. While the drilling cost comprises both fixed and variable expenses, total drilling length is used as the primary proxy for economic cost and serves as a key factor in the decision-making process for designing a GSHP system.

3. Results and Discussion

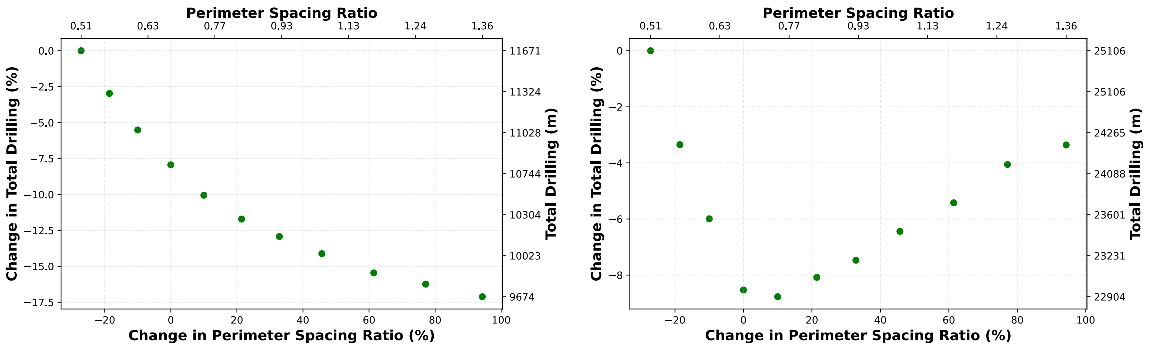
Simulations were conducted following the methodology described above, integrating GHEDesigner with Ray Tune for automated parameter exploration and optimization. After running the baseline case using the baseline parameter values, it was observed that the available land area significantly exceeded what was required to meet the original thermal load. To further investigate the sensitivity of the design parameters under more demanding conditions, additional simulations were conducted using 2x load scenario, representing double the original thermal load, respectively. The results and corresponding analyses are presented and discussed in this section.

3.1. Borehole Spacing

3.1.1. Perimeter spacing ratio

The perimeter spacing ratio is defined as the ratio between the spacing of boreholes along the perimeter of the field and that of boreholes within the interior region. A value greater than 1 indicates a wider spacing at the perimeter compared to the interior. In the 1x load case, the total drilling decreases nonlinearly as the perimeter spacing ratio increases, as shown in Figure 3a.

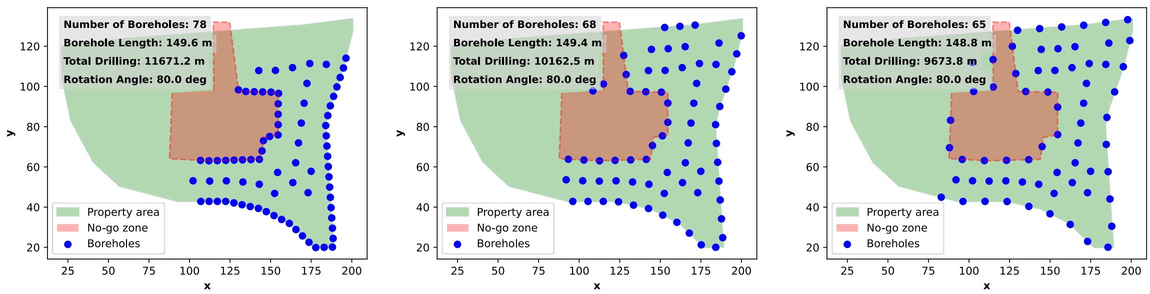
To identify the local minimum of this trend, an additional sensitivity analysis was conducted under the 2x load case, as shown in Figure 3b. The minimum total drilling is found when $s_{\text{per}} = 0.77$, representing a balance between thermal interference and active length requirements. In this case, the total drilling requirement is reduced by more than 8% by optimizing s_{per}. Unlike the 1× load case, the trend under higher load conditions differs because the available land area becomes more limited as the thermal demand increases. Consequently, the designer must place more boreholes along the perimeter to meet the thermal load. However, when the perimeter spacing ratio becomes excessively large, the boreholes are positioned densely in the interior area, leading to increased thermal interference. Moreover, the borehole-removal algorithm does not effectively re-optimize borehole positioning when perimeter spacing is treated independently, therefore causing the total drilling to increase. Therefore, for cooling-dominant designs, while utilizing the perimeter is advantageous, beyond a critical threshold, the penalty from thermal interference outweighs the capacity gains from the added boreholes.



(a) (b)

Figure 3 Sensitivity test of perimeter spacing ratio. (a) 1x load case; (b) 2x load case.

To further interpret the trend illustrated in Figure 3a, Figure 4 presents the borehole layout under different perimeter spacing ratios in the 1x case. It can be observed that the boreholes are in the lower right region of the property area when s_{per} is low (Figure 4a). The boreholes are packed more densely in this region to minimize spacing and avoid boundary conflicts. As s_{per} increases (Figure 4b), the layout algorithm prioritizes wider spacing on the boundary, forcing the boreholes to move towards the upper left direction. This movement results in increased interaction with the no-go zone. The average borehole spacing increases, and the total number of boreholes decreases as the thermal interaction among boreholes is reduced since boreholes are more widespread. Eventually, as more boreholes are relocated to satisfy the expanded perimeter spacing (Figure 4c), the total number of boreholes stabilizes. Since the active borehole length does not change much with the change in the perimeter spacing ratio, the total drilling follows a similar trend to that of the borehole number.



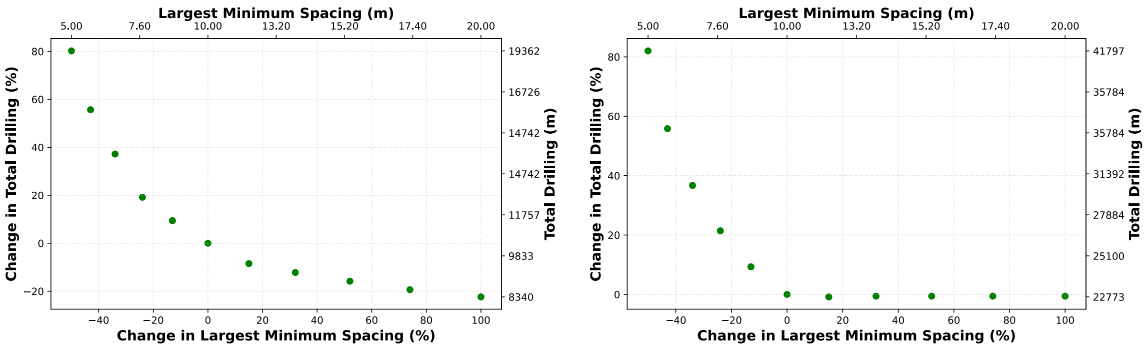
(a) (b) (c)

Figure 4 Borehole layouts under different perimeter spacing ratios in the 1x case. (a) $s_{per} = 0.51$; (b) $s_{per} = 0.93$; (c) $s_{per} = 1.36$.

3.1.2. Minimum spacing

The smallest minimum spacing (s_{min}) serves as a hard constraint that defines the minimum allowable distance between any two boreholes, whereas the largest minimum spacing (s_{max}) acts as a soft constraint, allowing limited flexibility in the optimization process. The hard constraint is typically determined based on engineering feasibility and drilling safety considerations, therefore s_{min} is fixed at 4m in this study, while only s_{max} is tuned during the search.

Results in Figure 5a show that the total required drilling follows a nonlinear decreasing trend as the s_{max} increases. Similarly, a 2x case was conducted to identify the local minimum. It is observed that the s_{max} is highly sensitive when it is below 10 m. Once s_{max} is greater than 10 m, the optimization consistently converges to the same borefield layout as illustrated in Figure 6, indicating that further increases in s_{max} have negligible effects on total drilling requirement. This trend also indicates that once the RowWise method has enough flexibility to converge to the optimal spacing, further increases in s_{max} no longer influence the spacing it chooses. Results in Figure 5a indicate that when available land is large, increasing s_{max} from 10 to 20 meters can reduce total drilling requirement by slightly more than 20%. However, as shown in Figure 5b, when available land is relatively small compared to the thermal load, increasing s_{max} beyond 10 meters has little impact on the total drilling requirement.



(a) (b)

Figure 5 Sensitivity test of the largest minimum spacing in (a) 1x load case and (b) 2x load case.

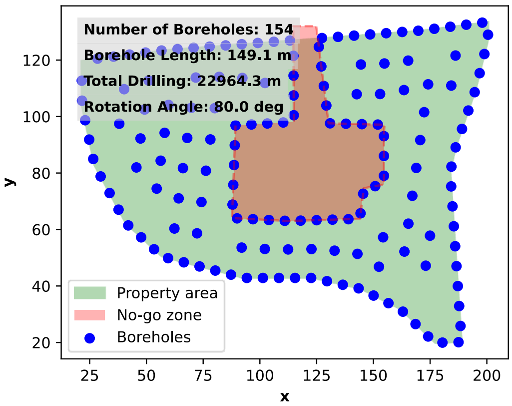


Figure 6 Borefield layout in 2x cases when the largest minimum spacing is greater than 10 m.

3.2. Borefield Rotation

The maximum possible search range for the borefield rotation extends from -90° to 90°, corresponding to orientations from due south to due north. In this study, r_{max} is fixed at 90° and only r_{min} varies. Since both r_{max} and r_{min} are defined within [-90°, 90°], an equivalent configuration could be achieved by fixing r_{min} = -90° and tuning r_{max} instead. This symmetric setup simplifies the parameter tuning.

Figures 7 and 8 show the sensitivity test results of rotation angle in 1x load case. The results indicate that variations in r_{min} do not show a distinct trend in total drilling length requirement. Most cases yield similar total drilling, except for the case when r_{min} = -90°.

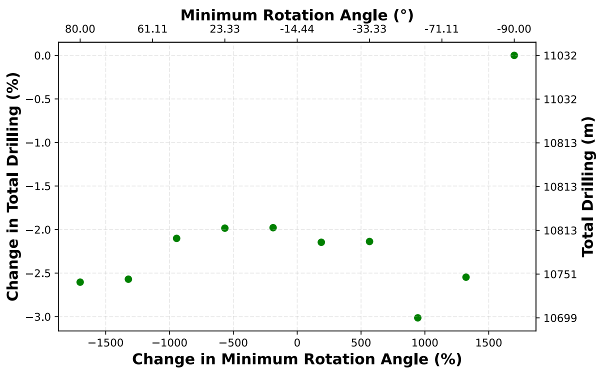
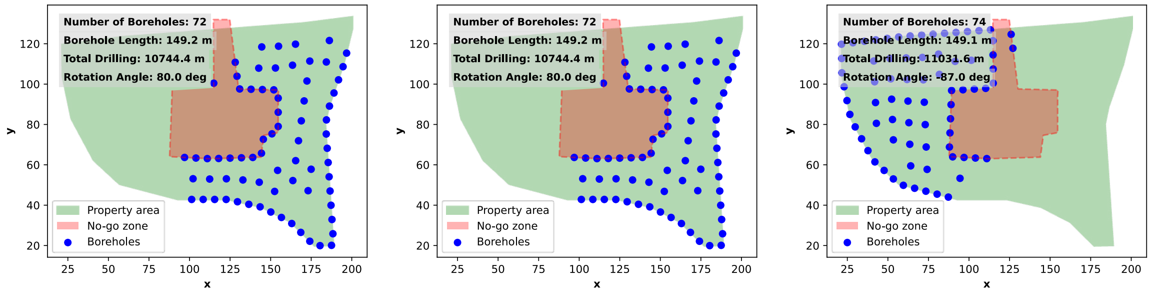


Figure 7 Sensitivity test of minimum rotation angle in 1x load case.

The distinct layout pattern observed at certain rotation angles can be attributed to the borehole removal algorithm, as indicated by Figure 8. For each rotation angle, the designer will first locate a vertex from which the borehole placement begins. Boreholes located farther from the vertex will be removed to yield a final borefield design. When the rotation angle is set to -90°, the identified vertex lies on the left side of the property area, causing the boreholes to cluster in that region. This spatial bias results in a distinctly different layout pattern compared to other rotation angles.



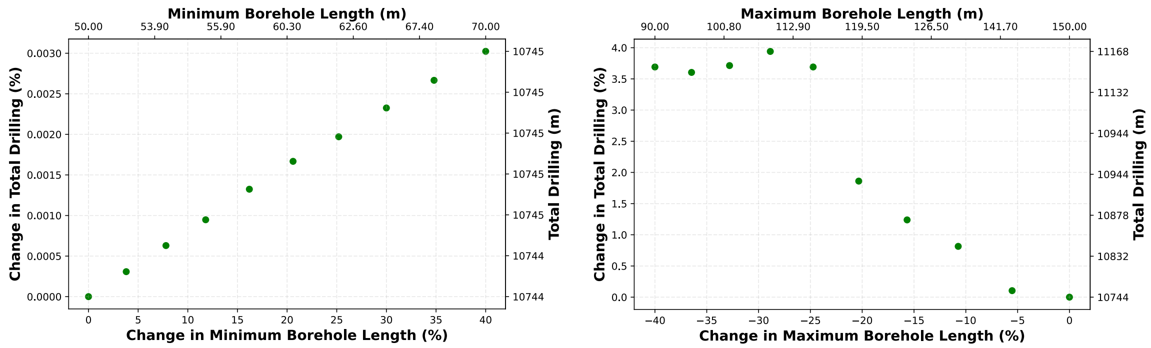
(a) (b) (c)

Figure 8 Layouts of borefield in 1x case with different rotation constraints. (a) $r_{\min}$ = 80°; (b) $r_{\min}$ = -5°; (c) $r_{\min}$ = -90°.

3.3. Borehole Length

The constraints of borehole length directly affect the thermal capacity that the GHE can deliver. The minimum cannot be too small, as it would require an excessive number of boreholes to meet the thermal demand, making the design economically impractical. Similarly, the maximum borehole length should not be too small, as it would make it impossible to satisfy the building demand.

Figure 9 shows the sensitivity test results of borehole length in the 1x case. The total drilling has a positive correlation with the minimum length and a negative correlation with the maximum length. Specifically, correlations between $l_{\min}$ and total drilling follow a nearly perfect linear relationship, while the correlation between $l_{\max}$ and total drilling also shows approximately linear when the constraint is relaxed ($l_{\max}$ > 119.5 m). However, the absolute changes in the total drilling are very subtle. This is primarily because the RowWise method generally assumes that the most efficient design for a given scenario is one that uses the longest possible boreholes and the fewest of them. As a result, adjusting the upper or lower bounds of these parameters has only a limited influence on the final borefield configuration and its associated cost.



(a) (b)

Figure 9 Sensitivity test of the length of borehole in the 1x load case. (a) $l_{\min}$; (b) $l_{\max}$.

3.4. Search Steps

Each 1x load design case takes around 10 seconds to complete. To minimize the influence of randomness and better evaluate the computational efficiency, the search steps sensitivity test was performed under a 2x load case. The running time of different rotation searching steps is shown on a log-scaled y-axis in Figure 10, where the results exhibit a nonlinear decreasing trend. The relative reduction in computation time gradually levels off and further increases offer minimal additional speedup. Meanwhile, the total drilling length (gray bars) remains nearly constant across all step sizes, demonstrating that increasing the rotation step has minimal influence on design accuracy while significantly reducing computation time. However, it is acknowledged that using an excessively large step beyond the tested range could risk missing the optimum and compromising the design accuracy.

Figure 10 Computational speed of different rotation search sizes in 2x load case.

4. Conclusions

This study presented a comprehensive parametric analysis of RowWise scheme for GHE borefield design using the integration of GHEDesigner and Ray Tune. The proposed workflow allows systematic exploration of geometric and operational parameters that govern the feasibility, efficiency, and computational performance of borefield design. The case study conducted with a commercial building located in Atlanta, GA, demonstrated how design constraints and search resolutions influence both the total drilling requirement and layout configuration under different load conditions.

Among the evaluated parameters, the perimeter spacing ratio and the largest minimum spacing were found to have the most pronounced effects on total drilling length requirement. Their sensitivity highlights the delicate balance between thermal interference reduction and land-use efficiency. In contrast, variations in rotation angle and borehole length constraints showed relatively minor influence on total drilling requirement, indicating that the layout generation process in GHEDesigner is robust to moderate changes in these parameters. The search step sensitivity analysis further revealed that computational time can be significantly reduced within the tested range without compromising design accuracy, offering practical guidance for efficient parameter tuning.

Overall, the findings emphasize the importance of parameter selection and constraint definition in optimizing GHE field designs. By identifying parameters with the strongest impact on performance and cost, this study provides practical guidance in GHE design. Future work will investigate additional cases and extend this methodology to multi-objective optimization that jointly considers thermal performance, life-cycle cost, and spatial constraints, enabling more intelligent and adaptive GHE design strategies for real-world building applications.

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