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Ground energy systems: from analysis to geotechnical design

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Ground energy systems: from analysis to geotechnical design

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ABSTRACT
Ground energy systems use the ground and groundwater beneath a site as a heat source or sink to reduce energy costs and improve the environmental performance of buildings. The design and performance of the ground element of these systems (boreholes and ground loops) are dominant factors in the capital and operating costs of the system, yet at present, such systems are often specified with little input from the geotechnical perspective. This paper reviews some of the existing design approaches from a geotechnical perspective, and identifies potential failure modes (short term, long term and regulatory related) for ground energy systems. Short term failures may result from deficiencies in the capacity of the infrastructure forming the ground element and/or from poor connection between the infrastructure and the ground. Long term failures may derive from mis-estimation of loads and/or ground parameters. Possible future directions in the design of ground energy systems are discussed, and the need for informed geotechnical input to ground energy system design is highlighted.

Introduction

There are increasing environmental and commercial pressures to reduce reliance on the traditional energy sources (derived primarily from fossil fuels) used to provide heat energy to buildings or industrial processes. Ground energy systems – defined as those thermally coupled to the sub-surface environment, allowing heat energy to be extracted from and/or rejected to ground and groundwater – represent one technology that can be used to reduce energy costs and improve the environmental performance of buildings. At present, such systems are generally specified using tools originating in the building services industry, often with only limited input from the geotechnical perspective – Ferguson and Woodbury (2005) estimated that of the 30,000 ground energy systems operating in Canada, very many of them had been developed without adequate input from geotechnical engineers or hydrogeologists.

In many cases the ground element of the system is considered only generically, with values of key parameters such as initial ground temperature, thermal conductivity and specific heat capacity being taken from the literature rather than from site-specific field or laboratory measurements. A review of recent design guidance, for example design guides produced by industry bodies in the United States (International Ground Source Heat Pump Association, 1996) and Canada (Geoexchange BC, 2007b) and more wide ranging texts such as Banks (2008), suggests that there is no general acceptance or promotion of factors or safety (on either a global or a partial basis), and how they should be applied to key loads or parameters.

Typically, design guidance recognises that costs of obtaining site-specific thermal parameters may be substantial, and can be a significant proportion of the capital cost of small-scale systems. Some guidance (e.g. International Ground Source Heat Pump Association, 1996) recommends that small scale ground energy systems (such as for an individual dwelling) may be designed using conservative assumptions and ground parameters taken from literature sources. The obvious analogy to traditional geotechnical processes is the design of shallow foundations for individual dwellings, which may not be subject to detailed design but are sized on the basis of generic information on likely loads and ground conditions. However, it should be recognised that the successful generic design of shallow foundations is often based on very extensive experience (held by the designers, contractors and local authorities) of building in that locality. When considering the merits of generic design of small scale ground energy system, consideration should be given to the available knowledge and experience of successful design, installation and operation of such systems in comparable ground conditions and localities.

For larger scale systems, design guidance typically recommends that that site-specific ground thermal parameters be determined (for example via a thermal response test; Marcotte and Pasquier, 2008a). There appears to be no mention of the application of factors of safety in commonly used design guidance, and the implication is that ground thermal parameters are used directly in subsequent calculations. This is in contrast to the methods used for most established geotechnical processes, where the need for appropriate factors of safety is accepted and specified in design codes.

This Paper discusses current practice in the design or analysis of ground energy systems used to heat and cool buildings, highlighting the ways in which it differs from that for other geotechnical processes. Potential failure mechanisms for ground energy systems are identified, and possible future developments in the geotechnical design of ground energy systems considered.

Ground energy systems

Buildings come in a vast range of materials, layouts and sizes and serve a variety of different purposes. One thing almost all buildings have in common is that they require heating and/or cooling at different times during the year. It is rare that buildings have an annual balance between the total energy required for heating and the total energy required for cooling. For example in western Europe, office buildings generally require much more energy for cooling over an annual cycle than for heating. Traditional methods of heating often rely on the burning of fossil fuels (either directly in oil or gas boilers in the building, or indirectly for generation of mains electricity). Traditional cooling systems are often based on electrically driven air conditioning systems which use mechanical refrigeration plant to cool the air within the building, exhausting the waste heat as warm air to the surrounding atmosphere.

Traditional heating and cooling systems use a large amount of energy, and generate significant amounts of carbon dioxide emissions. If energy use in buildings can be reduced, significant environmental and economic benefits will result. In Europe the Energy Performance of Buildings Directive (Commission of the European Communities, 2002), and resulting national guidance (Office of The Deputy Prime Minister, 2006) establishes requirements for the planning of new and refurbished buildings to ensure that appropriate energy conservation measures are adopted and that alternative sources of energy are considered.

A wide range of Low or Zero Carbon (LZC) technologies is available to provide some or all of the energy for buildings (Thorne, 2006). Ground energy systems represent one sub-set of these technologies, which by interacting with the thermal resource of the ground beneath or around a building can allow significant reductions in fossil based energy use. Drivers promoting the use of ground energy systems are summarised in Table 1.

In concept, ground energy systems are very simple. They involve using a sub-surface array of boreholes or other structures such as piles to exchange heat with the ground. In the absence of external influences, and below the relatively shallow zone of annual temperature variation, the ground acts as a large, thermally stable mass, whose temperature varies little during the year. Ground temperatures within 200 m of the surface typically reflect the mean annual air temperature at a site (in the UK, 10 to 14 °C). The stable ground temperature means that in the summer months the ground will be cooler than the surface air temperature, so heat can be rejected to the ground. Conversely, in winter the ground will be warmer than surface air temperature, and can be used as a heat source (Figure 1).

These systems are properly termed ground energy systems, but in academic and commercial literature are they are commonly referred to as ground source heat pumps or geothermal systems. However, the systems described are distinct from traditional geothermal energy systems which tap into rocks (generally at great depth, perhaps several kilometres below the earth's surface) that are significantly warmer than near surface rocks, and produce hot fluids (water or brines) which can be used for a range of purposes from power generation to district heating. Information on traditional geothermal systems can be found in Dickson and Fanelli (2003). In the UK such systems are rare. Prior to 2000 the only significant operational system was for a district heating system in Southampton, Hampshire (Barker *et al*., 2000). Since then, perhaps in response to rising energy prices, there has been a modest revival of interest in traditional geothermal systems, and one scheme has been taken to the investigation stage in north eastern England (Manning *et al*., 2007).

Ground energy systems are categorised into two principal types: open loop and closed loop. Open-loop systems (Preene, 2008) pump groundwater from the ground to the surface (Figure 2). The groundwater is then passed through a heat transfer system, before being disposed of (at a different temperature from before) either to waste or by re-injection back into the ground. In contrast, closed-loop systems do not abstract groundwater, but instead circulate a fluid through a loop of pipes (the ground loop) buried in the ground (Figure 3). The circulating fluid passes through a heat transfer system at the surface, and is then recirculated back through the buried ground loop, to exchange heat with the surrounding soil or rock. Characteristics of open loop and closed loop systems are summarised in Table 2.

The heat transfer system which allows the thermal loads from the building to be passed into the boreholes or ground loop often takes the form of one or more heat pumps. A heat pump is simply a mechanical device which uses a refrigerant vapour compression cycle to transfer heat efficiently from one reservoir to another. Ground energy systems are sometimes known as ground source heat pumps, but a heat pump (if used) is only one component of a successful system. Indeed, when used to provide cooling it may be possible for ground energy systems to use a plate exchanger for heat transfer, thereby avoiding the need for heat pumps.

Traditional approaches to analysis

While ground energy systems may seem novel to many in the geotechnical community, the concept has been applied in practice since the 1920s (Wang *et al*., 2007). However, large scale and systematic implementation of ground energy systems was rare before the 1970s when the method gained popularity in locations as diverse as Scandinavia and the United States. During that period a series of design tools evolved that were derived for use within the building services industry.

In many of the design methods the ground element of the system is not considered in detail, with parameters such as initial ground temperature, thermal conductivity and specific heat capacity being taken from literature values rather than from field or laboratory measurements. Some standard design methods for the first phase of application of ground energy systems are given in International Ground Source Heat Pump Association (1996) and Kavanaugh and Rafferty (1997). These methods appear to be written primarily for building services engineers, and the mechanical and electrical elements (pipework, heat pumps, building thermal loads) are dealt with in much more detail than the geotechnical elements. In particular,

i. They. do not obviously highlight that a significant proportion of the energy extracted from, or rejected to, the ground may not easily dissipate to some 'distant' source or sink, but will be stored in the ground immediately around the ground elements of the system. The importance of considering the ultimate source/destination of the energy extracted or rejected via closed loop boreholes is discussed later in the paper;

ii. While site-specific ground thermal parameters can be used if available, the methods appear to encourage the use of standard values of thermal properties in analytical solutions used to size the below-ground elements;

iii. In contrast to most geotechnical practice, factors of safety (either global or partial) do not appear to feature in system design;

iv. Some of the methods are intended to allow calculation by spreadsheet, or even by hand, and have therefore introduced some significant simplifications to the input data, especially the thermal loads associated with the building. Typically the heating and cooling demand for a building will vary cyclically over an annual cycle, mirroring approximately the outside air temperature (Figure 4). This is a complex temporally varying load, requiring an appropriate timestepping analysis to model it in any realistic way. To avoid the need to carry out such complex analysis, traditional methods may convert the transient thermal load applied to the ground energy system into a series of simpler block loads, or simplify the daily and hourly loads into equivalent monthly loads.

The above comments are not intended to be overly critical of traditional design methods, which have been used to design a large number of ground energy systems around the world that are operating successfully today. It should also be noted that not all current design approaches suffer from all of the shortcomings identified above. Eskilson (1987) presents non-dimensional thermal responses (termed "g-functions"), determined numerically for various bore field configurations, which may be used as a basis for ground element design. The effects of thermal recharge at the ground surface were addressed by Claesson and Eskilson (1987), and the approach forms the basis of the design code Earth Energy Designer (Claesson, 1991). An analytical approach that avoids the need for a particular borehole configuration to be part of a solutions library and enables consideration of the interaction between boreholes is presented by Lamarche and Beauchamp (2007).

However, Kavanaugh and Rafferty (1997) recognise the challenges and risks that come with successful application of traditional design approaches, not least of which is that the most critical design scenarios may occur several years after a system has been installed and commissioned, by which time there is a risk that significant changes in ground and groundwater temperature may have occurred. Some operational problems are beginning to be reported; Ferguson and Woodbury (2005) report a case of an open loop groundwater cooling system where the re-injection of the warm waste water appears to have resulted in temperature increases of about 6°C in the abstracted water over a 16 year period.

Recent developments in design

In the first years of the 21st century, ground energy systems began to be applied much more widely, both geographically and in terms of the type of buildings to which they were applied. For example in the UK, Wang *et al*. (2007) indicate that in 1999 there were probably only 10 significant ground energy systems, but by 2007 there may have been as many as 2000 in operation or under construction. Increased popularity brought the technology to the attention of a wider group of analysts and designers, including geotechnical specialists (Brandl, 2006) and hydrogeologists (Banks, 2008).

As a result new design guidance is beginning to become available, for example through the Geoexchange programme in Canada (Geoexchange BC, 2007a; 2007b). Some researchers have moved into industry and are questioning the validity of existing design assumptions (Marcotte and Pasquier, 2008b; Whitaker and Law, 2008). The potential benefits of obtaining relevant in-situ thermal parameters (using thermal response tests) are also being increasingly recognised (Marcotte and Pasquier, 2008a).

As ground energy systems are developed for larger and more complex buildings, there is increasing use of hybrid or 'bivalent' systems, where the ground energy element provides less than 100% of the building peak thermal load, with the remainder supplied by traditional systems. Table 3 shows a typical demand profile for an office development with a peak cooling demand of 1.3 MW. For the vast majority of the year the demand is less than 0.75 to 1 MW, so a ground energy system designed for the peak demand will be operating at a fraction of its capacity most of the time. A hybrid system, where a ground energy system of 0.75–1 MW capacity is used preferentially supplemented for a few hours per year by traditional systems at times of peak demand, will require the installation of lower capacity ground elements (boreholes, ground loops, etc). This will still allow significant reductions in energy costs and carbon dioxide emissions to be achieved, while substantially reducing capital costs.

Despite the recent developments, there remain significant differences between established analysis methods and geotechnical design as represented in, for example, Eurocode 7 (BSI, 1995). The remainder of this Paper will address these differences and consider how geotechnical approaches might be better incorporated into the design of ground energy systems.

Defining geotechnical design for ground energy systems

Following the convention of Geoexchange BC (2007a) a ground energy system can be subdivided into three key elements (Figures 2 and 3):

i. The source side (the below ground elements such as boreholes, ground loops and associated infrastructure);

ii. The load side (the building, its controls, users and the thermal load which results. For hybrid systems any bivalent heating/cooling systems are relevant); and

iii. The heat transfer system (the heat pumps, heat exchangers and associated control systems).

From a geotechnical perspective, it is interesting to note when comparing ground energy systems with traditional heating and cooling systems that the major capital costs (and the major potential operational cost savings) are associated with the source side, i.e. the ground elements. Thus the geotechnical design of the source side is crucial to an economically viable and successful system.

Design of the source side element of a ground energy system is conventionally based on heat transfer solutions of the type presented by Carslaw and Jaeger (1947). The mathematics governing the axisymmetric flow of heat to a vertical line or cylindrical sink in response to a temperature gradient is analogous to that for groundwater flow to a vertical pumped well. Marcotte and Pasquier (2008b) show that the solutions for transient heat flow to a line and a cylindrical sink (plotted in terms of the temperature difference at the borehole wall against time) are virtually identical; and comment that the line sink solution is advantageous in that it can be modified to allow for the effect of a steady horizontal groundwater cross-flow (Sutton, Nutter and Couvillion, 2003). As with closed form groundwater flow analyses, calculations may focus on transient or steady state conditions.

In transient flow with a steady removal of groundwater or heat, the distance of influence of the extraction (or injection) borehole will gradually increase over time, but (as a result of the axisymmetric geometry) at a decreasing rate. In practice, a steady state will be reached in which the rate of heat or groundwater extraction is balanced by influx through the ground surface, which (as recognised by Whitaker and Law, 2008) is not considered in some of the traditional analyses. Even where the role of heat influx from the ground surface is included in analysis it may not be recognised that, even after many years operation, unless the rate of heat extraction or rejection is relatively modest, much of the heat energy from the system will derive from the ground, rather than 'distant' sources or sinks. Banks (2008) reports analyses which indicate that for a typical closed-loop borehole after 25 years operation (in heating mode), only about $^{1}/_{3}$ of the heat energy is derived from diffuse heat influx at the ground surface; the remaining $^{2}/_{3}$ of the energy is derived from thermal storage in the ground around the borehole.

The essential starting point for a meaningful analysis of the source side element of a ground energy system is probably to carry out at least a conceptual heat flow balance for an appropriate control volume, analogous to a water balance in hydrogeology and groundwater flow problems. This is illustrated schematically in Figure 5. The potential importance of heat flux due to groundwater flow will increase with increasing hydraulic conductivity of the ground and hydraulic gradient across the site, and may well be negligible in low-permeability soils. Its neglect in the analysis of a ground energy system is probably conservative. Interaction between nearby ground energy systems may be taken into account using the principle of superposition; while consideration of all components of the heat flow balance will enable the effect of a ground energy system to be considered, together with the effects of, for example, a rise in ground or average atmospheric temperature due to climate change to be assessed.

Ideally, the net heat input should be equal to the net heat extracted over an annual cycle. Over a given period of time, any difference between the heat input and the heat extracted from the control volume will result in a change in the temperature of the ground, which will depend also on the specific heat capacities of the soil/rock and the pore fluid. This could cause the system to become gradually less effective over a period of several years, until it reaches a serviceability limit state in which it can no longer fulfil the function for which it was designed.

As ground energy systems become more popular, it will become increasingly necessary, especially in congested urban areas, to consider interaction between adjacent/nearby ground energy systems if the capacity of the ground to receive and/or give up heat is not to be exceeded. An approach based on the rigorous thermodynamic assessment of an appropriate control volume will clarify and facilitate this, in a way that reliance on standard formulae could never do. Of course, a detailed consideration of heat transfer rates local to the in-ground component will still be a necessary part of the design process.

Analogies with other geotechnical processes

Modern geotechnical design is based on the avoidance of limit states. The two most commonly considered are the ultimate limit state, generally associated with outright collapse; and a serviceability limit state, in which although outright collapse does not occur a performance criterion is not met – for example, deformations are excessive. Limit states are avoided by the application of factors of safety in the design calculations, generally to either the expected loads, to a key material property such as the strength, or to both. In geotechnical structures such as foundations, the loads are independent of the ground and are obvious, while in slopes and retaining walls the major part of the load is likely to result from the ground and in the case of a retaining wall may not be as easy to define.

A factor of safety may be applied to the load to allow for uncertainty in the quantification of the load, and perhaps for a change in the use or user of the structure resulting in an unforeseen future increase. A factor of safety may be applied to a material property such as the strength to allow for a degree of variability, although Eurocode 7 (BSI, 1995) states in the context of a soil that the strength used in calculations should be a moderately conservative estimate of that relevant to the limit state being considered. Factors of safety may be applied to either or both the load and the materials properties as an empirical way of guarding against a serviceability limit state being reached: this has traditionally been the approach in limit equilibrium analysis of geotechnical structures such as slopes, foundations and retaining walls. In modern geotechnical design against an ultimate limit state (e.g. Eurocode 7 **Combination 2 of Design Approach 1**, failure in the ground), the factor of safety is generally applied to the soil strength, with the loading conditions being taken as the most onerous.

A ground energy system must be designed to accommodate a certain thermal load, which is the part of the thermal demand required to heat and/or cool the building that is to be provided by the ground energy system. In principle either this load, or the parameters governing the heat transfer and storage properties of the ground, or both, could be factored to give a degree of additional system capacity to cope with increased thermal loads and/or lower than expected thermal performance. However, this could lead to an uneconomic design, resulting in turn in the client choosing a conventional heating and cooling system in place of a ground energy system on capital cost grounds. .In any case an underperforming system will in most applications not be potentially unsafe in the same way that an underdesigned foundation, retaining wall or slope could be. A ground energy system will not normally cause collapse or failure in the ground at the ultimate limit state: either it will perform as required to heat and/or cool the building, or it will not. Thus it is not clear that the concepts of serviceability and ultimate limit states are particularly helpful in the context of a ground energy system.

Nevertheless, the consequences of ‘failure’ of ground energy systems should not be trivialised. On commercial projects, the client employing the designer will have clear expectations of thermal loads and system coefficient of performance (CoP, a measure of efficiency) to be achieved by the ground energy system. If the system fails to achieve these targets there will be real impact on the client. If the building does not have a hybrid heating and cooling system (and relies entirely on a ground energy system), the occupied spaces will be subject to thermal discomfort, potentially affecting how the building can be used. If the building has a hybrid system, it should be possible to maintain thermal comfort for the occupiers but the traditional heating/cooling elements of the hybrid system will operate for more hours annually than planned. This will increase the building energy costs and carbon dioxide emissions above those expected by the client.

With respect to the nature and impact of failures, a ground energy system is more akin to a construction dewatering system or an array of sand drains to accelerate consolidation than to a foundation or a retaining wall. One significant difference, however, is that a groundwater control system or an array of sand drains can usually be observed over a relatively short time period and enhanced or remediated if its performance is poor. This is likely to be much less practicable in the case of a ground energy system, primarily due to the longer timescales before failure or underperformance becomes apparent. Post occupancy monitoring and evaluation may be required to determine whether the building and the ground energy system perform as intended and meet the user’s needs.

The foregoing discussion suggests that the application in the conventional sense of factors of safety to thermal loads or parameters would serve little purpose; and that a probabilistic approach, with the thermal loads and parameters selected to give a certain degree of confidence that the system will be able to perform to specification, may be a more appropriate design philosophy.

Failure modes for ground energy systems

While it appears unlikely that the ground element of a ground energy system could fail in a way that would be analogous to outright collapse, there are several ways in which a serviceability limit state could be reached. Reflecting the fact that ground energy systems receive a dynamic thermal load over a long period of time, these might be grouped as follows:

1. **Short term failure** (i.e. within one annual cycle). This might be viewed as the nearest analogy to an ultimate limit state in that it would be obvious and relatively immediate. It will generally occur within one annual cycle and will manifest in the ground energy system being unable to deliver the peak heating or cooling load – the system therefore fails to meet the thermal load applied to it. An alternative form of short term failure can occur in heating dominated systems which are significant net extractors of heat from the ground. Ground temperatures may fall and in extreme cases ground freezing may occur. If freezing occurs close to structures it can result in heave of base slabs, or lateral deformations (and cracks) in retaining walls (Brandl, 2006). Further ground movements may occur on thawing.

2. **Long term failure** (i.e. beyond one annual cycle but during the design life of the building). The ground energy system can meet the building thermal load requirement, but the heat flow does not balance sufficiently well over an annual cycle resulting in a gradual increase or decrease in the ground temperature and a gradual reduction in system efficiency, and eventually its capacity. Thermally, the ground is overstressed (in extreme cases of heating dominated loads ground freezing may occur, resulting in ground movements). Typically the system will work, but less and less effectively resulting in increased energy costs and increased carbon dioxide emissions. It will not deliver the promised thermal, economic and environmental performance, and is thus analogous to a serviceability limit state.

3. **Failure to meet regulatory standards.** Some forms of ground energy system are subject to formal regulation which governs the way they operate (e.g. abstraction licensing of open loop systems). Systems which are deficient in aspects of design and/or operation may breach their regulatory requirements, in either the short or the long term.

Short term failure will mainly be derived mainly from deficiencies in the capacity of the infrastructure forming the ground element and/or from poor connection between the infrastructure and the ground. Long term failures will be derived mainly from mis-estimation of loads and/or mis-estimation of ground parameters – including possibly a failure to carry out a thermodynamic control volume analysis. Examples of failure modes are given in Table 4. For most of these failure modes, increased involvement of geotechnical and hydrogeological design and modelling skills is the primary way that risk of failure can be reduced.

Where do ground energy systems go from here?

The drivers in Table 1 suggest that the rate at which ground energy systems are installed will increase, with the technology becoming more and more attractive in financial terms as energy prices continue to rise. The source side of a ground energy system has a huge impact on the capital cost, operating costs and the efficiency of ground energy systems – more and more obviously so than many traditional energy systems. Sound geotechnical design is therefore essential to the efficiency and economic effectiveness of ground energy systems.

Geotechnical specialists should expect ground energy systems to become a larger part of their collective workload. The geotechnical design of ground energy systems is currently within the ambit of a relatively small number of specialists; thus there will be a need for the development of expertise and appropriate design and analysis tools, to allow designs to be carried out consistently by a wider group of practitioners. The geotechnical community has seen this sort of development before, for example in finite element analysis (as a new analytical approach), and geosynthetics (as a new field of application). While both of these are still relatively specialist areas of geotechnical expertise, the number of geotechnical engineers involved in each has grown enormously over the past 20 years or so.

The issues of increasing popularity and global climate change will require more detailed consideration of the likely long-term performance and sustainability of ground energy systems. This will require the development and application of increasingly sophisticated, coupled heat and groundwater flow models in addition to consideration of local heat transfer rates. It is likely that a detailed understanding of these will remain the preserve of researchers and specialists; what will probably happen is therefore a distillation of these techniques into more user friendly programs and guidance for routine use. This has happened with other forms of geotechnical construction, in particular embedded retaining walls, for which the use of relatively simple soil-structure interaction programmes is now commonplace.

The use of site-specific data, including relevant soil thermal properties and consideration of potential interactions with other ground energy systems and of the local groundwater regime, will increase; thus there will be a need for the development of standard investigation procedures and testing protocols (e.g. **Sanner *et al*, 2005**; Clarke *et al*, 2008). A probabilistic approach to parameter and load specification may well be adopted; there is some precedence for this approach in dynamic system models used in complex water balance problems (Volpe and Voss, 2005). Failures will occur and will hopefully be investigated and documented: the fact that such failures may occur over long after construction and commissioning should not prevent the geotechnical community learning from them, as it did from the delayed failure of retaining walls and cut slopes in London Clay. Thus design tools are likely to continue to evolve and ground energy systems become increasingly refined, even after some rapid development over the next five years or so.

Any large scale adoption of ground energy systems will require quite detailed consideration of overall heat balance and interaction effects, and some form of regulatory intervention such as specific licensing requirements for ground energy systems may well be inevitable.

Conclusion

Informed geotechnical input will become increasingly essential to ground energy system design. Full consideration of the overall energy balance for heat flows into and out of the ground will become more important as the number of ground energy systems increases and the impacts of climate change begin to have an effect. Coupled heat and fluid flow models will be needed for fundamental investigation and detailed assessment, especially of large complex systems. They will also need to be developed to form the basis of simpler tools and programs that can be used with confidence by less specialist geotechnical engineers for the routine design of small and medium systems. Site-specific data on soil thermal properties, and appropriate testing procedures, will be increasingly required. A probabilistic approach to design parameters and thermal loads might be appropriate. There should be an expectation that serviceability failures of the types described in Table 4 will take place; some of these will occur gradually over a long period of time. Geotechnical specialists must be able to investigate, understand and document such failures, so that the community as a whole can develop an improved understanding of the complex of factors governing the performance of ground energy systems, and hence improved design methods.

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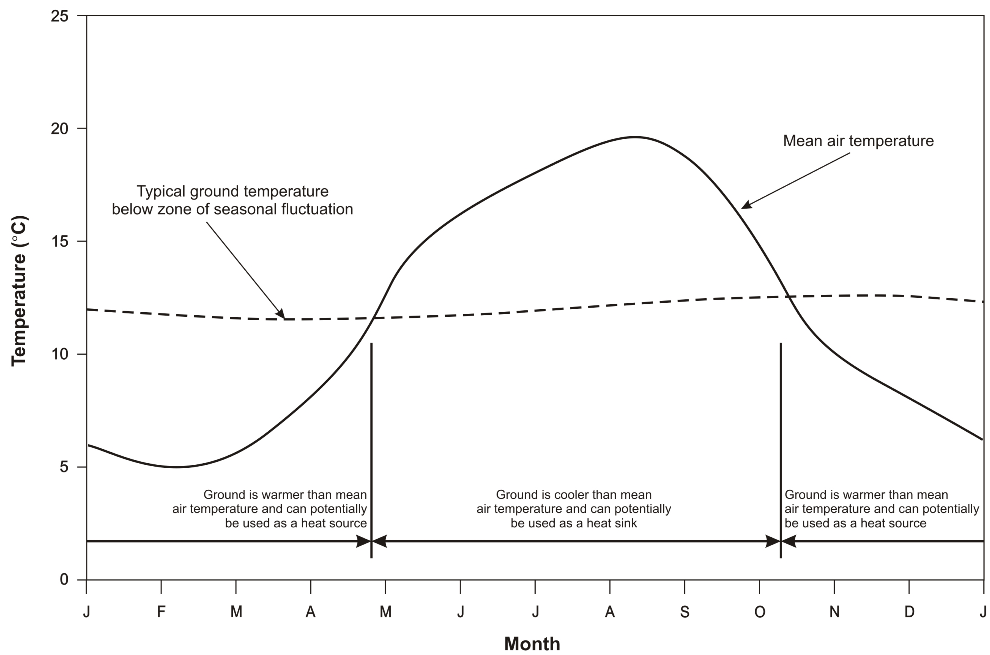

Figure 1: Relationship between surface air temperature and ground temperature

At depths of more than a few metres the annual variation in ground in much less than the annual variation in mean air temperature. In the summer the ground is cooler than the air temperature and can potentially be used as a heat sink. In the winter the ground is warmer than the mean air temperature and can potentially be used as a heat source. Temperatures based on UK conditions.

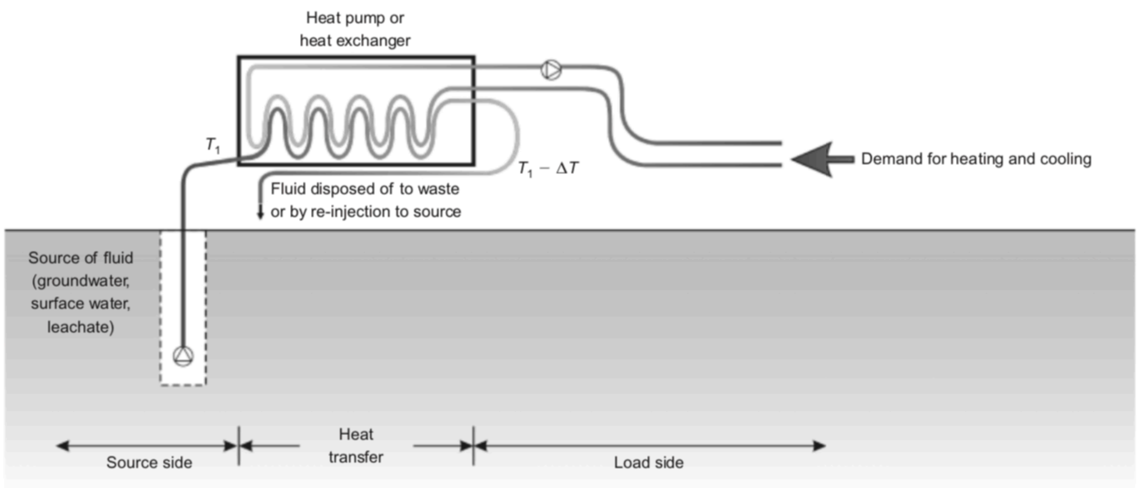

Figure 2: Open loop ground energy system

Groundwater is abstracted from the source (typically one or more boreholes), passed through a heat pump or heat exchanger and disposed of to either to waste (sewer or watercourse), or by re-injection to the source (typically by one or more aquifer re-injection boreholes)

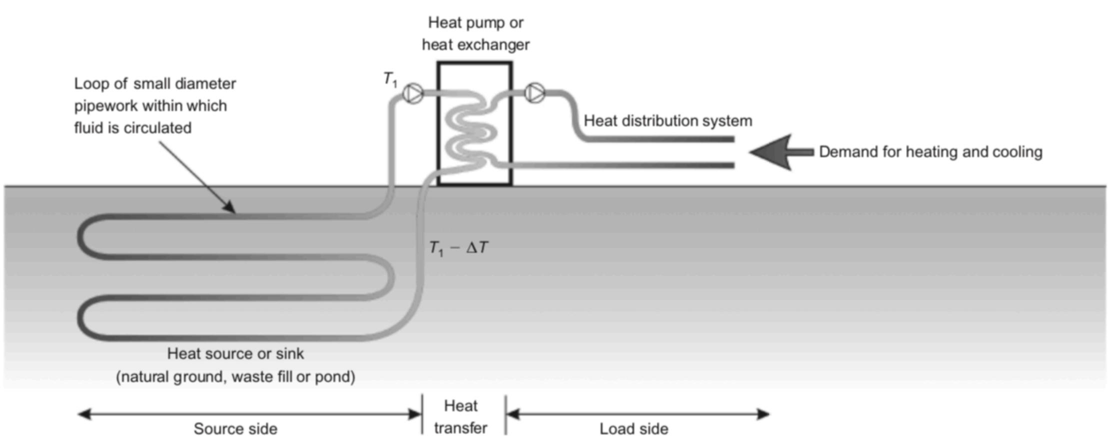

Figure 3: Closed loop ground energy system

A thermal transfer fluid is circulated through a closed circuit of pipework embedded in the ground, thereby allowing the building heat pump system to reject or extract heat from the ground. The ground loop can be configured into shallow trenches, an array of vertical boreholes, or can be incorporated into the building piles and other foundations

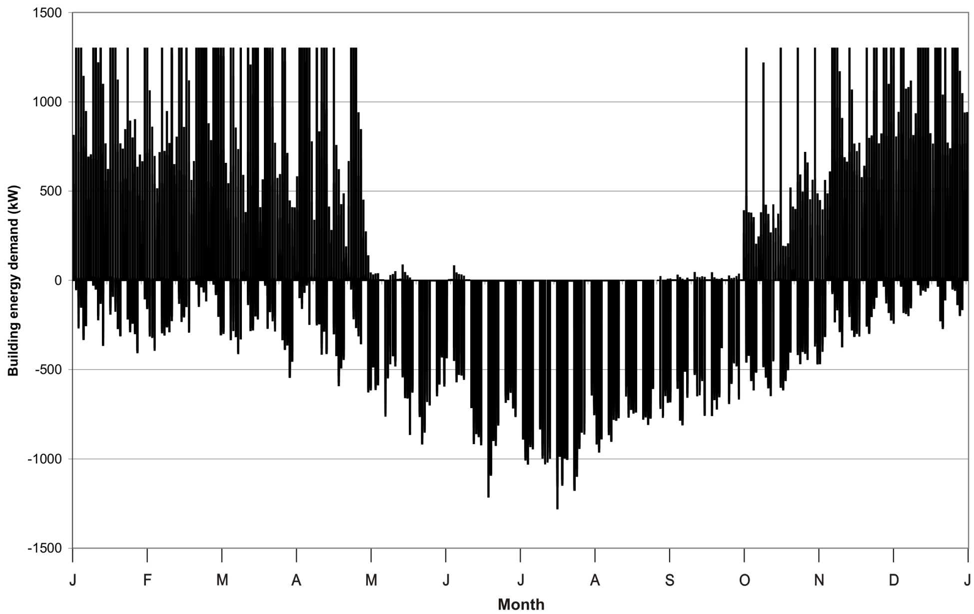

Figure 4: Schematic example of thermal loads applied to a ground energy system during the annual cycle

Energy demands for heating are denoted as positive, energy demands for cooling are negative

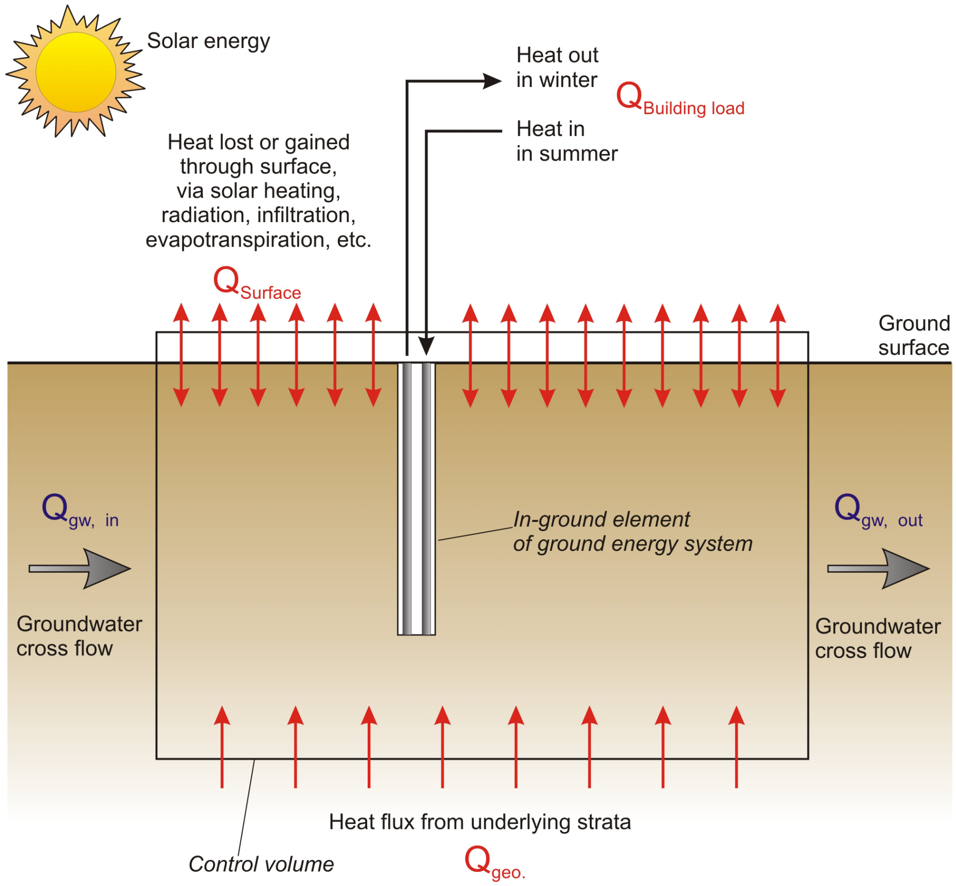

Figure 5: Schematic heat flow balance for a control volume around a ground energy system (after Banks, 2008)

Table 1: Drivers for the use of ground energy systems

Driver	Detail	Notes
Energy conservation	Modern building design focuses on reducing the energy demand of buildings variety of active and passive measures (Boyle, 2005; Thorne, 2006). Ground energy systems offer the chance to significantly reduce the energy consumed to heat and cool a building.	Ground energy systems do require external power in order to operate (unlike for example wind turbines and some forms of renewable energy). However, they are very energy efficient. Systems using heat pumps typically can provide 3 to 5 units of heat energy for every unit of electrical energy consumed (this is expressed as a coefficient of performance (COP) of 3 to 5).
Environment	Ground energy systems are classified as low or zero carbon (LZC) systems, and can offer significant reduction in carbon emissions compared to traditional systems.	At present buildings are responsible for around half of the UK's carbon emissions **(Department of Trade and Industry, 2006).**
Economics	Ground energy systems can offer significantly lower annual operating costs compared to traditional heating and cooling systems.	The economic advantage stems mainly from the reduced energy consumption.
Regulation	In the UK and the rest of Europe, regulations applicable to significant new and refurbished buildings require that designers consider ways that at least 10 per cent of the building energy demand can be met from LZC sources.	The requirement to consider potential use of LZC systems for buildings is detailed in, UK regional and national policy
Change in building needs	There is an increasing expectation by many users of commercial buildings that some form of cooling will be provided to control building temperatures. Ground energy systems can be an effective way of providing comfort cooling.	The combination of change in office working practices (with increased density of heat generating office equipment) and predicted increases in summer temperatures, mean that, without cooling, thermal discomfort in buildings will be a significant problem in the future.
Space and practicality	Traditional cooling systems typically require some plant space at roof level, for cooling towers or other plant that rejects building heat to air. Ground energy systems used for cooling can be entirely located in basement plant rooms, freeing up additional space that can be sold or let.	Space on the upper floors a building may often be the most expensive of desirable. The value released by avoiding the need for roof level plant rooms can potentially be a significant factor in the financial assessment of cooling systems based on the ground energy concept.

Table 2: Characteristics of open loop and closed loop ground energy systems

Characteristic	Open loop systems	Closed loop systems
Requirements for groundwater abstraction and re-injection	All open loop systems involve abstraction of groundwater. For many open loop systems it is impracticable or unsustainable to discharge the water to sewer or surface water; in those circumstances the water must be re-injected into the aquifer.	Groundwater abstraction and re-injection not required.
Regulatory constraints	In many countries the abstraction and discharge of groundwater is closely regulated. Open loop systems will be subject to the constraints of any such legislation.	In many countries there is currently little or no regulation of the ground element of closed loop ground energy systems. One issue that may be regulated is to ensure that boreholes are adequately sealed or grouted to avoid the creation of seepage pathways from the surface and between different geological units.
Dependence on favourable hydrogeological conditions	Open loop systems are only practicable when significant water-bearing strata (which collectively form an 'aquifer') are present beneath a site.	Closed loop systems do not require the presence of an aquifer, and can be practicable in a wide range of geological settings.
Number and capacity of boreholes	Under favourable hydrogeological conditions, where borehole yields are significant, relatively small number of abstraction boreholes can supply large peak demands. For example a borehole yielding 25 l/s could provide a peak thermal output of 500 kW.	The peak thermal capacity of a closed loop borehole is typically much less than that of an open loop borehole. Closed loop systems typically require much greater number of boreholes than equivalent open loop systems. A typical 100 m deep closed loop borehole could have peak thermal output in the range 4 to 7 kW.
Requirements for heat transfer system	Depending on the water temperatures required by the building system, open loop systems can operate using a heat exchanger only, without the need for a heat pump. This improves energy efficiency as there is no additional energy requirement to power the heat pump compressor.	Closed loop systems almost always use heat pumps as the heat transfer mechanism.
Ability to handle annual imbalanced thermal loa	Where open loop systems discharge to waste they can operate successfully with very unbalanced thermal loads, where heating or cooling demand dominates during the annual cycle. Where aquifer re-injection is used open loop systems work best where the annual total of heating energy and annual total of cooling energy are approximately balanced. If the thermal load is unbalanced there is a risk that warmer/cooler water from the injection boreholes will migrate to the abstraction boreholes (a phenomenon termed 'thermal breakthrough') which will affect system efficiencies.	Closed loop systems work best where the annual total of heating energy and annual total of cooling energy are approximately balanced. If the thermal load is unbalanced there is a risk of long term year-on-year changes in ground temperature which will affect system efficiencies.

Characteristic	Open loop systems	Closed loop systems
Potential for off-site thermal impacts	Where open loop systems discharge to waste, there is potential that that the discharge of warmer/cooler water to a surface water course will cause environmental impacts. Where aquifer re-injection is used advective flow of warmer/cooler groundwater over extended periods (typically several years) can potentially result in plumes of warmer/colder groundwater migrating off-site.	For many closed loop systems heat flux in the ground is predominantly by conduction. Resulting zones of ground heating and cooling migrate only slowly, reducing the risk of significant off-site thermal impacts.
Constraints on locating boreholes making up the ground element	Although open loop systems typically require relatively modest numbers of boreholes, it is preferable that boreholes be spaced as widely apart as practicable to minimize interference between boreholes. This is especially the case where aquifer re-injection is used, when the distance between abstraction and re-injection boreholes has a direct influence on the risk of thermal breakthrough.	Because of the large number of boreholes typically required for closed loop systems, and the need to arrange them on a grid pattern to maintain a minimum horizontal separation between boreholes, significant site areas may be needed to accommodate the borehole array.

Table 3: Example of cooling load for office building

Cooling demand	No. of hours exceeding demand level in one year
1250 kW	1
1000 kW	58
750 kW	318
500 kW	891
250 kW	1556

Notes: Based on simulation of a commercial development in Dublin, Ireland

Table 4: Examples of failure modes for ground energy systems

Failure type	Possible cause	Possible mitigation measures to be adopted in design
Short term (infrastructure)	i. Lack of sufficient number of boreholes/inappropriate borehole design/inadequate water pump capacity of open loop boreholes to provide water flow rate to meet peak load	Ensure peak loads are accurately defined; use of realistic borehole capacities in design, based on site-specific data and ideally a programme of test pumping; allowance for interference between boreholes when using test data from single trial borehole to assess average borehole capacities in multiple borehole arrays; use of hybrid systems to supplement ground energy system at times of peak demand
	ii. Lack of sufficient number of boreholes/length of closed loop boreholes to meet peak seasonal load without fluid circulating temperature moving outside acceptable range **(with heating dominated loads there is a risk of ground freezing and associated ground movements)**	Ensure peak loads are accurately defined; use of realistic borehole capacities in design, based on site-specific data and ideally a programme of thermal response testing in trial boreholes; allowance for interference between boreholes when using test data from single trial borehole to assess average borehole capacities in multiple borehole arrays; use of hybrid systems to supplement ground energy system at times of peak demand
	iii. Lack of heat pump capacity/circulating pump capacity to meet peak load	Ensure peak loads are accurately defined; appropriate sizing of heat pump/circulating pump to meet load; use of hybrid systems to supplement ground energy system at times of peak demand
	iv. Control system problems causing inability to deploy all of the theoretical installed capacity	Control system protocols should recognise possible interaction between boreholes (i.e. certain combinations of boreholes in use result in a reduced average borehole output, compared to a borehole operated in isolation); control system should be appropriate for the highly variable thermal loads typically applied to ground energy systems
Short term (connection)	i. Inappropriate design and/or installation of open loop or closed loop boreholes meaning that an individual borehole cannot deliver the short term peak water (abstraction or re-injection) or thermal output assumed in design	Ensure peak loads are accurately defined; use of realistic borehole capacities in design, based on site-specific data and ideally on-site testing; allowance for interference between boreholes when using test data from single trial borehole to assess average borehole capacities in multiple borehole arrays; use of hybrid systems to supplement ground energy system at times of peak demand
	ii. Inappropriate design/installation of pipework system linking boreholes to the building means that the thermal and water outputs available at the boreholes cannot be delivered to the heat transfer system (e.g. excessive head losses in pipework)	Ensure peak loads are accurately defined; appropriate sizing of pipework to develop turbulent flow where efficient heat transfer is desired and laminar flow elsewhere; accurate estimation of friction losses and appropriate sizing of pumps; insulation of pipework where necessary

Failure type	Possible cause	Possible mitigation measures to be adopted in design
	iii. Inadequate allowance for interference between boreholes within an array, resulting in average borehole outputs less than assumed in design	Modelling approach used in design should allow for cumulative effects due to interference between boreholes in arrays; parameters from single test boreholes should be applied appropriately; use of hybrid systems to supplement ground energy system at times of peak demand
Long term (loads)	i. Long term annual unbalanced loads (i.e. the net thermal input/output to the ground) exceed those used in design (either due to unrealistic design assumptions, or due to inappropriate operation of building by users)	Ensure that annual heating and cooling loads are accurately defined, and that the annual heating load and annual cooling load applied to the ground energy system are sufficiently closely balanced that natural heat inputs and outputs will prevent long term changes in ground temperatures; set building control system protocols so that users cannot inadvertently apply excessive unbalanced loads to the ground energy system; use of hybrid systems to handle unbalanced portion of annual load
	ii. Building life is extended beyond that assumed by the designer, and the cumulative effect of unbalanced loads causes problems	Ensure that appropriate design life is used in analysis; ensure that annual heating and cooling loads applied to the ground energy system are sufficiently closely balanced that natural heat inputs and outputs will prevent long term changes in ground temperatures; use of hybrid systems to handle unbalanced portion of annual load
Long term (ground parameters)	i. Ability of ground to store and buffer short term thermal peaks of load is less than assumed in design	Use of ground parameters based on site-specific data and ideally on-site testing; use of hybrid systems to supplement ground energy system at times of peak demand
	ii. Amount of energy from unbalanced annual loads that migrates away from (or migrates to) the site by groundwater flux (and other mechanisms) is less than assumed in design	Modelling approach used in design should allow for effect of groundwater flow (and other mechanisms) on heat transfer; use of ground parameters based on site-specific data and ideally on-site testing
	iii. Thermal breakthrough occurs between abstraction and re-injection boreholes (open loop only)	Ensure that risk of thermal breakthrough is modelled in design process; use of ground parameters based on site-specific data and ideally on-site testing; arrange configurations of abstraction and re-injection boreholes to minimise peak and mean hydraulic gradients between boreholes
	iv. Net abstraction of groundwater causes excessive depletion of aquifer groundwater levels/water resources (open loop only)	Assessment of drawdown, impact on water resources and neighbouring abstractions to be part of design process; net abstraction of groundwater to be minimised (e.g. by re-injection of water)

Failure type	Possible cause		Possible mitigation measures to be adopted in design
	v.	Water quality is worse than anticipated, hence causing clogging/corrosion problems (open loop only).	Use of water quality parameters based on site-specific data; design to allow for effect of potentially poor water quality (e.g. by use of corrosion resistant materials or by inclusion of water treatment)
Breach of regulatory standards	i.	Permitted volumes of groundwater abstracted and/or discharged by an open loop system are exceeded, because cumulative load applied to ground energy system is greater than that used when deriving the volumes used on the regulatory permit	Ensure that annual heating and cooling loads are accurately defined, and that corresponding annual water volumes are estimated appropriately; set building control system protocols so that users cannot inadvertently abstract groundwater in such volumes that regulatory permits are breached; use of hybrid systems to handle annual loads that exceed permitted groundwater volumes
	ii.	Unacceptable reduction on available water resources at neighbouring sites as a result of abstraction from an open loop system	Identify groundwater-related features (such as existing abstraction boreholes) on neighbouring sites; assessment of drawdown, impact on water resources and neighbouring abstractions to be part of design process; net abstraction of groundwater to be minimised (e.g. by re-injection of water)
	iii.	Unacceptable thermal impact (change in ground, groundwater or surface water temperature) at neighbouring sites or at locations specified in regulatory permits	Identify environmental constraints and any sensitive nearby locations (e.g. existing ground energy systems on neighbouring sites); modelling approach used in design should allow for appropriate mechanisms of off-site (and cross-site) heat migration (e.g. advection, conduction); use of ground parameters based on site-specific data and ideally on-site testing
	iv.	Unacceptable risk of migration of groundwater contamination along potential seepage pathways created by ground element (boreholes, ground loops, etc)	Design of boreholes to take into account any near surface or deeper contamination or zones of poor water quality; borehole design to include grout seals at appropriate levels to ensure that artificial seepage pathways are not created