Deep Boreholes for Ground Source Heat Pump Systems – Scandinavian Experience and Future Prospects

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ABSTRACT

Ground source heat pump (GSHP) systems are commonly used in Sweden for both residential and commercial buildings. However, there are several key differences compared with GSHP systems utilized in the USA. Scandinavian systems are often heating-only, and instead of using grouted boreholes, groundwater-filled boreholes are often used. These boreholes are cased from the ground surface to the usually shallow bedrock. A single or double U-tube is commonly suspended in the borehole. These boreholes are often deeper than those commonly used in the USA. The average borehole depth has increased over time, and the average borehole depth for ground heat exchangers installed in 2013 in Sweden was 171 m (561 ft.) Boreholes as deep as 250-300 m (820-984 ft) are not uncommon and there is interest among installers of using even deeper boreholes. Incentives for deeper boreholes include limited area for drilling, pre-existing boreholes on neighboring properties, and deeper-than-usual layers of soil and unconsolidated rock.

This paper reviews current Scandinavian practice for borehole design and discusses installations with boreholes 300 m (984 ft) deep or deeper. Aspects of the design include using larger pipe sizes or double U-tubes to keep pressure losses acceptable, larger borehole diameters to accommodate the larger pipe sizes, increased short-circuiting due to the long lengths, and design temperatures for heating-dominant systems due to the geothermal gradient.

INTRODUCTION

Approximately one fifth of the two million single-family houses in Sweden are today heated with a ground source heat pump (GSHP) (Gehlin et al. 2015). The typical domestic GSHP is a 5-10 kW (17,060-34,120 Btu/hr) capacity heat pump connected to a 100-200 m (328-656 ft) deep vertical groundwater-filled borehole in hard rock. Ground heat exchangers used in Scandinavia are commonly closed-loop systems, fitted with a single U-tube. The uppermost 6 m (20 ft.) or more of the borehole is cased with a steel casing and sealed to the bedrock to protect the groundwater from surface pollution (SGU 2008).

According to the Swedish Geological Survey Well Database, the average borehole depth for GSHP systems has increased from 100 m (328 ft.) in 1995 to 171 m (561 ft.) in 2013 (Gehlin et al. 2015) (see Fig. 1). For single-family houses the increasing borehole depth is a result of more efficient heat pumps, as well as the trend to utilize GSHP with higher installed capacities to avoid the use of auxiliary heating by electric resistance heaters.

The trend towards deeper boreholes is however more pronounced for commercial GSHP systems, where there

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is space, time and money to save by drilling fewer but deeper boreholes. Large GSHP systems in Scandinavia are now commonly drilled to a depth of 200-300 m (656-984 ft.). The three largest GSHP systems in Scandinavia today are Akershus Hospital, Norway, with 228 boreholes to a depth of 200 m (656 ft.), Karlstad University Campus, Sweden, with 204 boreholes of 240-250 m (787-820 ft.) depth, and SOK Logistic Centre in Sibbo, Finland, with 150 boreholes to 300 m (984 ft.).

Incentives for deeper boreholes include limited area for drilling, pre-existing boreholes on neighboring properties, and deeper-than-usual layers of soil and unconsolidated rock. For pure heat extraction systems there is also an interest in taking advantage in the increased temperature with depth, due to the geothermal gradient, however, as is shown in this paper, this issue is not as simple as some tend to believe.

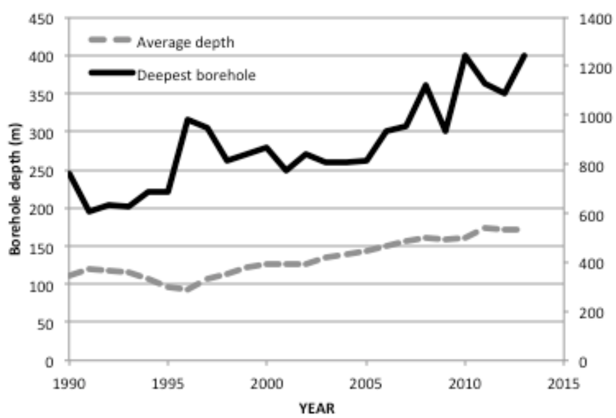

Figure 1 Average borehole depth and deepest borehole, from SGU Well Database (Gierup 2015).

This paper reviews current Scandinavian practice for borehole design and discusses technical, thermal and economic considerations with boreholes drilled to 300 m (820 ft.) depth or more. Aspects discussed include using larger pipe sizes or double U-tubes to keep pressure losses acceptable, larger borehole diameters to accommodate the larger pipe sizes, increased short-circuiting due to the long lengths, and design temperatures for heating-dominant systems due to the geothermal gradient.

SCANDINAVIAN DESIGN OF GSHP BOREHOLES

The typical Scandinavian GSHP design and design conditions differ from GSHP systems in many other countries. This has to do with climatic and geological conditions, as well as issues related to building codes and other regulations, energy source availability and pricing.

Geological and Climatic Conditions

The Swedish geology is predominantly crystalline rock with shallow overburden, generally high quartz content, and high thermal conductivity. Groundwater level is generally high (a few meters below the ground surface). There are areas with rich overburden and sedimentary deposits, mainly in the south and middle parts of Sweden and on the islands Öland and Gotland. Similar conditions with predominantly crystalline rock and high groundwater levels are found in Norway and Finland. The Swedish Geological Survey (SGU) has provided guidelines for construction of wells for GSHP systems since 1997(SGU 2008), and collects data on all groundwater wells and GSHP boreholes in Sweden through the Well Database.

The Swedish well construction guideline requires steel casing of the uppermost part to a minimum depth of 6 m (20 ft.) and with at least 2 m (7 ft.) drilled into hard bedrock and sealed with concrete. The guidelines allow for ungrouted, groundwater-filled boreholes, which is how the vast majority of Scandinavian borehole heat exchangers are constructed.

The Scandinavian climate is heating dominated, but for commercial GSHP systems both heating and cooling are used. Average ground temperature varies between 11°C (51.8°F) in the south and 2°C (35.6°F) in the north.

Design Conditions

Scandinavian GSHP systems are generally designed for a minimum design EFT of 0°C (32°F), though in the northern part of Sweden the minimum temperature may be allowed to fall below 0°C (32°F). Boreholes are allowed to freeze at maximum heating load conditions.

Closed-loop single U-tubes are the most commonly used collectors, though for commercial GSHP systems double U-tubes are often used. Tube size is typically 40x2.4 mm (1½") PN10 SDR17 PE100 for single U-tubes and 32x2.0 mm (1¼") PN10 SDR17 PE100 for double U-tubes. Coaxial ground heat exchangers have been used occasionally. A 20-28% ethanol/water solution is predominantly used as heat carrier fluid in the collector pipes.

DEEP BOREHOLES

Boreholes for deep geothermal use (direct use and power production) have limited potential in Scandinavia. The market is completely dominated by shallow geothermal energy systems such as typical GSHP systems with vertical boreholes in rock. These boreholes are rarely drilled deeper than 300 m (984 ft.) in Scandinavia, and less than that in central Europe and North America. Hence experience from ground heat exchangers in boreholes deeper than 300 m (984 ft.) is scarce. Rybach and Hopkirk (1995) discuss two converted "dry" geothermal boreholes in Switzerland. The 1700 m (5577 ft.) borehole at Reinach, near Basel, and the 2300 m (7546 ft.) deep borehole at Weggis are both used for heating of buildings. They conclude that the economics depend not only on the size and proximity of the energy user, but also on the temperature at which heat is to be delivered. They also conclude that failed geothermal or hydrocarbon exploration boreholes are feasible to use for GSHPs provided that the full drilling cost is not included. Kohl et al. (2002) also cover the Weggis borehole and Kohl et al (2000) describe the performance over two consecutive years of operation of a 1200 m (3937 ft.) deep borehole that was drilled in the early 1990's in Weissbad, Switzerland. The borehole was initially meant to reach a waterfilled fracture for deep geothermal heat extraction, but the formations proved to be dry, and the project was abandoned. Instead a borehole heat exchanger was installed to use the borehole with a GSHP. The temperature at the bottom of the borehole was measured at 45°C (113°F). Huchtemann and Müller (2014) and Dijkshoorn et al. (2013) treat a 2500 m (8202 ft.) deep borehole with a coaxial borehole heat exchanger for space heating and cooling of a university building in the city Aachen, Germany.

More recent examples of deep boreholes drilled purposely as borehole heat exchangers are reported from Switzerland and Norway. In mid-March 2015, a European geothermal drilling company reported (De Varreux 2015) that they had installed their first 750 m (2460 ft) deep borehole heat exchanger ("geothermal probe") in Lausanne, Switzerland. The borehole is the first in a series of 150 deep borehole heat exchangers to be installed during the period 2015-2018 to provide district heating to a new housing and commercial complex area. The heat exchanger was a HPR (high pressure) PN80 double U-tube with outer diameter 50 mm (2"). In 2014 the same company installed eight borehole heat exchangers to a depth of 500 m (1640 ft.), heating 64 apartments in four buildings (De Varreux 2015). Schwenke (2013) describes the Skoger School project in Drammen, Norway, which is heated by five boreholes of 500 m (1640 ft) depth. The boreholes are fitted with single U-tube collectors with OD 50 mm (2") and ID of 44 mm (1.7"). The borehole has a diameter of 140 mm (5.5").

Holmberg et al. (2015) show results from numerical model simulations of borehole heat exchangers of 600 m (1969 ft), 800 m (2625 ft) and 1000 m (3281 ft) depth. The borehole is fitted with a coaxial heat exchanger consisting of a central polypropylene pipe and an outer thin polyethylene liner, as described in more detail by Acuña (2013). The simulations are done to describe performance over time, and to determine average specific thermal load and energy extracted. A geothermal gradient of 0.02 K/m (0.006 K/ft.) was used. The authors conclude that deep borehole heat exchangers can sustain a higher average specific heat load than conventional borehole heat exchangers due to the higher temperature level in the borehole, and that deep boreholes may be suitable for GSHP installations in areas with limited space and negatively balanced load profiles.

Pipe and Pressure Considerations

The difference in density between the borehole filling and the heat transfer fluid in the piping may be an issue in deep boreholes. If the heat transfer fluid has a lower density the resulting external pressure on the pipe may cause buckling. Common SDR-17 polyethylene pipes can withstand an external pressure of 1.4 bar (20.3 psi) whereas SDR-11 pipes can handle 5.7 bar (82.7 psi) before buckling (Kalantar 2015). Figure 2 shows the differential pressure versus depth for three combinations of heat carrier fluid and borehole filling. The worst-case for a groundwater-filled borehole occurs when a less dense antifreeze mixture is used – as shown in Figure 2, it's possible that there is a risk of buckling when SDR-17 is used and borehole depth exceeds 300 m (984 ft).

However, although the vast majority of boreholes in Scandiavia are groundwater filled, there are situations where grouting is required. During the grouting process the grouting mixtures are heavier than the heat transfer fluids and will cause an external pressure on the pipe. Available grouting mixtures vary in density from 1100 to 2000 kg/m^3 (69-125 lb/ft^3) during injection, where the heavier materials usually have higher thermal conductivities. As shown in Figure 2, differential pressures significantly exceed buckling limits for thermally-enhanced grout, regardless of the heat carrier fluid. It is common practice to use pressurized SDR-11 pipes for grouted boreholes, but even then, it may be impossible to safely grout the borehole in one step without allowing part of the grout to set up. A multi-step grouting process adds complexity and costs.

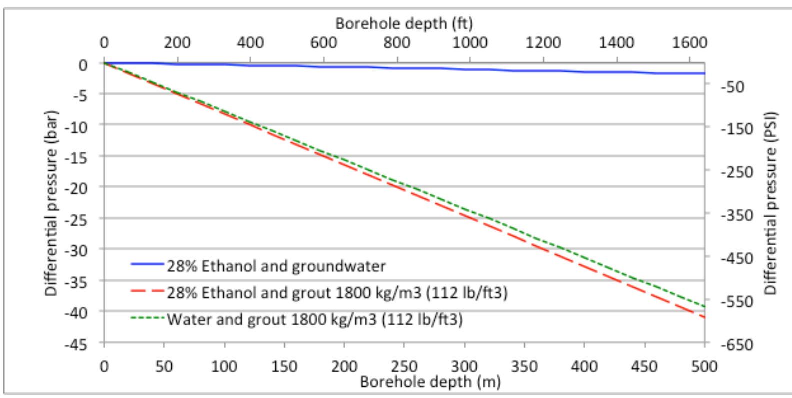

Figure 2 Differential pressure in borehole with un-pressurized pipes.

Pipes are installed in the borehole when the ground temperature is at undisturbed conditions. In groundwater filled boreholes the pipe will expand or contract due to heating/cooling during operation. If the pipe is heated to temperatures above those experienced during installation, the expansion may cause the U-bend to repeatedly push against the bottom of the borehole. This has occasionally led to failure of the pipe. The linear coefficient of thermal expansion for PE100 is $1.3 \cdot 10^{-4}$ m/m·K (ft/ft·K), which means that a 300 m (984 ft) pipe will change 0.6 m (1.9 ft.) in length when changing temperature from 0°C (32°F) to 15°C (59°F), while a 500 m (1640 ft) pipe will change approximately 1 m (3.28 ft.). Therefore, care must be taken to suspend the U-tube higher in deeper boreholes.

Considerations Related to Drilling

The governing drilling techniques for GSHP borehole drilling in Scandinavia today are air-driven or water-driven down-the-hole-hammer (DTH) drilling. With common compressors suitable for urban use, of up to 35 bar (507.6 psi), and lift capacity of 50-70 kN (5.62-7.87 tons) for air-driven DTH drilling, the theoretical maximum borehole depth is 300 m (984 ft.), where the counter pressure from groundwater will be too high for the hammer to work. For water-driven DTH drilling, there is no counter-pressure from groundwater, but a limiting factor is flow losses to fractures in the rock. Even larger DTH drill rigs with capacity of DTH drilling to 800 m (2625 ft.) depth exist in limited numbers, but are infeasibly large for urban drilling.

GSHP boreholes are usually produced at low-cost with small demands on drilling precision. The deviation from targets depends partly on drilling speed and to some extent on the geological structure. The deviation increases with depth, and is not linear. This means the risk for intersecting another borehole increase with borehole depth. Higher demands on precision involve smaller tolerances, increased material cost and fuel consumption, and decreased overall rate of penetration, leading to higher costs for deep boreholes.

Thermal Considerations

The heat energy budget for the subsurface is largely a balance between the surface boundary conditions and geothermal heat flux from the centre of the earth. Insolation varies with time and location, but for Scandinavia the average annual net insolation is on the order of a 100 W/m² (31.7 BTU/hr/ft²), while the geothermal heat flux is in the range of 0.04-0.09 W/m² (0.013-0.029 BTU/hr/ft²) (Banks 2012). Hence the contribution to GSHP systems from geothermal heat is small compared to that of insolation. The geothermal heat flux causes a thermal gradient that is superimposed on the annual average ground surface temperature, increasing the ground temperature with depth. In Scandivanian bedrock the geothermal gradient is on the order of 1-3°K per 100 m (0. 3-0.8°K per 100 ft). That means that if the annual average ground surface temperature is 10°C (50°F) and the geothermal gradient is 1.5°K/100 m (0.0046°K/ft.), then the temperature at 300 m (984 ft.) depth will be 14.5°C (58°F) and at 500 m (1640 ft.) depth it will be 17.5°C (63.5°F).

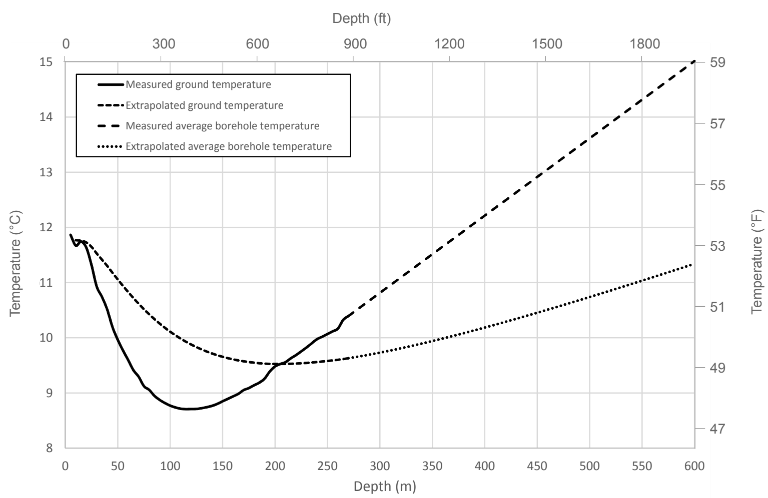

Figure 3 Measured ground temperature in a 270 m (886 ft.) deep borehole at Norra Frescati, Stockholm..

In urban areas (where deep boreholes are of the most interest) heat leakage from buildings can significantly impact the temperature profile along the borehole. The building footprint provides a stable heat flux from the building to the ground. The thermal front may reach more than 100 m (328 ft.) below the surface depending on how many years buildings have existed on the site. In Figure 3 the ground temperature was logged at 5 m (16 ft.) intervals down a 270 m (886 ft.) borehole in Stockholm, where the average ground surface temperature for an undisturbed green field site would be 8°C (46°F). The measured temperature gradient is stable between 150 m (492 ft) and 270 m (886 ft). Above that, the temperature measurements show considerable influence of a nearby building, leading to 100 m (328 ft) deep "heat wave". Ground temperature and average ground temperature to depth are extrapolated below 270 m. The "heat wave" means that the presumed advantage of deeper boreholes (higher average ground temperature) can be difficult to realize on urban sites with disturbed ground temperatures. For example, on this site, a borehole 350 m deep would have approximately the same average temperature as a 100 m deep borehole.

All vertical ground heat exchangers are affected by short-circuiting – that is, heat transfer between the upward-flowing and downward-flowing legs of the heat exchanger. Though this is often negligible for typical boreholes, the short-circuiting effect increases as either the depth or conductance between the legs increases and/or as the mass flow rate in the heat exchanger decreases. (I.e. there is a direct relationship between the short-circuiting heat transfer and the number of transfer units (NTU) as there would be for any heat exchanger. With regards to short-circuiting heat transfer we prefer a very low effectiveness, though). As with conventional heat exchangers where the LMTD or ε-NTU approaches may be used, multiple approaches to analyze this problem may be utilized. Marcotte and Pasquier (2008) and Beier et al. (2012) suggested approaches for estimating the mean temperature difference. Hellström (1991) derived expressions (*cf.* pp. 94-99) that give an effective borehole thermal resistance that includes the thermal short-circuiting effect. See also Claesson and Hellström (2011). These expressions are derived for two idealized boundary conditions – the borehole wall being at a uniform temperature and the borehole having a uniform heat transfer rate – neither of which applies perfectly. A mean value between the two expressions can be taken as a best approximation. Both expressions are formulated to give the ratio of the effective borehole thermal resistance to the local or two-dimensional borehole thermal resistance (R_b). These two expressions are calculated for an otherwise-typical groundwater-filled borehole where the flow rate has been fixed at 3.1 m³/h (13.65 GPM) and the results are shown in Figure 4. As can be seen there, at 100 m (328 ft), the ratio is less than 1.02, so the short-circuiting has less than a 2% effect on the effective borehole thermal resistance. However, for deep boreholes the short-circuiting effect can increase significantly if the flow rate is not increased proportionally.

Apart from the short-circuiting effect inside the borehole, which increases with depth, the temperature difference between the top and the bottom of the borehole will to some extent counteract the initial benefit of the geothermal gradient. During heat extraction, the heat transfer fluid will increase in temperature as it travels from top to bottom, and will be warmest at the U-bend. On its way up, the fluid will at some point along the borehole reach a level where the surroundings are colder than the fluid, and hence the fluid will start rejecting heat to the ground. This point occurs where the local borehole temperature equals the current average borehole temperature, and will change over time, moving upwards, as the borehole temperature evens out. This effect will be increasingly significant for deeper boreholes.

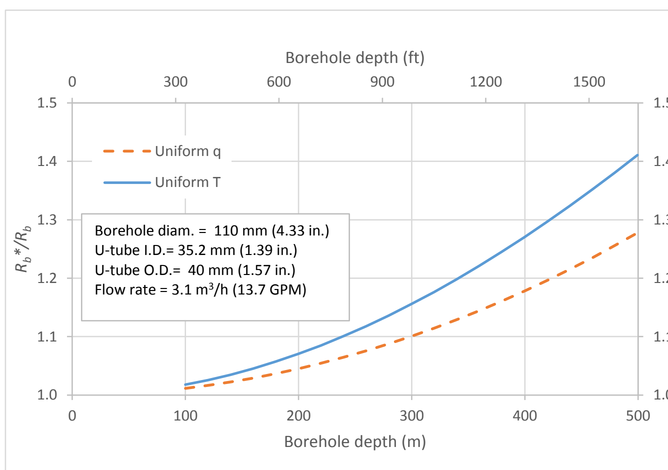

Figure 4 Effect of thermal short-circuiting on effective borehole thermal resistance.

Head Loss Considerations

Another aspect of deep borehole design is the possibility for excessive pressure loss leading to high circulating pump energy consumption. In order to keep the pressure drop reasonable, large diameter U-tubes and/or double U-tube heat exchangers may be needed, and, consequently, larger diameter boreholes may also be necessary. As an example, consider a case with a nominal design heat extraction rate of 40 W/m (41.6 Btu/hr/ft) where the design flow rate is chosen so that a 4°C (7.2°F) temperature difference across the ground heat exchanger is maintained. Pressure drops under design conditions have been calculated for single (1U) and double (2U) U-tubes made from SDR-17 HDPE with outer diameters of 40 mm (1.57 in.) and 50 mm (1.97 in.). The pressure drop vs. borehole length for the heat exchangers are compared in Figure 5 to Mescher's (ASHRAE 2011) criterion that a properly designed borefield should be kept to less than 25 ft (7.6 m) of head loss with a total system pressure drop of maximum 50 ft (15.2 m). As the borehole gets deeper, it is harder and harder to meet the criteria and even the larger diameter double U-tube fails to meet the criterion at 500 m (1640 ft).

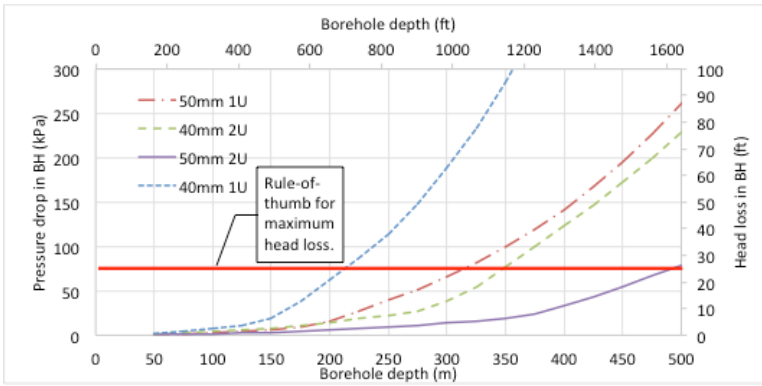

Figure 5 Pressure drop for 40 mm (1.57 in.) and 50 mm (1.97 in.) single and double U-tubes.

Economic Considerations

The cost per drilled meter is not a linear function. There is first of all a setup cost for each borehole. The uppermost steel cased 6 m (20 ft.) or more through the overburden and at least 2 m (7 ft.) into bedrock is 3-5 times more expensive per unit than the un-cased borehole below. In theory the real drilling cost increases exponentially with depth due to increasing energy use and wearing of the drill bit. At a certain depth, depending largely on the hardness of the rock, the drill bit must be recovered and changed due to wearing. This procedure is time consuming and increasingly complicated as the borehole depth increases. The risk for complications along the borehole due to borehole deviation, clogging of the borehole, etc., increases with increasing depth. For practical reasons most drillers charge the same price per unit of length down to at least 200 m (656 ft.). For deeper intervals an estimate of additional cost would be in the order of 10% for the following 50 m (164 ft.), and around 20% if the borehole be drilled deeper (Geotec 2015). Drill rigs used for oil drilling use a different technique - decidedly more expensive than DTH drilling.

CONCLUSIONS

As Scandinavian GSHP boreholes tend to be drilled to increasing depth, there are a number of factors to consider in evaluating the benefits of deeper boreholes. Typical reasons for drilling to greater depth include reaching higher temperatures due to the geothermal gradient, decreasing the number of boreholes so that less upper steel casing is needed, and being able to use smaller land areas for the well field in urban areas. These advantages can be offset by several factors. The thermal efficiency of the deeper heat exchanger is negatively influenced by increasing thermal short-circuiting between the upward and downward channels, as well as the temperature gradient itself, causing increased heat losses from the heat transfer fluid on its way to the surface. For urban sites, the ground temperature profile may deviate significantly from the undisturbed case, such that average ground temperature does not increase with depth as quickly as anticipated. Installation costs per unit length of borehole may be significantly higher due to increased drilling and grouting costs. Another complicating factor is the increased pressure drop, which will, even for larger pipe sizes and double U-tubes, make it difficult to keep pump energy consumption suitably low, as the depth approaches 500 m (1640 ft.). Complications with thermal efficiency, actual temperature profiles and pumping energy must be carefully considered in any deep borehole design. Likewise, for situations where available surface area is scarce, deep boreholes may or may not be a good solution, but the economics with increased drilling and installation costs must also be considered.

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