

Hoofdstuk 5 – Ondiepe geothermie – Horizontale bodemwarmtewisselaars

5.1. Principe

Horizontale lussen werken grotendeels als ondergrondse zonnecollectoren: in de winter extraheren we warmte uit de ondiepe grond rond de sleuf en in het zomerseizoen rekenen we op het feit dat dit uitgeput warmtereservoir opnieuw zal worden bijgevuld. De lussen kunnen worden gebruikt voor verwarming en voor koeling, maar het is een minder optimaal opslagsysteem.

De volgende factoren zijn belangrijk voor het rendement van het systeem:

- Het gebied boven de lus (de horizontale oppervlakte van de warmtewisselaar) moet groot genoeg zijn om tijdens het zomerseizoen voldoende zonne- en atmosferische warmte te kunnen opnemen.
- De grondgeleidbaarheid moet groot genoeg zijn om de warmte efficiënt aan de lus te kunnen overdragen, en het contact tussen de grond en de leiding moet “thermisch efficiënt” zijn (of m.a.w. de overgangsweerstand moet laag zijn).
 - ⇒ Opvullen rond, direct boven en onder de leiding met fijn kwarts-rijk zand zal zorgen voor een goede thermische geleidbaarheid in de zone rond de leiding, en een goed thermisch contact tussen leiding en bodem.
- De leiding moet vervaardigd zijn uit een duurzaam, sterk en thermisch geleidende materiaal.
- De vloeistof in de warmtewisselaar moet efficiënt warmte met de lus kunnen uitwisselen; het mag niet te visceus en moet van lage toxiciteit zijn (in geval van lekkage); het moet een vriespunt hebben dat onder de minimum gebruikstemperatuur van het systeem ligt, en mag idealiter niet brandbaar zijn.

Zoals besproken in hoofdstuk 3, nemen de thermische geleidbaarheid en de volumetrische warmtecapaciteit van de geologische materialen toe naarmate deze materialen natter worden, te wijten aan het feit dat deze eigenschappen aanzienlijk hoger zijn voor water dan voor lucht. Als deze materialen bevroren, neemt hun thermische geleidbaarheid weer toe (als gevolg van de hogere thermische geleidbaarheid van ijs). Hun volumetrische warmtecapaciteit daalt daarentegen.

Een overzicht van de verschillende types horizontale bodemwarmtewisselaars werd gegeven in hoofdstuk 2.

5.1.1. De diepte van de sleuf

Dit wordt bepaald door verscheidene factoren (Banks 2008):

- De leiding moet geïsoleerd worden van dagelijkse schommelingen van de temperatuur (> enkele tientallen cm)
- De leiding moet dieper dan de gewone vorstdiepte liggen (hoewel er zich ijs kan vormen rond de collector door warmte-extractie)
- De leiding mag niet te diep liggen, zodat de zonnestralingen in de zomer het ondiepe bodem warmte reservoir kunnen aanvullen (de VDI 2001a suggereert een diepte van 1.2-1.5m)

5.1.2. Dragervloeistof

De dragervloeistof is meestal een oplossing van water en antivries. Het circuleert bij turbulente stroming, met het oog op een efficiënte warmte-overdracht (Banks 2008). Volgens Rosen et al. (2001) mag het vriespunt niet hoger dan -8°C te zijn. De belangrijke factoren van de drager vloeistof zijn: viscositeit, ontvlambaarheid, vriespunt, thermische eigenschappen, stabiliteit, lage toxiciteit, bij voorkeur biologisch afbreekbaar (milieu toxiciteit is meer bepalend in ondiepe horizontale lussystemen, vanwege het grotere risico op schade).

Ethyleen-glycol is een populaire keuze in Europa; het heeft goede thermische eigenschappen en is biologisch afbreekbaar in de natuur. Het is echter giftig in hoge concentraties en is verboden in grondlussensystemen in een aantal Amerikaanse staten.

Het debiet van de drager vloeistof wordt gedefinieerd door twee voorwaarden:

- De warmte-overdrachtsnelheid moet resulteren in aanvoer- en retourtemperaturen die geschikt zijn voor de warmtepomp (evenwicht tussen warmteoverdracht op het grond-lus grensvlak en op de verdampers van de warmtepomp waar $Q = S_{VCCar} \cdot \Delta\theta \cdot F$ met $\Delta\theta = 4 - 5^\circ\text{C}$, F het stromingsdebiet, S_{VCCar} de specifieke warmtecapaciteit)
- De stroming moet 'turbulent' zijn

VDI (2001a) beveelt aan dat de temperatuur van de vloeistof die terugkeert naar de warmtepomp vanuit de lussen in de grond niet mag afwijken van meer dan $\pm 12^\circ\text{C}$ van de ongestoorde grondtemperatuur onder basisbelasting (wekelijks gemiddelde) omstandigheden, of door meer dan $\pm 18^\circ\text{C}$ onder piek omstandigheden.

5.1.3. Materiaal voor de lussen

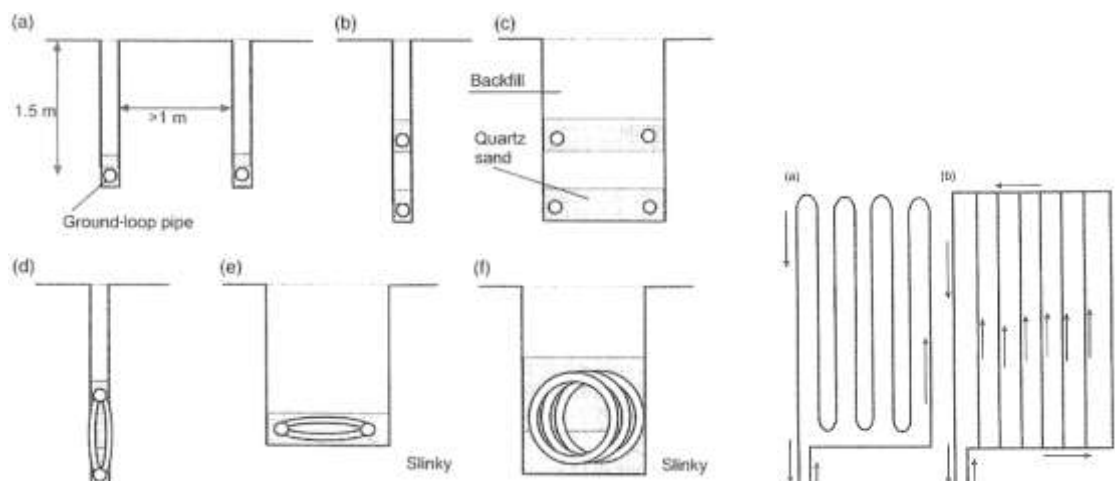
Koper heeft een zeer hoge thermische geleidbaarheid, maar is erg duur en is niet bijzonder veerkrachtig (corrosie, schade door latere graafwerken). De grondlus is daarom normaal gemaakt van een kunststof. Polyethyleen (= polyethene) heeft een hoge thermische geleidbaarheid en is sterk en duurzaam. Gemiddelde dichtheid polyethyleen (MDPE) en hoge dichtheid polyethyleen (HDPE) kunnen worden gebruikt in ondiepe aardlussen, onder meer omdat ze temperaturen tot 60°C kunnen verdragen. Omdat aardlussen onder operationele druk van 2-3 bar komen, worden leidingmaterialen gebruikt met een druk rating van ten minste klasse PN6 (6 bar). Hogere druk ratings zijn echter ook gebruikelijk. De warmtepomp is meestal uitgerust met een drukgevoelige trip-schakelaar of drukbeveiliging/pressostaat (als er een lek in de bodem lus is, moet de warmtepomp stoppen).

De inwendige diameter (ID) is doorgaans nominaal tussen de 19-32mm. Grondlusleidingen worden meestal geleverd in rollen, klaar om te worden gebruikt in rechte lengtes of als opgerolde systemen ('Slinkies') in een sleuf.

5.2. Uitvoeringsmethode

5.2.1. "Horizontally-trenched, Closed-Loop Ground Heat Exchanger (GHEX)" (IGHSPA 2009, Banks 2008)

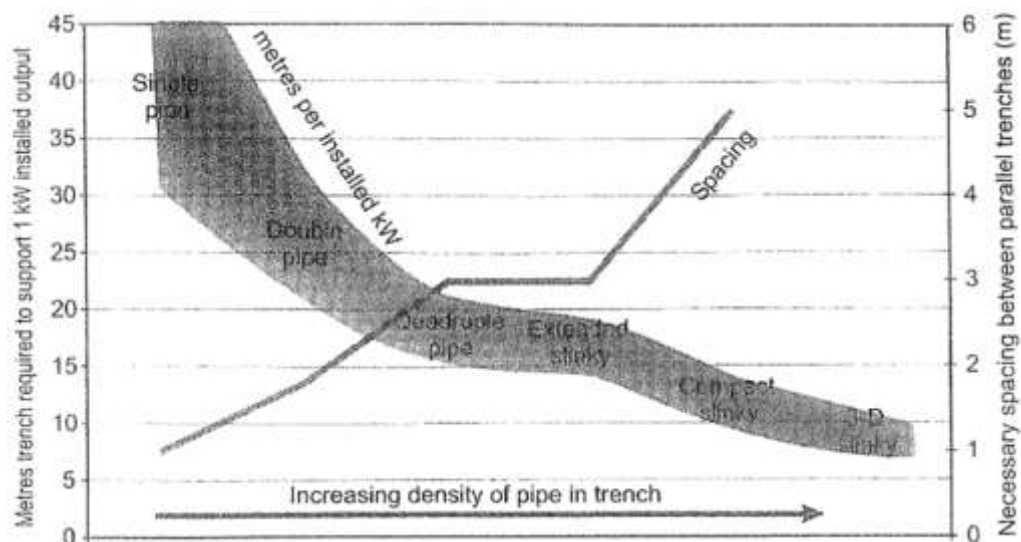
Figuur 1 en Tabel 1 beschrijven de verschillende mogelijke geometrieën van de installatie (Banks, 2008).



Figuur 1. LINKS: mogelijke configuraties van horizontale grondlussen in sleuven: (a) enkel-pijp in parallel sleuven; (b) verticaal geïnstalleerde dubbel-pijp systeem (aanvoer en retour); (c) 'vierkante' 4-pijp systeem (twee aanvoer, twee retour); (d) verticaal geïnstalleerde 'slinky'; (e) horizontaal geïnstalleerde 'slinky'; (f) drie-dimensionnelle spiral 'slinky' (pijpen zijn in geleidend kwartszand ingebed) – **RECHT:** Twee mogelijke manieren om installatie van parallelle sleuven van enkel-pijp systeem (a) in series; (b) in parallel (Banks 2008)

Tabel 1. Verschillende configuraties van horizontale warmtewisselaars (volgens Banks 2008)

Systeem	Warmtevermogen	Tussenafstand	Opmerkingen
Enkele leiding	10 ... 15 W.m ⁻¹ (droog grond) tot 30 ... 40 W.m ⁻¹ (verzadigde grond)	1m	
'slinkies' in sleuven	Tot 100 W.m ⁻¹	3 à 5m	Sleuf lengte teruggebracht tot 25% à 45% in vergelijking met enkele leiding Groot aantal buizen en volume dragerfluidum
2-buizen systeem	50 à 60% meer dan enkele leiding	1,8m	Meest efficiënt met kort verwarmingseizoen (minimale interferentie tussen de buizen)
4-buizen systeem	120 à 125% meer dan enkele buis	2,5 à 3,6m	Sleuf lengte teruggebracht tot 40% à 45% in vergelijking met enkele leiding



Figuur 2. Indicatieve relatie (niet geschikt voor ontwerp) tussen specifiek geïnstalleerde warmteproductie (aantal meters van sleuf die nodig zijn voor 1kW WP vermogen) en nodige tussenafstand tussen parallel sleuven voor verschillende configuraties van horizontale grondlussen (Banks 2008).

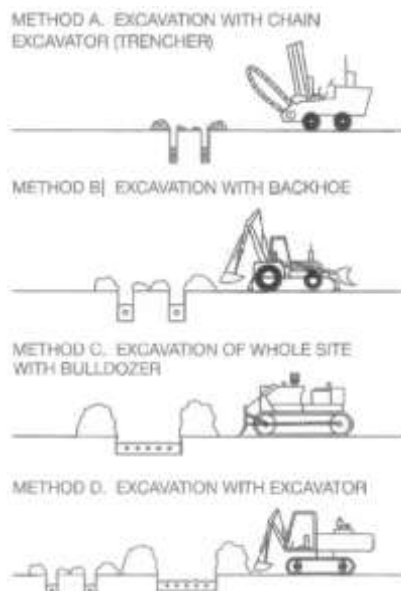


Figure 3. Uitgravingsuitrusting (IGHSPA 2009)

General trenching requirements guidelines (IGHSPA 2009)

- Looping the wire intermittently will keep it relatively close to the pipe. Use one strand of wire per trench when there are multiple pipes in the trench.
- Remove rocks left in the bottom of the trench to minimize the possibility of damaging the pipe during installation. If rock with sharp or jagged edges is present in the bottom (or in the sidewalls) of the trench, the trench should be dug approximately 15cm deeper than pipe placement design requires (or placed at least 15cm away from the sidewall), allowing the trench bottom to be bedded (or backfilled) with approximately 15cm of loose soil or sand. If no rock with sharp or jagged edges is present, the pipe can rest on the trench bottom without bedding, including near or against the sidewall, but still needs to be backfilled.
- High density polyethylene (HDPE) expands and contracts with changes in loop temperature: loop and header pipe should be "snaked" in the trench to accommodate movement associated with this expansion and contraction.
- Trench bottoms can be wet/muddy or have a small amount of standing water. If the trench is flooded to the point the pipe floats, the trench should be pumped out, and the pipe must be secured in position during backfilling to ensure it is buried at the appropriate depth and location.
- If trenches are deeper than the maximum OSHA recommended safe depth, make sure trenches are beveled, stepped, or shorn in accordance with OSHA requirements for the soil conditions present. If there is water in the trenches, do not use any electrically powered device while standing in the water in the trench.⁽¹⁾
- When backfilling around the pipe, use approximately 15cm of loose soil or sand to ensure there are no voids around the pipe and that the pipe has good earth contact throughout.
- When backfilling, remove all rocks with sharp edges or rocks bigger than a golf ball from the loose soil used to bed around the pipe. After the pipe is bedded with at least 15cm of loose soil or sand, trenching spoils can be used to backfill the trench.
- In areas with heavy clay soils, the trenching spoils are often large clumps of clay. Do not drop large clumps into the trench or allow them to fall directly on the pipe before bedding it with loose soil. The clumps typically will not break up and as a result, leave air gaps around the pipe.
- After bedding around the loop and header piping, the backfill should be watered in (if sufficient water is available) to settle the loose soil around the pipe to ensure there are no air gaps along the length of the pipe and to aid in soil compaction.
- When the trench has been backfilled to approximately 0.3m from finished grade, place warning tape in the trench, and then, finish backfilling.
- For a system with multiple supply and return headers, the circulating fluid temperature in all supply piping will essentially be the same and the circulating fluid temperature in all return piping will essentially be the same. Multiple supply headers can be installed together, touching, or in very close proximity without affecting loopfield performance. Similarly, multiple return headers can be installed in close proximity to one another. It is good practice to try to separate the supply lines from the return lines in the header trench by 30cm or more whenever possible. However, no unnecessary effort (insulating between the supply and return lines, digging a dedicated supply line header trench, or a dedicated return line header trench, etc.) needs to be made above and beyond spacing the lines out in the trench. Doing so would unnecessarily drive up installation costs for minimal benefit. The effects of thermal interference between supply and return piping is generally very minimal.

⁽¹⁾ Zie ook aanbevelingen van de CNAC n°96

Installing the horizontally-trenched GHEX piping (IGHSPA 2009)

Regardless of the excavation equipment used for a given horizontally-trenched GHEX installation, the length of pipe, depth of pipe, pipe spacing, trench spacing, or slinky configuration specified in the GHEX design must be adhered to during installation. However, trenches can change direction as necessary to avoid obstacles or be wrapped around the structure or other existing site features, if necessary. Straight trenches and square corners are not mandatory. During horizontally-trenched GHEX installation, use the following guidelines:

- Inspect the trench to ensure that all rocks are removed.
- Inspect the pipe as it is laid out beside the trench for cuts, kinks, or other damage.
- Pressure test the piping in accordance with the IGSHPA Design and Installation Standards.

For a multiple-pipe application, the first layer of pipe should be laid on the bottom of the trench, and then, the trench should be backfilled to the necessary level. After backfilling to the proper level, the soil should be watered in and compacted to ensure that the next layer of pipe is placed with proper separation from the first. This process should be repeated on each additional layer of pipe until all of the pipe has been installed according to the horizontally-trenched GHEX design. Additionally, for a standing multiple pipe application (chain-trenched application), the fluid returning from the ground source heat pump to the GHEX should flow through the shallowest pipe and return to the heat pump from the deepest pipe. This takes the last run of the fluid supplying the ground source heat pump through the coolest soil in summer and the warmest soil in winter. When there are multiple GHEX loop pipes laying in a wide trench application, the connection order and flow direction of supply and return is irrelevant. If the soil at the site is a heavy clay in a dry climate, it may shrink away from the pipe as the soil dries during the summer cooling cycle. In such cases, use a sand fill around the pipe to maintain contact with the pipe. The sand fill will not shrink away from the pipe when it dries. Use caution when using sand as a backfill material because sand has extremely poor heat transfer characteristics when it is dry. Another

option would be to install a drip line whenever this situation exists to help prevent the soil from drying out.

Pipe bend radius and kink prevention (IGHSPA 2009)

When a standing multiple-pipe, horizontally trenched (non-slinky) GHEX layout is installed, the piping will need to be brought back on top of itself when the pipe run reaches the end of the trench. For example, a 2-pipe standing configuration will be installed by placing a pipe run at the bottom of the trench. When the end of the trench is reached, proper backfilling procedures will need to be followed to ensure proper spacing between the two runs, and then the pipe will be brought back on top of itself to complete the piping run in the trench. Care needs to be taken to ensure that the pipe does not kink at the return bend at the end of the trench. Figure 6 shows the return bend options for any multi-pipe GHEX configuration. Extreme care should be taken if the large radius with support option is used (Figure 6). If this option is selected for the installation, hand backfilling around the bend is mandatory. The large radius with no support option must not be used as the potential to kink the pipe is too great.

When bending a pipe using a large radius, always hand backfill around the bend to prevent kinks, and always follow the manufacturer's recommendations for minimum pipe bend radius (regardless of whether the pipe is laying horizontally in the bottom of the trench or standing vertically in the trench). The minimum bend radius for HDPE piping is 25 times the diameter of the pipe.

Aardlussen: lucht als een dragervloeistof (Banks 2008)

Water oplossingen worden meestal gebruikt omdat water een enorme specifieke warmtecapaciteit heeft. Systemen met circulatie van lucht kunnen ook gebruikt worden, voor voorverwarming of passieve koeling (meestal voor ventilatielucht).

Een ventilator moet aangedreven worden om de lucht in de leiding te laten circuleren, wat energie verbruikt. VDI (2004) is van mening dat dergelijke aardlussen niet energie-efficiënt zijn, tenzij de lucht een temperatuurverschil van minstens +/- 2 °C kan bereiken ten opzichte van de buitentemperatuur. De leidingen zijn meestal gemaakt van polyetheen, PVC of beton en worden geïnstalleerd in sleuven met een diepte tussen 1,5 en 3m. Er moet aandacht worden besteed aan problemen van condensatie en hoe dergelijk condensaat wordt verzameld.

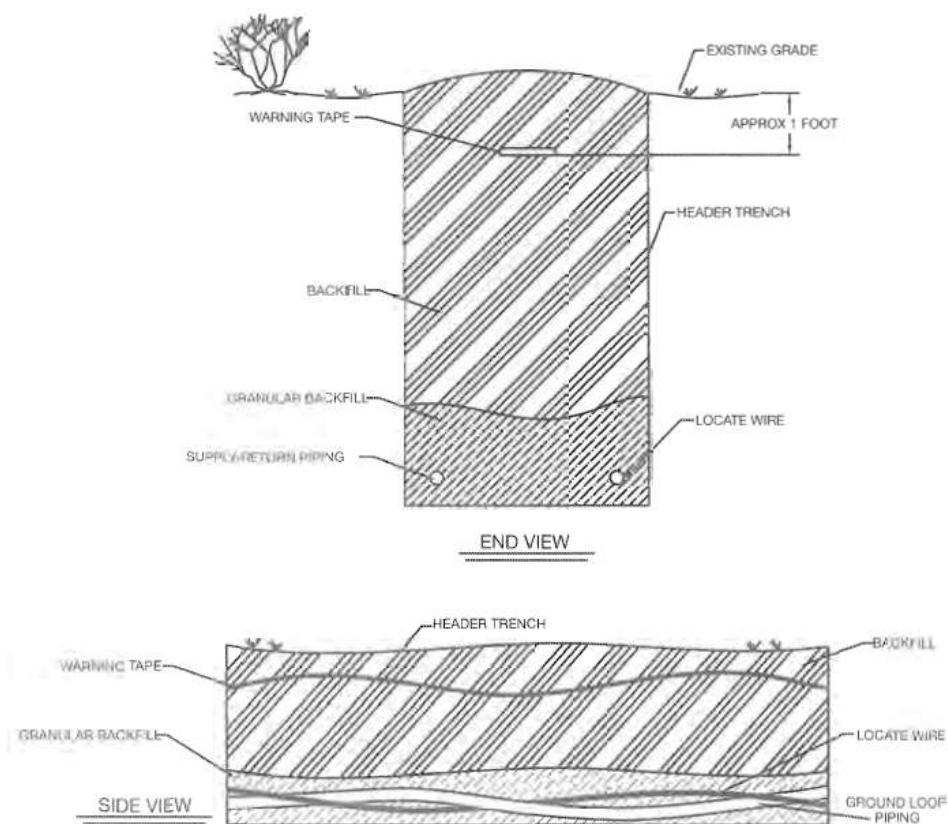


Figure 4. Reader Trench Details (IGHSPA 2009)

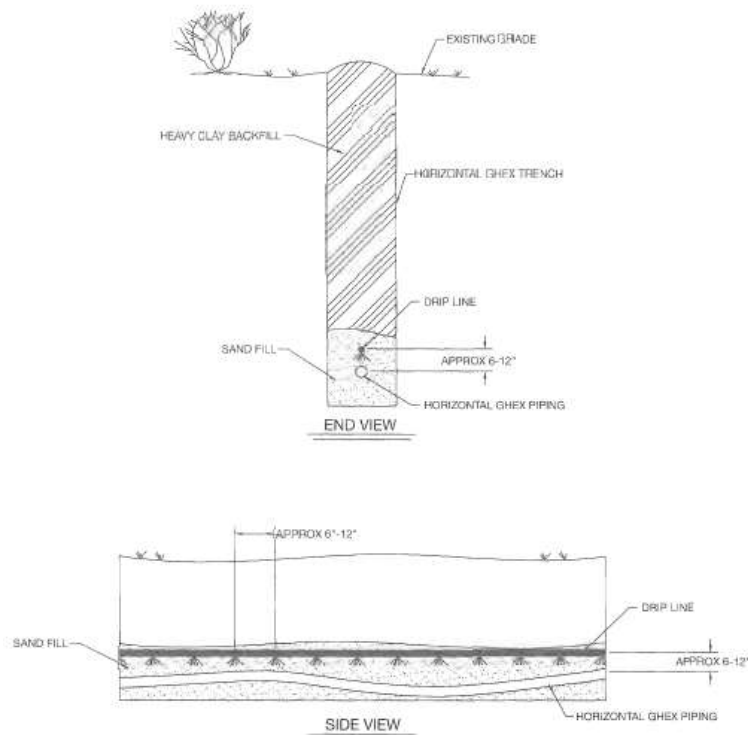


Figure 5. Drip Line Details (for Dry Climates & Heavy Clay Soils) (IGHSPA 2009)

PREFABRICATED U-BEND		<ul style="list-style-type: none"> • BEST • HIGH CRUSH RESISTANCE
90° ELBOWS		<ul style="list-style-type: none"> • BETTER
LARGE RADIUS WITH SUPPORT		<ul style="list-style-type: none"> • GOOD • HAND BACKFILL REQUIRED
LARGE RADIUS WITH NO SUPPORT		<ul style="list-style-type: none"> • UNACCEPTABLE • DO NOT USE

Figure 6. Return Bend Options for Horizontal Piping (IGHSPA 2009)

5.2.2. “Horizontally-bored, Closed-Loop GHEX” (IGHSPA 2009)

Installatie van horizontale geboorde grondlussen kunnen ook door middel van een horizontale of directionele boormachine uitgevoerd worden. Deze installatie gebeurt typisch in drie stappen:

IGHSPA (2009):

- Bore the hole from behind the header trench, down through the header trench to the end of the loop run;
- Attach the U-bend and tremie line to the hole reamer bit at the end of the borehole, and pull everything back to the header trench;
- Detach the U-bend and tremie line from the drill string, and pull the tremie back out of the hole to the end of the field, while simultaneously grouting the entire borehole.

“Typically the HDD machine operator will bore down at an angle to a depth slightly below the depth specified by the GHEX design, level off in the horizontal plain at that depth for the predetermined distance, and then, angle upward to emerge at the surface at the end of the loopfield. At that point, the U-bend and tremie are attached to the end of the drill string. As the drill string is pulled back out of the hole, the U-bend and tremie line are pulled into place. Once the drill string is pulled completely back to the beginning of the hole, the U-bend and tremie line are disconnected in the header trench, and the tremie is pulled back to the end of the hole as it is grouted from beginning to end”.

Het horizontaal boorproces is geïllustreerd in Figuren 7a en 7b.

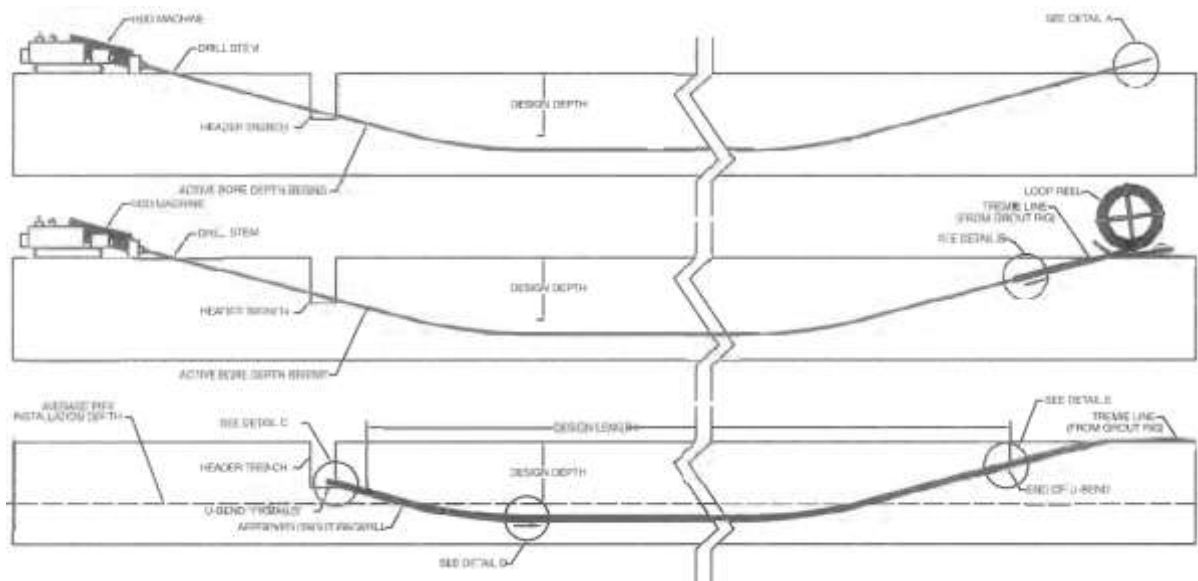


Figure 7a Horizontally bored loop installation process (IGHSPA 2009)

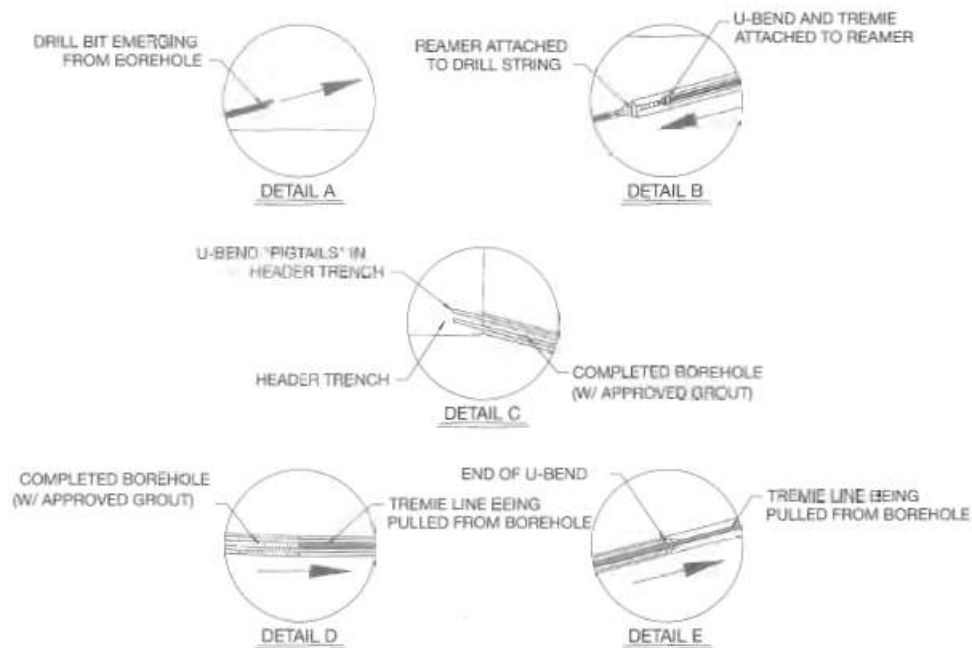


Figure 7b Horizontally bored loop installation details (IGHSPA 2009)

Hole collapse has been used as a reason for not grouting horizontal boreholes. However, there is no way to guarantee that a horizontal borehole will collapse completely and uniformly around GHEX piping. IGHSPA recommends that all horizontally-bored holes be grouted from end to end to ensure good contact between the earth and the GHEX piping and to protect the integrity of environmental groundwater supply (IGHSPA 2009).

5.3. Dimensioneren

5.3.1. Horizontally-trenched, Closed-Loop GHEX Design (IGHSPA 2009)

1. Define the design heating or cooling load and select GSHP equipment.
2. Lay out the GHEX by selecting pipe sizes for the ground loops that meet turbulence and head loss constraints and using a header arrangement that balances flow between the ground loops and facilitates flushing and purging of the GHEX.
3. Estimate the design heating or cooling month run fraction using a bin analysis or graphed data.
4. Estimate the thermal properties (thermal conductivity and diffusivity) of the ground formation into which the horizontally-trenched GHEX will be installed.
5. Determine the soil temperature at the average depth that the horizontally-trenched GHEX will be installed at the end of the design month based on location and estimated thermal diffusivity of the soil.
6. Determine the soil resistance from tabled data for the selected pipe configuration in the trench accounting for estimated thermal conductivity of the soil.
7. For multiple trench installations, account for trench spacing on ground loop performance based on center-to-center trench spacing and the number of trenches in parallel.
8. Calculate the total design heating or cooling pipe length, and divide by the number of trenches to determine the length of pipe in each trench.
9. Calculate the length of each trench by dividing the pipe length per trench by the length of pipe per unit trench length based on the pipe configuration in the trench.
10. Revise the design, as necessary, to meet potential space limitations on the installation site by varying the depth and spacing of the trenches to adjust the length of the trenches, or, if necessary, consider another pipe configuration in the trench.

The total required length of pipe $L_{H,P}$ (heating) or $L_{C,P}$ (cooling) arranged in a given configuration at design conditions is given by:

$$L_{H,P} = \frac{HC_D \left(\frac{COP_D - 1}{COP_D} \right) (R_P + R_S P_M S_M F_H)}{T_{S,L} - \left(\frac{EWT_{min} + LWT_{min}}{2} \right)} \quad (\text{heating})$$

$$L_{C,P} = \frac{TC_D \left(\frac{EER_D + 3.412}{EER_D} \right) (R_P + R_S P_M S_M F_C)}{\left(\frac{EWT_{max} + LWT_{max}}{2} \right) - T_{S,H}} \quad (\text{cooling})$$

The per trench design length of pipe ($L_{H,P/T}$ or $L_{C,P/T}$) and the design length of each trench for heating ($L_{H,T}$ or $L_{C,T}$) can be calculated using:

$$L_{H,P/T} = \frac{L_{H,P}}{N_T} \quad \text{and} \quad L_{H,T} = \frac{L_{H,P/T}}{N_P} \quad (\text{heating})$$

$$L_{C,P/T} = \frac{L_{C,P}}{N_T} \quad \text{and} \quad L_{C,T} = \frac{L_{C,P/T}}{N_P} \quad (\text{cooling})$$

With N_T = number of trenches that the total pipe design length is divided among and N_P = number of pipes in each trench, meter_{pipe}/meter_{trench}. The number of trenches is usually equal to the number of nominal tons of heat pump heating capacity (1T = 3.517 kW), based on the use of nominal ¾ -inch (1.905cm) pipe in the trench. If larger diameter pipe is used in the trench, the relationship between flow rate, turbulence, and head loss must be balanced. The number of pipes in each trench is determined by the configuration of the pipe in the trench.

HC_D (TC_D)= heat pump heating (cooling) capacity at design heating (cooling) conditions (in W)
COP_D = coefficient of performance at design heating conditions (-)
EER_D = energy efficiency ratio at design cooling conditions (-)
R_P = pipe thermal resistance (in mK/W)
R_S = soil thermal resistance at steady-state (in mK/W)
P_M = multiplier to account for pipe diameter other than ¾ inch (1.905cm) (-)
S_M = multiplier to account for trench spacing (-)
F_H, F_C = run fraction in heating (cooling) mode during heating (cooling) design month (Jan. or July) (-)
$T_{S,L}, T_{S,H}$ = design soil temperature for heating (cooling) at average horizontal GHEX pipe depth (in K)
EWT_{min}, EWT_{max} = minimum (maximum) entering water temperature at heating (cooling) design conditions (in K)
LWT_{min}, LWT_{max} = minimum (maximum) leaving water temperature at heating (cooling) design conditions (in K)

IGSHPA standard specifies a minimum pressure rating of 11 bar (160 psi) for horizontal ground loop piping, which requires a maximum DR ratio of 11 for PE3408 pipe and has a thermal resistance of 0.08 mK/W.

Design soil temperature $T_{s,L}$ and $T_{s,H}$

The temperature of the soil in the top 6m of the earth's surface varies with location, time of year, and depth. The proper design of the horizontally bored GHEX depends on good estimates for the minimum ($T_{s,L}$) and maximum ($T_{s,H}$) soil temperatures at the average GHEX burial depth that occur during the design heating and cooling periods of January and July, respectively. The temperature of the soil can be estimated using:

$$T_s(d, t) = T_M - A_s \cdot \exp \left[-d \left(\frac{\pi}{365\alpha} \right)^{1/2} \right] \cdot \cos \left[\frac{2\pi}{365} \left(t - T_0 - \frac{d}{2} \cdot \left(\frac{365}{\pi\alpha} \right)^{1/2} \right) \right]$$

$$T_s(d, t_{min}) = T_{s,M} - A_s \cdot \exp \left[-d \left(\frac{\pi}{365\alpha} \right)^{1/2} \right]$$

$$T_s(d, t_{max}) = T_{s,M} + A_s \cdot \exp \left[-d \left(\frac{\pi}{365\alpha} \right)^{1/2} \right]$$

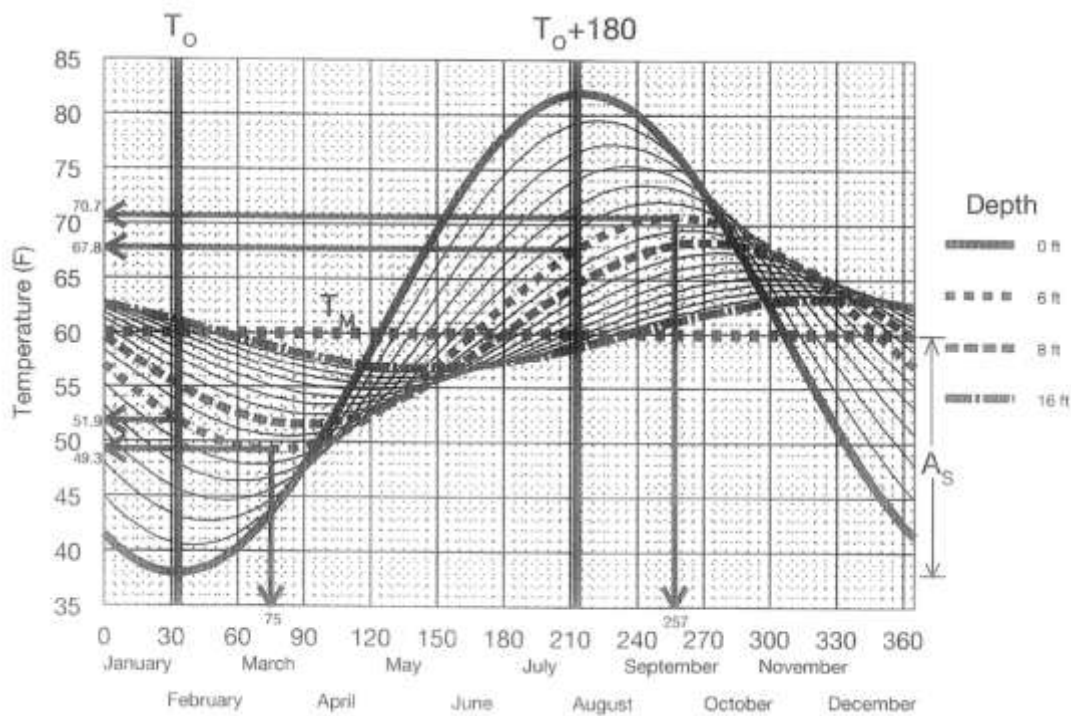


Figure 8. Example of soil temperature estimates for Louisville, KY (IGSHPA 2009)

These equations require an estimate for the soil thermal diffusivity, which is a function of soil type and moisture content (zie hoofdstuk 3), along with the parameters T_M , A_s and T_0 which are functions of location (zie KMI informatie voor België).

$T(d, t)$ = earth temperature at soil depth (d) after (t) days from 1st January
 $T(d, t_{min})$ = annual minimum earth temperature at soil depth (d)
 $T(d, t_{max})$ = annual maximum earth temperature at soil depth (d)
 T_M = mean earth temperature in top 3m
 A_s = earth surface temperature annual swing above and below T_M
 T_0 = number of days after 1st January to minimum earth surface temperature
 d = depth into soil from earth's surface
 t = time delay after 1st January
 $t_{min} = T_0 + \frac{d}{2} \cdot \left(\frac{365}{\pi\alpha} \right)^{1/2}$ = number of days after 1st January when $T(d, t_{min})$ occurs
 $t_{max} = T_0 + \frac{d}{2} \cdot \left(\frac{365}{\pi\alpha} \right)^{1/2} + \frac{365}{2}$ = number of days after 1st January when $T(d, t_{max})$ occurs
 α = soil thermal diffusivity

Soil thermal resistance and trench spacing multiplier

Soil thermal resistance (R_s) represents the resistance to heat transfer between the outer wall of the buried pipe and the design heating or cooling soil temperature ($T_{s,L}$ and $T_{s,H}$). The resistance to heat transfer in the soil around the buried piping of a horizontally-trenched GHEX, for an average depth of at least 1.5m, is a function of the thermal conductivity of the soil, the number, diameter and configuration of the pipes in the trench, and the distance between horizontal trenches for multiple trench systems.

The thermal conductivity of the soil depends on:

- the type of soil (which is defined by the percentage of sand, silt, and clay),
- the density of the soil,
- the water content of the soil.

For a given soil type, the density does not change significantly, but the water content can change during the year, depending on the type of soil and the level of precipitation for that location. Sandy soils do not hold water well and will tend to exhibit large swings in water content and thermal conductivity depending on season and precipitation levels, while clay soils tend to hold water very well, and the water content and thermal conductivity will not vary as much throughout the year. For the design of the horizontally-trenched GHEX, it is important to select the lowest soil thermal conductivity that could be expected for the soil type and location of the installation. Because the moisture and thermal stability of soil generally increases with depth in the soil, higher design values for soil thermal conductivity can be used as the average depth of the horizontally-trenched GHEX piping system is increased.

ASHRAE (2005) provides apparent thermal conductivity values for different soil types based on work by Salomone and Marlowe (1989). Included is the normal range that can be expected for each soil type, low values for the design of systems where ground heat exchange systems are being designed to meet worst-case conditions and high values for analysis of systems where maximum heat transfer rates are predicted. For the design of horizontally-trenched GHEX, the lower values shown in Table 2 are satisfactory unless better information is available.

According to ASHRAE (2005), although thermal conductivity varies greatly over the complete range of possible water contents for a soil, that range can be narrowed if it is assumed that the water content of most field soils lie between the wilting point and the field capacity of the soil. Wilting point (W.P.) is the water content below which a plant cannot draw water from the soil through its root system and begins to wilt (to be used for soils susceptible to drought). The field capacity (F.C.) is the water content that the soil can maintain against drainage affected by gravity (to be used for soils that will remain moist to wet throughout the year). Thermal conductivity was measured over the entire water content range at average dry density and one standard deviation either side of average.

Table 2. Typical apparent thermal conductivity values for soils [W/mK] – ASHRAE (2005)

Soil type	Normal range	Recommended values for design ²	
		Low ³	High ⁴
Sands	0.6-2.5	0.8	2.25
Silts	0.9-2.5	1.6	2.25
Clays	0.9-1.6	1.1	1.6
Loams	0.9-2.5	0.95	2.25

² Reasonable values for use when no site or soil-specific data are available

³ Moderately conservative values for minimum heat loss through soil

(use in soil heat exchanger or earth-contact cooling applications) – from Salomone and Marlowe (1989)

⁴ Moderately conservative values for maximum heat loss through soil (use in peak heat loss calculations) – from Salomone and Marlowe (1989)

Table 3. Thermal properties for various soils from Remund (1989) (1 Btu/hr ft F = 1.73 W/mK; 1 ft²/day = 0.09 m²/day)
(volumetric soil water content in %)

Soil ¹	USDA System ²			Field Density Class ³ (g/cm ³ -lb/ft ³)	Soil Water Content		Thermal Conductivity ⁴ (Btu/hr ft F)		Thermal Diffusivity ⁵ (ft ² /day)	
	Sand (%)	Silt (%)	Clay (%)		W.P.	F.C.	W.P.	F.C.	W.P.	F.C.
Bendare (Clay)	1.7	25.5	72.9	L (1.10-68.8)	30.1	39.8	0.42	0.55	0.29	0.33
				M (1.20-75.1)		37.2	0.51	0.62	0.33	0.36
				H (1.30-81.4)		35.1	0.63	0.70	0.37	0.38
Sharpsburg (Silty-Clay-Loam)	3.5	58.2	38.3	L (1.30-81.4)	16.5	31.3	0.39	0.77	0.32	0.45
				M (1.40-87.6)		28.6	0.53	0.79	0.41	0.46
				H (1.50-93.6)		26.5	0.64	0.83	0.45	0.47
Moody (Silty-Loam)	12.5	65.6	21.9	L (1.40-87.6)	9.1	23.5	0.40	0.75	0.39	0.49
				M (1.50-93.9)		21.7	0.48	0.83	0.43	0.52
				H (1.60-100)		20.1	0.60	0.92	0.50	0.58
Cecil (Clay)	35.0	17.8	47.2	L (1.40-87.6)	17.7	26.6	0.79	1.07	0.57	0.64
				M (1.50-93.9)		24.6	0.97	1.12	0.67	0.66
				H (1.60-100)		23.0	1.09	1.16	0.71	0.68
Kranzburg (Clay-Loam)	35.5	36.4	28.1	L (1.50-93.9)	11.5	21.7	0.60	0.90	0.50	0.57
				M (1.60-100)		20.2	0.73	1.00	0.58	0.62
				H (1.70-106)		18.7	0.88	1.05	0.65	0.58
Brookings (Sandy-Clay-Loam)	45.6	22.7	31.8	L (1.50-93.9)	13.1	21.1	0.64	1.03	0.50	0.65
				M (1.60-100)		19.6	0.80	1.05	0.60	0.66
				H (1.70-106)		18.1	0.93	1.05	0.65	0.65
Grovena (Sandy-Loam)	53.4	35.3	11.3	L (1.50-93.9)	4.9	13.6	0.40	0.81	0.42	0.64
				M (1.60-100)		13.4	0.51	0.92	0.51	0.68
				H (1.70-106)		12.6	0.62	1.04	0.58	0.75
Vienna (Sandy-Loam)	66.5	21.0	12.5	L (1.50-93.9)	5.9	15.6	0.47	0.92	0.48	0.68
				M (1.60-100)		15.4	0.62	0.97	0.60	0.68
				H (1.70-106)		14.6	0.74	1.05	0.67	0.72
Lamours (Sandy-Loam) or (Loamy-Sand)	78.5	11.4	9.7	L (1.60-100)	4.2	12.1	0.47	0.87	0.48	0.68
				M (1.70-106)		11.9	0.65	1.10	0.63	0.80
				H (1.80-113)		11.1	0.80	1.21	0.74	0.87
Maddock (Loamy-Sand)	87.6	5.8	6.8	L (1.60-100)	3.3	11.7	0.42	0.97	0.45	0.77
				M (1.70-106)		11.5	0.49	1.07	0.50	0.80
				H (1.80-113)		10.7	0.50	1.20	0.48	0.87
Fordville (Sand)	100.0	0.0	0.0	L (1.60-100)	0.70	5.0	0.20	0.71	0.25	0.71
				M (1.70-106)		5.0	0.28	0.95	0.32	0.89
				H (1.80-113)		5.1	0.39	1.04	0.42	0.92

1. Soil series name - USDA textural class included in parenthesis.
2. According to USDA System sand, silt, and clay particle size limits.
3. M = average dry density for field soils below approximately 6 feet with indicated USDA particle size breakdown and should be used unless better information is available. L and H indicate one standard deviation below and above average, respectively.
4. Wilting point (W.P.) thermal conductivity is lowest expected value in the field. Field Capacity (F.C.) thermal conductivity is highest expected value in the field, except for saturated condition.
5. Wilting point (W.P.) thermal diffusivity is lowest expected value in the field. Field Capacity (F.C.) thermal diffusivity is highest expected value in the field, except for saturated condition.

Soil thermal resistance (R_s) values have been calculated using CLGS (a program developed by IGSHPA to determine steady-state soil resistance for any pipe diameter, configuration in the trench, number and spacing of trenches, and soil thermal conductivity) for several commonly-used pipe configurations for a soil thermal conductivity range between 0.35 to 2.4 W/mK. Tables 4 and 5 contain R_s values for 2 examples of pipe configurations in "standing", "laying," and "rectangular" configurations that represent the most popular methods used for installing horizontally-trenched GHEX systems. More configurations are discussed in the IGSHPA manual. Interpolation can be used to determine R_s for values of soil thermal conductivity between tabled values. All calculations for R_s are based on the use of ¾-inch (1.905 cm) pipe and a pipe multiplier (P_M) has been defined to adjust the soil resistance if 1 or 1-1/4-inch (3.175 cm) pipe is used. Included in Tables 4 and 5 is a trench spacing factor (S_M) which was developed to adjust soil resistance for thermal interference between parallel trenches and is expressed in terms of number of parallel trenches and center-to-center spacing (S_{cc}) between trenches. For more than six trenches in parallel, S_M does not increase significantly and can be assumed the same as for six trenches. Linear interpolation can be used to estimate S_M when either the number of trenches or S_{cc} or both, fall between tabled values.

Table 4. Soil resistance R_s and trench spacing multiplier S_M - 1-pipe (values of thermal conductivity k_{soil} are expressed in Btu/hr ft F with 1 Btu/hr ft F = 1.73 W/mK; values of sol thermal resistance R_s are expressed in hr ft F/Btu with 1 hr ft F/Btu = 0.578 mK/W)

k_{soil}	Single Trench R_s	Trench Spacing Multiplier (S_M)				
		# Trenches	Center-Center Trench Spacing (S_{cc})			
			11	9	7	5
0.20	3.92	2	1.01	1.02	1.04	1.07
		4	1.01	1.02	1.05	1.12
		6	1.01	1.03	1.06	1.14
0.50	1.65	2	1.02	1.04	1.07	1.12
		4	1.03	1.06	1.11	1.20
		6	1.04	1.07	1.12	1.23
0.75	1.12	2	1.03	1.04	1.08	1.13
		4	1.04	1.07	1.13	1.23
		6	1.04	1.08	1.14	1.27
1.00	0.85	2	1.04	1.05	1.08	1.13
		4	1.05	1.08	1.14	1.25
		6	1.06	1.09	1.15	1.29
1.40	0.61	2	1.05	1.07	1.10	1.15
		4	1.07	1.10	1.16	1.28
		6	1.07	1.11	1.18	1.33

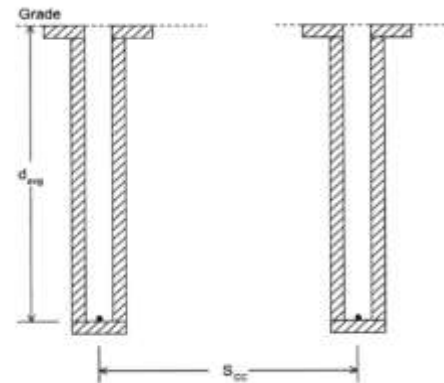
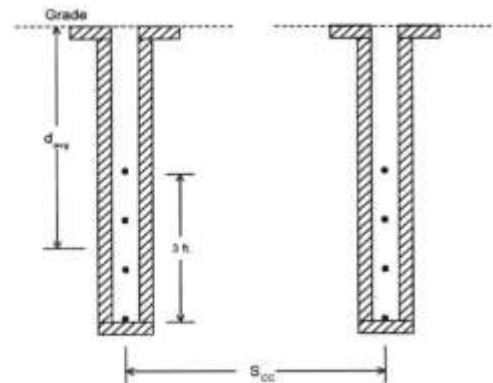


Table 5. Soil resistance R_s and trench spacing multiplier S_M - 5-pipe standing (values of thermal conductivity k_{soil} are expressed in Btu/hr ft F with 1 Btu/hr ft F = 1.73 W/mK; values of sol thermal resistance R_s are expressed in hr ft F/Btu with 1 hr ft F/Btu = 0.578 mK/W)

k_{soil}	Single Trench R_s	Trench Spacing Multiplier (S_M)				
		# Trenches	Center-Center Trench Spacing (S_{cc})			
			11	9	7	5
0.20	7.30	2	1.01	1.03	1.07	1.15
		4	1.02	1.05	1.11	1.24
		6	1.02	1.05	1.12	1.27
0.50	3.27	2	1.04	1.07	1.12	1.21
		4	1.06	1.11	1.20	1.38
		6	1.06	1.12	1.23	1.44
0.75	2.26	2	1.05	1.09	1.15	1.23
		4	1.08	1.14	1.24	1.43
		6	1.09	1.15	1.27	1.50
1.00	1.73	2	1.06	1.10	1.16	1.25
		4	1.10	1.17	1.27	1.47
		6	1.12	1.18	1.31	1.55
1.40	1.27	2	1.07	1.11	1.17	1.26
		4	1.11	1.18	1.30	1.50
		6	1.13	1.20	1.35	1.60



1. Equivalent to a 56-inch pitch x 36-inch diameter slinky.

Table 6 summarizes the various piping configurations and provides information helpful in the proper layout of these configurations based on pipe diameter and required flow rate for turbulence under most flow conditions. Also provided are recommended minimum piping depths in the trench and a brief description of the flow path in the trench. From a piping perspective, one, two, and four pipe configurations are usually achieved by unrolling the pipe and laying it out in the trench to achieve the number of pipe passes required. For five or more (sometimes four) pipes in the trench, the slinky is commonly used where the pipe is configured into multiple loops with proper offset spacing between loops to achieve the equivalent number of pipe passes in the trench. (IGSHPA's Slinky Installation Guide provides details on the layout and construction of the slinky to provide between 4 and 12 meter of pipe per meter of trench.) The "standing" configurations are generally installed in a trench constructed using a chain trencher, with a trench width usually between 6 and 30cm. The "laying" and "rectangular" configurations would be installed in a trench constructed using a backhoe or excavator with a 0.6 to 1m wide bucket. Stacked "laying" configurations have been used when laying two slinkies in a single trench, where the trench has been excavated deeper than would be used for a single slinky, with a minimum of 1m of backfill placed between the slinky layers.

Table 6. Common Pipe and Trench Configurations for ¾, 1, and 1 ¼ -inch Pipe Diameters (resp. 1.905 cm, 2.54 cm, 3.175 cm)

Table	Pipe Configuration ²	# Flow Paths per Trench	D _p (in)	GPM per Flow Path	Single Trench Capacity (Ton)	Minimum Recommended Depths ³ (ft)			Common Application
						d _{avg}	d _{bp}	d _{tp}	
Table 4	1-Pipe ⁴	½	¾	3.0	½	6	6	6	Two trenches contain a single pipe, out in one trench and back in another, with one flow path.
			1	4.5	¾				
			1-¼	6.0	1				
Table 5	2-Pipe Standing ⁵	1	¾	3.0	1	6	7	5	One trench contains two pipes, out-back, with one flow path.
			1	4.5	1-½				
			1-¼	6.0	2				
Zie IGSHPA 2009	4-Pipe Standing ⁵	1	¾	3.0	1	6	7.5	4.5	One trench contains 4 pipes, out-back-out-back or a 56° pitch slinky, with one flow path.
			1	4.5	1-½				
			1-¼	6.0	2				
	5-Pipe Standing ⁵	1	¾	3.0	1	6	7.5	4.5	One trench contains a 36° pitch slinky with one flow path.
			1	4.5	1-½				
			1-¼	6.0	2				
	8-Pipe Standing ⁵	1	¾	3.0	1	6	7.5	4.5	One trench contains an 18° pitch slinky with one flow path.
			1	4.5	1-½				
			1-¼	6.0	2				
	2-Pipe Laying ⁵	1	¾	3.0	1	6	6	6	One trench contains two pipes, out-back, with one flow path.
			1	4.5	1-½				
			1-¼	6.0	2				
	4-Pipe Laying ⁵	1	¾	3.0	1	6	6	6	One trench contains 4 pipes, out-back-out-back or a 56° pitch slinky, with one flow path.
			1	4.5	1-½				
			1-¼	6.0	2				
	5-Pipe Laying ⁵	1	¾	3.0	1	6	6	6	One trench contains a 36° pitch slinky with one flow path.
			1	4.5	1-½				
			1-¼	6.0	2				
	8-Pipe Laying ⁵	1	¾	3.0	1	6	6	6	One trench contains an 18° pitch slinky with one flow path.
			1	4.5	1-½				
			1-¼	6.0	2				
	4-Pipe Rectangular	1	¾	3.0	1	6	7	5	One trench contains 4 pipes, out-back-out-back, with one flow path.
			1-¼	6.0	2				
		2	¾	3.0	2				One trench contains 4 pipes, 2 out-2 back, with two parallel flow paths.
			1-¼	6.0	4				
	2-Layer 4-Pipe Laying ⁵	1	¾	3.0	1	7.5	8	6	One trench contains two 56° pitch slinkies, hooked in series with one flow path.
			1	4.5	1-½				
		2	¾	3.0	2				One trench contains two 56° pitch slinkies, two parallel flow paths.
			1-¼	6.0	4				
	2-Layer 5-Pipe Laying ⁵	1	¾	3.0	1	7.5	9	6	One trench contains two 36° pitch slinkies, hooked in series with one flow path.
			1	4.5	1-½				
		2	¾	3.0	2				One trench contains two 36° pitch slinkies, two parallel flow paths.
			1-¼	6.0	4				
	2-Layer 8-Pipe Laying ⁵	1	¾	3.0	1	7.5	9	6	One trench contains two 18° pitch slinkies, hooked in series with one flow path.
			1	4.5	1-½				
		2	¾	3.0	2				One trench contains two 18° pitch slinkies, two parallel flow paths.
			1-¼	6.0	4				

1. Trench configurations assume header trench is located at one end of loopfield.
2. See indicated table for schematic of pipe configuration in the trench.
3. Minimum recommended average burial depths for the configuration (d_{avg}) for the bottom pipe (d_{bp}) and for top pipe (d_{tp}) and to reach thermally stable soil conditions. Burial depth (d_{avg} and associated d_{bp} and d_{tp}) should be adjusted downward (by up to 0.6m) in extremely cold or hot climates.
4. 1-Pipe configuration requires two trenches, one for the supply line away from the header trench and a second for the return line to the header trench, thus only 1/2 of the flow path exists in a single trench.
5. Configuration will be attained using a slinky with appropriate pitch to obtain equivalent meters of pipe per meter of trench.

Pipe diameter multiplier

The soil thermal resistance (R_s) values were given for ¾ -inch (1.905 cm) polyethylene pipe. Using 1 or 1- ¼ inch (2.54 to 3.175cm) pipe is known to increase heat transfer because the pipe outside surface is located farther from the center of the pipe and has larger surface area. A simple correction for pipe diameter was developed by calculating soil thermal resistance for the 1 and ¼ -inch (2.54 to 3.175cm) pipes and taking those

values and dividing them by the soil thermal resistance for the ¾ -inch (1.905 cm) pipe for the corresponding soil thermal conductivity and pipe configuration, as defined by:

$$P_M = \frac{R_s(D_p, k_s, \text{configuration})}{R_s(\frac{3}{4}\text{inch}, k_s, \text{configuration})}$$

The resulting data were correlated by the number of pipes in the trench, averaged across all pipe configurations, and a curve-fit was fitted to the results, as shown in Figure 9. The curve-fit results for the corresponding range of number of pipes in the trench (N_p) are summarized in Table 7.

Table 7. Pipe diameter multiplier (P_M) for ¾ , 1, and 1-1/4 inch PE pipe (resp. 1.905cm, 2.54cm, and 3.175cm)

D_p (in)	Pipe Diameter Multiplier Equation	Notes ¹
¾	$P_M = 1.0$	R_s based on ¾" pipe
1	$P_M = 0.9492 + 0.0093N_p - 0.0005N_p^2$	for $1 \leq N_p < 8$
	$P_M = 0.990$	for $N_p \geq 8$
1-¼	$P_M = 0.8877 + 0.0254N_p - 0.0026N_p^2 + 0.0001N_p^3$	for $1 \leq N_p < 8$
	$P_M = 0.978$	for $N_p \geq 8$

1. N_p = number of pipes in the trench.

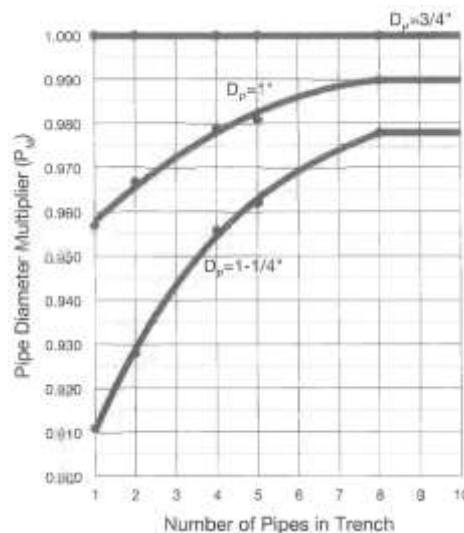


Figure 9, Pipe Diameter Multiplier (P_M) vs. Number of Pipes in Trench

Horizontally-trenched bored GHEX design Worksheet (IGSHPA 2009)

Proper design of a horizontally-trenched GHEX requires reliable heating and cooling load design data and heat pump selection; consideration of domestic hot water generation; identification of installation location and soil identification; specification of horizontal trench design parameters and proper layout of the horizontal loopfield; and application of the heating or cooling design equations to determine the required pipe and trench lengths. Part of the heat pump selection is based on specification of the minimum and maximum entering water temperatures from the horizontally-trenched GHEX, along with the water flow rate that the GHEX must accommodate, each of which are critical parameters in the proper design of the horizontally-trenched GHEX system. Hot water generation, by either a dedicated water-to-water GSHP or a desuperheater in the space heating and cooling GSHP, will affect the horizontal loopfield design. Installation location determines the soil temperatures at the average depth of pipe burial and soil type determines the thermal properties for design. Layout of the horizontally-trenched loopfield, in terms of number of flow paths, pipe diameter, and maximum flow distance are considered to accommodate required water flow rate to achieve proper turbulence for heat transfer, in a heating dominant design, and to control head loss to keep pumping power at an acceptable level at heating or cooling design conditions. Application of the appropriate design equation using design data for the ground and trench configuration results in the required total length of pipe for heating or cooling. The piping configuration in the trench is then utilized to determine the length of the individual trenches.

Worksheets have been developed for both heating mode dominant and cooling mode dominant design (see IGSHPA 2009). The worksheets (reproduced in IGSHPA 2009) are broken into sections to allow input for heat pump design and energy analysis data, domestic hot water generation, location information and identification of soil thermal properties, loopfield layout, and design data for the horizontal GHEX for the calculation of the total length of pipe and trench. Additional calculations can be made to refine horizontally trenched GHEX design lengths in a table at the bottom of each worksheet.

5.3.2. Horizontally-bored, Closed-Loop GHEX Design (IGHSPA 2009)

The soil temperature is taken at the average GHEX pipe depth to account for annual variation in soil temperature present in the top 6m of the soil profile. The steps in designing the horizontally-bored, closed-loop GHEX include:

1. Define the design heating or cooling load and select GSHP equipment based on the EWT and GPM that the GHEX will be designed for.
2. Lay out the GHEX by selecting pipe sizes for the ground loops that meet turbulence and head loss constraints and using a header arrangement that balances flow between the ground loops and facilitates flushing and purging of the GHEX.
3. Estimate the design heating or cooling month run fraction and the annual heating and cooling ground loads using a bin analysis or graphed data.
4. Determine the deep-earth temperature where the horizontally-bored GHEX will be installed.
5. Estimate the thermal properties (thermal conductivity and diffusivity) of the ground formation into which the horizontally-bored GHEX will be installed.
6. Select borehole completion information (borehole diameter, U-bend pipe size, and grout thermal conductivity) that will be used in the installation.
7. Determine the ground loop resistance from tabled data for the selected U-bend pipe size accounting for design month run fraction, ground formation thermal conductivity, borehole diameter, and grout thermal conductivity.
8. Calculate the total design heating or cooling borehole length and divide by the number of horizontal bores to determine the active borehole length.
9. Adjust the heating or cooling design lengths to account for unbalanced ground loads, if necessary.
10. Revise the design, as necessary, to meet potential space limitations on the installation site by balancing the number and spacing of horizontal bores against boring lengths that can be achieved on the site.

The design heating or cooling horizontal bore lengths that result directly from the equations and data presented below are for residential and light commercial GSHP applications with a relatively small number of ground loops spaced such that they minimally interfere with each other. If the heating and cooling ground loads are relatively unbalanced, then borehole length multipliers are utilized for one, two, or three-layer horizontal borefields that account for borehole spacing and adjust borehole lengths for long-term energy depletion or build-up in the soil or rock in and around the horizontally-bored GHEX. For GSHP applications that require a large number of horizontal bores in a grid arrangement and have heating and cooling ground loads that are extremely unbalanced, it is highly recommended that the designs lengths obtained with the methods presented in this section be checked against commercial ground loop design software tools (GCHPCalc, GLHEPRO, GLD, etc.) that are designed to account for unbalanced ground loads and the influence of borehole spacing. The equations presented here are not to be used for the design of large commercial horizontally-bored, closed-loop GHEX systems.

Design equations

The total borehole design length is given by:

$$L_{H,T} = \frac{HC_D \left(\frac{COP_D - 1}{COP_D} \right) (R_B + R_G F_H)}{T_{S,L} - \left(\frac{EWT_{min} + LWT_{min}}{2} \right)} \quad (\text{heating})$$

$$L_{C,T} = \frac{TC_D \left(\frac{EER_D + 3.412}{EER_D} \right) (R_B + R_G F_C)}{\left(\frac{EWT_{max} + LWT_{max}}{2} \right) - T_{S,H}} \quad (\text{cooling})$$

The individual borehole design lengths ($L_{H,B}$ or $L_{C,B}$) and the design length of each trench for heating ($L_{H,T}$ or $L_{C,T}$) can be calculated using:

$$L_{H,B} = \frac{L_{H,T}}{N_B} \quad (\text{heating})$$

$$L_{C,B} = \frac{L_{C,T}}{N_B} \quad (\text{cooling})$$

With N_B = number of boreholes connected to the heat pump system

HC_D (TC_D) = heat pump heating (cooling) capacity at design heating (cooling) conditions, W

COP_D = coefficient of performance at design heating conditions, dimensionless
 EER_D = energy efficiency ratio at design cooling conditions, dimensionless
 R_B = borehole thermal resistance, m.K/W
 R_G = steady-state thermal resistance of ground surrounding the borehole, m.K/W
 P_M = multiplier to account for pipe diameter other than ¾ inch (1.905cm), dimensionless
 S_M = multiplier to account for trench spacing, dimensionless
 F_H, F_C = run fraction in heating (cooling) mode during heating (cooling) design month (Jan. or July), dimensionless
 $T_{S,L}, T_{S,H}$ = design soil temperature for heating (cooling) at average horizontal GHEX pipe depth, K
 EWT_{min}, EWT_{max} = minimum (maximum) entering water temperature at heating (cooling) design conditions, K
 LWT_{min}, LWT_{max} = minimum (maximum) leaving water temperature at heating (cooling) design conditions, K
IGHSPA standard specifies a minimum pressure rating of 11 bar (160 psi) for horizontal ground loop piping, which requires a maximum DR ratio of 11 for PE3408 pipe and has a thermal resistance of 0.08 m.K/W

Design soil temperature

Horizontally-bored GHEX piping systems can be buried at any depth, but piping closest to the ground surface should be at a minimum depth of 1.8 to 2.4 meters, with 4.5m being a recommended minimum depth to achieve a depth where soil temperatures remain fairly constant throughout the year. Due to the horizontal nature of horizontally bored GHEX piping systems, a large surface area is required to contain the GHEX footprint. Many times the required length of horizontally-bored GHEX cannot be fit on the property at one depth and a second (or third) layer of horizontal bores may be required to provide the necessary heating or cooling ground load for the installed heat pump capacity. If multiple-pipe layers are to be utilized, then it is recommended that the first pipe layer be located at a minimum 4.5m depth and a minimum 4.5 center-to-center spacing between loops (both vertically and horizontally) be utilized as a starting point for design to reduce the thermal interference between loops in the horizontal grid. If the average burial depth of two or three borehole layers is below 6m, then the design soil temperature ($T_{S,L}$ and $T_{S,H}$) can be estimated as the described in section 5.3.1.

Thermal properties of the ground and ground thermal resistance

Ground thermal resistance (R_G) can be calculated according:

$$R_G = \frac{\ln(\frac{D_{g,0}}{D_p})}{2\pi k_g}$$

Where k_g is the thermal conductivity of ground around the pipe, $D_{g,0}$ is the diameter of ground surrounding the pipe affected by heat transfer, and D_p is the diameter of the pipe.

Borehole thermal resistance R_B

Heat transfer from the pipe to the borehole wall does not depend on the orientation of the borehole, and the discussion for vertically-bored GHEX piping systems applies equally well to horizontally-bored GHEX piping systems.

Ground loop resistance

Ground loop resistance represents the total resistance to heat transfer at design heating or cooling conditions between the circulating fluid in the pipe and the design month earth temperature at the average depth of GHEX piping system burial, defined as ($R_B + R_G F_H$) and ($R_B + R_G F_C$). The ground loop resistance includes the effects of borehole thermal resistance (pipe size and geometry in the borehole, the grout thermal conductivity, and borehole diameter), ground thermal resistance (soil thermal conductivity and borehole diameter), and the run fraction for the design heating or cooling month. To simplify the determination of ground loop resistance, tables have been constructed (see IGHSPA 2009, pp5-85 to 5-87), which express ground loop resistance as a function of run fraction in heating (F_H) or cooling (F_C) soil thermal conductivity (k_{soil}), borehole diameter (DB) and grout thermal conductivity (k_{grout}) for nominal U-bend diameters of ¾ -inch (1.905cm). Interpolation between tabled values is acceptable. Care must be used when extrapolating beyond tab led values, especially on the low end of the tab led variables.

Unbalanced correction factor (B_M)

If the average depth of the horizontally-bored piping system is deeper than about 2.4m (below which ambient weather conditions at the ground surface will have little effect on the energy balance in the ground surrounding the buried GHEX piping) then application of the unbalanced ground load correction factor is highly recommended and becomes more important as the average depth of the piping system increases. The bore length multiplier (B_M) is based on the net annual ground energy adjusted for the design heating or cooling length and the temperature difference between the loop and the ground (the Normalized Net Annual Ground Load - NNAGL), the thermal properties of the soil and rock surrounding the GHEX, the spacing of the boreholes along a row, and the number of rows in the bore field. B_M -values for soil and rock thermal conductivity/diffusivity combinations of 1.2-0.04; 1.7-0.054; 2.25-0.067; 2.8-0.08; 3.3-0.09; and 3.8-1.11 (W/mK – m²/day) are provided in the IGHSPA (2009) manual.

Design sheets

Proper design of a horizontally-bored GHEX requires reliable heating and cooling load design data and heat pump selection; consideration of domestic hot water generation; specification of horizontal loopfield design parameters; proper layout of the horizontal borefield; application of the heating or cooling design equations to determine the required borehole lengths; and adjustment for unbalanced annual ground loads to assure long-term GHEX performance.

Worksheets are provided in IGHSPA (2009) to document the selection of the water-to-air or water-to-water GSHP units for the design space heating or cooling loads. Part of the heat pump selection is based on specification of the minimum and maximum entering water temperatures from the vertical GHEX, along with the water flow rate that the GHEX must accommodate, each of which are critical parameters in the proper design of the horizontal GHEX system. Hot water generation, by either a dedicated water-to-water GSHP or a desuperheater in the space heating and cooling GSHP, will affect the horizontal loopfield design, and procedures are provided in IGHSPA (2009) to account for hot water generation. Layout of the horizontal borefield, in terms of number of horizontal bores, U-bend diameter, and maximum boring length are considered to accommodate required water flow rate to achieve proper turbulence for heat transfer in a heating dominant design and to control head loss to keep pumping power at an acceptable level at heating or cooling design conditions. Application of the appropriate borehole design length equation using design data for the ground and borehole results in the required total length of horizontal borehole for heating or cooling. Adjustment of that length may be required for an unbalanced annual ground energy load.

In an effort to simplify the design of the horizontal GHEX and provide a method to easily document the design, worksheets have been developed for both heating mode dominant and cooling mode dominant design in IGHSPA (2009). The worksheets are broken into sections to allow input for heat pump design and energy analysis data, domestic hot water generation, borefield layout, design data for the horizontal GHEX, calculation of the total borehole design length, and adjustment for unbalanced annual ground energy load. Additional calculations can be made to refine the horizontal GHEX design lengths in a table at the bottom of each worksheet.

5.4. Case histories

Op het internet (bv. www.retscreen.net) zijn enkele case studies voor kleinere toepassingen te vinden. Details van installatie en rendement worden echter niet gegeven.

Meer gedocumenteerde voorbeelden i.v.m. grotere toepassingen zijn weergegeven in

- Banks (2008)
- Said et al (2009)
- Naili et al. (2012).

The Green House, Annfield Plain (zie Banks 2008): The Green House is a major 3000 m² modern office complex in a former coalmining area of County Durham, UK. Most of the available land area around the building was used to install a huge network of horizontal slinky trenches (fifteen 55 m long slinky trenches, containing a total of 6500 m pipe, to deliver peak loads of 80 kW heating and 30 kW cooling; ie. 10 m trench per 1 kW installed capacity). It proved difficult to integrate this work with the rest of the construction process, and to protect loops and manifolds from wandering excavators and bulldozers