Ground Heat Exchanger Design Tool with RowWise Placement of Boreholes

Jeffrey D. Spitler **Timothy West** **Xiaobing Liu**

ABSTRACT

Simulation-based design tools have been used since the late 1980s for designing ground heat exchangers (GHE) used with ground source heat pump (GSHP) systems. The ground heat exchanger simulations used in these tools rely on thermal response functions known as g-functions. Because of the significant computational burden in computing g-functions for even a single configuration, the design tools have relied on libraries of pre-computed g-functions. These g-functions were available for standard configuration shapes, such as lines, rectangles, open rectangles, L-shapes, and U-shapes. Standard shapes are often sub-optimal. For any building on a site, the available land may preclude use of a standard shape. For large GSHP systems with significantly imbalanced annual heat rejection and extraction loads, large rectangular fields may experience significant heat build-up (or heat draw-down) in the interior of the field. This paper describes a new ground heat exchanger design tool capable of automatically selecting and sizing both standard and irregular configurations. The focus of this paper is a method for creating, selecting and sizing irregular configurations where the available land area and "no-go" zones are described as irregular polygons.

INTRODUCTION

Development of thermal response functions, known as g-functions, by Prof. Claesson of Lund University and his graduate students (Claesson and Eskilson 1985, 1988) allowed simulation of ground heat exchangers with multiple vertical boreholes, accounting for borehole-to-borehole thermal interference. The effects of thermal interference are particularly important for larger ground heat exchangers used with GSHP systems serving commercial and institutional buildings. Simulation-based design tools such as GLHEPRO (Spitler 2000) and EED (BLOCON 2015) use pre-calculated libraries of g-functions for standard shapes (lines, rectangles, etc.) because, up until recently, computation of g-functions was too time-consuming to be done "on the fly".

However, in situations where the annual heat rejection and extraction are significantly imbalanced, long-term temperature build-up or draw-down can drive the total drilling requirements to infeasibly high levels. Spitler, et al. (2020) compared designs based on a library rectangular g-function to a custom configuration where the boreholes were wrapped around the building. For this specific case, wrap-around configurations could achieve drilling savings of 34-43% depending on the depth constraint. The design of the wrap-around configuration took many engineer-hours to locate the boreholes, iteratively adjusting the number of boreholes and borehole positions, and calculating g-

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functions (taking many computer hours) for each configuration. Methods for automatically placing boreholes in an optimal[1] or near-optimal manner are of significant interest.

Bayer, et al. (2014) described a method for designing GHE starting with a pre-defined configuration and systematically removing boreholes based on their effectiveness. Robert and Gosselin (2014) described a GSHP system optimization that selected uniformly spaced rectangular borehole fields. This paper describes a recently developed design tool, GHEDesigner[2], which can automatically select and size borehole configurations (that is, place the boreholes and determine the depth that meets the design temperature constraints.) The focus of this paper is the addition of a new algorithm for creating and selecting borehole configurations – the RowWise algorithm.

GHEDESIGNER

GHEDesigner (Ground Heat Exchanger Designer) is a recently developed simulation-based design tool for ground heat exchangers. An earlier version, GHEDT (Ground Heat Exchanger Design Tool) was described by Cook (2021). It serves a similar purpose to other simulation-based design tools such as GLHEPRO (Spitler 2000) and EED (BLOCON 2017) but has new features. The most significant feature being the capability to both select and size a ground heat exchanger configuration. It has several search routines for selecting configurations, including:

- The unconstrained square/near-square search will search a domain of square (n x n) and near-square (n-1 x n) boreholes, with uniform spacing between the boreholes.
- Uniform and bi-uniform constrained rectangular searches will search domains of rectangular configurations that have either uniform spacing or "bi-uniform" spacing – that is, uniform in the x direction and uniform in the y direction, but the two spacings may be different.
- The bi-uniform constrained zoned rectangular search allows for rectangular configurations with different interior and perimeter spacings.
- The bi-uniform polygonal constrained rectangular search (BUPCRS) can search configurations with an outer perimeter and no-go zones described as irregular polygons. This is still referred to as a rectangular search because it is still based on a rectangular grid, from which boreholes that are outside the perimeter or inside a no-go zone are removed.

By comparison, GLHEPRO sizes a user-specified configuration. EED has features to automatically search constrained rectangular borehole fields and allow conversion of a user-specified irregularly shaped field to an equivalent rectangular field. It does not allow automated placement of irregularly shaped borehole fields.

GHEDesigner relies on an integer bisection search to select the configuration. Each configuration is simulated for the design period, giving a ground heat exchanger exiting fluid temperature (GHE ExFT) for each time step. The search parameter, the excess temperature, is the maximum temperature difference by which the design temperature constraints are exceeded. The bisection search looks for the root but returns the configuration with the smallest magnitude but negative excess fluid temperature as the design. The different search domains above have been chosen to be unimodal; here this means that the excess fluid temperature always decreases as the number of boreholes are increased. This means that there is only one root.

GHEDesigner uses pygfunction (Cimmino 2018) to compute the long time step (LTS) g-functions on the fly. By

[1] Finding a true global optimum for large fields is not currently feasible – global large scale optimization methods that could actually optimize placement of hundreds of boreholes are a current area of research and, in the authors' opinions, seem likely to be reduced to practice for GHE design in the near future

[2] The authors plan to release an open-source version of the design tool, named GHEDesigner, with the RowWise algorithm in 2022. See: https://github.com/BETSRG/GHEDesigner

default, the equivalent borehole model (Prieto and Cimmino 2021) with eight non-uniform finite line sources per borehole (Cook 2021) is used to allow rapid computation for any borefield geometry. A single g-function can be computed on a standard desktop PC in a few seconds. For sizing purposes, five g-functions are computed for different depths and interpolated between. Borehole thermal resistance and short time step (STS) g-functions can be computed for single U-tube, double U-tube, and co-axial configurations.

GHEDesigner uses an improved hybrid time-step scheme as recommended by Cullin and Spitler (2011). The duration and length of monthly peak loads as well as average monthly loads are automatically determined from hourly loads. GHEDesigner can also size based on an hourly simulation, but this becomes rather slow. Unlike GLHEPRO, but like EED, the user currently has to specify the ground heat rejection/extraction loads rather than loads on the heat pump(s). Heat pump models will be added in the future.

ILLUSTRATIVE EXAMPLE

To better illustrate the process that the RowWise and search algorithms use, a specific example is used in this paper, based on (1) an actual medical office building in Stillwater, Oklahoma, from which the building footprint and property boundaries are taken, and (2) a medical outpatient building from the DoE commercial buildings library (USDOE 2022), simulated in Stillwater, Oklahoma, from which the load profile is taken. The library medical outpatient building has a floor area of 3804 m^2 (40,946 sq. ft.) and annual heat rejection that is 11.6 times the annual heat extraction; the annual loads are significantly imbalanced. For purposes of creating several examples, the simulated hourly loads were scaled as described in the results section. The property boundary (orange line) is irregularly shaped, and the building footprint and a no-go zone (gray lines) for utility easements are shown in Figure 1. The property boundary and no-go zones are represented as counterclockwise lists of points.

ROWWISE METHODOLOGY

The RowWise method systematically distributes boreholes across a property, if needed, or can reduce the footprint of the borehole field, if desirable. The goal of this method is to place boreholes in a way that both retains the row structure that borefields often have as well as efficiently utilizing space available on the property. Retaining the row structure should simplifies locating the boreholes during drilling and reduce the complexity of the header piping system. The RowWise algorithm has two parts. For a specified target spacing, the RowWise placement algorithm generates many fields with different rotations, returning the field with the maximum number of boreholes. The RowWise search algorithm searches target spacings, calling the RowWise placement algorithm, and evaluating the borefields' exiting fluid temperature and total drilling to find a good design.

To utilize the space available on a property, the user specifies two minimum spacings, an inter-row minimum spacing and intra-row minimum spacing. Together, these determine the maximum number of boreholes that can be placed on the available property. The design intra-row spacing will often be higher than the minimum intra-row spacing, as borehole positions are adjusted in the algorithm to take full use of the available space along each row. Figure 1 shows sample results with the blue lines representing each row and the blue dots representing the boreholes. The right-hand figure uses independent perimeter borehole target spacing.

A further option in the RowWise algorithm is a separate input minimum spacing for the perimeter boreholes, which allows reduced perimeter spacing. This is often advantageous. In addition to the minimum spacing and property inputs[3], other inputs control the row rotations, setting the range of rotation and rotation step size.

[3] Property boundaries and no-go zones are input as polygons with points specified in counterclockwise order.

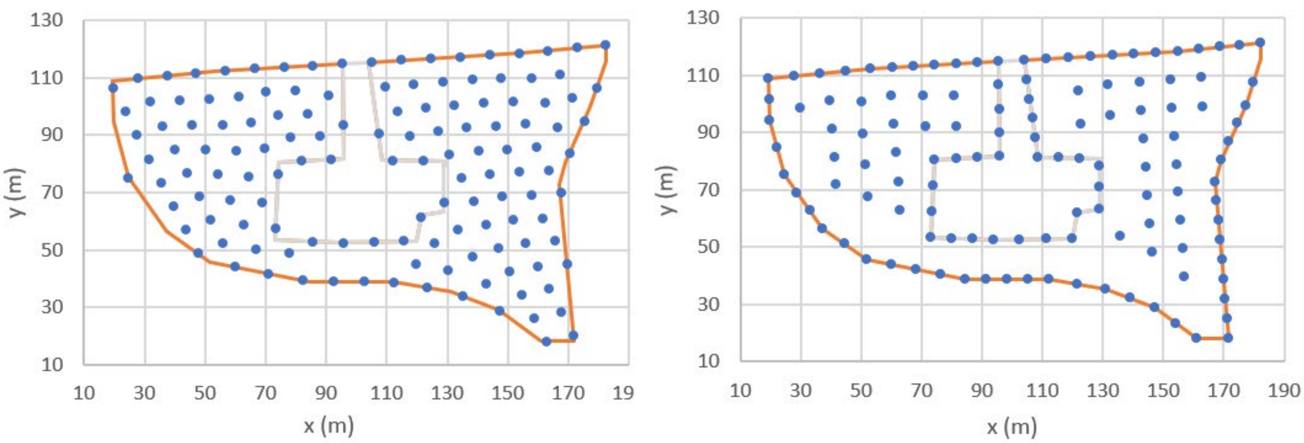

Figure 1 Sample RowWise fields. The left field uses the standard RowWise algorithm, (90° clockwise row rotation) but the right field uses independent perimeter spacing (86° clockwise row rotation).

RowWise Placement Algorithm

The RowWise placement algorithm has an outer loop that controls the row rotation (angle of each row from horizontal). The user can specify the range and rotation step size. We have commonly used 0°-90° for the range of rotation and 0.1° for the rotation step size. For any particular rotation, the algorithm starts by determining the direction normal to the rows and finds the lowest and highest point on the property boundary relative to that direction. The algorithm then determines the maximum number of rows that can fit on the property while maintaining at least the minimum inter-row spacing. The row spacing is then adjusted upwards to fully use the property, with rows going through the highest and lowest points on the property boundary.

The next major step is the borehole placement in each row. For each row, the algorithm finds the intersections between the row and the property boundary as well as any no-go zones. These intersections are used to subdivide the current row into smaller colinear row segments (avoiding the no-go zones). Boreholes are distributed along each row segment based on the minimum intra-row spacing, adjusted upwards to make full use of each row segment. If the row segment is smaller than the minimum intra-row spacing, a single borehole is placed in the middle of the row segment. An exception would be the case where the distance across a no-go zone or irregular property boundary is less than the minimum intra-row spacing. In that case, the row segment on which boreholes can be placed is shortened to maintain the minimum intra-row spacing.

An option is to separately treat the perimeter, in which case the interior boreholes are distributed as described above; boreholes are then placed uniformly along each perimeter segment at or above the specified perimeter spacing.

The borehole distribution across a property boundary varies unpredictably with the row rotation. Therefore, boreholes are placed for each row rotation step, and the rotation that gives the maximum number of boreholes is selected[4]. This is significant because the possible number of boreholes varies widely with rotation, and, in turn, the total drilling[5] required varies widely with rotation, as shown in Figure 2 for cases with and without separate treatment of the perimeter. For both cases, minimum inter-row and intra-row spacings of 5m were used. For the case with separate treatment of the perimeter, a perimeter spacing of 4m was used.

[4] We note that choosing the rotation with the maximum number of boreholes reflects an unproven assumption – that maximizing the number of boreholes for a given minimum spacing is desirable. It should, at the least, give the maximum capacity.

[5] Total drilling is the number of boreholes multiplied by the final design depth.

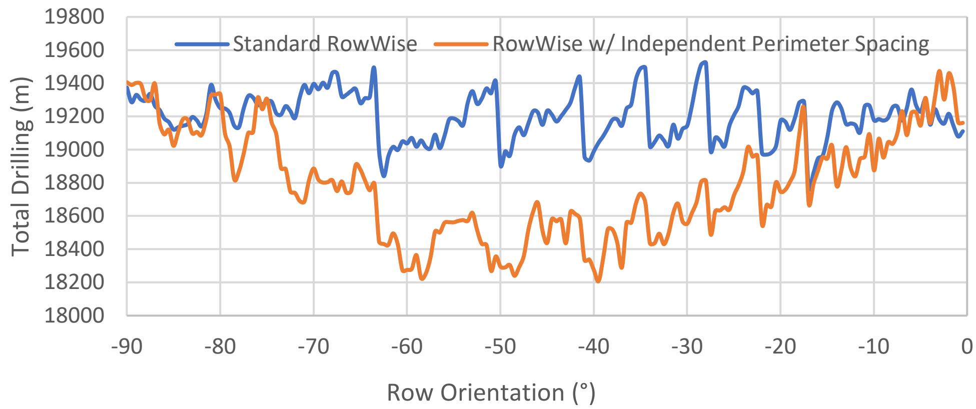

Figure 2 Sensitivity of total drilling to row orientation

RowWise Search Algorithm

In order to automatically select and size RowWise configurations, a search algorithm that finds a minimal cost design that will meet the design temperature constraints is needed. This section presents the current search algorithm, which is organized as a one-dimensional search by keeping the minimum inter-row and intra-row spacings to be the same and keeping the minimum perimeter spacing at a fixed ratio to the other spacing. In addition to the inputs for the RowWise placement algorithm described above, the search algorithm requires several additional user inputs: maximum target spacing, maximum borehole depth, and parameters related to the optional use of an exhaustive search at the end: the number of fields evaluated and a spacing increment for exhaustive searches. As described below, the search algorithm makes an initial determination of the domain, then follows one of two search procedures, optionally followed by an exhaustive search near the solution given by the first search procedure.

Initial Domain Determination

The solution may lie in one of three domains, which might be described as follows: (1) no feasible solution – load is larger than can be supported by available property using the maximum number of boreholes corresponding to the minimum target spacing; (2) the available property is adequate and will be fully utilized using spacing somewhere between the minimum and maximum target spacing; (3) the available property is more than adequate and using the maximum target spacing would still result in more boreholes than needed. The domain is determined by generating a RowWise configuration for both the minimum and maximum target spacings. If the excess temperature is positive for both cases, there is no feasible solution – domain (1) - and an error message is returned. If the excess temperature is positive for the maximum target spacing and negative for the minimum target spacing, the solution lies in domain (2) and the spacing search with optional exhaustive search will be performed. If the excess temperature is negative for the maximum target spacing and negative for the minimum target spacing, the solution lies in domain (3) and the borehole removal search will be initiated. These searches are described in the following two sections.

Spacing search with optional exhaustive search

If this search is used, the design solution will fall somewhere between the minimum spacing field and the maximum spacing field. So, a bisection search is performed on the target spacing domain. During each iteration of the search, excess temperature is evaluated based on maximum borehole height and a target spacing halfway between the current maximum and minimum spacing. Based on this outcome, half the domain will be eliminated at each step. If the maximum number of iterations is reached (10 by default) or the maximum and minimum fields produce the same excess temperature (within a tolerance), the field corresponding to the minimum target spacing is returned since it is guaranteed to have a negative excess temperature.

Because the domain is not perfectly unimodal, e.g., a slight increase in target spacing can sometimes return a field with more boreholes and more or less total drilling required, it may be worthwhile to search for a better solution near the design solution. This is done with a one-dimensional exhaustive search in the target spacing. (At the time of this writing, we have not yet found a better solution using the exhaustive search, but it seems likely that there will be cases where a better solution might be found.) The search procedure is illustrated in Figure 3, where the number of boreholes and excess temperature are plotted versus the search step. The first two search points correspond to the minimum and maximum target spacings. The blue circles represent the bisection search, with the solution represented by step 11, which has a target spacing of 8.57 m, an excess temperature of -0.15°C, and 139 boreholes. The orange triangles represent the exhaustive search, which evaluates target spacings between 8.07 m and 9.07 m, at intervals of 0.1 m. The final result corresponds to step 11; that is, the exhaustive search didn't provide a better solution. After the configuration is selected, a final sizing step would adjust the borehole depth downwards to give an excess temperature of 0°C.

Borehole removal search

For situations where the available land area exceeds what is needed, it is desirable to give a working design with fewer boreholes and less trenching than would be achieved with the maximum target spacing, using all the land area. The search algorithm we have developed starts with the maximum target spacing configuration determined in the domain search, then has two steps: (1) sorting the boreholes in some order of desirability, e.g. distance from a point on the building where the piping will enter the mechanical room, and (2) using a bisection search to systematically reduce the number of boreholes in such a way that the least desirable locations are preferentially removed. An alternative is to leave the boreholes sorted in rows, such that the boreholes will be removed row-by-row. This search proceeds in a similar way to the target spacing search and continues until the maximum number of iterations has been reached or when the maximum and minimum fields are within 1 borehole of being the same size. This search is not followed by an exhaustive search, but the final depth is again calculated to give 0°C excess temperature.

EXAMPLES

The BUPCRS (Cook 2021) has a similar goal to the RowWise search – it distributes the boreholes around the available land area and therefore we use it to verify that the RowWise algorithm is working and giving reasonable results. For this example, the hourly loads were scaled by 5X to test the sizing for domain (2). For both algorithms, minimum and maximum spacing were set to 5m and 12m respectively. The RowWise algorithm investigated row orientations between -90° and 0° at increments of 0.5°. Figure 4 illustrates the RowWise search algorithm iterations. Figure 3 shows the resulting borefields from the two methods. In addition, a case where the RowWise algorithm was tested with perimeter minimum spacing was scaled to be 70% of the minimum interior spacing. Figure 5 compares the results for final borehole depth, number of boreholes, total drilling length, and calculation time. For this case, the standard RowWise search takes about 3 times as long as the BUPCRS but gives a 12% savings in total drilling. With scaled perimeter spacing, the RowWise method gives an 18% savings in total drilling. The RowWise placement algorithm needs further refinement to improve its computational speed.

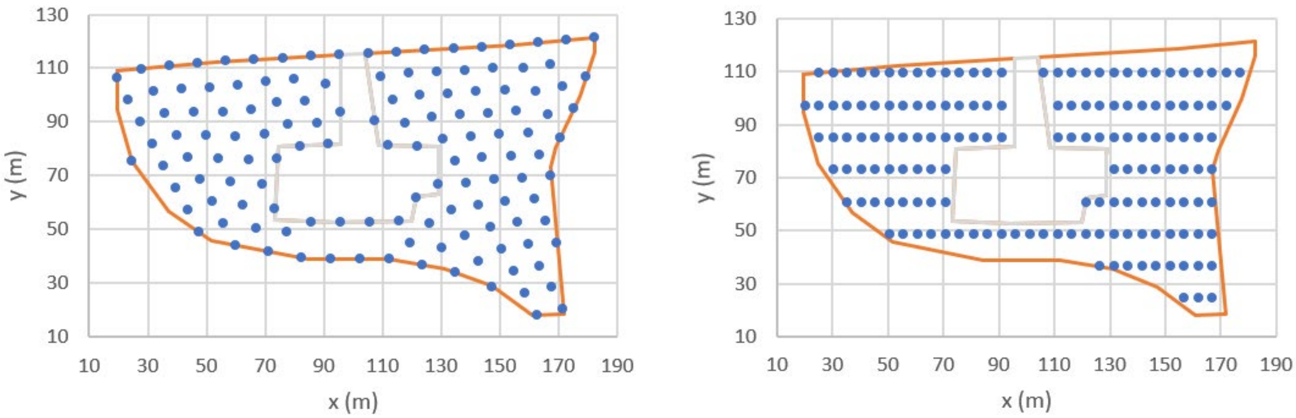

Figure 3 Design solutions for the RowWise without independent perimeter spacing (left) and BUPCRS (right) algorithms

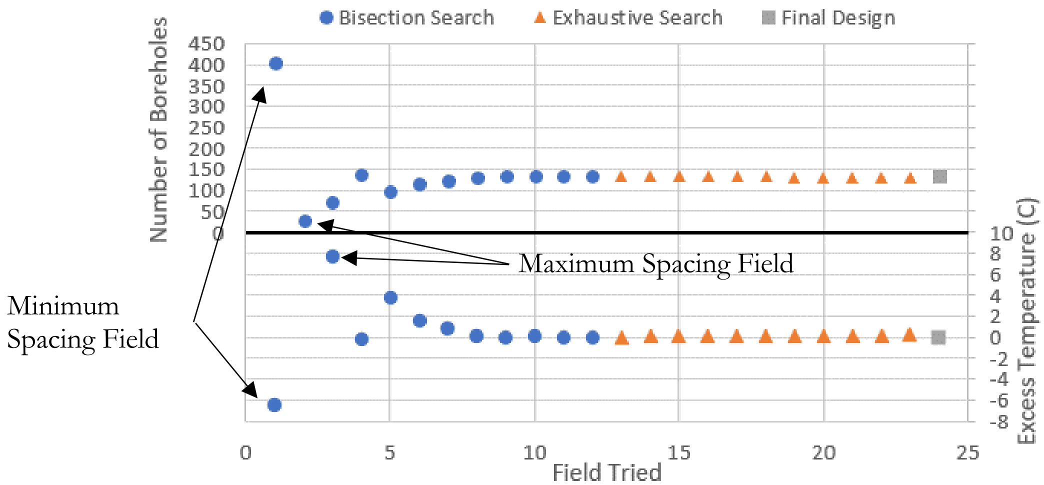

Figure 4 Search points used to find best design

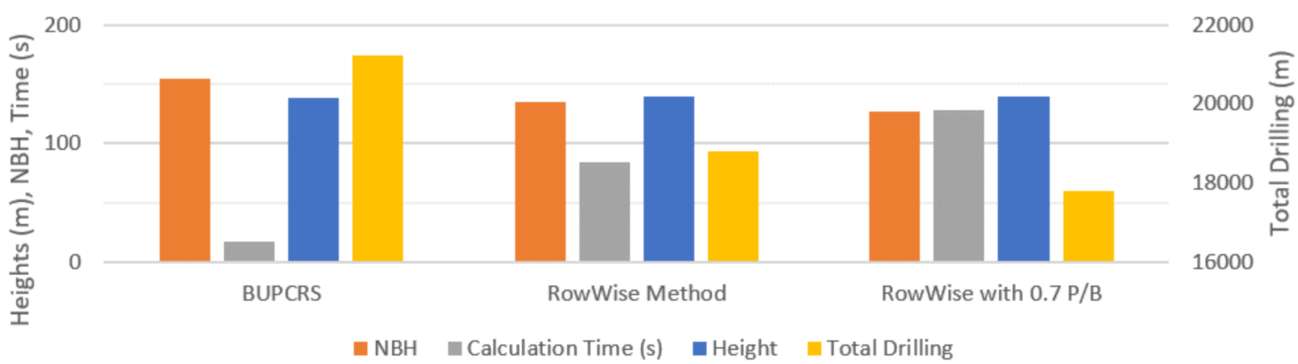

Figure 5 Comparison of BUPCRS and RowWise search algorithms

CONCLUSIONS AND RECOMMENDATIONS

This paper describes a borehole placement and configuration search algorithm that we refer to as RowWise. It can take advantage of irregularly shaped properties and allows automated designs that were not previously possible. Compared to another newly developed algorithm that uses a rectangular grid and removes boreholes in no-go zones, the RowWise algorithm shows considerable progress with one example giving an 18% decrease in total drilling required.

Space precluded presentation of more examples, and a more comprehensive investigation of different geometries is needed. Furthermore, the optimization used for the design has been organized as a one-dimensional search with the minimum intra-row and inter-row spacing set equal, and the perimeter spacing, where "independent" was actually set to be a fixed ratio to the interior spacings. Further development of multi-dimensional optimization is needed. At present, this optimization will still have to be parameterized. Finally, the design does not currently consider the cost of drilling and trenching, but rather uses total drilling length as the metric to minimize, while making use of a user-specified maximum spacing to limit excessive spacing between the boreholes. Development of a cost model and additional research into drilling and trenching costs are needed to support minimizing first costs or life cycle costs rather than drilling lengths.

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