Shallow Geothermal Energy: An Emerging Technology

Guillermo Andres Narsilio and Lu Aye

Abstract Shallow geothermal energy systems use the upper few metres of the ground below the surface to provide space heating and cooling efficiently. Well-designed systems render year-round coefficient of performance (COP) of about four or more. In closed-loop geothermal systems, high-density polyethylene (HDPE) or cross-linked polyethylene (PEX) pipes are embedded in trenches, boreholes or into geostructures (e.g. piles) to form ground heat exchangers (GHEs), whose function is to access this sustainable geothermal energy. A large proportion of electricity worldwide is generated from fossil fuels. Substituting commonly used electric heating and cooling systems with shallow geothermal ones could significantly decrease peak energy consumption and greenhouse gas emissions given their high COPs and high primary energy ratios. This chapter summarises the fundamental principles of the technology, the various factors that affect the thermal performance of different types of GHEs and their impacts on the capital and operating costs of geothermal systems. In addition, this chapter provides an overview of what the future might hold in terms of using geostructures with a dual purpose, as load-bearing-buried structures and as GHEs. Consideration is given to common design methods and an example is presented using a simplified design method. The chapter highlights the importance of directing additional efforts in research and development of the performance of ground loop systems.

Keywords Ground-coupled heat pumps · Energy efficiency · Ground heat exchangers · Sustainability · Greenhouse gas emission reduction

G. A. Narsilio
Geotechnical Engineering, Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Melbourne, VIC 3010, Australia

L. Aye (✉)
Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Melbourne, VIC 3010, Australia
e-mail: lua@unimelb.edu.au

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1 Introduction

The previous chapters have let readers see that there exists and will continue to persist for some time, an inexorable increase in global energy demand driven by world population growth and the desire to pursuit a higher 'quality of life'. Indeed, the human population and associated annual energy consumption per capita have grown at exponential rates since the industrial revolution (Glassley 2010). This growing demand may be satisfied by either increasing energy supply, for example, by using the low-carbon energy supply technologies such as the ones presented in this book (or by finding new ways to exploit once uneconomical oil and gas reservoirs) or by good management and reducing demand for energy. Better yet, the energy and environmental dilemma may be addressed by a combination of these two sides of the equation, increasing energy supply while reducing (deaccelerating really) demand. Finding renewable energy sources with low greenhouse gas emissions and using energy-efficient technologies help tackling both sides of the energy problem. Therefore, the long(er)-term solution relies on slowing down and hopefully reducing global energy demand and the use of fossil fuels.

Geothermal energy is a vast and adaptable resource that can help satisfying the aforementioned needs. Geothermal energy can be used for power generation as well as for the provision of space heating, space cooling and hot water to residential, commercial and industrial buildings (de Moel et al. 2010; Glassley 2010; Johnston et al. 2011).

If one put aside those volcanic regions where geothermal energy is readily available near the surface, then geothermal energy can be harnessed in two different forms (Fig. 1). The first form generates electricity with turbines that use the heat extracted using water from kilometre deep boreholes that reach strata where temperatures exceed 175 °C. This heat source has tremendous potential, and steady progress has been made to aim producing electricity on a commercial scale. The other form, which is well established outside Australasia, uses the ground to provide year-round efficient space heating and cooling, and sometimes domestic hot water as well (Amatya et al. 2012; Banks 2008; Brandl 2006; Preene and Powrie 2009; Loveridge and Powrie 2014). This chapter focuses on the latter form, also known as *ground source heat pump (for heating), ground-coupled heat pump (for heating and cooling), geoexchange* or often times just referred to as *shallow geothermal energy* technology.

Shallow geothermal energy technology can contribute to lower or smoothing peak electricity demand. This shift in reducing demand instead of increasing supply has driven industry and researchers around the world in developing analytical and numerical models to help predict, and thus design and optimise, these systems. For the geotechnical and geoenvironmental community, this concerns the thermo-geomechanical response of the ground to the exchange of heat, and the pursuit of smaller, cheaper and more efficient ground heat exchangers (GHEs) since the main barrier to shallow geothermal systems is usually high initial capital costs associated with the drilling needed for the installation of GHEs. Professor Brandl in

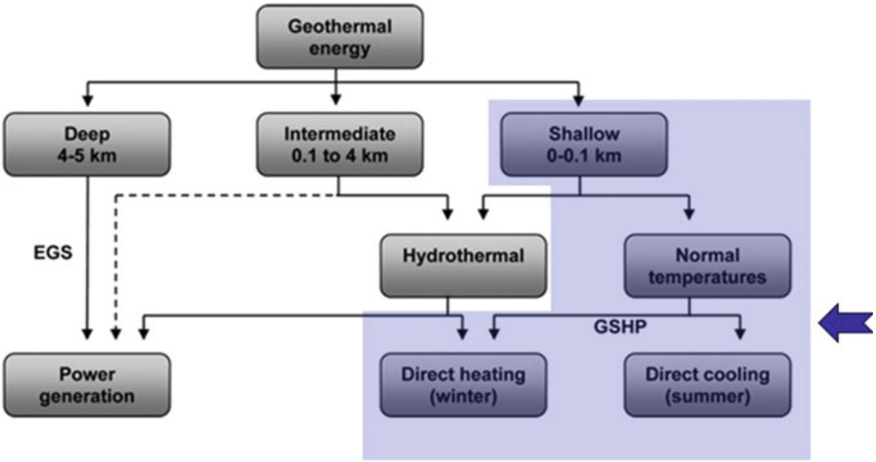

Fig. 1 Geothermal energy: power generation versus heating and cooling. This chapter focuses on the latter technology

his Rankine Lecture (Brandl 2006) promoted the use of any geostructure in contact with the ground (e.g. structural piles) to be used as GHEs. Current trends in research points towards using not only piles as heat exchangers (i.e. energy piles or energy foundations), but retaining walls, tunnel linings, parking lots and even roads. This strategy may significantly reduces the capital costs of geothermal systems. GHE research has accelerated in the past 5–10 years. During this time, two complementary research efforts have been pursued. One focused on the geomechanical considerations of using load-bearing geostructures; and another focused purely on the thermal performance, in order to better understand and maximise the energy transfer between the ground and the GHEs (thus potentially reducing drilling costs).

For an effective shallow geothermal system design, the thermal performance of GHEs should be predicted accurately. A summary of the most commonly used existing analytical solutions and some of the most practical numerical models for simulation of vertical GHEs can be found in Loveridge et al. (2018). In this chapter, we introduce the technology and present key aspects related to the current design of GHEs and recent developments in this area.

2 Shallow Geothermal Energy Systems

In *shallow geothermal energy* systems, the ground within a few tens of metres from the surface is used as a heat sink in summer and/or as a heat source in winter for cooling and heating buildings (Fig. 2) (Johnston et al. 2011; Narsilio et al. 2014). Within about 100–200 m of the surface, the ground temperature is typically close to

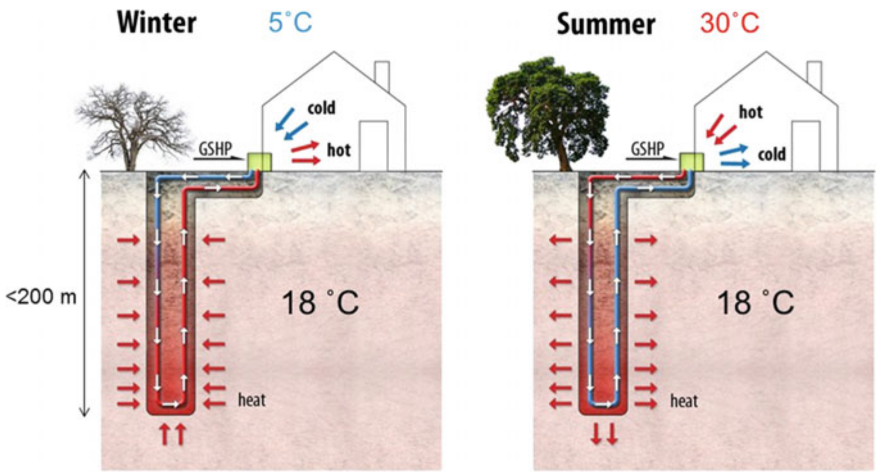

Fig. 2 Schematic of a shallow geothermal energy system in heating (winter) and cooling (summer) modes. Typical temperatures of a temperate climate. Figure not to scale

the mean atmospheric temperature, much below the 175 °C temperatures normally required for power generation.

To illustrate this important feature of shallow geothermal energy systems, Fig. 3 shows ground temperatures measured for approximately 2 years at an experimental site in Parkville, Victoria (the University of Melbourne's main campus in Australia). The figure depicts the naturally occurring ground temperatures variations at the site. While the ambient air temperature in Melbourne varied between 2.3 and 41.1 °C over the 2 years shown in Fig. 3, below about 10 m, the ground temperature was relatively constant at 18.6 °C, making the ground a good sink or source of heat throughout the year (Colls 2013; Colls et al. 2012).

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In general, ground temperature is influenced by solar radiation and ambient air temperature up to approximately 5–10 m of depth depending on the soil and/or rock conditions. Daily and seasonal temperature fluctuations can be significant. Bellow these depths, the average thermal gradient arises primarily from the heat within the Earth's core, and is between 20 and 30 °C increase per kilometre (Banks 2008). As a result, the ground temperature within the first couple of hundred metres below the ground surface is considered constant for all practical purposes and is in principle close to the local mean annual ambient air temperature. Consequently, the ground

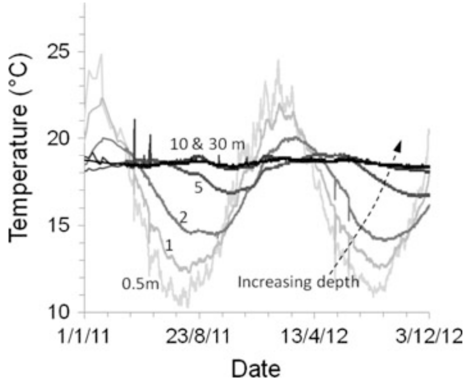


Fig. 3 Measured ground temperatures (at selected depths) over time in Parkville, Victoria (Australia). Data from Colls (2013)

tends to be warmer than the ambient air during winter and cooler during summer. This statement is true regardless of geology and location (except for volcanic regions where the Earth's ground heat fluxes are stronger).

3 Key Components

In shallow geothermal energy systems, three key components can be identified: (i) the primary circuit, (ii) the ground-coupled heat pump (GCHP), and (iii) the secondary circuit. These two main circuits are connected via the ground-coupled heat pump. The primary or ground circuit comprises the ground heat exchanger (GHE) system. The GHE system is in close contact with the ground to facilitate extraction or rejection of heat via the selected carrier fluid. The secondary circuit is located within the building or industrial process that requires to be heated or cooled, and where this thermal energy is distributed.

The GCHP interfaces between these two circuits. In winter, the GCHP extracts heat from the carrier fluid circulating in the ground loops (typically water), it upgrades the heat, and it delivers it to the building that requires heat. The return cooled fluid is reinjected into the ground loops to heat up again and complete the cycle. In summer, the reverse happens with the GCHP extracting unwanted heat from the building and rejecting it to the ground. Thus, the GCHP moves and upgrades heat between the building and the ground via GHEs, and it does so very efficiently due to the year-round narrow temperature range of the ground closer to applied loads.

Both circuits should be carefully designed considering the technical specifications of the link between the two (i.e. the ground-coupled heat pump). A brief description of the primary circuit, as the main component that differentiates shallow geothermal systems from other more common heating and cooling systems, and the basic functioning principles of heat pumps are included next. Fewer details are included in this chapter regarding the secondary circuit, because in most cases, it is treated and designed following standard guidelines common to air-source heat pumps and other conventional heating and cooling systems.

3.1 Primary Circuit: Ground Heat Exchangers (GHEs)

Either open- or closed-loop systems can be used when designing a shallow geothermal system (Preene and Powrie 2009). In open-loop systems groundwater is used directly as the heat transfer fluid, while in closed-loop systems a heat transfer fluid is circulated through absorber pipes embedded into the ground.

Open-loop systems can be used in sites boosting certain ground permeability and geochemistry (mineralogy) (among other considerations); closed-loop systems do not typically require any particular hydrogeological conditions and can be implemented almost anywhere since the circulating fluid is never in direct contact with the ground. In contrast, groundwater is pumped out of the ground and it is returned after heat has been exchanged in open-loop systems. Therefore, care must be taken in selecting the location of the return system, so that the groundwater intake temperature is not adversely affected. When hydrogeological conditions are favourable and large volumes of water can be handled, open-loop systems present major advantages over closed ones: they can be simpler and more efficient. However, clogging or bio-fouling in the wells and heat exchangers are some of the operational problems that open systems are prompted to. The temperature fluctuations cause minerals to dissolve and to re-precipitate leading to clogging (Brandl 2006). Additionally, maintenance costs tend to be higher in open-loop systems due to the use of submersible pumps. Given the potential environmental and operational concerns associated with open-loop systems, and the potential for widespread adoption of closed-loop systems, this chapter focuses on the latter.

Ground heat exchangers (GHEs) are typically designed in close-loop systems to be placed vertically or horizontally. HDPE or PEX pipe loops can be placed in (i) small diameter vertical boreholes that are between 30 and 200 m in depth (typically 100 m) (Fig. 4a), (ii) in trenches between approximately 1 and 2 m in depth, typically outside the footprint of the building to be serviced (Fig. 4b) or (iii) in any structure of residential, commercial and industrial buildings that are in intimate contact with the ground (e.g. the foundations) (Fig. 4c).

Typical borehole GHEs contain one or more U-shaped loops made of HDPE or PEX pipes and thermo-fused fittings. These are generically known as “absorber pipes” (Fig. 4). The heat is transferred between the ground and the heat carrier fluid contained in the absorber pipes primarily by conduction through the ground, the grout and the pipe walls. Convective heat transfer then dominates within the carrier fluid in the absorber pipes. In the case of horizontal GHEs, either U-shaped loops or “slinky” configurations are normally employed. The slinky configuration maximises the length of absorber pipe per linear metre of trench (Fig. 4b).

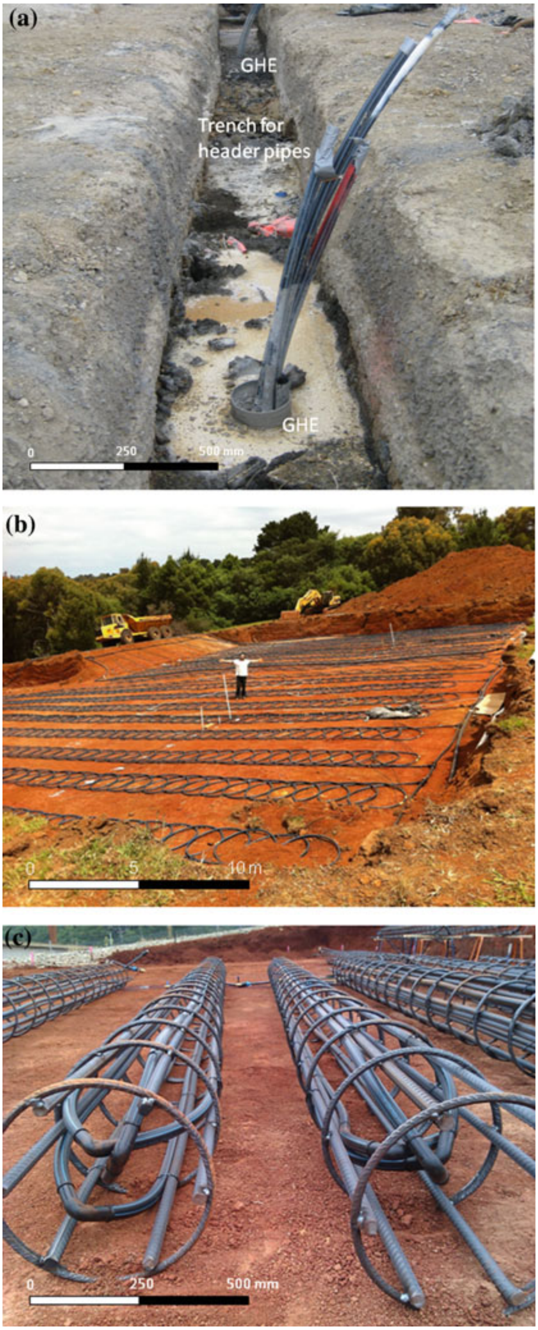


Fig. 4 Primary circuit. Examples of different types of closed-loop ground heat exchangers (GHEs) before backfilling/grouting/concreting: **a** vertical borehole GHEs, **b** horizontal Slinky^{TM} GHEs, **c** energy piles

Vertical systems are inherently more efficient than horizontal systems because the latter are more susceptible to daily and seasonal temperature variations. As a result, horizontal systems require more land to accommodate and longer lengths of pipe. However, under certain conditions, the time shift that exists in the ground temperature at relatively shallow depths (e.g. 2 m depth in Fig. 3—typical depth of GHE in horizontal systems) may become beneficial. In addition, a horizontal system is normally more cost-effective than a vertical system, and it is the preferred option when there is indeed enough surface land available. While a horizontal geothermal system may be less efficient to operate, the increased running costs is typically lower by the cost savings arising from cheaper horizontal trenching. However, depending on soil conditions, if battering is required for trenching, the total cost of groundworks may become larger than vertical drilling, in which case a shallow geothermal energy system with vertical GHEs may result more cost-effective than with horizontal GHEs. For a detailed analysis of the cost of vertical GHEs systems, refer to Lu et al.'s works and references cited therein (Lu et al. 2017a, b).

Environmental risks and mineral precipitation issues are clearly minimised or eliminated in closed GHE systems since the heat transfer fluid is kept isolated from the ground. Furthermore, licenses to extract groundwater are not required as it is the case in Australia for open-loop systems (Johnston 2012), this is valid in Australia, but readers should check their local legislation.

The heat transfer fluid is typically water. However, when sub-freezing temperatures are expected to be reached when the geothermal heating, ventilation and air-conditioning (HVAC) system operates in heating mode, a water-antifreeze solution is used instead (e.g. a mix of water with methanol, ethanol or propylene glycol); sub-freezing temperature is not common in Australia and in other temperate climates, but common in Northern Europe, Korea, parts of China and North America.

3.2 Ground-Coupled Heat Pumps (GCHPs) and Fluid Circulation Pumps

When operating in heating mode, the set temperature is typically higher than the ground temperature. The use of a cooler source, the ground, to heat a building apparently contradicts the second law of thermodynamics. Heat pumps use electrical or mechanical work to cleverly upgrade the thermal energy to adequate levels and to overcome this apparent contradiction.

A schematic representation of a heat pump is shown Fig. 5. Let us explore the basic operating principles in heating mode. In general, heat transfer occurs when there exists a temperature and/or phase change in a material. Heat transfer associated with phase changes is substantially larger than the ones that correspond to only temperature changes. The refrigerants (working fluids) used in heat pumps change phases from liquid to gas or vice versa at suitable operating temperatures and pressures, achieving efficient heat transfer.

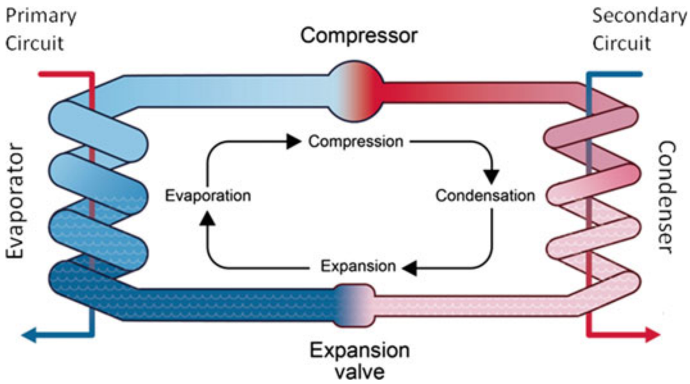


Fig. 5 Schematic representation of a heat pump cycle in heating mode

In Fig. 5, relatively "cool" refrigerant in *liquid* state receives, via an internal heat exchanger, heat from the relatively "warm" water or water-antifreeze solution that comes from the ground loops (i.e. the primary circuit acts as a heat source). At this "evaporator", the *liquid* refrigerant becomes *vapour*, cooling the water or water-antifreeze solution in the process. The "cooled" heat transfer fluid of the primary circuit is reinjected into the GHE to be warmed up again by the ground. The refrigerant temperature must be lower than that of the water arriving from the GHEs (so heat flows to it). The refrigerant boiling point must be below the entering water temperature at relatively low pressure. Next, the now warm(er) refrigerant *vapour* is compressed, which further increases the temperature of the refrigerant vapour. The much hotter, high-pressure refrigerant vapour leaving the compressor is hotter than the secondary circuit (i.e. the heat sink), and thus heat flows from the refrigerant to the building and eventually condenses at high pressure (see "condenser" in the figure). The now *liquid* refrigerant is still at much higher temperature and pressure than at which it boiled. So, the hot *liquid* refrigerant is depressurised as it passes through an expansion valve, returning the pressure and temperature of the liquid to its original conditions prior to the evaporator to restart the cycle. In cooling mode, the process is reversed: the condensation of the refrigerant heats the heat transfer fluid in the primary circuit, which is re-cooled by the ground.

GCHPs require energy input mainly to the compressor but also to circulation pumps that move the fluid within the primary circuit. However, the heat output is typically much larger than the energy input required: GCHPs typically produce about 3.5–5.5 kWh of thermal energy for every 1 kWh of electricity used. The ratio of these values defines a "coefficient of performance" or COP. GCHP COPs of between 3.5 and 5.5 are typical and higher than yearly average air-source heat pumps' COPs (Southard et al. 2014). This is inherently true because heat pump COP increases with decreasing temperature difference between the heat sink and the heat source (Banks 2008), and these temperature differences fluctuate significantly more when air is used as the heat sink/source, as opposite to the ground (Fig. 3).

Therefore, GCHPs are generally and inherently more energy efficient than air-source heat pumps since the averaged ground temperature is always closer to the set ambient building temperature than the external ambient air is.

3.3 Secondary Circuit: Distribution of Heating and/or Cooling

The secondary circuit distributes the thermal energy generated by the GCHP, for instance, throughout buildings (space heating and cooling), greenhouses (heating), ice data centres (cooling), dewatering (heating), ice rinks (cooling), aquatic centres (heating), among others. The distribution systems can use either water, air or refrigerant as the transfer medium. In residential applications, the use of airflow and return ducts under the floor or ceiling or in both are common; as well as the use of radiators or fan coil units mounted close to locations of high thermal loads (e.g. near windows) when water instead of air is the heat transfer fluid of choice. Hydronic heating in the floor slab is also common. Proper fresh air intakes typically form part of the secondary circuit to maintain good and healthy air quality.

The distribution schemes are the same as for conventional heating, ventilation and air-conditioning (HVAC) systems, for which standard references exist. However, it is worth noting that the GCHP's output air or water temperatures may be marginally lower than that from other conventional HVAC systems, therefore, the design of ducting and piping in the secondary circuit must take into consideration this difference.

The heating and cooling loads of a building can also be estimated following well-established procedures found in the HVAC literature. The main factors influencing the computation of heating and cooling include climate, construction forms and orientations, building envelope (materials used in the building), the effects of solar radiation and shading, ventilation, internal lights and appliances, occupancy and building use and purpose. Designers and engineers have the opportunity to control some of these factors, particularly for new builds, in such a way that heating and cooling demands are reduced and if possible, balanced, so that the GCHP systems are more cost-effective to install and operate.

4 Design: An Overview and Simplified Approach

The design approach for shallow geothermal systems may be multidisciplinary, and includes the following: (i) the estimation of thermal demands, (ii) the selection of GCHPs and configuration and (iii) the design of the layout, number and length of GHEs and header manifold and (iv) the design of the distribution system. The installation is considered complete with the commissioning of the system. Johnston (2012) summarises this process and presents a simplified approach which is are briefly described next.

4.1 Thermal Load

Standard HVAC guidelines can be followed to estimate the thermal demand to be satisfied by the shallow geothermal system. Best practices include the hourly or daily estimation of thermal loads. Peak thermal load design may lead to unnecessarily expensive and overdesign of the GHE system. Thermal load estimation procedures and software that follow the recommendations set by ASHRAE *Handbook of Fundamentals* (ASHRAE 2012) or by ACCA *Manual J* or *Manual* J_{AE} are recommended (IGSHPA 2011).

4.2 GCHP Selection and GHE Configurations

The selection of a GCHP or cluster of GCHPs involves the consideration of a number of factors. When heating loads to be satisfied by the geothermal system are much higher than the cooling loads, a moderate over-sizing of the GCHP(s) of about 10–15% may be justified; however, the GCHP(s) should not be oversized by more than 25% of the design cooling load (IGSHPA 2011).

Once a GCHP (or cluster of GCHPs) is chosen, the designer must carefully inspect its specifications. The key factors to inspect may include (Johnston 2012):

- The entering water temperature (EWT) to the GCHP and the leaving water temperature (LWT): If the LWT is close to sub-zero (Celsius) temperature at the lowest design heating conditions, then an antifreeze solution is required in the primary circuit. The potential for freeze heaving of the ground must be also considered in this case.
- The COP of the GCHP: It varies with EWT which is the temperature at which the heat transfer fluid returns from the ground loops. One would attempt to maximise COP. COP increases with the length of the ground loops, so here the designer must balance GHE installation costs (primarily driven by drilling and earthwork costs, directly proportional to pipe length) against the target predominant operating COP.
- The flow rate of the heat transfer fluid in the ground loops: One must find a balance between pipe diameters that render turbulent flow (to maximise heat transfer) and that minimises head loses (to avoid requiring a bigger circulation pump).
- The characteristics of the thermal output: e.g. output temperature and airflow for a ducting distribution system; output water temperature and flow characteristics for a hydronic system.

Refer to the *ASHRAE Handbook* (ASHRAE 2012) for more details on other factors that may need to be considered but whose discussion is beyond the scope of this chapter.

4.3 GHE Layout and Total Length

Depending on the size of the land available for the shallow geothermal installation, one must decide on the type of GHE system to use, either vertical or horizontal. In addition, in newly built buildings with significant foundations that may include large diameter piles, one must consider converting them into energy piles, a practice that is not currently common (except for perhaps in Switzerland) but is becoming promising and the focus of further R&D given the potentially reduced capital costs involved (Lu and Narsilio 2018).

Commercial buildings with large foundations would typically require to satisfy high thermal loads, for which horizontal systems are usually not adequate. However, horizontal systems are usually a more cost-effective alternative than vertical GHEs in the case of residential buildings (CGC 2010), provided that there is inadequate land space available. If not, vertical systems or a combination of both vertical and horizontal systems may be considered.

Once a decision is made on a vertical or horizontal GHE system, then the total length of the ground loop is determined. This total length of pipe is then distributed into a number of borehole GHEs or trench GHEs, whose number is established by also deciding on the length of each borehole or trench. Land and local earthwork machinery availability would play a role in these decisions; however, as a first approximation, designers may consider a thermal yield of approximately 40–60 W m^{-1} of vertical GHE or of 10–30 W m^{-2} of horizontal GHE to initially estimate the length and number of vertical or horizontal GHEs required, respectively. These are the rule of thumbs and as such should only be used as an initial guide and never for the final design. A proper GHE length design is influenced by a number of factors that affect the thermal performance of GHEs such as hydrogeological conditions, thermal properties of the ground and their variability, borehole/trench size, loop orientation, location, thermal properties of the backfill or grout, pipe sizes and spacing and most importantly, the actual thermal loads to be satisfied and the ratio of heating to cooling energy demand. The Canadian GeoExchange Coalition (CGC) and the International Ground Source Heat Pump Association (IGSHPA) offer design manuals that contain more refined methods of loop design (CGC 2010; IGSHPA 2011). Commercial software tools are also available for this purpose, including GLD, GLHEPRO, EED, 4EE and TRNSYS among others. Infinite source line model, finite line source model and cylindrical line source model are some of the models on which the commercial software are based.

The method summarised by IGSHPA to estimate the lengths of GHE loop can be used here to demonstrate the general principles of design. When in heating mode, the total length L of vertical boreholes with single U-shaped loops can be estimated as (IGSHPA 2011):

$$L = \frac{Q_{\mathrm{h}}\left(\frac{\mathrm{COP}-1}{\mathrm{COP}}\right)\left(R_{\mathrm{b}} + R_{\mathrm{g}}F_{\mathrm{h}}\right)}{T - \left(\frac{\mathrm{EWT_{min}} + \mathrm{LWT_{min}}}{2}\right)} \tag{1}$$

where Q_h is the GCHP heating capacity at design heating conditions, T is the far-field ground temperature at the site, COP is the coefficient of performance at design conditions, R_b represents the borehole thermal resistance, R_g is the ground thermal resistance, F_h represents the proportion of the time the GCHP has to run to provide the heat required during the design heating month (also known as run fraction), EWT_{min} is the design entering water temperature (to the GCHP), and LWT_{min} is the leaving water temperature. The LWT_{min} controls the minimum temperate of the heat transfer fluid reinjected into the ground. For temperature climates and whenever possible, LWT_{min} should be kept sufficiently above 0 °C otherwise a water-antifreeze solution instead of just plain water is needed in the GHEs.

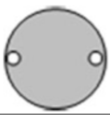
GCHP manufactures usually provide Q_h and COP as a function of EWT_{min} and LWT_{min} as part of pump's technical specifications. On the other hand, the use of the building indicates the value for F_h. R_b can be estimated in a number of different ways, IGSHPA uses the following formula (IGSHPA 2011):

$$R_b = \frac{1}{SF_b k_{grout}} + \frac{\ln(d_o/d_i)}{4\pi k_p} \tag{2}$$

where k_{grout} is the grout thermal conductivity, d_o and d_i are the outer and inner diameters of the ground loop pipes, k_p is the grout thermal conductivity, and SF_b is a dimensionless shape factor that captures the effects of pipe separation within the ground loop in relation to the diameter of the borehole d_b and the pipe outer diameter d_o. Table 1 can be used to estimate parameters α and β, so that SF_b can be found as:

$$SF_b = \alpha(d_b/d_o)^{\beta} \tag{3}$$

Table 1 Coefficients for SF_b (IGSHPA 2011; Johnston 2012; Narsilio et al. 2012)

Configuration	α	β
	20.10	−0.9447
	17.44	−0.6052
	211.91	−0.3796

The ground thermal resistance can be estimated as:

$$R_g = \frac{\ln(d_g/d_b)}{2\pi k_g} \quad (4)$$

where d_g is the diameter of the ground around the borehole GHE affected by its operation, where little change in temperature is observed in the long term (usually taken as approximately 5 m), and k_g is the ground thermal conductivity.

Let us use a residential building in Melbourne, Australia to exemplify the estimation of the total length of GHE required to satisfy the typical peak heating demand of 15 kW based on the simplified approach outlined above and first presented by Johnston (2012). Readers can also compare these results against those obtained from the use of the mobile application 'geothermal' (Fig. 6), which are derived based on IGSHPA and ASHRAE methodologies. Once again, the results from the mobile application should only be used as a guide for pre-design and not for the actual design of these systems.

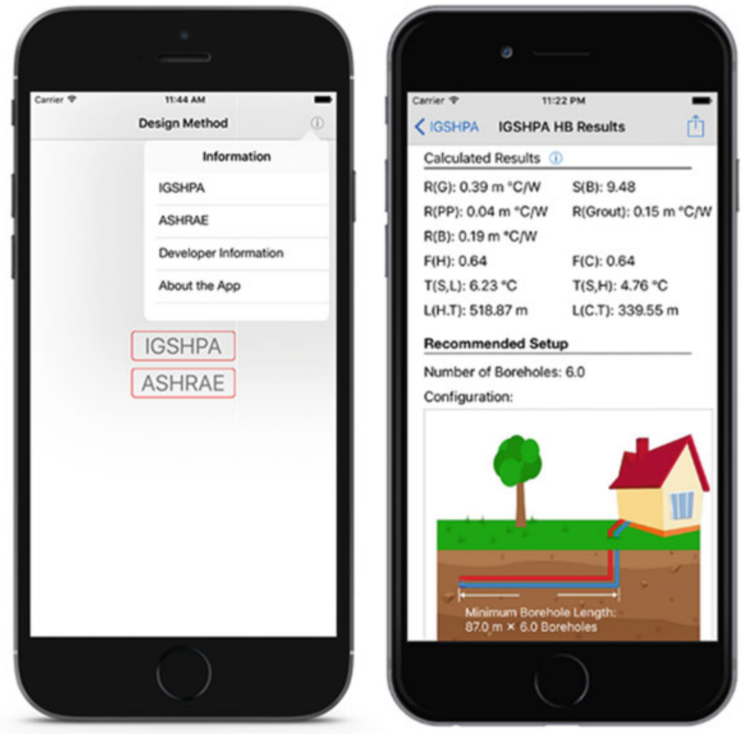


Fig. 6 Screenshot of the mobile application 'geothermal' and GHE total length results for a geothermal system *Source* http://geothermalapp.com

Vertical borehole GHEs containing single U-shaped loops will be considered. The borehole diameter is set at 114.3 mm (4.5 in.) and the HDPE pipe outer diameter is selected at 25 mm with an standard dimension ratio (SDR) of 11 (i.e. wall thickness of 2.27 mm). Thermal testing of the HDPE, the ground and the grout reveal thermal conductivities of 0.45, 1.15 and 2.2 (W m^{-1} K^{-1}) respectively. To satisfy the 15 kW peak heating demand, a 15 kW capacity GCHP is selected. Its manufacturer's technical specifications show that the GCHP operates at a COP of 4 when the EWT_{min} is 7 °C and the LWT_{min} is 4 °C. Assuming a working family living in this residential building, a run fraction of 0.6 is chosen for this example. For Melbourne, the far-field ground temperature is approximately 18 °C (Fig. 3). Following Eqs. (1) through (4), with the input variables summarised above, the required total GHE length L is calculated at approximately 310 m. This total length can be distributed into 3 vertical GHEs of just over 100 m in depth each, 5 m apart. Since more drilling companies are able to drill 50 m boreholes, another option to consider is spreading the total length of GHE into 6 vertical GHE boreholes of just over 50 m in depth, again with a 5 m spacing provided that there is enough land availability.

The ratio of heating to cooling energy exchanged with the ground must be also considered. For cases with balanced heating and cooling loads (i.e. the heat in kWh extracted from the ground in winter is approximately equal to that rejected to the ground in summer), then no correction is necessary. However, for thermally unbalanced cases (e.g. more heat is extracted from the ground than it is rejected in a yearly basis) then a gradual overall increase or decrease of the ground temperature could be expected. Since COP is (amongst other factors) a function of the ETW, this longer term ground temperature variations may reduce the shallow geothermal system efficiency and even cause problems associated with ground overheating or ground heaving due to freezing if the thermal imbalance is not properly accounted for. Continuing with the Melbourne residency example, if 20 and 12 MWh were the total yearly heating and cooling energy extracted and rejected from/to the ground, respectively, then an unbalanced ground load correction factor of 1.1 would be required following the IGSHPA design method. This translates to an increase of the total GHE length to approximately 342 m. The variation to the total GHE length is directly proportional to the thermal imbalance, thus the previous suggestion to engineer the buildings to render balanced thermal loads.

The method exemplified above for heating mode is similar to that followed to estimate the total GHE loop length in cooling mode. Designers must select the critical length to be used in the final design. Using the EED software with the input data of the aforementioned example, a ground loop design with 6 vertical GHEs, 5 m apart in a 2 × 3 grid pattern, rendered a total GHE length L of 286 m (i.e. 6 GHEs to approximately 48 m). The use of double U-shaped loops would reduce this total length to about 242 m, representing a saving of an entire 48 m-deep vertical GHE over the single U-shaped loop choice.

5 Energy Geostructures

Energy geostructures are foundations or other buried geotechnical structures which have absorber pipes embedded so that they can have a dual purpose, structural as well as thermal. Effectively, the addition of HDPE pipes converts these buried structures into ground heat exchangers that form part of a shallow geothermal system. Therefore, the need for construction of special-purpose GHEs is removed or minimised in an attempt to reduce capital costs for the system (Lu and Narsilio 2018; Loveridge et al. 2018), however cost savings may not always be achieved (Park et al. 2015).

Piles are the most common type of energy geostructure. Energy piles were first trialled in the 1980s in northern Europe (Brandl 2006). Their application has expanded in time (e.g. Amis and Loveridge 2014; Amatya et al. 2012), but their numbers are still small compared to the total shallow geothermal installations worldwide. Demonstration projects using walls, tunnel linings and slabs as ground heat exchangers soon followed the first pile installations (Adam and Markiewicz 2009) and a number of new initiatives are being considered, for example for the AUD 11 billion Melbourne Metro Rail Project in Australia (Narsilio et al. 2016a, b), in the Seoul Metro in Korea, and in the Paris and Torino Metro Projects in Europe. However, these types of energy geostructures are less common than piles since the embedment of geothermal pipe loops may not be as straightforward to achieve in real-life projects, and design methods are just in their infancy.

Energy pile shallow geothermal systems tend to incur lower capital costs than traditional vertical GHEs systems such as boreholes (Lu and Narsilio 2018; CIBSE 2013). In terms of design, given the geometrical resemblance to borehole GHEs, ‘traditional’ thermal design methods can be adapted for use with piles (e.g. Pahud 2007; Eskilson 1987). However, as pointed by Loveridge and Powrie (2013a) and Loveridge et al. (2018), there remain some limitations of such approaches. Additionally, approaches for the geotechnical design of piles subject to thermal changes are under development (e.g. Mimouni and Laloui 2014; Loria and Laloui 2016). By contrast, there are not any standard design and analysis approaches for other structures, thus every project must proceed on a case by case basis, typically using complex detailed numerical schemes (Narsilio et al. 2016a, b; di Donna and Barla 2016; Nicholson et al. 2014) or analytical solutions highly constrained by underlying assumptions not always applicable. The proliferation of underground infrastructure, particularly for public transport (e.g. metro tunnels, sewage tunnels, underground train stations) has prompted the desire to take advantage of these structures to harness thermal energy from the ground. While energy-piled foundations are typically used to provide renewable heat to the buildings they support, for train stations’ retaining walls and tunnel linings converted into special GHEs, the user of the heat may be a third party. The inclusion of third parties places additional logistical, legal and bureaucratic barriers for the adoption of the technology. It is only through a holistic, multidisciplinary and multi-sectoral approach which can see this and many other low-carbon and energy-efficient technologies integrated in future infrastructure and construction developments.

Research into the application of energy geostructures has focused in two main areas; (i) the geomechanical effects of using buried bearing structures also as heat exchangers and thermal batteries (e.g. Bourne-Webb et al. 2009; Stewart and McCartney 2014); (ii) the thermal performance of these structures and the pursuit of energy efficiency maximisation (e.g. Loveridge and Powrie 2013b; Bidarmaghz et al. 2016b; Bidarmaghz and Narsilio 2016). Both these areas have the aim of minimising uncertainty and risk in design, facilitating reduction in capital costs and hence an increase in technology uptake.

Designers must ensure that the heat pump and the energy geostructures operate within an acceptable temperature range to (i) protect the structure from extreme temperature changes that may impact on the geotechnical performance, and (ii) ensure that the heat pump operates within its optimal efficiency range. The upper bound temperature limits will depend on the heat pump, typically about 40–45 °C, the lower bound is generally taken as 0–2 °C to avoid ground freezing (GSHPA 2012), although lower fluid temperatures can potentially be tolerated (Loveridge 2012; Loveridge et al. 2012). A detailed review of recent research on energy geostructures in both these areas can be found in Loveridge et al. (2018), covering analysis approaches and the field and model scale testing that has been used to inform those approaches.

5.1 Energy Piles

A key difference between energy piles and typical vertical borehole GHEs is that for the former, the number of piles, configuration and length are not primarily designed to fulfil the (thermal) loads of the building, but rather for its geomechanical structural stability. This leaves little room for optimisation of the geothermal ground loop design, as the main design parameters, like the pile (i.e. GHE) length and separation, are pre-determined. Therefore, the provision of 100% of the heating and cooling energy required (thermal load) cannot be guaranteed and instead a hybrid system must often be used, to complement the produced geothermal energy using auxiliary means (Bidarmaghz et al. 2016a; Narsilio et al. 2015). The design challenge here is to maximise the thermal energy that the geothermal system can provide using the already designed energy piles. Currently, there exist limited design approaches.

Some integrated building simulation software packages allow analyses of all components of a ground-coupled heat pump system from the in ground components to the delivery of heating and cooling, e.g. EnergyPlus (Fisher et al. 2006) or TRNSYS (Klein et al. 2017). Ground-coupled heat pump models were reviewed by Do and Haberl (2010) and found they are typically aimed at borehole heat exchanger design, but a standalone implementation of TRNSYS for application to energy piles is available (Pahud 2007). In addition, a range of analytical solutions are used to determine the changes in temperature for a given thermal demand. This allows to determine the amount of energy that is available within certain temperature limits. Given that fast runtimes are required to process thermal load input data, which may vary on an hourly basis and cover the service life (i.e. decades), analytical solutions may be preferred over numerical solutions. However, some numerical tools have been implemented with sufficient computational efficiency that they provide reasonable alternatives (e.g. Pahud 2007) including the use of advanced machine learning techniques (Makasis et al. 2018).

To simplify the thermal problem most analysis approaches separate the temperature change into a number of zones for which different solutions are applied, the change in circulating fluid temperature, ΔT_f, can be given by:

$$\Delta T_{\mathrm{f}} = \Delta T_{\mathrm{ground}} + \Delta T_{\mathrm{pile}} + \Delta T_{\mathrm{pipe}} \tag{5}$$

If analytical techniques are adopted then the ground temperature change is calculated using a transient temperature response function (G_g) calculated at the pile wall (i.e. at $r = r_b$, where r_b is the radius of the pile):

$$\Delta T_{\mathrm{ground}} = \frac{q}{2\pi\lambda_{\mathrm{g}}} G_{\mathrm{g}}(t, r) \tag{6}$$

where k_g is the ground thermal conductivity (W m^{-1} K^{-1}), q is the applied thermal power (W m^{-1}) and t is the elapsed time (s). The temperature response function or G-function can take a number of different forms as summarised in Table 2.

G-functions are temperature response functions originally developed for borehole heat exchangers by Eskilson (1987) using the superposition borehole model (SBM), and are now adopted more generally to describe any function that relates the temperature change in the ground surrounding a vertical GHE to the applied thermal load q (Loveridge et al. 2018). G-functions are typically expressed as a dimensionless form of Eq. (6), which is as follows:

$$\Phi = G_{\mathrm{g}}(Fo, r^*) \tag{7}$$

where Φ is the dimensional temperature response, $\Phi = 2\pi k_{\mathrm{g}} \Delta T / q$, Fo is the Fourier number or dimensionless time with $Fo = \alpha_{\mathrm{g}} t / r_{\mathrm{b}}^2$ and $r*$ is a dimensionless geometry factor, often expressed as radial coordinate divided by heat exchanger length, α_g is the ground thermal diffusivity. Full details of these solutions are not included here since they are readily available in the literature (Bourne-Webb et al. 2016a).

All the models assume that the ground is homogeneous and isotropic, with no initial temperature gradient and no groundwater flow. Such factors are known to affect the temperature changes around vertical ground heat exchangers (e.g. Signorelli et al. 2007; Bidarmaghz et al. 2016b), but are more difficult to account for by analytical means. G-functions are normally plotted for a constant q (Fig. 7), but as q varies in actual routine operation it is necessary to use some form of temporal superposition and/or load aggregation (Claesson and Javed 2011) to

Table 2 Summary of types of *G*-function that can be used with piles

Model	Reference	Description	Comments
Infinite Line Source (ILS)	Carslaw and Jaeger (1959)	Infinitely long and thin heat source. Homogeneous medium	Infinite length implies that long-term steady-state behaviour is neglected
Infinite (Hollow) Cylindrical Source (ICS)	Carslaw and Jaeger (1959), Ingersoll et al. (1954), Kakaç and Yener (2008), Bernier (2001)	Assumes an infinitely long hollow cylinder which acts as a heat source embedded in a homogeneous medium	Long-term steady-state behaviour is neglected. Gives larger temperature changes than the ILS at short time periods. Is equivalent at longer time periods
Superposition Borehole Model (SBM)	Eskilson (1987)	Uses numerically exact calculation based on a finite line heat source, with superposition for multiple boreholes	Calculated numerically. SBM *G*-functions must be pre-programmed into software codes for different combinations of multiple boreholes. Widely used approach
Analytical Finite Line Source (FLS)	Eskilson (1987), Zeng et al. (2002), Lamarche and Beauchamp (2007)	Using a mirrored virtual line sink approach to simulate the ground surface, these *G*-functions provide an analytically exact version of SBM	The mid-depth or the average temperature of the GHE is used as the reference temperature. Recent works focuses on simplifying the math (Claesson and Javed 2011)
Solid Cylinder Model (SCM)	Man et al. (2010)	Heat flow into and out of the heat exchanger is simulated. The model has been presented in both infinite and finite forms	Studies by Loveridge and Powrie (2013b) suggest that the SCM may provide a sensible upper bound for piles, providing the finite version of the model is used
Pile *G*-Functions	Loveridge and Powrie (2013b)	Derived numerically based on SBM. *G*-functions presented as upper and lower bound solutions	The functions typically fall between the SCM and the log linear simplification of the FLS

Source Loveridge et al. (2018)

determine the overall temperature change, $\Delta T(t)$ resulting from $q(t)$ over the lifetime of a geostructure.

The most frequently adopted type of *G*-function is the SBM and other finite line source (FLS) approaches which are readily implemented in accessible borehole design software that is sometimes used for piles. However, this approach has not been extensively validated for piles and may over predict induced temperature

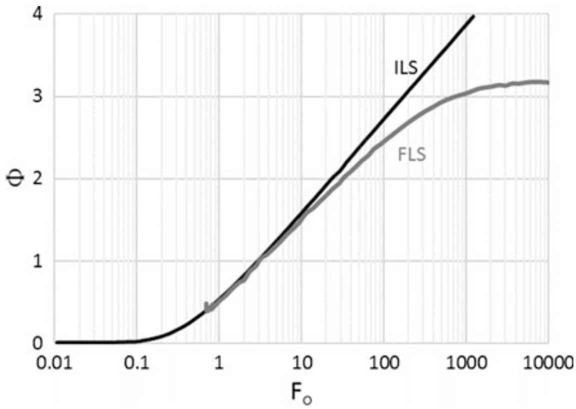


Fig. 7 Example of a *G*-function for an infinite line source (ILS) model and a finite line source (FLS) model (aspect ratio 33)

changes due to the short length of piles (e.g. Wood et al. 2010). Nevertheless, this limitation would be conservative. Following a similar approach to the SBM, Loveridge and Powrie derived upper and lower bound G-functions based on pile geometries rather than on a line source (Loveridge and Powrie 2013b). This newer approach was only validated on short-term thermal response tests of small diameter piles and awaits longer term validation and critical assessment for larger diameters.

The absence of appropriate field data sets to validate models and help assign the most appropriate boundary conditions also remains a barrier to further development. Despite the fact that analytical solutions have been developed to capture the thermal performance of GHEs, most of the assumptions bring limitations. Numerical models solving the governing heat transfer equations have surged in an attempt to overcome such limitations. This includes 1D finite difference models (e.g. Gehlin and Hellström 2003) and finite element (FE) models in 2D (e.g. Austin et al. 2000; Sharqawy et al. 2009) and 3D (e.g. Bidarmaghz 2014; Ozudogru et al. 2014; Signorelli et al. 2007; Narsilio et al. 2018).

5.2 Energy Walls

Despite energy wall case studies been in operation for over a decade, very limited published analyses exist, with most relying solely on numerical simulations (ICConsulten 2005; Soga et al. 2014; Bourne-Webb et al. 2016b; di Donna et al. 2017; Coletto and Sterpi 2016). There exists, however, two other approaches, but not widely adopted: (i) Sun et al. (2013) have proposed an analytical solution based on heat conduction. Many assumptions used in the analysis of energy piles have been used in this model, with the addition of a convective heat transfer boundary condition for the inside face of a retaining wall. The model was tested against full numerical simulations and a limited dataset from the Shanghai Museum of Nature History (Sun et al. 2013); (ii) Kurten et al. (2015) applied an approach based on electrical analogy and uses numerical computation of a sequence of "thermal" resistances. This model has been validated against full numerical simulations and model scale laboratory tests (Kürten et al. 2015).

5.3 Energy Tunnels

Tunnel linings with embedded geothermal pipe loops are also relatively rare, thus there is no routine design and analysis practice yet. Numerical simulation is the most common approach to assess temperature changes and heat transfer rates. Studies have been conducted in both two (Franzius and Pralle 2011) and three dimensions (Nicholson et al. 2014; Bidarmaghz et al. 2017; di Donna and Barla 2016). The structure internal boundary condition is very important, as the air inside the tunnel can be used as a heat source together with the ground (Zhang et al. 2014), as well as the effect of groundwater impacting on the energy efficiency of energy tunnels (di Donna and Barla 2016; Bidarmaghz and Narsilio 2018; Barla et al. 2016). Analytical solutions have also been proposed (e.g. Zhang et al. 2013).

6 Summary/Conclusion

Well-designed shallow geothermal energy systems represent a highly effective, sustainable, and economic technology for space heating and cooling, as well as for domestic hot water (but there are competitive alternatives to the latter). This is particularly important to address and help to mitigate the consequences of climate change. This emerging technology has a growth rate of 10% per annum over recent years in some parts of the world, however, the capital costs of installation need to be reduced to increase penetration in emerging markets. In localities where the shallow geothermal industry is just being established, the installation costs are still high. To have a mature shallow geothermal industry providing efficient, clean heating and cooling for our buildings it is imperative that engineers, architects, developers, regulators, politicians and the general public are educated, trained and accredited. There exists a relatively good understanding of the technologies associated with the "above-ground" components of shallow geothermal energy systems. While these can always be improved further, the best opportunity to reduce costs may lie on the "below-ground" components of geothermal energy systems. The use of structures as GHEs is a clever attempt at this aim and is gaining traction worldwide. Current GHE design methods were briefly discussed and references to full descriptions provided. In contrast, these guidelines do not yet exist for energy geostructures but academic references in this developing front were included in this chapter. In order to address this shortcoming, an increasing number of (geotechnical and mechanical) research groups are undertaking a number of research and demonstration projects to understand how effective the technology is under a range of different conditions. Research and development are being directed to more appropriate guidelines for the design and operation of a variety of GHEs types and configurations.

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