

# An Analysis on Cost Reduction Potential of Vertical Bore Ground Heat Exchangers Used for Ground Source Heat Pump Systems

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## ABSTRACT

The cost for installing ground heat exchangers (GHXs) used for ground source heat pump (GSHP) systems usually accounts for more than 30% of the total cost of a GSHP system and it is the biggest contributor to the cost premium of GSHPs compared with conventional HVAC systems. This study evaluates the cost reduction potential of several possible improvements in borehole heat transfer and bore field layout. A detailed cost model for GHX installation was updated and new features were added to account for various GHX designs, geological conditions, and drilling technologies. Coupled with a well-established GHX sizing program, a systematic study was conducted to assess the impacts of these improvements on the needed total drilling length and resulting cost under various geological and loading conditions. Finally, improvements with significant potential to reduce GHX installation cost are recommended.

## 1. INTRODUCTION

The geothermal heat pump (GHP), also referred to as a ground source heat pump (GSHP), is a proven technology that can provide space conditioning and water heating with efficiencies higher than conventional heating, ventilation, and air-conditioning (HVAC) systems. This technology possesses great potential to become a mainstream technology for satisfying the thermal demands in the built environment. Analysis from the ongoing Geothermal Vision Study indicates that 100% retrofitting of commercial and residential markets with GHPs has the potential to save on the order of 6 quadrillion Btu per year (Liu et al. 2018). However, the current high installation costs and long payback periods limit the attractiveness of GHP installation in the United States. The cost of installing ground heat exchangers (GHXs) used for GHPs accounts for more than 30% of the total cost of a GHP system (NYSERDA 2017), and it is the biggest contributor to the cost premium of GHPs compared with conventional HVAC systems.

Information on the current practice for GHX design, installation, and associated costs was collected through a national survey. In addition, possible improvements in GHX design and borehole drilling were investigated through an extensive literature review, as well as discussions with industry professionals and technology providers. An existing cost model for the closed-loop vertical bore ground heat exchanger (VBGHX), which is the most commonly used GHX in the United States, was updated and expanded to account for various borehole heat exchanger (BHE) designs, geological conditions, and drilling technologies. This updated cost model can predict a detailed cost breakdown for each task of the installation processes.

This study evaluates the cost reduction potential of several possible improvements in borehole heat transfer and bore field layout. Baseline specifications were first developed for typical installation scenarios that cover a large fraction of the residential and commercial market. Coupled with a widely accepted VBGHX sizing program, a systematic study was conducted to assess the potential of various technology improvements in reducing the needed total drilling length and the associated cost under various geological and thermal loading conditions. Finally, recommendations were made for reducing the installed cost of VBGHX while retaining performance.

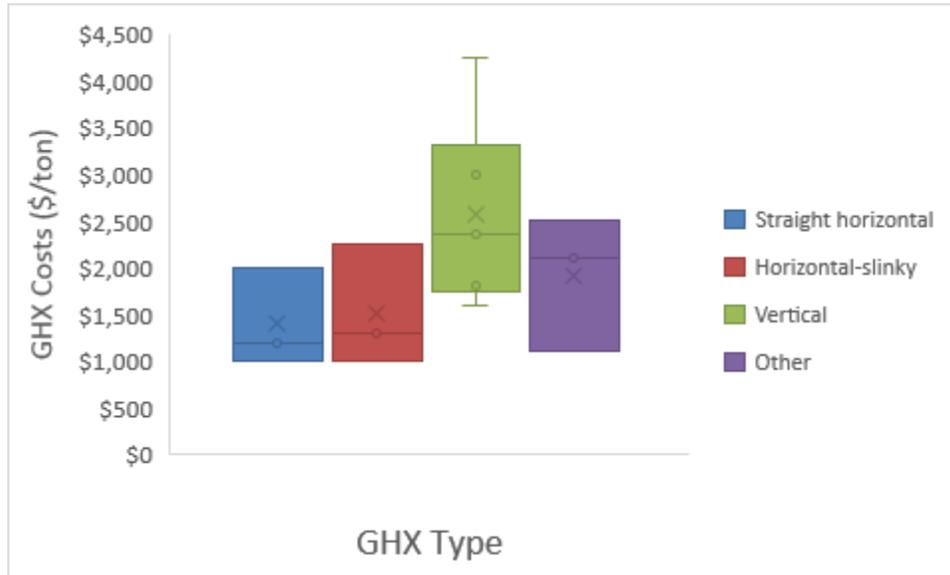
## 2. SURVEY OF CURRENT PRACTICE AND ASSOCIATED COSTS FOR INSTALLING GROUND HEAT EXCHANGERS

A survey questionnaire was designed to collect information about the typical design and installation practices for various GHXs. The survey was organized into five sections: (1) general information about survey respondents, (2) specifications of GHXs, (3) specifications of drilling and grouting, (4) other nondrilling costs (e.g., site survey, site restoration), and (5) comments on possible solutions to reduce GHX cost. Survey questionnaires and results are presented in an accompanying report (Liu et al. 2018). Following conclusions are drawn based on the survey results:

- The most commonly used GHXs is VBGHXs although VBGHXs are more expensive than other types of GHXs. This is because of their moderate land requirement and small environmental effects.
- The most common design of VBGHXs in the United States use a single U-tube heat exchanger loop made with high-density polyethylene (HDPE) pipes. In a single U-tube design, the heat transfer fluid flows down one leg of a U-shaped plastic tube and flows up through the other. The space between the U-tube and the borehole wall is filled with grout to prevent water and contaminants from migrating along the vertical borehole. Survey results indicate various brands of grouting materials, including both standard and thermally enhanced grouts.

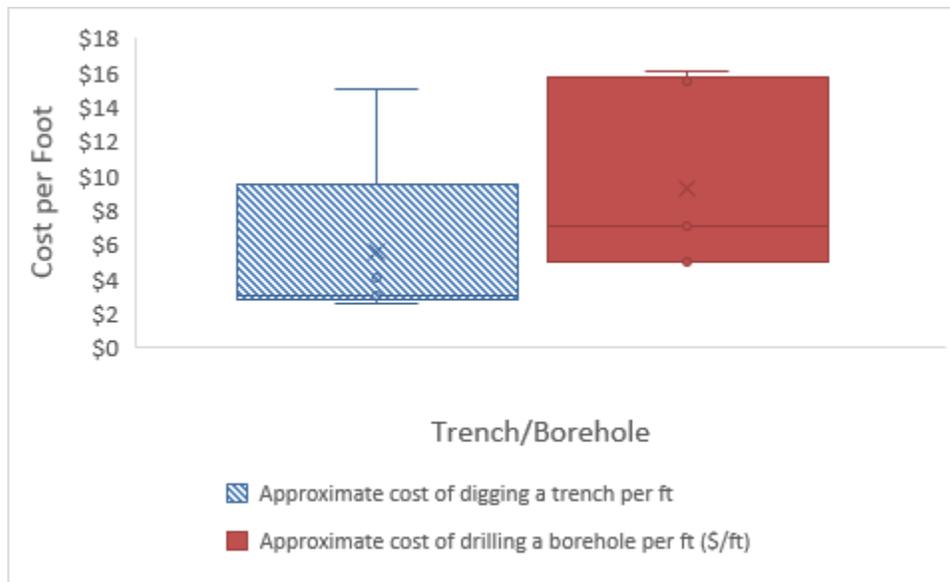
- Typical depth of the vertical bore is 200–400 ft and the typical bore diameter is 4.75–5.75 in. Mud rotary, air rotary, and downhole hammer are commonly used drilling rigs. Typical rate of penetration (ROP) of vertical bore drilling is 60–150 ft/h.
- The costs of drilling vertical bores vary widely (\$5.0–\$15.5/ft) and geological formations encountered during drilling is one of the factors that determines the costs of drilling.

Figure 1 shows the survey results of the normalized costs (dollars per cooling ton) of various GHX types with a box plot. The normalized costs of VBGHX vary from \$1,600/ton to \$4,250/ton, and the average is \$2,350/ton. The average normalized cost of the horizontal-slinky GHXs is just slightly higher than that of the straight horizontal GHXs. The “other” GHX is standing column wells (SCW), as indicated by the survey respondent. SCW is a semi-open loop system that uses groundwater to provide a heat sink and source for GHP systems.



**Figure 1: Survey results of the normalized costs (dollars per cooling ton) of various GHX types.**

Figure 2 shows the survey results of the normalized costs of horizontal trenches (dollars per linear foot of horizontal trench) and vertical bores (dollars per linear foot of vertical bore). The cost of drilling vertical bores varies widely (\$5.0–\$15.5/ft) and is about twice the cost of digging horizontal trenches. The normalized drilling cost is below \$10/ft when drilling in drift, shale, sandstone, or limestone, but it could cost more than \$15/ft when drilling in granite.



**Figure 2: Survey results of the normalized costs (dollars per linear foot) of vertical bores and horizontal trenches.**

Figure 3 shows the survey results of ROP of the drilling process. As indicated by the box chart, ROP varies from 50 to 200 ft/h and the typical range (i.e., within the 25th and 75th quartiles) is 60–150 ft/h. Survey results indicate that the ROP is affected by the geological formations encountered during drilling.

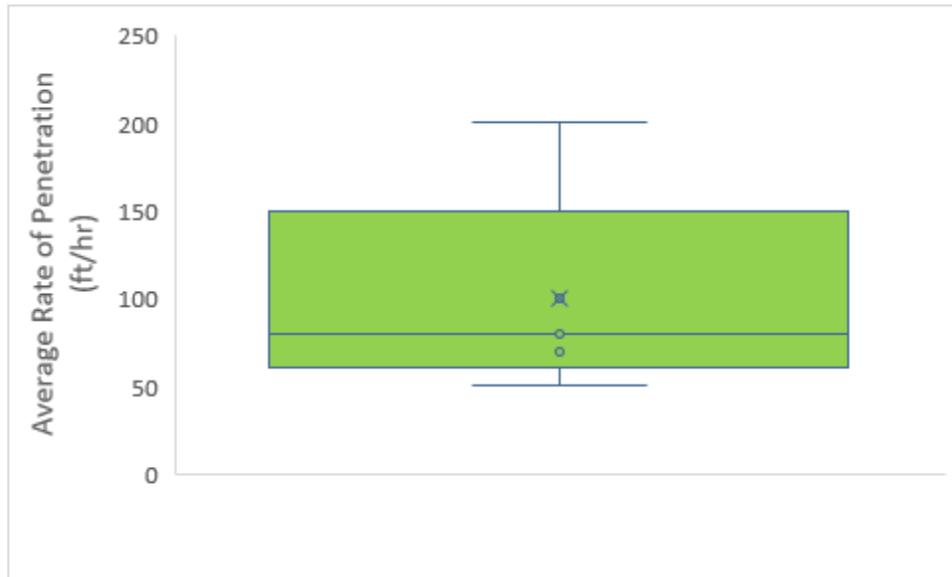


Figure 3: Survey results of vertical bore drilling ROP.

### 3. ASSESSMENT OF COST REDUCTION POTENTIAL OF VERTICAL BORE GROUND HEAT EXCHANGERS

The focus of this study is the VBGHs because it is the most commonly used GHXs in the United States. With a typical VBGH design as a baseline, the cost reduction potential resulting from various possible improvements in the design and installation of VBGHs is assessed. The methodology, investigated improvements, and assessment results are presented below.

#### 3.1 Methodology

A three-step procedure, depicted in Figure 4, was used to evaluate the cost reduction resulting from a given improvement. The first step is to determine the needed total bore length and associated cost of a baseline VBGH for satisfying a given thermal load. The second step is to make an improvement in one of three aspects, including drilling, borehole heat exchanger (BHE) design, and bore field configuration, then determine the needed total bore length and associated cost of the improved VBGH for satisfying the same thermal load. The third step is to evaluate the resulting changes in the total bore length and the cost resulting from the improvement.

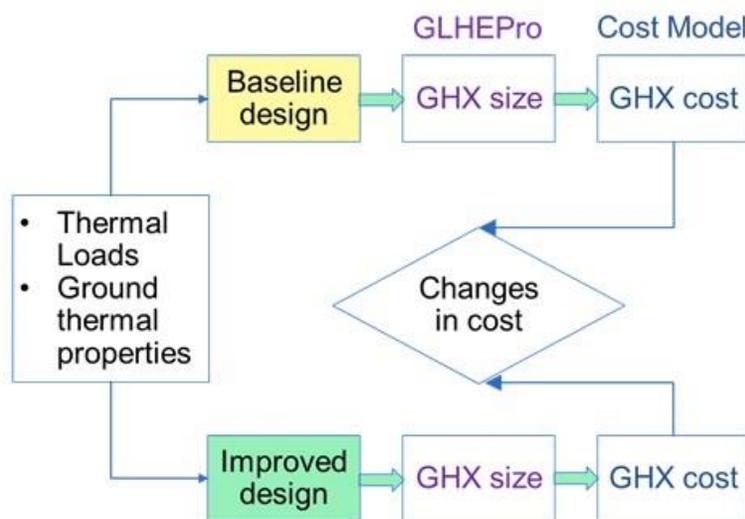


Figure 4: Procedure for evaluating cost reduction of improvements in VBGHs.

The thermal loads were computed using building energy simulations for a GHP system serving a reference building at various climate zones. The total bore length needed to satisfy the thermal load is determined with GLHEPro (Spitler et al. 2017), which is a commercial

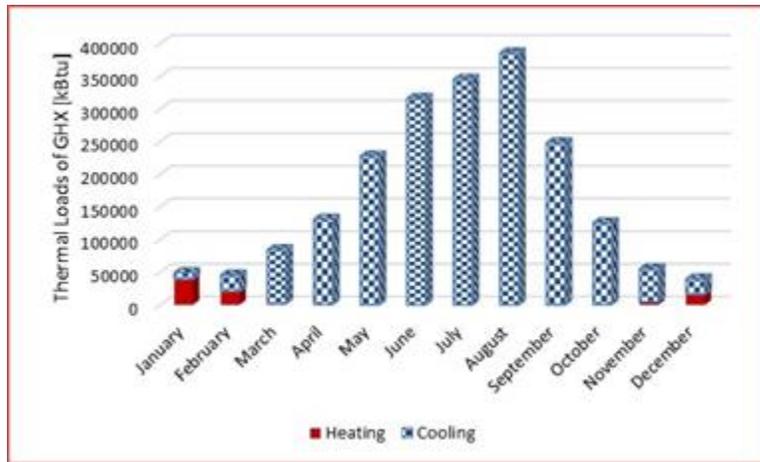
software for sizing VBGHXs based on the widely accepted g-function method developed by Eskilson (1987). The installed cost a given VBGHX is calculated with an updated cost model for VBGHXs, which was originally developed by Finger et al. (1997).

**3.1.1 Reference Building**

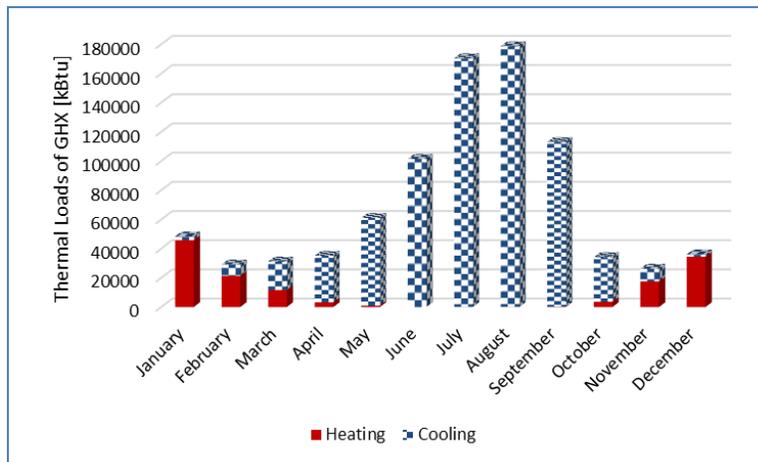
The US Department of Energy (DOE) commercial reference building model (NREL 2011) for a medium-sized office was adopted to determine the thermal load of the VBGHX. The modeled office building has a floor space of 53,620 ft<sup>2</sup>. A distributed GHP system was modeled to provide space heating and cooling to the reference building. The distributed GHP system conditions each zone of the building with an individual water-to-air heat pump (WAHP). Multiple WAHPs are connected to the VBGHX through a common water loop. Four different ground formations were selected to represent the typical range of various ground formations. Thermal properties of the four ground formations are listed in Table 1. Three different locations (Atlanta, Georgia; Seattle, Washington; and Helena, Montana) were selected to represent different thermal load profiles—significantly imbalanced, moderately imbalanced, and nearly balanced—as shown in Figure 5.

**Table 1. Thermal properties of four different ground formations**

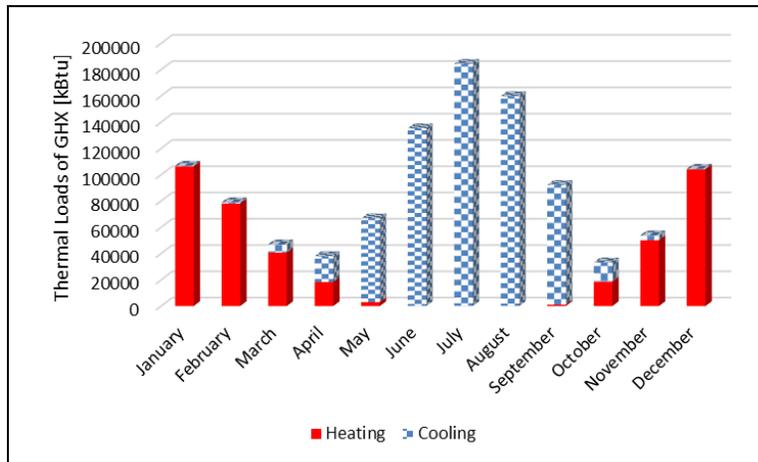
	Thermal conductivity (Btu/[h-ft-°F])	Density (lb/ft <sup>3</sup> )	Specific heat (Btu/[lb-°F])	Volumetric heat (Btu/[°F-ft <sup>3</sup> ])
Dense rock	2	200	0.1997	39.93
Average rock	1.4	175	0.1997	34.94
Heavy soil (damped)	0.75	131	0.2298	30.1
Heavy soil (dry)	0.5174	100	0.2498	24.98



(a)



(b)



(c)

**Figure 5. Monthly thermal loads at three locations: (a) Atlanta, Georgia (significantly cooling-dominated load profile); (b) Seattle, Washington (moderately cooling-dominated load profile); and (c) Helena, Montana (nearly balanced load profile).**

### 3.1.2 Updated cost model for VBGHXs

Finger et al. (1997) developed a cost model for VBGHX installation based on information collected from eight site visits. This model can output a detailed breakdown of labor, material, and equipment cost of installing an individual VBGHX and the overall cost for implementing a bore field, which includes multiple VBGHXs. The overall bore field cost includes the cost for installing each individual VBGHX and all the related distributed costs, such as locating underground utilities, moving rigs to the job site, connecting heat exchangers in each individual bore, and restoring the drilling site.

The original model was updated in this project with information collected from the survey and other resources. In addition, the cost model is further improved to (1) account for the cost of casing; (2) estimate drilling performance (i.e., ROP) based on user-specified geological conditions and user-selected drilling technology; and (3) automatically update material costs based on user's specifications, including heat exchanger configuration and materials of pipe, grout, and heat transfer fluids. Required user inputs of the updated cost model are listed below.

- BHE design
  - Borehole depth
  - Borehole diameter
  - Heat exchanger loop configuration (single U-tube, double U-tube, or coaxial)
  - Materials of grout, pipe, and heat transfer fluid

- Casing information (cost, depth, time)
- Drill rig to be used (rotary or percussive)
- Geological conditions (thickness and type of various soil/rock layers along the depth of a borehole)
- Total number of boreholes

Based on these user inputs, the updated cost model calculates the costs of labor, material, and equipment associated with each step of a VBGHX installation, based on following assumptions:

- The ROP of a drill rig does not change with the bore depth (i.e., constant penetration speed along the depth of a vertical bore).
- The cost for designing a bore field was calculated as 10% of the bare-bone cost of a bore field, which accounts for only the labor, material, and equipment costs for implementing a bore field. In addition, the profit and overhead (including contingency) of the bore field installation were accounted for as 20% of the sum of the bare-bone installation cost and the bore field design cost.

The installed costs of VBGHXs for a typical residential application (with a 4-ton capacity), including both the cost of implementing each individual VBGHX and the distributed costs, at different ground formations were calculated with the updated cost model and compared with the survey results from Battocletti and Glassley (2013). The comparison shows that the predicted costs match well with the survey results—about 3-8% higher than the survey results depending on the ground formation. It indicates that the updated cost model can predict the installed cost of a VBGHX with reasonable accuracy.

### 3.1.3 Baseline VBGHX Design

Specifications of the baseline VBGHX is described below:

- Boreholes with a 5.5 in. diameter are laid out in a square array with 20 ft center-to-center spacing.
- The total number of boreholes and the depth of each bore are sized to maintain the supply fluid temperature from the VBGHX within a desired range—from 12.5°F below to 27.5°F above the undisturbed ground temperature at a given location. The depth of each individual vertical bore in the base case will not exceed 400 ft.
- A single U-tube heat exchanger loop is made with HDPE pipe.
- Standard bentonite grouting is used ( $K = 0.4 \text{ Btu/h-ft-}^\circ\text{F}$ ).
- The heat transfer fluid is a 20% aqueous solution of ethanol.
- A 50 ft steel casing from the ground surface is included.

### **3.2 Investigated improvements**

Improvements in three categories were investigated, including borehole heat transfer and bore field design. Table 2 lists the key BHE design parameters of the baseline VBGHX and 11 improved cases, each with one or several of the following borehole heat transfer improvements:

- Thermally enhanced (TE) pipe with  $0.43 \text{ Btu/(h-ft-}^\circ\text{F)}$  thermal conductivity
- TE grouts with 1.6 or  $1.0 \text{ Btu/(h-ft-}^\circ\text{F)}$  thermal conductivity
- TE fluid, which increases heat transfer inside the heat exchanger loop by 35%
- Small boreholes with 4.5-in. bore diameter (BD)
- Alternative heat exchanger loops, including double U-tube and coaxial loops. Double U-tubes are connected in parallel and inserted in the same vertical bore. Coaxial loops contain an inner pipe and an outer pipe. Heat transfer fluid flows down through the annulus between the two pipes and flows up through the inner pipe, or in a reversed direction. The annular space between the outer pipe and the borehole wall is filled with grouting materials.

Table 2 also lists the calculated borehole thermal resistance (BTR) in each case. As shown in the table, applying TE grout reduces BTR significantly—59% and 46% reduction in cases #1 and #2, respectively, compared with the baseline. TE pipe results in a small reduction (8%) in BTR as shown in case #3. TE fluid has little impact on BTR—only 2% reduction in case #4. Double U-tube loop alone (case #5) results in 45% reduction in BTR, which is very close to the reduction resulting from applying TE grout. Downsizing the bore diameter alone (cases #6) results in a 19% reduction in BTR, which is larger than the reduction from applying TE pipe or TE fluid. Combining downsized bore diameter with a double U-tube (case 7) results in 63% reduction in BTR, which is larger than applying the best grout. On the other hand, the reduction in BTR is not significant (less than 15%) by applying the coaxial exchangers even when combined with downsized bore diameter or TE grout (cases #8 through #10). A combination of TE grout (with  $1.6 \text{ Btu/(h-ft-}^\circ\text{F)}$  thermal

conductivity), double U-tube pipe, TE pipe, and TE fluid results in 86% reduction in BTR, which is the largest among all the investigated cases.

**Table 2. Borehole heat exchanger designs of baseline and improved cases**

No.	Case name	Borehole thermal resistance (°F/Btu/[h-ft])	Materials			Borehole design	
			Grout (Btu/[h-ft-°F])	Pipe	Fluid type	Loop type	Bore diam (in.)
	Baseline	0.4205	0.43	0.225	Water	Single U-tube	5.5
1	Grout_1.6	0.1736	1.6	0.225	Water	Single U-tube	5.5
2	Grout_1.0	0.2287	1	0.225	Water	Single U-tube	5.5
3	TE pipe <sup>a</sup>	0.3873	0.43	0.4	Water	Single U-tube	5.5
4	TE fluid	0.4124	0.43	0.225	TE fluid	Single U-tube	5.5
5	D-U-Tube <sup>a</sup>	0.2313	0.43	0.225	Water	Double U-tube	5.5
6	BD_4.5	0.3416	0.43	0.225	Water	Single U-tube	4.5
7	D-U-Tube <sup>a</sup> and BD_4.5	0.1542	0.43	0.225	Water	Double U-tube	4.5
8	Coaxial <sup>b</sup> with BD_4.5	0.3921	0.43	0.225	Water	Coaxial	4.5
9	Coaxial <sup>b</sup> with BD_5.5 and Grout_1.0	0.3959	1	0.225	Water	Coaxial	5.5
10	Coaxial <sup>b</sup> with BD_4.5 and Grout_1.0	0.3639	1	0.225	Water	Coaxial	4.5
11	Bundle case	0.0596	1.6	0.4	TE fluid	Double U-tube	4.5

<sup>a</sup>Made with HDPE pipe (0.75 in. diameter and SDR-11 pressure rating).

<sup>b</sup>Made with HDPE pipes: 1 in. diameter inner pipe and 4 in. diameter outer pipe.

Table 3 lists prices of the improved materials and alternative heat exchanger loops used in this study. Because of currently limited applications of coaxial loops and TE pipes, their market prices are not available to authors of this paper. It is assumed that the TE pipe has the same price as the standard HDPE pipe and that the TE fluid has the same price as standard propylene glycol.

**Table 3. Prices of improved materials and loops used for borehole heat exchangers**

Item	Price (\$)
Double U-tube loop	1.04 per linear foot of borehole
Coaxial loop	1.0 <sup>a</sup> per linear foot of loop
TE pipe	0.26 <sup>b</sup> per linear foot of pipe
TE fluid	14.6 <sup>c</sup> per gallon

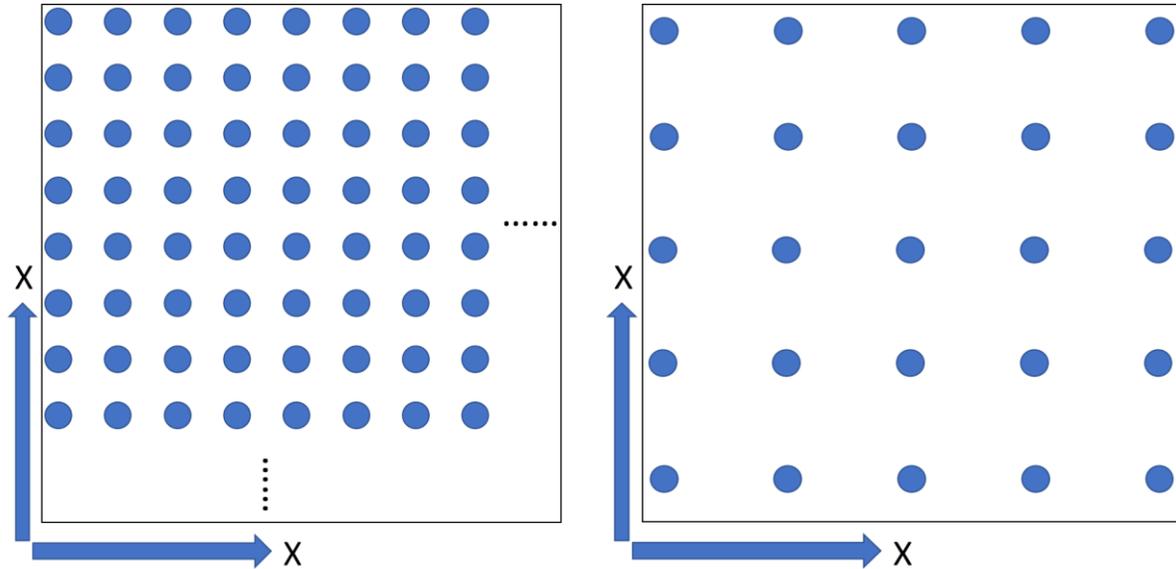
TE grout with 1.0 Btu/(h-ft-°F) thermal conductivity	1.0 per gallon
TE grout with 1.6 Btu/(h-ft-°F) thermal conductivity	1.5 per gallon

<sup>a</sup>Include both the inner (1 in. diameter) and outer (4 in. diameter) pipes.

<sup>b</sup>Assuming at the same price of the standard HDPE pipe (0.75 in. diameter and SDR-11 pressure rating).

<sup>c</sup>Assuming at the same price of propylene glycol (\$800/55 gal).

The impact of bore field design on the cost of a VBGHX was also investigated through a parametric study. In this study, it was assumed that the available land area for installing the bore field was fixed, but bore spacing and bore depth could be adjusted to satisfy the design criterion as discussed before. Figure 6 shows that as the spacing between boreholes (indicated by the blue dots) increases the bore number is reduced. Therefore, to satisfy the given thermal load, bore depth must be increased. The upper limit of the bore depth was set to 1,000 ft in this study.

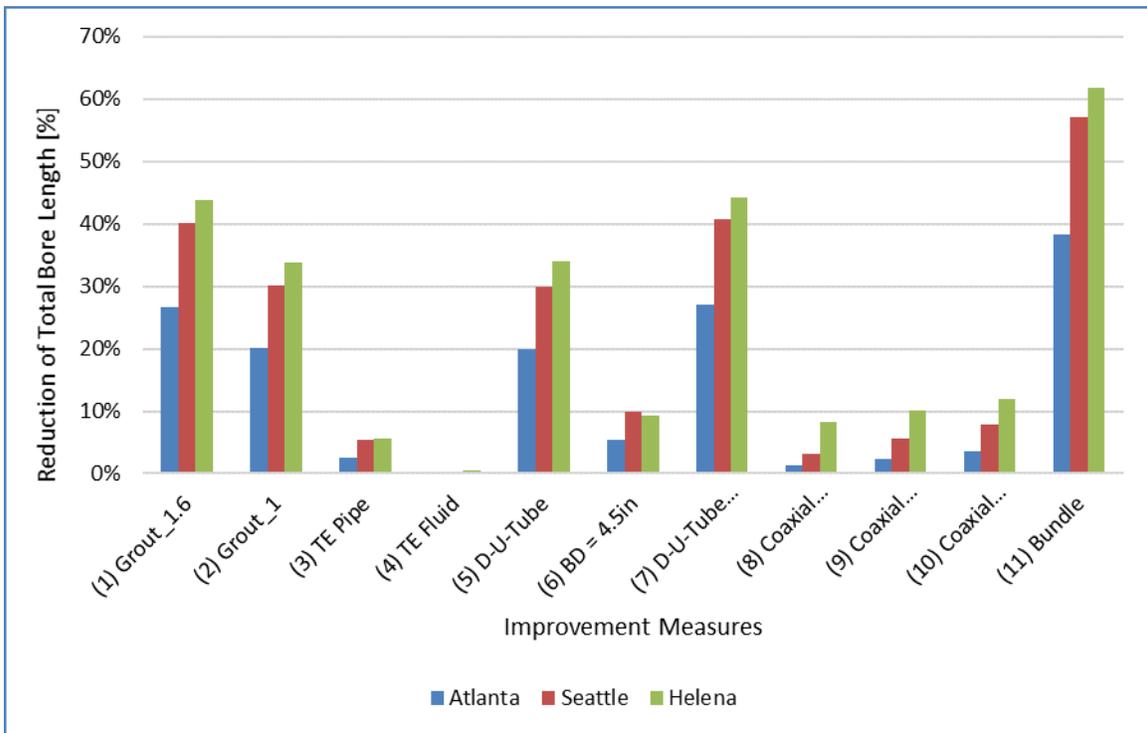


**Figure 6. Bore field configuration with increased bore spacing within a fixed land area.**

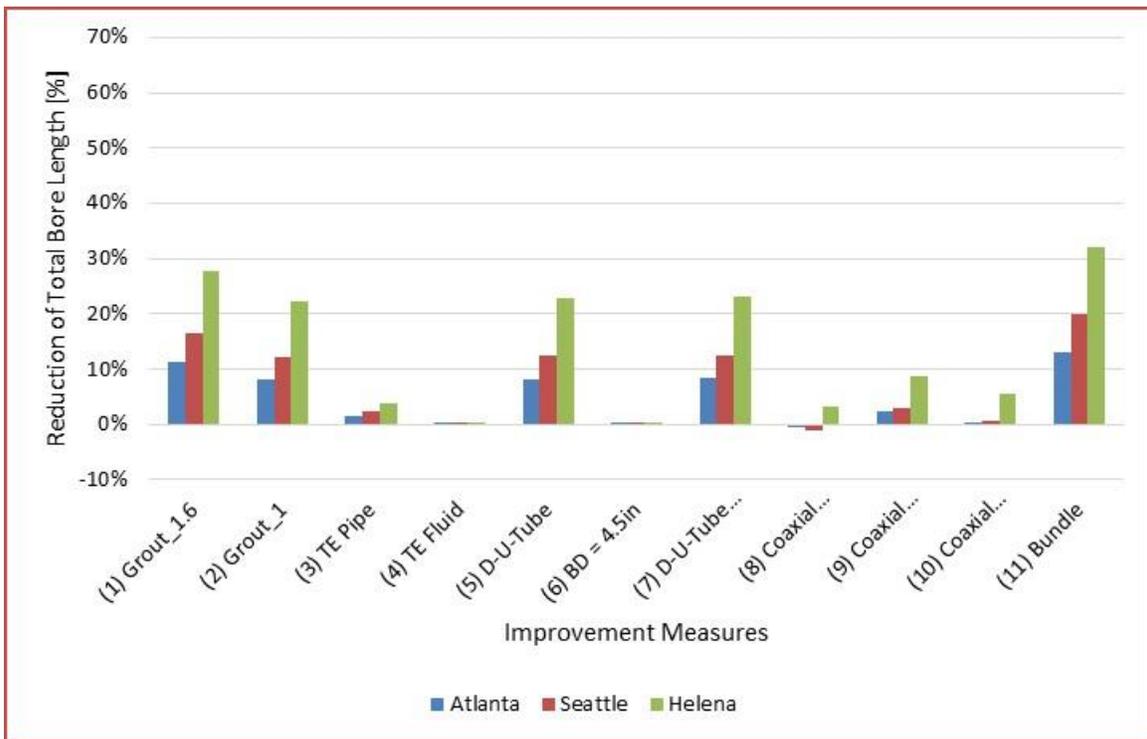
### 3.3 Results

#### 3.3.1 Effectiveness of Improving Borehole Heat Transfer

Figures 7 (a) and (b) show percentages of total bore depth reduction in the 11 improved cases at the three different locations. Figure 7 (a) shows results with a high ground thermal conductivity (GTC) value, while Figure 7 (b) shows results with a low GTC value.



(a)



(b)

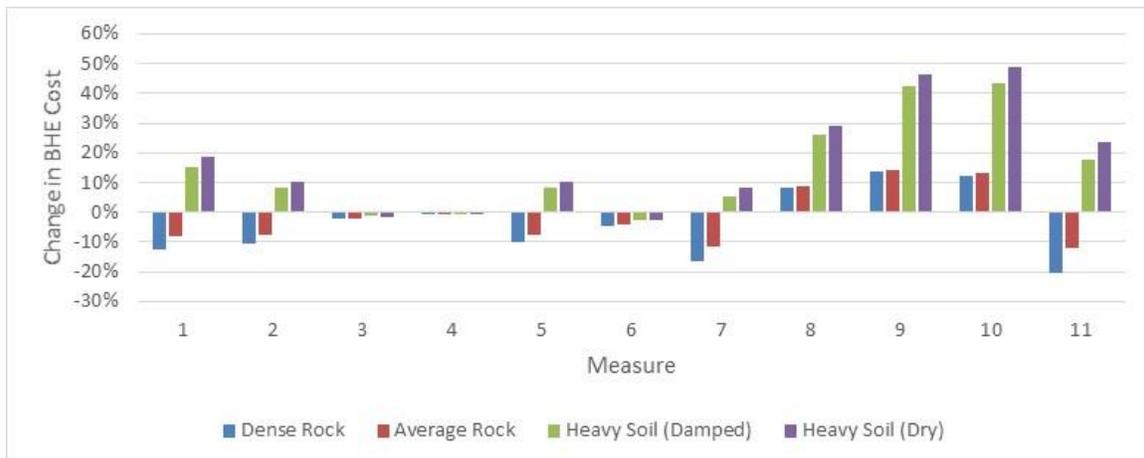
**Figure 7. Percentages of total bore length reduction resulting from improvements in borehole heat transfer: (a) With high GTC (2 Btu/h-ft-°F); and (b) With low GTC (0.52 Btu/h-ft-°F).**

For achieving the same ground heat transfer performance (i.e., keeping the leaving water temperature from the VBGHX within the same range overall a 20 year period), the following trends can be observed from these figures:

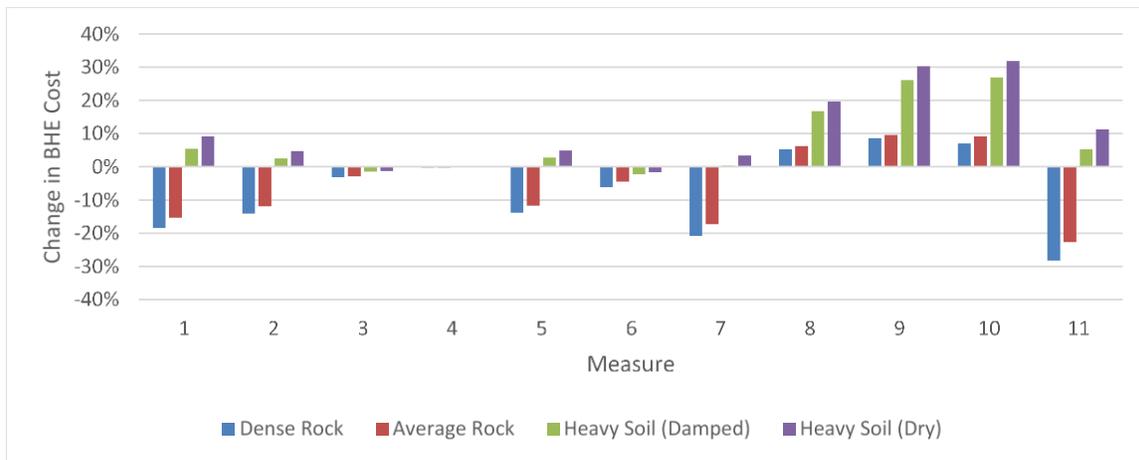
- GTC affects the bore length reduction potential resulting from borehole heat transfer improvement—more reduction occurs at places with higher GTC.
- The thermal load profile also plays a key role in bore length reduction. For a given improvement, more bore length reduction can be expected if the thermal loads (heat extraction and heat rejection) are more balanced on an annual basis.
- TE grout and double U-tube loops can most effectively reduce bore length compared with other individual improvements. Applying coaxial heat exchangers can reduce the required bore length, but the reduction was less than 12% in all the investigated cases. Downsizing borehole diameter results in a moderate bore length reduction (5–9%) at places with a higher GTC, but it is not effective where GTC is low. TE pipe and TE fluid have a very small impact on the bore length since the heat transfer resistance of the pipe wall and inside the heat exchanger loop is much smaller than other components of the BTR if the flow inside the loop is turbulent.
- Combining all the individual improvements, the required bore length for satisfying a given thermal load can be reduced by 38–62% when GTC is 2 Btu/(h-ft-°F), but the percentages become smaller (13–32%) when GTC is only 0.52 Btu/(h-ft-°F).

Figures 8 (a), (b), and (c) show the cost reduction percentages of individual BHE resulting from the 11 different improvements. The numerical number in the horizontal axes of these figures is the index number of each improvement as listed in Table 2. Each figure shows cost reduction percentages at one of the three locations (with different thermal load profiles), and bars with assorted colors indicate different ground formations. The following trends can be observed from these figures:

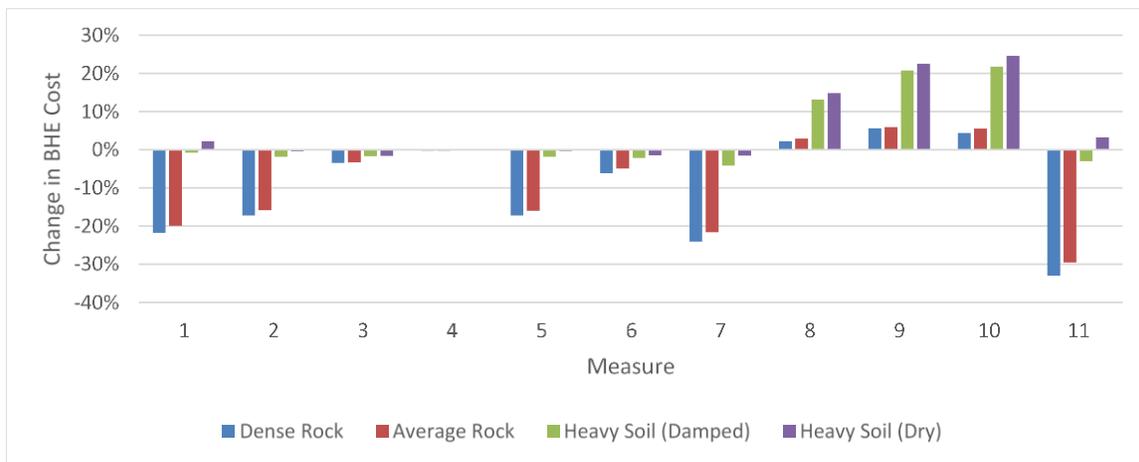
- Although applying all the investigated improvements can reduce the required total bore length, the impacts of the improvements on the cost of implementing a BHE are different and they are strongly dependent on the cost for applying an improvement and the GTC where the BHE is installed. Moderate cost reductions (the negative percentages shown in Figure 22) are realized by applying TE grout, double U-tube, or both (cases 1, 2, 5, 7, and 11) at locations with relatively high GTC values (e.g., dense rock). However, the installed cost of a BHE could increase because of applying the same improvements at a ground formation with low GTC value (e.g., dry soil), which indicates that the cost reduction due to the shortened bore length is less than the cost premium of the TE grout or the double U-tube loop.
- Applying the coaxial heat exchangers results in increased cost in all investigated cases. This is because while using coaxial heat exchangers can shorten the required bore length (Figure 21), their cost is much higher than that of the conventional single U-tube loop.
- Applying TE pipe and TE fluid, or downsizing borehole diameter (cases 3, 4, and 6) can slightly reduce the installed cost of a BHE (less than 6% cost reduction) in all the investigated cases because these improvements can shorten the required bore length and associated labor and equipment cost without any cost premium. As discussed earlier, it is assumed that the prices of the improved materials are the same as those of the conventional materials (Table 13). This result indicates that it is not worth the cost to use more expensive pipe and heat transfer fluid for BHEs.
- Applying all the individual improvements together, the installed cost of a BHE can be reduced by up to 33% (e.g., at Helena, Montana, and with dense rock), but this will also increase the installed cost by up to 24% in other applications (e.g., at Atlanta, Georgia, and with dry soil). This result indicates that improving borehole heat transfer by applying expensive materials and heat exchangers can reduce the installed cost of BHEs if the ground formation has high GTC and the thermal loads are nearly balanced. However, these improvements are not recommended as a cost reduction measure in areas with low GTC and imbalanced thermal loads. This is because the thermal resistance of the ground formation and the thermal interactions among BHEs are the dominant factors affecting the performance of a VBGHX so that improving borehole heat transfer is not cost effective.



(a)



(b)



(c)

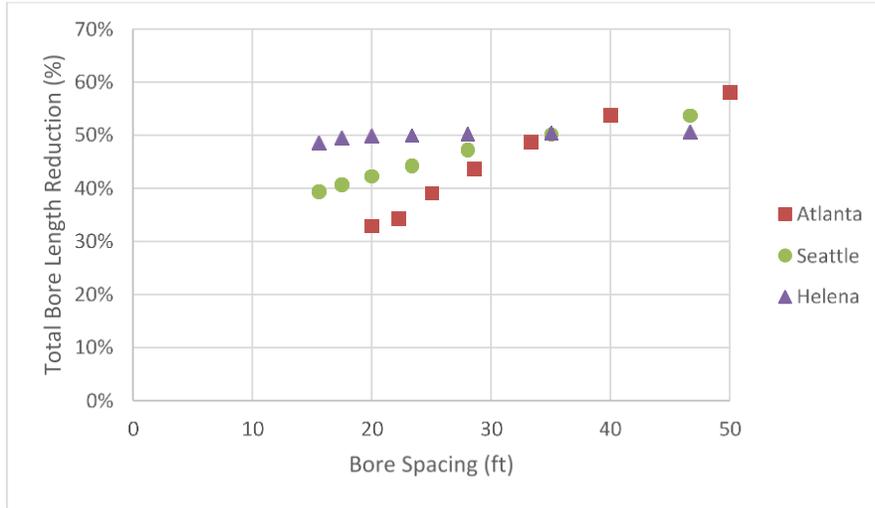
**Figure 8. Changes of borehole heat exchanger cost resulting from improvements in borehole heat transfer: (a) Atlanta, Georgia (with significantly cooling-dominated load); (b) Seattle, Washington (with moderately cooling-dominated load); and (c) Helena, Montana (with nearly balanced load).**

### 3.3.2 Effectiveness of Improving Bore Field Design

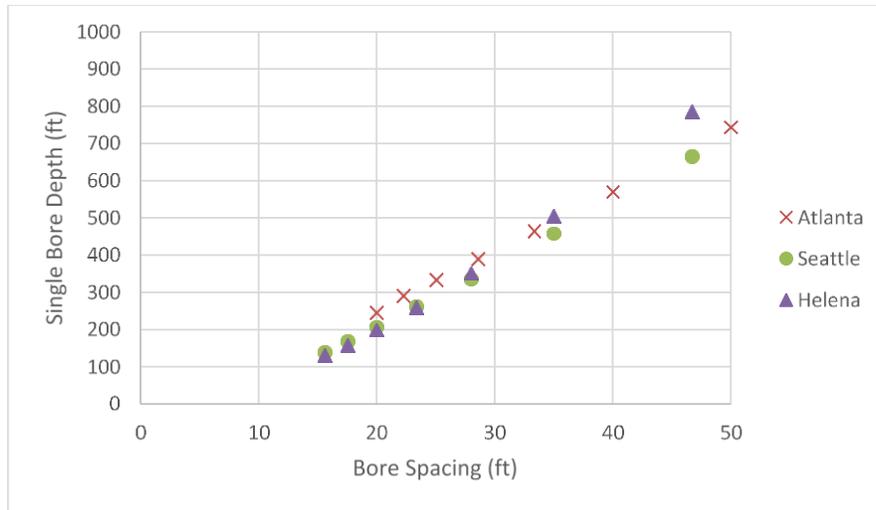
In addition to borehole heat transfer improvement, the impacts of increasing bore spacing within a fixed land area (Figure 6) were investigated through a parametric study. In this study, all the BHEs in a bore field used single U-tube loops but they were improved by using the thermally enhanced materials (grout, pipe, and fluid) and smaller (4.5 in) bore diameter. After each change in the bore spacing, the resulting borehole numbers and the needed depth of each borehole were calculated. Figures 9 and 10 show (a) the reduction of the total bore length of the entire bore field and (b) the needed depth of each individual BHE with high and low GTC values, respectively. The data series in these figures represent various locations (i.e., thermal load profiles). Following trends can be observed from Figures 9 and 10:

- Increasing bore spacing can further reduce the required total bore length of an entire bore field if the thermal loads are not balanced. For cases with balanced thermal loads (e.g., at Helena, Montana), increasing bore spacing beyond 15 ft at a ground formation with a high GTC (or 30 ft at a ground formation with a low GTC) does not further reduce the total bore length. On the other hand, increasing bore space from 20 to 30 ft in Atlanta, Georgia (with significantly imbalanced thermal loads) would reduce the total bore length by about 45% compared with the baseline when GTC is high (34% reduction when GTC is low). This is about 12–20 percentage points more reduction, depending on GTC value, than that resulting from just improving borehole heat transfer alone (indicated by data points with 20 ft spacing). The impact of bore spacing on the total bore length reduction is smaller (about 8–16 percentage points more reduction) for a bore field with moderately imbalanced thermal loads (e.g., at Seattle, Washington).
- The depth of individual boreholes increases linearly with the increasing of bore spacing. At places with a high GTC [2 Btu/(h-ft-°F)], the needed individual bore depth is less than 400 ft after increasing bore spacing to 30 ft (and thus reducing the total

borehole numbers quadratically). In contrast, the needed individual bore depth must be increased to more than 450 ft for a 30 ft bore spacing when GTC is low (0.52 Btu/[h-ft-°F]).

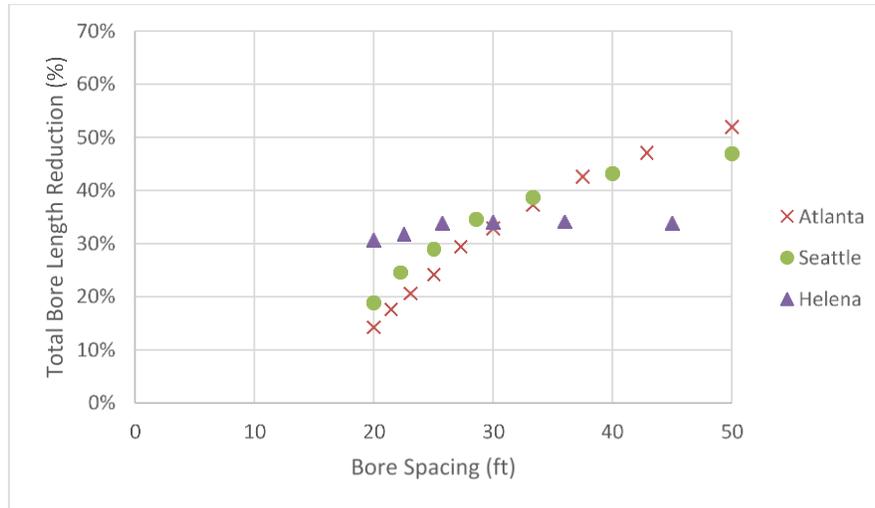


(a)

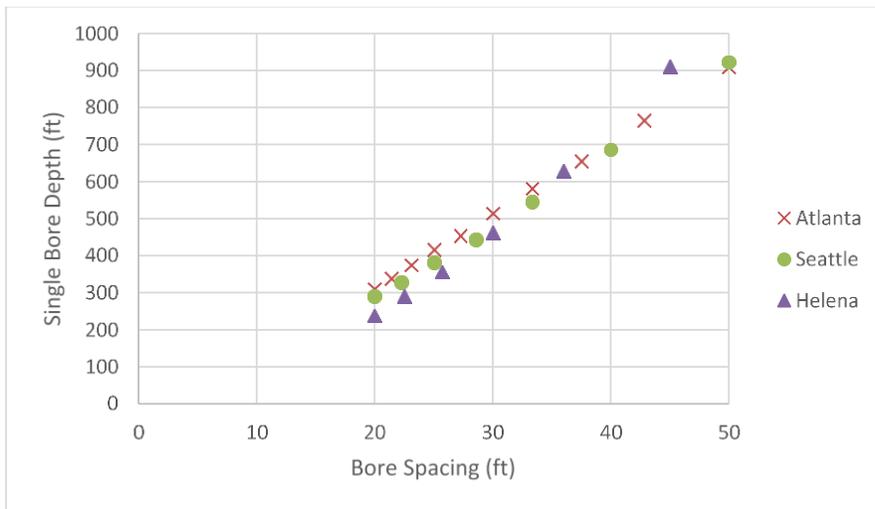


(b)

**Figure 9. Changes in (a) total bore depth of a bore field and (b) depth of individual borehole resulting from increasing bore spacing (with high GTC—2 Btu/[h-ft-°F]).**



(a)

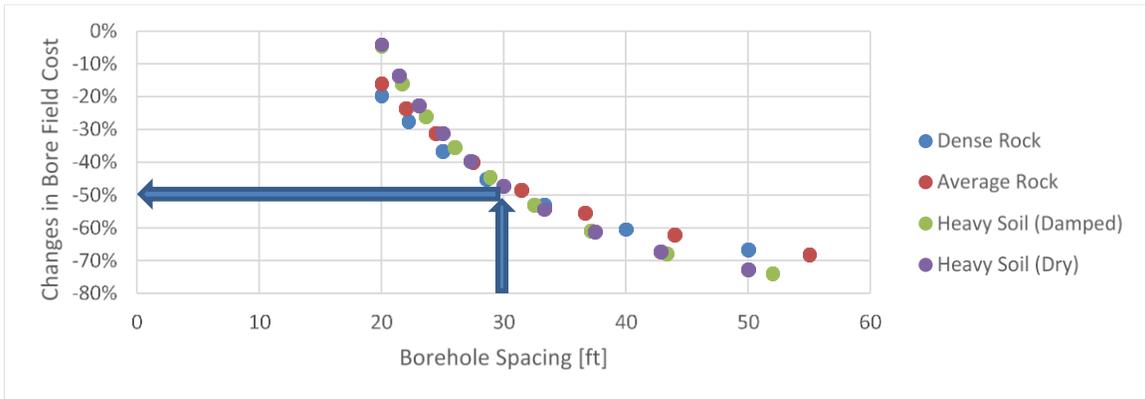


(b)

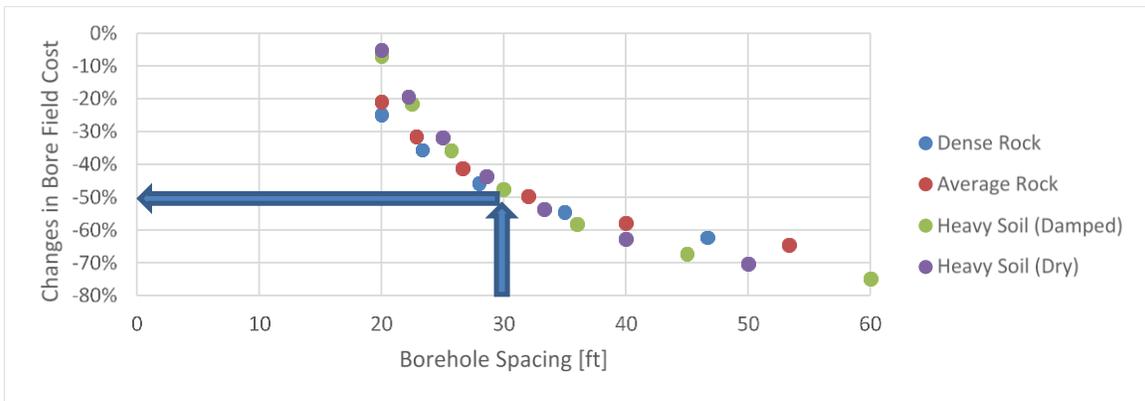
**Figure 10. Changes in (a) total bore depth of a bore field and (b) depth of individual borehole resulting from increasing bore spacing (with high GTC— $0.52 \text{ Btu}/[\text{h}\cdot\text{ft}\cdot^\circ\text{F}]$ ).**

Figures 11 (a), (b), and (c) show the reduction in bore field cost, which includes both the costs for implementing each individual BHE and the distributed costs, as discussed in Section 3.1.2, resulting from improving both the borehole heat transfer and the bore field layout. Each figure shows cost reduction percentages at various locations (i.e., thermal load profiles); data points with assorted colors indicate different ground formations.

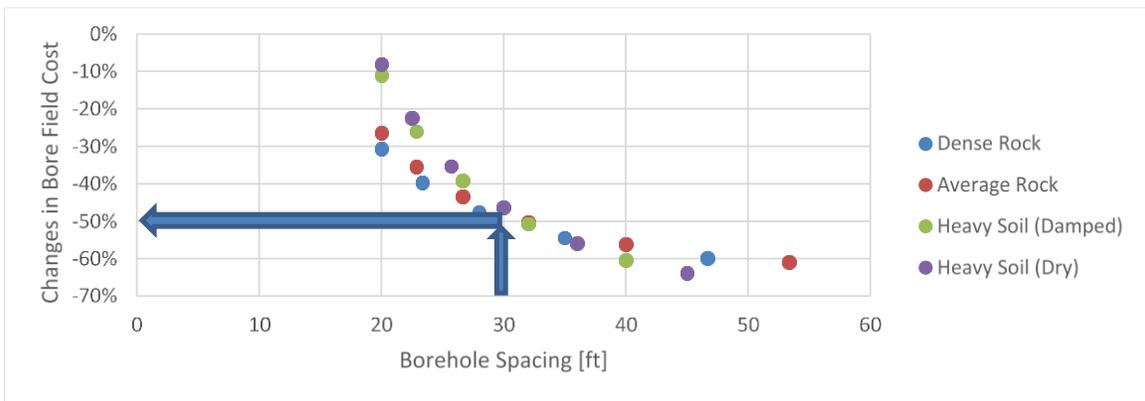
These figures indicate that the total bore field cost can be reduced by up to 50% by improving borehole heat transfer and increasing bore spacing to 30 ft. Increasing bore spacing will not only reduce the total bore length and the related drilling cost but will also reduce some distributed costs because of the reduced bore numbers (e.g., the costs of horizontal piping and relocation of drill rigs). Figure 11 also indicates that the cost reduction resulting from improving the bore field layout is more effective at places with high GTC and imbalanced thermal loads. However, the slope of cost reduction decreases after increasing bore spacing beyond 30 ft.



(a)



(b)



(c)

**Figure 25. Changes in total bore field cost resulting from improving borehole heat transfer and bore field layout: (a) Atlanta, Georgia (with significantly cooling-dominated load); (b) Seattle, Washington (with moderately cooling-dominated load); and (c) Helena, Montana (with nearly balanced load).**

#### 4. CONCLUSIONS AND RECOMMENDATIONS

The cost reduction potential of various improvements in borehole heat transfer and bore field layout was evaluated under various geological and thermal loading conditions through a parametric study, using an updated cost model for VBGHX installation and a well-established sizing program for VBGHX. Following conclusions can be drawn from this study regarding the bore length or cost reduction potential of various improvements, while achieving the same ground heat transfer performance (i.e., keeping the leaving water temperature from the VBGHX within the same range overall a 20-year period).

- Among the investigated improvements in borehole heat transfer, thermally enhanced grout and double U-tube loop are the most effective measures for reducing the required bore length for satisfying a given thermal load.
- Ground thermal conductivity at a given location determines the magnitude of bore length reduction resulting from a given improvement in VBGHX design. At places with high ground thermal conductivity, more than 60% reduction in total bore length can be achieved by improving the borehole heat transfer.
- Borehole heat transfer improvements result in moderate (less than 30%) cost reduction at ground formations with high thermal conductivity (e.g., higher than 1.4 Btu/h-ft-°F); however, it might result in an increase in VBGHX cost at ground formations with low thermal conductivity (e.g., less than 0.75 Btu/h-ft-°F).
- For VBGHXS having multiple vertical bores, increasing bore spacing (up to 30 ft) and bore depth can reduce bore numbers and the required total bore length. It therefore can reduce the overall bore field cost by up to 50%.

Because the best solution for reducing the cost of a VBGHX depends on many factors, further study is recommended to develop guidelines on how to best use different technologies to effectively reduce the cost of VBGHXS and result in minimized cost of GHP systems. Following research and development is recommended to reduce the cost of VBGHXS:

- Develop new GHXS that require less drilling of vertical bores or that can be implemented with low-cost drilling techniques;
- Expand the capabilities of VBGHX sizing and simulation program to allow optimization of borehole field so that the required total bore length can be reduced while satisfying the thermal demands; and
- Improve mobility and automation of drilling machines to reduce the time and labor needed for drilling vertical boreholes.

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