

## Assessment of Design Procedures for Vertical Borehole Heat Exchangers

Eleonora Sailer<sup>1</sup>, David M.G. Taborda<sup>2</sup> and James Keirstead<sup>2</sup>

<sup>1</sup>AECOM, Chelmsford, CM1 1HT, UK, formerly Imperial College London, UK

<sup>2</sup>Imperial College London, Dept. Civil & Environmental Engineering, London SW7 2AZ UK

eleonora.sailer@aecom.com

**Keywords:** Borehole heat exchanger, low enthalpy systems, ground source heat, design guidelines

### ABSTRACT

The use of ground source energy systems is a well-established method to provide low cost heating to buildings, diversify the energy mix and help meeting increasingly stricter sustainability targets. However, considerable uncertainties remain over their efficient design, with several standards, guidelines and manuals being proposed over the last few years. This paper aims at providing insight into the implications to the design of a vertical borehole heat exchanger of the adoption of different design procedures. The hypothetical case of a typical dwelling located in London, UK, is analysed in order to highlight the impact on the final design of the chosen methodology. Moreover, a parametric study using an analytical design procedure was performed to point out the influence of various factors, such as borehole characteristics and thermal properties of the ground. It is shown that there are considerable discrepancies between design methods and that uncertainties in some input parameters, such as the thermal properties of the ground, which for relatively small systems are often selected from tables rather than measured in situ, may have a substantial influence on the length of borehole required.

### 1. INTRODUCTION

Borehole Heat Exchangers (BHE) are one type of Ground Source Heat Pump (GSHP) systems and are classified as low enthalpy geothermal systems since they make use of low temperature differences. A GSHP system is composed of a heat exchanger, a heat pump (HP) and the space distribution system. The ground heat exchanger is essentially made of one or more pipes in which a carrier fluid flows at lower temperatures than that of the ground, thus absorbing the heat from the ground and delivering it to the heat pump. The heat pump then absorbs the heat from the fluid and transfers it to the heat distribution system, releasing at the end a colder carrier fluid.

Although BHEs are being constructed for more than half century, there is a lack of regulation from standards institutions in European and North American countries, meaning that the choice of the procedure to use is left to the experience of the designer. This has resulted in general technical and installation standards being developed for heat pumps and other components by trade associations, societies and industry led organisations. In Europe the countries that have more extensively produced standards and guidelines for BHEs are those where the market is more developed, namely Austria, Germany and Switzerland (Sanner, 2008); more recently, Italy (Capozza et al., 2012), which uses as reference the calculation procedures presented by ASHRAE (ASHRAE, 2011; Kavanaugh and Rafferty, 2014), and the UK (MCS, 2013) have issued guidelines on this topic. Moreover, as stated by Dehkordi and Schincariol (2014), different countries have begun introducing regulations for BHEs. However, these are mainly regarding temperature thresholds and distances from properties, wells, contaminant sources and other facilities, with only few of them giving actual guidelines for the design of the system. This paper aims to give an outline of available standards, guidelines and manuals for the design of BHEs and to compare the proposed design procedures by highlighting the respective assumptions and input parameters.

The design of BHEs depends on many factors which are more or less controllable by the designer. It is therefore important to have a good understanding of the operating principles of such a system. BHEs consist of tubes, in which the carrier fluid flows, placed in a borehole that is either grouted with fill material (mixture of cement, water and bentonite at different percentages or concrete) in order to ensure a stable borehole wall, or filled with water, if it is stable (Sanner, 2011b). This type of system makes use of the constant ground temperature at depths below 15 m, which, in many cases, can be approximated to the average annual air temperature (Banks, 2008). The pipes are typically in plastic material, thermally fused and are usually of U-shape (therefore called U-pipes) bent at the bottom of the borehole. In one borehole, a single or double U-pipe can be installed. The amount of heat transferred between the carrier fluid and the ground depends on many factors, such as the disposition of the pipes, the convective heat transfer in the tubes and the thermal characteristics of the materials inside the borehole (Hellström, 1998), as well as the properties of the ground, such as its thermal conductivity and temperature. The thermal resistances related to the elements composing the BHE, which are the only parameters that can be managed by the designer, are encapsulated in the borehole thermal resistance  $R_b$ . This parameter gives a measurement of the efficiency of the BHE (Sanner, 2011b). It is clear that the lower the borehole thermal resistance (which is the inverse of the thermal conductivity), the better the performance of the BHE.  $R_b$  should therefore be kept as much as possible close to 0 mK/W. According to Sanner et al. (2003), the use of thermally enhanced grout can lead to a considerable reduction in the borehole thermal resistance and therefore in the losses in temperature between fluid and ground. Moreover, with the use of double U-pipes, which present a larger heat exchange area and therefore enable greater heat transfer, the borehole thermal resistance can be reduced by up to 30-90% (Zeng et al., 2003).

In order to analyse these aspects of the sizing of a BHE, the design of a vertical closed loop for a single housing unit located in the UK has been performed. Moreover, a sensitivity analysis, using an analytical design procedure (ASHRAE), has been carried out to highlight the influence of some of the input parameters, such as heat exchanger properties and ground parameters.

## 2. DESIGN METHODS

The table below summarises the available guidelines, standards and manuals for the design of BHE in Europe and USA. All the methods outlined refer either to simplified procedures applicable to small systems ( $< 30\text{kW} \div 45\text{kW}$ , depending on the country, and mainly only for heating purposes) or to analytical procedures suitable only for preliminary design in the case of larger systems, where more detailed analysis with software to account for the variation of the temperature, as well as detailed investigations for ground parameters, are recommended.

Some guidelines are geographically restricted, since the input values are established accordingly to site specific graphs or tables. This is the case of the Swiss and Austrian design procedures, which for this reason have not been presented in detail. Similarly, the Italian guideline (Capozza et al., 2012) and the IGSHPA method (IGSHPA, 2009) are not presented, as they are largely based on the proposal by ASHRAE (ASHRAE 2011; Kavanaugh and Rafferty 2014). Indeed, the main difference between the IGSHPA and the ASHRAE methods resides in the recommended procedure for evaluating the long term temperature change in the ground: while in the latter this is calculated using an analytical procedure, in the former this is accounted for through a correction factor that can be established from graphs according to the annual energy load, the ground thermal conductivity and borehole spacing. These procedures are described in detail in Sailer (2014).

Generally, the design of Ground Source Heat Systems is based on different parameters related to various factors that influence the whole system, such as heating/cooling load from the buildings, characteristics of the heat pump, ground parameters and parameters concerning the heat exchanger (pipes, fill material and carrier fluid). Most of the simplified procedures base the design on values of specific heat extraction rate (W/m) related to ground thermal conductivity (W/mK). As stated by Sanner (1999), the specific heat extraction depends on the heat transfer capacity of the ground, the operation hours, the interference between BHEs in large or nearby systems, the borehole diameter, fill material and disposition of the pipes. It is important to note that the tables of specific heat extraction proposed by the different guidelines often do not take into account the specifications of the borehole and their applicability is typically restricted to specific ranges of some of the abovementioned parameters. It should be also mentioned that ground water flow is usually disregarded when designing BHEs, which is a reasonable assumption if the flow velocity is of the order  $< 10^{-9}$  (Claesson and Eskilson, 1988).

STANDARDS AND GUIDELINES					
Country	Organisation	Number	Title	Year	Type of procedure
Austria	Österreichischer Wasser- und Abfallverband	ÖWAV RB 207	Systems for the exploitation of geothermal heat	2009	Simplified
Germany	Verein Deutscher Ingenieure	VDI 4640 Blatt 1-4	Thermal use of the underground part 1–4	2001–2010	Simplified
Switzerland	Schweitzer Ingenieure- und Architektenverein	SIA 384/6	Erdwärmesonden	2010	Simplified
Italy	Ricerca sul Sistema Energetico	---	Linee Guida per la progettazione dei campi geotermici per pompe di calore	2012	Analytical
United Kingdom	Microgeneration Certification Scheme	MCS MIS 3005 Issue 4.0	Requirements for contractors undertaking the supply, design, installation, set to work, commissioning and handover of microgeneration heat pump systems	2013	Simplified
MANUALS					
Country	Organisation	Chapter	Title	Year	
USA	International Ground Source Heat Pump Association (IGSHPA)	Ch. 5: Design of closed-loop ground Heat Exchanger	GSHP Residential and Light Commercial Design and Installation Guide	2009	Analytical
USA	American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE)	Ch. 34: Geothermal energy	ASHRAE Handbook- HVAC Applications	2011	Analytical

**Table 1: Available guidelines, standards and manuals for the design of BHE in Europe and USA**

### 2.1 VDI 4640

This guideline allows the calculation of required borehole length based on established and tabulated heat extraction rates (W/m) for given operation hours (1800 or 2400 h/yr) and ground thermal conductivities. The applicability of this design process is constrained by a series of conditions: the length of individual BHE must be between 40 m and 100 m, the distance between BHEs of length of 40 to 50 m must be at least 5m and at least 6 m for BHEs of length greater than 50 m, while double U-pipes with DN 20, DN 25 or DN 32 must be

used. Moreover, it is not applicable to scenarios where a large number of small systems exist in a limited area and it is valid for heat extraction only (VDI 4640 – Blatt 2, 2001).

The calculation of the necessary borehole length  $L_{BHE}$  is carried out using a simple expression (Sanner, 2011a):

$$L_{BHE} = \frac{P_{Ground}}{N_{tot} \cdot P_{BHE}} \quad (1)$$

where  $N_{tot}$  is the total number of BHEs,  $P_{BHE}$  is the specific heat extraction rate, and  $P_{Ground}$  is the heat to be extracted from the ground, which can be evaluated using equation (2):

$$P_{Ground} = q_{h,HP,out} \left( 1 - \frac{1}{SPF} \right) \quad (2)$$

where  $q_{h,HP,out}$  is the heat pump capacity and SPF is the seasonal performance factor.

As mentioned before, this procedure is restricted for systems with double-U pipes. The Swiss norm SIA 384/6 introduces a correction factor for the use of a single-U pipe which increases the length of the BHE from a minimum of ca. 11% to a maximum of ca. 34% depending on the ground thermal conductivity. This is due to the fact that with a single-U tube the heat exchange surface is smaller, leading to less heat conduction. It can also be observed that this method does not take into account the properties of the fill material or any fluid properties. Moreover, it is specified that the values of the tables are restricted to isolated small systems, since the presence of larger systems in a limited area would create thermal interaction and alter the ground temperature and the effectively possible heat extraction from the ground. Indeed, Reuß and Sanner (2000) recommend that when more systems are implemented in the same area, the heat extraction rate should be reduced by about 10-20%. Additionally, they also suggested that if the operation time is evaluated to be less than 1000 h/year, the length of the borehole can be reduced by 10%, because higher heat extraction rate can be obtained with lower operation hours.

## 2.2 MCS MIS 3005

Similar to the VDI 4640 procedure, the borehole length is calculated by establishing the heat extraction rate, which is determined based on the thermal conductivity of the ground and its temperature (assumed to be equal to the mean air temperature) and for specified operating hours. The tables are valid for heat extraction only (including hot water) and for boreholes arranged in a line with a minimum borehole spacing of 6 m. Moreover, this procedure is rather prescriptive in terms of borehole characteristics, since it is assumed that it has a diameter of 130 mm, where a single U-tube of 32 mm OD SDR-11 made of PE100 pipe with thermal conductivity = 0.420 W/mK and 52 mm pipe centre–pipe centre shank spacing is installed and thermally enhanced grout with thermal conductivity = 2.4 W/mK is used. With respect to the fluid, the proposed extraction rates were established for systems where 25% Mono Ethylene Glycol thermal transfer fluid with  $Re > 2500$  is employed. This procedure is also not applicable in scenarios where a large number of systems are installed in a small area. Having determined the necessary heating capacity of the heat pump  $q_{h,HP,out}$ , the design length can be established with equations (1) and (2).

Clearly, being such a prescriptive method, it provides higher levels of assurance regarding the performance of the BHE. However, it also restricts the choice of possible system characteristics by the designer, meaning that one needs to establish whether to apply increasing or reduction factors when some of the specifications assumed by the method are not followed. For example, the specification of a thermally enhanced grout of thermal conductivity 2.4 W/mK is obviously thermally performant, but could result in higher costs. If, instead, a regular fill material is used, then the length should be increased. Conversely, if double-U pipes are installed, as seen previously, the length could be decreased by 10-20%.

## 2.3 ASHRAE procedure

The ASHRAE procedure is an analytical procedure for the calculation of the length of BHEs that is based on the proposal by Kavanaugh and Rafferty (1997). It expands the solution for a cylindrical heat source established by Ingersoll (1954) by introducing a series of factors that take into account the characteristics of the BHE, such as its geometry, disposition and materials used, as well as the thermal resistance of the ground as developed by Carslaw and Jaeger (1947) for different heat pulses (up to 10 years) (De Carli et al., 2003). Moreover, once the number and disposition of the BHEs is defined, this method allows the estimation of the change in ground temperature after a given number of years of operation, also known as temperature penalty.

The procedure consists first of the calculation of the total lengths required for the BHE to meet the cooling and heating demands. Once those are evaluated, the total design length  $L_D$  can be chosen as the greater of the two obtained lengths. This value is subsequently compared to that obtained considering the mean seasonal efficiencies of the system, which is then optimised iteratively in order to ensure that the difference in ground temperature is close to 0°C over an operation period of 10 years.

The main equations used in this procedure to establish the length of a BHE in the case of heating only are presented below. For a detailed outline of all the components of the method, refer to Kavanaugh and Rafferty (2014).

### 2.3.1 General equation for calculation of the total length of a borehole heat exchanger

The total length of a BHE can be determined using:

$$L_h = \frac{q_a R_{ga} + q_{g,h} (R_b + PLF_{m,h} R_{gm} + F_{sc} R_{gd})}{\theta_g - \left( \frac{\theta_{wi} + \theta_{wo}}{2} \right)_h - \theta_p} \quad (3)$$

where  $q_a$  is net annual average heat transfer to the ground,  $R_{ga}$ ,  $R_{gm}$ ,  $R_{gd}$  are the effective thermal resistances of the ground for annual, monthly and daily heat pulses, respectively,  $q_{g,h}$  is the heat pump heat rate from ground in heating (evaporator),  $R_b$  is the borehole thermal resistance,  $PLF_{m,h}$  is the partial load factor,  $F_{sc}$  is the short circuit heat loss factor,  $\theta_g$ ,  $\theta_{wi}$  and  $\theta_{wo}$  are the temperatures of the ground, the BHE inlet and outlet fluid, respectively, and  $\theta_p$  is the temperature penalty.

### 2.3.2 Equivalent thermal resistance of borehole

The equivalent thermal resistance of the borehole  $R_b$  relative to the interface between carrier fluid and borehole wall is given by the sum of the thermal resistance of the pipe in which the fluid flows ( $R_{pp}$ ), the thermal resistance of the fill material ( $R_{gr}$ ) and the thermal resistance of the eventual external tube ( $R_t$ ). The thermal resistance of the pipe,  $R_{pp}$ , is given by:

$$R_{pp} = \frac{\left[ \frac{1}{2\pi\lambda_{pp}} \ln\left(\frac{d_e}{d_i}\right) + \frac{1}{\pi d_i h_i} \right]}{N_{pipes}} \quad (4)$$

where  $\lambda_{pp}$  is the thermal conductivity of the pipe material,  $d_e$  is the external diameter of the pipe,  $d_i$  is the internal diameter of the pipe,  $h_i$  is the convective heat transfer coefficient and  $N_{pipes}$  is the number of pipes in the BHE.




The resistance of the fill material,  $R_{gr}$ , depends on the number of pipes installed in the BHE: for single-U pipes, the relationship (5) proposed by Remund (1999) can be used:

$$R_{gr} = \frac{1}{S_b \lambda_{gr}} \quad (5)$$

where  $\lambda_{gr}$  is the ground thermal conductivity and  $S_b$ , the factor of short-circuit, is given by:

$$S_b = \beta_0 \left( \frac{D_b}{d_e} \right)^{\beta_1} \quad (6)$$

In the expression above,  $D_b$  is the borehole diameter and  $\beta_0$  and  $\beta_1$  are geometric factors given in Table 2.

Configuration			
	(A)	(B)	(C)
$\beta_0$	20.10	17.44	21.91
$\beta_1$	-0.9447	-0.6052	-0.3796

**Table 2: Values of geometric factors of single-U heat exchanger -  $\beta_0$ ,  $\beta_1$  (Kavanaugh and Rafferty, 2014)**

For double-U pipes, the equation established by Hellström (1991) can be employed to determine  $R_{gr}$ :

$$R_{gr} = \frac{1}{2\pi\lambda_{gr}} \left[ \ln\left(\frac{D_b}{d_e}\right) - \frac{3}{4} + \left(\frac{D}{D_b}\right)^2 - \frac{1}{4} \ln\left(1 - \left(\frac{D}{D_b}\right)^8\right) - \frac{1}{2} \ln\left(\frac{\sqrt{2}D}{d_e}\right) - \frac{1}{4} \ln\left(\frac{2D}{d_e}\right) \right] \quad (7)$$

where  $D$  is the distance between the pipes.

### 2.3.3 Resistance of the ground

The equivalent thermal resistance of the ground is evaluated based on the dimensionless Fourier number (8), which depends on the time of operation ( $\tau$ ), the bore diameter ( $D_b$ ) and the thermal diffusivity of the ground ( $\alpha$ ). A BHE system can be modelled by three heat pulses and therefore three equivalent thermal resistances are considered: the annual thermal resistance ( $R_{ga}$ ) refers to a heat pulse of 10 years (3650 days), because it is assumed that this period of time is sufficient to stabilise the heat flux exchanged with the ground (Capozza et al., 2012); the monthly thermal resistance ( $R_{gm}$ ) is calculated considering a 1 month (30 days) pulse, while a 6 h (0.25 days)

pulse is used to determine the daily equivalent ground thermal resistance ( $R_{gd}$ ). For each operation time a different Fourier number can be computed and the ground thermal resistances can be evaluated through the G-Function (9):

$$F_o = \frac{4\alpha_g \tau}{D_b^2} \quad (8)$$

$$G = 0.0758 \ln(F_o) + 0.1009 \quad (9)$$

Subsequently, the magnitudes of  $R_{ga}$ ,  $R_{gm}$  and  $R_{gd}$  can be calculated as the ratio between the value of the G-Function corresponding to each heat pulse and the thermal conductivity of the ground.

### 2.3.4 Temperature penalty

The variation in temperature over a given operation time (usually 10 years) can be calculated considering the disposition of the BHEs in the borehole field and the thermal storage capacity of the parallelepiped of ground affected by the operation of a given heat exchanger. In fact, as stated by Kavanaugh and Rafferty (2014), if a borehole surrounded at all four sides is considered, the surface of radius  $0.5d_s$ , where  $d_s$  is the spacing between BHEs, can be considered adiabatic and all the heat that is not exchanged is stored ( $Q_{stored}$ ), changing the ground temperature. This long-term estimate for the change in ground temperature is designated as temperature penalty and can be calculated using:

$$\theta_p = \frac{N_4 + 0.5N_3 + 0.25N_2 + 0.1N_1}{N_{tot}} \theta_{pl} \quad (10)$$

where  $N_1$ ,  $N_2$ ,  $N_3$  and  $N_4$  are the number of BHEs surrounded at one, two, three and four sides, respectively,  $N_{tot}$  is the total number of BHEs in the field (i.e.  $N_{tot} = N_1 + N_2 + N_3 + N_4$ ) and  $\theta_{pl}$  is the temperature penalty for a BHE surrounded at all four sides, which can be determined using:

$$\theta_{pl} = \frac{Q_{stored}}{\rho c_p d_s^2 L} \quad (11)$$

where  $\rho$  and  $c_p$  are the density and volumetric heat capacity of the ground, respectively,  $L$  is the borehole length, while the stored heat,  $Q_{stored}$ , can be calculated following the procedure outlined in Kavanaugh and Rafferty (2014). Alternatively, Philippe et al. (2010) have established a correlation function  $F$  to evaluate the temperature penalty. Its use is restricted by various assumptions, such as number of boreholes, which has to be between 4 and 144, and the ratio between borehole depth and spacing which has to lie between 0.05 and 0.1.  $F$  can be determined through tabulated coefficients correlated to various geometric parameters of the borehole field and the ground thermal diffusivity.

## 3. DESIGN EXAMPLE

A simple dwelling of standard dimensions (ca. 70 m<sup>2</sup>) situated in London (UK) was analysed and the design of a BHE was performed with the methods outlined above. The ground conditions corresponding to the location are described in Table 2.

LONDON		
Thermal conductivity of the ground – Clay [W/mK]	$\lambda_g$	1.8 <sup>1</sup>
Specific heat capacity by mass – Clay [J/kgK]	$c_p$	920 <sup>2</sup>
Density – Clay [kg/m <sup>3</sup> ]	$\rho_g$	2100 <sup>3</sup>
Undisturbed ground temperature – mean annual air temperature in London Heathrow [°C]	$\theta_g$	11.3 <sup>4</sup>

<sup>1</sup>VDI 4640 - Blatt 1 and Banks et al. (2013)      <sup>2</sup>engineeringtoolbox.com      <sup>3</sup>VDI 4640 - Blatt 1  
<sup>4</sup>MCS MIS 3005

**Table 2: Ground parameters for dwelling located in London (UK)**

### 3.1 Heat demand estimate

The energy demand of the building is one of the critical design parameters since it affects the size of the heat pump, which has to be able to produce the required heat, which in turn influences the dimensions of the heat exchanger. The energy demand has two main implications for the design of a ground heat exchanger (Urchueguía and Sikora, 2011): the change in ground temperature in the long term due to the base load (i.e. energy demand of a whole season) and changes in ground behaviour due to degradation of the buried pipes during peak load (i.e. maximum amount of power that the heat pump has to supply).

Although in most design scenarios the energy demand is an input parameter, it is important to understand how it is established and on what it depends. It should be noted that, as stated by Dunbabin and Wickins (2012), every estimation of the buildings' heat gains/losses

is affected by numerous uncertainties. However, it has been shown that the energy demand of a building is rarely overestimated, meaning that a factor of safety taking into account these uncertainties could be introduced.

The heat demand of the analysed dwelling has been established through the Cambridge Housing model, which provides estimates of the energy consumption and CO<sub>2</sub> emissions based on a dataset of 14951 representative English dwellings. Specifically, Dwelling 1557 has been selected and values from the building physics model have been used. The space heating requirement [kWh] has been converted to heating power by assuming 8 h of heating operation time per day, which was then multiplied by a factor of 1.5 to take into account that the energy requirements have been estimated with average temperatures and not the minimum temperatures for each month and in order to consider the aforementioned uncertainties. The total peak load was estimated to be 6.70 kW and the total annual peak heating demand was ca. 7800.00 kWh. A heat pump of 8 kW heat capacity was chosen in order to satisfy at least 100% of the total peak load, as indicated in MCS MIS 3005.

### 3.2 Comparison between different methods

The design was performed following the three different design procedures outlined above. The input parameters were chosen in order to guarantee, where possible, the applicability of the VDI 4640 and the MCS MIS 3005 guidelines, as defined in the previous sections. The most important input parameters are listed in Table 3, while the outcome of the design methods is presented in Table 4.

HEAT PUMP		
Design heating capacity of the heat pump [W]	$q_{h,HP,out}$	8000
Hours of operation [h]	$\tau_h$	1800
Coefficient of performance	COP	4.13
Seasonal coefficient of performance	SCOP	3.8
Heat to be extracted from the ground [W]	$P_{ground}$	5895 <sup>3</sup>
PIPE		
External diameter of pipe [m]	$d_e$	0.032 <sup>1</sup>
Internal diameter of pipe [m]	$d_i$	0.026 <sup>1</sup>
Thermal conductivity of pipe material [W/mK]	$\lambda_{pp}$	0.42 <sup>2</sup>
Number of pipes of the BHE	$N_{pipes}$	2
BOREHOLE		
Borehole diameter [m]	$D_b$	0.13
Total number of boreholes	$N_{tot}$	2
Distance between boreholes [m]	$d_s$	10.00
FILL		
Thermal conductivity of fill material [W/mK]	$\lambda_{gr}$	0.85

<sup>1</sup> Baietto et al. (2010)      <sup>2</sup> Banks (2008)      <sup>3</sup> calculated

**Table 3: Input parameter for the design of the BHE**

Method	Specific extraction rate [W/m]	Borehole Heat Exchangers		
		Number	Length of single BHE [m]	Total Length [m]
VDI 4640 – specific heat extraction rate - general values	60	2	49.00	<b>98.00</b>
VDI 4640 – specific heat extraction rate - specific values	35-50	2	84.00-59.00	<b>168.00 -118.00</b>
MCS MIS 3005	35	2	84.00	<b>168.00</b>
ASHRAE	---	2	114.00	<b>228.00</b>

**Table 4: Results of total design length of BHE with different design methods**

The results vary over a rather large range, from a minimum of 98.00 m (VDI 4640 – general values) to a maximum of 228.00 m (ASHRAE) of total BHE length. The discrepancies between the results may be due to the different assumptions for which the tables of the German and British guidelines have been established and were not necessarily observed when selecting the input parameters. For example, the VDI 4640 is valid for double-U pipes, which would explain the difference in length of 60 m (with the most conservative value of heat extraction rate). Indeed, a BHE with double-U pipes is more thermally performant, resulting in a greater heat exchange surface, thus reducing the borehole thermal resistance and hence the overall length of the BHE. Regarding the MCS MIS 3005, a higher value of grout thermal conductivity than that used for the design is assumed, namely 2.4 W/mK. A brief calculation using the ASHRAE method for a grout thermal conductivity of 2.4 W/mK led to a total length of 173.00 m, which is significantly closer to the result yielded by the MCS MIS 3005 procedure. Clearly, this demonstrates that designers need to be aware of the impact of using the latter procedure with less performing grout and adjust the obtained length accordingly.

In conclusion, given that there is a deviation of up to 43% between the lengths determined using the different methods and that the simplified methods do not include correction factors to take into account deviations in design from their assumptions, it is suggested that analytical design methods should be used even when dealing with small systems and that the designers should be fully aware of the restrictions and assumptions behind such methods. Clearly, the size of the GSHP system has two main implications which should be of greatest concern of the designer: first, the economic impact of the installation of the BHE, which is strictly related to its length, i.e. depth of penetration in the ground and amount of material (e.g. pipes and grout) needed, and second, the right size of the GSHP system determines the long term performance of the system, prevents collateral effects (such as extreme low fluid temperatures, turn-offs of the heat pump or significant changes in ground temperature) and, with the right use by the system owners, guarantees high seasonal efficiencies and a reduction in energy consumption.

#### 4. SENSITIVITY ANALYSIS OF INPUT PARAMETERS FOR THE ASHRAE METHOD

A sensitivity analysis on some of the parameters influencing the design of BHEs using the ASHRAE procedure was performed, in order to quantify the impact on the design length of selected factors. The results are presented as the required total borehole length divided by the capacity of the heat pump (8 kW). This normalised length allows the evaluation, for cases with similar conditions (i.e. small systems used only for heating), of the required borehole length when analysing systems with different HP capacities. The reference values are those outlined in the previous section, while the parametric study is defined in Table 5.

GROUND PARAMETERS			
Thermal conductivity of the ground	$\lambda_g$	Clay: 1.2÷3.0 <sup>1</sup> Sand moist: 1.0÷1.8 <sup>1</sup> Sand wet: 2.0÷3.0 <sup>1</sup>	W/mK
GEOMETRIC PARAMETERS			
Spacing between boreholes	$d_s$	5.0÷20.0	m
PIPES			
Number of pipes of the heat system	$N_{pipes}$	2÷4	adim
FILL MATERIAL			
Thermal conductivity of fill material	$\lambda_{gr}$	0.6÷2.4	W/mK
CARRIER FLUID PARAMETERS			
Temperature difference between ground temperature and outlet fluid temperature	$\Delta\theta_{gw}$	6÷11	°C

<sup>1</sup> VDI 4640 - Blatt 1 (2010)

**Table 5: Analysed parameters in sensitivity analysis and range of variation for each parameter.**

##### 4.1 Ground parameters: ground thermal conductivity

In the ASHRAE method, the thermal conductivity of the ground is used when evaluating the ground resistance and the long term temperature penalty. Figure 1 shows the effect on the design length of this material property for BHEs equipped with both single-U and double-U pipes constructed in sand and clay deposits. As the thermal conductivity and, as a consequence, the thermal diffusivity ( $\alpha = \lambda/\rho c_p$ ), increases, the length of the borehole decreases by up to 30%. While it can be seen that BHEs with single-U and double-U pipes display the same trend, the use of double-U pipes reduces the required length of the borehole by 30÷45%, with this difference increasing for higher values of the thermal conductivity of the ground. Regarding the comparison between the different materials, it can be observed that the required borehole length is greater for systems in sands than in clays. This is because the thermal diffusivity of sands tends to be larger, due to the lower specific heat capacity and density of the sand used in the analysis. It can be therefore stated that, assuming soils with approximately equal thermal conductivity, BHEs installed in materials with lower diffusivities will require lower lengths.

The obtained results, which show that the dimension of the BHE is very sensitive to the chosen values of ground properties, demonstrate that the profile and conditions of the ground should be carefully investigated prior to the design stage. The thermal conductivity,  $\lambda$ , of soils and rocks depends on the thermal conductivity of the solid phase (minerals or combination of minerals), the porosity of the material and the thermal conductivity of the fluid within the pores (water at 10° has a thermal conductivity of 0.6 W/mK, while that of air is 0.026 W/mK) (Danzer and Klein, 2014). Moreover, contrary to the heat capacity, the thermal conductivity cannot be expressed as a linear function of the volume fractions of the elements constituting the soil, with different approaches to determine  $\lambda$  being proposed by Rees et al. (2000). In order to evaluate the in situ thermal conductivity, Thermal Response Tests (TRT) based on the linear heat source can be carried out (e.g. Loveridge et al., 2013), while the thermal diffusivity can then be determined by assuming values of specific heat capacity. As stated by Kavanaugh and Rafferty (2014), for small GSHP systems, a TRT is typically not economically viable. Therefore, the ground properties should be determined, where possible, with site-specific records or in situ density and water content tests.

##### 4.2 Carrier fluid: temperature difference between ground temperature and outlet fluid temperature

The temperature of the carrier fluid is a critical parameter in the design of BHEs as it influences the dimensions and the efficiency of the system. The difference  $\Delta\theta_{gw}$  between the temperature of the BHE outlet fluid (i.e. heat pump inlet) and the temperature of the ground in heating mode should vary within the range of 6÷11K, as suggested by Capozza et al. (2012), in order to provide a good balance between economical operation and performance. This parameter determines the average fluid temperature ( $\theta_{w,av} = (\theta_{wi} + \theta_{wo})/2$ ), since both the

temperature of the ground and the thermal jump of the heat pump, that are used to compute the inlet and outlet temperatures, are fixed parameters. It should however be noted that this temperature difference will not be constant during operation, since it depends on the heat demand.

As shown in Figure 2, for the abovementioned range of temperature difference, the higher its value, the smaller the required length, since the heat extraction from the ground is higher. It should be noted, however, that a high difference between ground and fluid temperature can lead to higher changes ground temperature and therefore greater distances between the boreholes would be necessary to guarantee adequate performance. Moreover, since  $\Delta\theta_{gw}$  varies according to the heat extracted from the ground, a colder fluid temperature will be generated with shorter BHE and higher heat demand. Therefore, in order to avoid extremely low fluid temperatures, it is instead suggested that conservative values should be chosen.

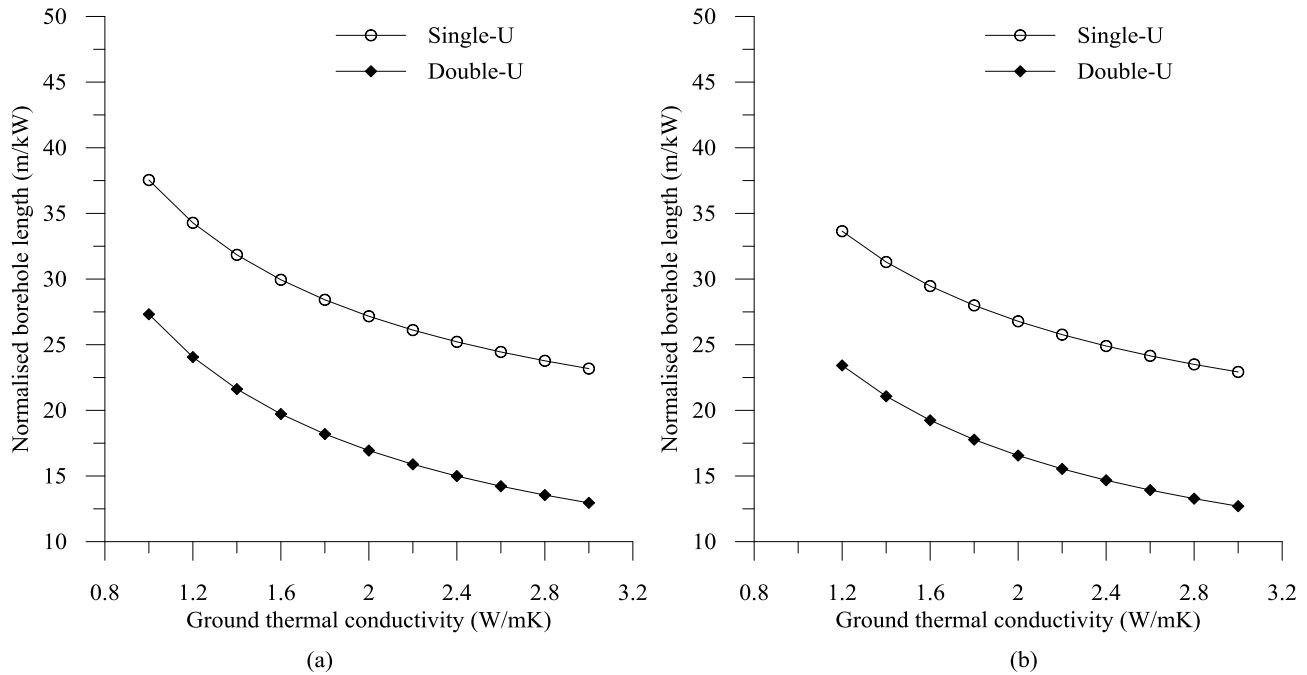


Figure 1: Variation of normalised borehole length with thermal conductivity for (a) sandy deposits and (b) clay deposits.

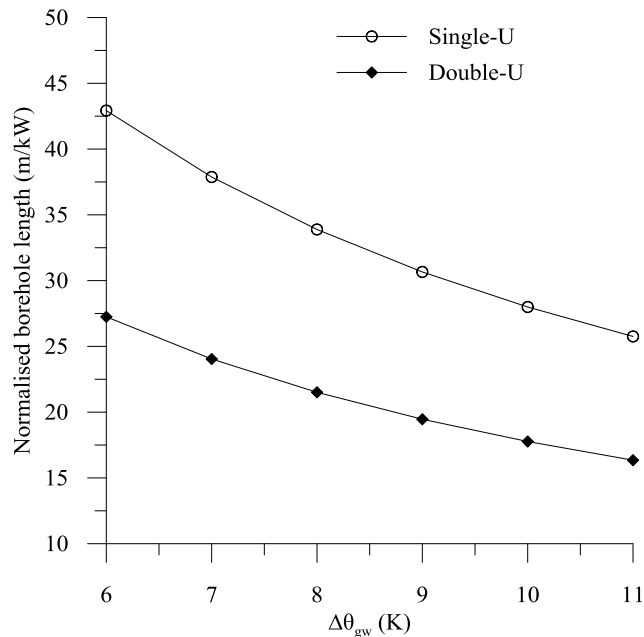


Figure 2: Variation of normalised borehole length with the temperature difference between ground temperature and outlet fluid temperature ( $\Delta\theta_{gw}$ )



### 4.3 Borehole characteristics: borehole spacing

In the ASHRAE method, the borehole spacing has a minimal impact on the required total length of the BHE, as shown in Figure 3(a). Systems with single-U and double-U pipes show the same trend, with a small initial decrease in length (of 5% and 7%, respectively) when spacing between boreholes increases from 5 to 8 m, while for larger values of spacing the change is negligible. This is due to a lower temperature penalty being obtained for larger values of spacing between boreholes. Indeed, the temperature penalty reduces to about 0.2°C when the borehole spacing reaches 8 m, a value which no longer affects the BHE design. The recommendations of most of the guidelines to a minimum spacing between boreholes of 6 m can be attributed to this fact. Moreover, this effect is more pronounced in systems with double-U pipes as they extract more heat per unit length and, therefore, develop higher temperature penalties.

### 4.4 Fill material: grout thermal conductivity

As it can be seen in Figure 3(b), the influence of the thermal conductivity of the grout,  $\lambda_{gr}$ , is much more pronounced in BHEs with single-U tubes than in those where double-U tubes are installed. This is mainly due to the fact that, in the latter case, the thermal resistance of the borehole,  $R_b$ , is already very small, meaning that only marginal reductions of this quantity are possible by increasing the thermal conductivity of the grout, which translate into very minor changes in borehole length. Perhaps, this might be the reason why the German guideline gives specifications for double-U pipes only. For BHEs with single-U pipes, a maximum decrease in the required borehole length of about 35% can be achieved, though it can be seen that the effect of increasing the thermal conductivity of the grout decreases for higher values of this parameter. Indeed, varying  $\lambda_{gr}$  from 0.7 to 1 leads to a reduction in the total length of 18%, while a similar change in  $\lambda_{gr}$  from 1.8 to 2.1 results in a decrease in length of only 3%.

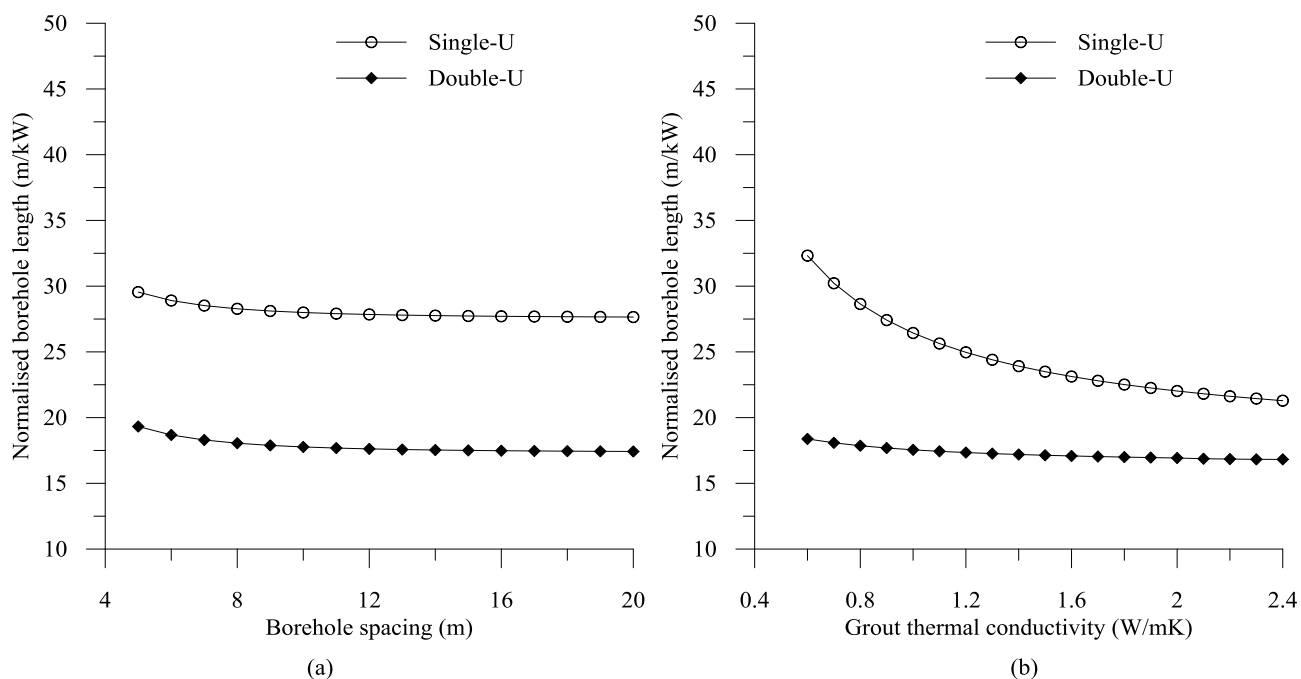


Figure 4: Variation of normalised borehole length with (a) borehole spacing and (b) grout thermal conductivity.

## 5. CONCLUSIONS

Different design methods – simplified and analytical – available in Europe and the USA for Borehole Heat Exchangers used in small systems have been outlined. It has been shown that the size of a BHE depends on many parameters, some of which are not considered in all the identified guidelines. The estimated energy demand of the system has a major impact on the final dimensions of a GSHP system and therefore needs to be carefully established. The comparison between the three identified design procedures showed that there is a great discrepancy between the determined BHE lengths, mainly due to the fact that the simplified methods are based on tabulated values established according to different assumptions. These have a significant influence in the obtained design and need to be taken into account when applying such methods. A sensitivity analysis performed on the analytical ASHRAE method revealed the impact of some of the input parameters, which led to differences in length of up to 40%.

Given the differences in the lengths yielded by the various methods, the inherent uncertainties in designing using tabulated values and the relevance of certain input parameters, it appears that analytical methods provide the most methodic and efficient form of designing BHEs for small systems. Moreover, the results obtained in the performed parametric studies reinforce the notion that ground parameters should be evaluated with as much in situ data as possible in order to ensure that the installation of the GSHP will be economically sustainable and that the performance throughout the design life of the system meets the actual low carbon emission goals.

## REFERENCES

- American Society of Heating, Refrigerating and Air-Conditioning Engineers: *Geothermal Energy in 2011 ASHRAE Handbook - HVAC Applications*, Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers (2011), 34.1-34.20.
- Banks, D.: *An Introduction to Thermogeology: Ground Source Heating and Cooling*, Oxford, Blackwell Publishing (2008).
- Baietto, A., Pochettino, M., and Salvatici, E.: *Progettazione di impianti geotermici. Sonde verticali e pozzi d'acqua*, Palermo, Dario Flaccovio Editore (2010).
- Capozza, A., Galgaro, A., and Zarrella, A.: *Linee Guida per la progettazione dei campi geotermici per pompe di calore*, Milan, Ricerca Sistema Energetico (2012).
- Carslaw, H. S., and Jaeger, J. C.: *Conduction of Heat in Solids*, Oxford, UK, Clarendon Press (1947).
- Claesson, J., and Eskilson, P.: Conductive heat extraction by a deep borehole: analytical studies. In: Eskilson, P. (ed.), *Thermal Analysis of Heat Extraction Boreholes*, Doctoral dissertation, Department of Mathematical Physics, University of Lund, Sweden (1987).
- Danzer, J., and Klein, R.: Geothermische Parameter zur Dimensionierung von Erdwärmesondenanlagen, *Forum Geoökol.* **25** (1) (Energiewende), (2014), 16-21.
- De Carli, M., Del Bianco, R., Fellin, F., Manente, M., Tonon, M., and Zecchin, R.: Sviluppi nelle pompe di calore: il terreno come sorgente termica, *Convegno Aicarr*, Padova, (2003).
- Dehkordi, S., and Schincariol, R.: Guidelines and the design approach for vertical geothermal heat pump systems: current status and perspective, *Canadian Geotechnical Journal*, **51** (999), (2014), 1-16.
- Dunbabin, P., and Wickins, C.: *Detailed analysis from the first phase of the Energy Saving Trust's heat pump field trial*, London, Department of Energy and Climate Change (2012).
- Hellström, G.: *Ground heat storage, Thermal Analysis of Duct Storage Systems, I Theory*, University of Lund, Department of Mathematical Physics, Lund, Sweden (1991).
- Hellström, G.: Thermal performance of borehole heat exchangers, *The Second Stockton International Geothermal Conference* (1998).
- Ingersoll, L. R.: *Heat conduction with engineering, geological, and other applications*, Rev. edition. Madison, Wisconsin, University of Wisconsin Press (1954).
- International Ground Source Heat Pump Association: *Ground Source Heat Pump Residential and Light Commercial: Design and Installation Guide*, International Ground Source Heat Pump Association, Oklahoma State University (2009).
- Kavanaugh, S. P., and Rafferty, K. D.: *Ground-Source Heat Pumps: Design of geothermal systems for commercial and institutional buildings*, American Society of Heating, Refrigerating and Air-Conditioning Engineers (1997).
- Kavanaugh, S. P., and Rafferty, K. D.: *Geothermal Heating and Cooling: Design of Ground-Source Heat Pump systems*, American Society of Heating, Refrigerating and Air-Conditioning Engineers (2014).
- Loveridge, F., Holmes, G., Powrie, W., and Roberts, T.: Thermal response testing through the chalk aquifer in London, UK, *Proceedings of the ICE - Geotechnical Engineering*, **166**, (2013), 197-210.
- Microgeneration Installation Standard: *MIS 3005 Issue 4.0. Requirements for contractors undertaking the supply, design, installation, set to work, commissioning and handover of microgeneration heat pump systems*, London, Microgeneration Installation Standard (2013).
- Österreichischer Wasser- und Abfallwirtschaftsverband: *ÖWAV-RB 207 - Thermische Nutzung des Grundwassers und des Untergrunds – Heizen und Kühlen*. [Online, accessed 11/07/2014]. Available from: <http://www.oewav.at/>.
- Philippe, M., Bernier, M., and Marchio, D.: Sizing calculation spreadsheet: vertical geothermal borefield, *ASHRAE Journal*. **52** (7), (2010).
- Rees, S. W., Adjali, M. H., Zhou, Z., Davies, M., and Thomas, H. R.: Ground heat transfer effects on the thermal performance of earth-contact structures, *Renewable and Sustainable Energy Reviews*, **4** (3), (2000), 213-265.
- Remund, C. P.: Borehole thermal resistance: laboratory and field studies, *Transactions-American Society of Heating Refrigerating and Air Conditioning Engineer*, **105**, (1999), 439-445.
- Reuß, M., and Sanner, B.: Design of closed loop heat exchangers, *International Summer School on Direct Application of Geothermal Energy*, (2000), 147-156.
- Sailer, E.: *Design of Closed Loop Ground Source Heat Pump Systems*, Imperial College London, MSc Thesis (2014).
- Sanner, B.: Kann man eine Erdwärmesonde mit Hilfe von spezifischen Entzugsleistungen auslegen? *Geothermische Energie*, **26-27/99**, (1999), 1-4.
- Sanner, B., Karytsas, C., Mendrinis, D., and Rybach, L.: Current status of ground source heat pumps and underground thermal energy storage in Europe, *Geothermics*. **32** (4), (2003), 579-588.

- Sanner, B.: Guidelines, standards, certification and legal permits for ground source heat pumps in the European Union, *9th International IEA Heat Pump Conference 20th – 22nd May*, Zürich, Switzerland (2008).
- Sanner, B.: BHE design examples. In: Mc Corry, M. and Jones, G. L. (eds.) *Geotrained Training Manual for Designers of Shallow Geothermal Systems*, Brussels, Geotrained, European Federation of Geologists (2011a), 123-127.
- Sanner, B.: Design of borehole heat exchanger. In: Mc Corry, M. and Jones, G. L. (eds.) *Geotrained Training Manual for Designers of Shallow Geothermal Systems*. Brussels, Geotrained, European Federation of Geologists (2011b), 121-122.
- Schweitzer Ingenieur- und Architektenverein: *SLA 384/6. Erdwärmesonden*, Zürich, Schweitzer Ingenieur- und Architektenverein (2010).
- Sikora, P., and Urchueguía, J.: Design of horizontal collectors. In: Mc Corry, M. and Jones, G. L. (eds.) *Geotrained Training Manual for Designers of Shallow Geothermal Systems*. Brussels, Geotrained, European Federation of Geologists (2011), 133-138.
- Solids – Specific Heats. [Online, accessed 20/07/2014]. Available from: <http://www.engineeringtoolbox.com/>
- Urchueguía, J., and Sikora, P.: Energy load. In: Mc Corry, M. and Jones, G. L. (eds.) *Geotrained Training Manual for Designers of Shallow Geothermal Systems*. Brussels, Geotrained, European Federation of Geologists (2011), 107-120.
- Verein Deutscher Ingenieure: *VDI 4640 – Blatt 1. Thermal use of the underground. Fundamentals, approvals, environmental aspects*. Düsseldorf, Verein Deutscher Ingenieure (2010).
- Verein Deutscher Ingenieure: *VDI 4640 – Blatt 2. Thermal use of the underground. Ground source heat pump systems*. Düsseldorf, Verein Deutscher Ingenieure (2001).
- Zeng, H., Diao, N., and Fang, Z.: Heat transfer analysis of boreholes in vertical ground heat exchangers. *International Journal of Heat and Mass Transfer*. **46** (23), (2003), 4467-4481.