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SOIL THERMAL PROPERTIES AND THE EFFECTS OF GROUNDWATER ON CLOSED LOOPS

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ABSTRACT

This article provides hydraulic and thermal properties of soils and rocks. The impact of groundwater flow on the estimation of soil/rock thermal conductivity from test data was also examined. The purpose of this study, however, is to examine the means of reduction of energy consumption in buildings, identify GSHPs as an environmental friendly technology able to provide efficient utilisation of energy in the buildings sector, promote using GSHPs applications as an optimum means of heating and cooling, and to present typical applications and recent advances of the DX GSHPs.

Keywords: Renewable energy technologies, Sustainable development, Earth heat energy, Built environment.

1. INTRODUCTION

One of the fundamental tasks in the design of a reliable ground source heat pump system is properly sizing the ground source heat exchanger length (i.e., depth of boreholes). Recent research efforts have produced several methods and commercially available design software tools for this purpose (Freeze and Witherspoon, 1967; Isiorho and Meyer, 1999). These design tools are based on principles of heat conduction and rely on some estimate of the ground thermal conductivity and volumetric specific heat. These parameters are perhaps the most critical to the system design, yet adequately determining them is often the most difficult task in the design phase.

A further complication in the design of ground source heat pump systems is the presence of ground water. Where groundwater is present, flow will occur in response to hydraulic gradients and the physical process affecting heat transfer in the ground is inherently a coupled on of heat diffusion (conduction) and heat advection by moving ground water. In general, groundwater flow can be expected to be beneficial to the thermal performance of closed-loop ground heat exchangers since it will have a moderating effect on borehole temperatures in both heating and cooling modes.

2. GROUNDWATER FLOW

Underground water occurs in two zones: the unsaturated zone and the saturated zone. The term 'groundwater' refers to water in the saturated zone. The surface separating the saturated zone from the unsaturated zone is known as the 'water table'. At the water table, water in soil or rock pore spaces is at atmospheric pressure. In the saturated zone (below the water table), pores are fully saturated and water exists at pressures greater than atmospheric. In the unsaturated zone, pores are only partially saturated and the water exists under tension at pressures less than atmospheric.

Groundwater is present nearly everywhere, but it is only available in usable quantities in aquifers. Aquifers are described as being either confined or unconfined. Unconfined aquifers are bounded at their upper surface by water table. Confined aquifers are bounded between two layers of lower permeability materials. In practice, the boreholes of ground-loop heat exchangers may partially penetrate several geologic layers.

The governing equation describing flow through porous media is Darcy (1856)

$$q = S\, dh/dx \quad (1)$$

Where q is the specific discharge, (volume flow rate per unit of cross-sectional area), S is the hydraulic conductivity, and h is the hydraulic head. The specific discharge is related to average linear groundwater velocity, v, by:

$$v = q/n \quad (2)$$

Where n is the porosity and is introduced to account for the difference between the unit cross-sectional area and the area of the pore spaces through which the groundwater flows (Fetter, 1980; Freeze and Cherry, 1989). By applying the law of conservation of mass to a control volume and by making use of Darcy's Law (Eq. 1), an equation defining the hydraulic head distribution can be derived. Transient groundwater flow with constant density can then be expressed in Cartesian tensor notation as:

$$S_s \frac{\partial h}{\partial t} - \frac{\partial}{\partial x_i}\left(K_{ij} \frac{\partial h}{\partial x_i} \right) = R^* \quad (3)$$

Since groundwater at 43.3°C (an extreme temperature limit expected in GSHP applications) has a specific gravity of approximately 0.991, the assumption of constant density flow for low-temperature geothermal applications may be considered valid.

3. HEAT TRANSPORT IN GROUNDWATER

Heat can be transported through a saturated porous medium by the following three processes:

- Heat transfer through the solid phase by conduction.
- Heat transfer through the liquid phase by conduction, and
- Heat transfer through the liquid phase by advection.

The governing equation describing mass or heat transport in groundwater is a partial differential equation of the advection-dispersion type (Freeze and Cherry, 1979). By applying the law of conservation of energy to a control volume, an equation for heat transport in groundwater can be found and can be expressed as:

$$nR\frac{\partial T}{\partial t}+v_i\frac{\partial T}{\partial x_i}-\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial T}{\partial x_i}\right)=Q^* \qquad (4)$$

Where the velocity v_i is determined from the solution of Eq. 3 and T is the temperature of rock/water matrix. If the groundwater velocity is zero, Eq. 4 reduces to a form of Fourier's Law of heat conduction (Fournier and Rowe, 1966; Eggen, 1990). The diffusion coefficient tensor D_{ij} is modeled as an effective thermal diffusivity given by:

$D^* = k_{eff}/\rho_l C_l$ (5)

The effective thermal conductivity k_{eff} is a volume-weighted average thermal conductivity of the saturated rock matrix and can be expressed using the porosity as:

$k_{eff} = nk_l + (1-n)\ ks$ (6)

It is necessary to distinguish between the conductivity and thermal capacity of the water and soil/rock in this way to account for the fact that heat is stored and conducted through both the water and soil/rock, but heat is only advected by the water. Similarly, it is necessary to define a retardation coefficient R accounting for retardation of the thermal plume, which results from, differences in the liquid and solid volumetric heat capacities:

$$R=\frac{1+(1-n)\rho_s C_s}{n\rho_l c_l} \qquad (7)$$

Darcy's Law indicates that flow is dependent on both the local hydraulic gradient and the hydraulic conductivity of the geologic material. Heat transfer is dependent on the flow velocity and the thermal properties of the material. The thermal properties of soils and rocks are functions of mineral content, porosity and degree of saturation. Of these, porosity may be considered the most important property simply because of the origin and nature of soils and rocks. Rocks originate under higher heat and pressure environments than soils and consequently generally possess lower porosities.

4. SOIL THERMAL MEASUREMENTS

The soil thermal measurements were carried out using KD2 Pro thermal properties analyser (Figure 1). The KD2 Pro is a handheld device used to measure thermal properties (Figure 2). The KD2 Pro is a battery-operated, menu-driven device that measures thermal conductivity and resistivity, volumetric specific heat capacity and thermal diffusivity. It consists of a handheld controller and sensors inserted into the medium to be measured (Figure 3). The single-needle sensors measure thermal conductivity and resistivity, while the dual-needle sensor also measures volumetric specific heat capacity and diffusivity (Figures 4-6).

k is the thermal conductivity (W/m °K)

R is the thermal resistivity (m °K/W)

C is the specific heat capacity (MJ/m^3 °K)

D is the thermal diffusivity (mm^2/s)
r is correlation coefficient

4.1. Specifications

KD2 Pro has been designed for ease of use and maximum functionality. Operating environment as follows:

Controller: 0-50 °C
Sensors: -50 to +150 °C
Battery life 1800 readings in constant use
Accuracy ±5

If the temperature of the sample medium is different from the temperature of the needle, the needle must equilibrate to the surrounding temperature before beginning a reading.

Carslaw and Jaeger (Fournier and Truesdell, 1973) modeled the temperature surrounding an infinite line heat source with constant heat output and zero mass in an infinite medium. When a quantity of heat Q (Jm^{-1}) is instantaneously applied to the line heat source, the temperature rise at distance r (m) from the source is:

$$\Delta T = \frac{Q}{4\prod kt} \exp\left(\frac{-r^2}{4Dt}\right) \quad (8)$$

Where k is the thermal conductivity (W/m °K), D is the thermal diffusivity (mm^2/s) and t is time (s). If a constant amount of heat is applied to a zero mass heater over a period of time, rather than as an instantaneous pulse, the temperature response is:

$$\Delta T = \frac{q}{4\prod k} Ei\left(\frac{-r^2}{4Dt}\right) \quad (9) \qquad 0<t \leq t_1$$

Where q is the rate of heat dissipation (W/m), t_1 is the heating time and Ei is the exponential integral (Carslaw and Jaeger, 1959). The temperature rise after the heat is turned off is given by:

$$\Delta T = \frac{q}{4\prod k} [-Ei\left(\frac{-r^2}{4Dt}\right) + Ei\left(\frac{-r^2}{4D(t-t_1)}\right)] \quad (10) \qquad t>t_1$$

Material thermal properties are determined by fitting the time series temperature data during heating to Eq. .9 and during cooling to Eq. 10. Thermal conductivity can be obtained from the temperature of the heated needle (single needle), with r taken as the radius of the needle.

Diffusivity is best obtained by fitting the temperatures measured a fixed distance (the KD2 Pro uses 6 mm) from the heated needle (k is also determined from these data). Volumetric specific heat (W/m^3 °K) is determined from k and D:

$$C = k/D \quad (11)$$

In each case, k and D are obtained by a non-linear least squares procedure (Abramowitz and Stegun, 1972), which searches for values of k and D, which minimise the difference between modeled and measured sensor temperatures. Most experiments will not occur under constant temperature conditions. An additional linear drift factor is included in the inverse procedure. This reduces errors substantially.

(Kluitenberg *et al.*). (Marqardt, 1963) give solutions for pulsed cylindrical sources that are not ideal line heat sources. For a heated cylindrical source of radius a (m) and length 2b (m), with temperature measured at its centre, the temperature rise during heating (zero<t≤t$_l$) is:

$$\Delta T = \frac{q}{4\prod k} \int_{r^2/4Dr}^{\infty} U^{-1} \exp(-U) \exp[-(a/r)^2 U] I_o(2au/r) erf\left(\frac{b}{r}\sqrt{u}\right) du \quad (12)$$

Figure-1. KD2 Pro thermal properties analyser

Figure-2. Data storage device

During cooling (t>t$_l$) it is:

$$\Delta T = \frac{q}{4\prod k} \int_{r^2/4Dr}^{r^2/4D(t-t_l)} U^{-1} \exp(-U) \exp[-(a/r)^2 U] I_o(2au/r) erf\left(\frac{b}{r}\sqrt{u}\right) du \quad (13)$$

$I_o(x)$ represents a modified Bessel function of order zero, erf(x) is the error function and u is an integration variable. As pointed out by (Kluitenberg *et al.*). (Darcy, 1856), $\exp\,[-(a/r)^{2}u]$ I_o $(2au/r)$ approaches unity as a/r approaches zero, and $erf\left(\frac{b}{r}\sqrt{u}\right)$ approaches unity as b/r approaches infinity, reducing Eqs. (12 and 13) to Eqs. (9 and 10).

Figure-3. Handheld controller and sensors

5. GROUND CHARACTERISTICS

It is important to determine the depth of soil cover, the type of soil or rock and the ground temperature. The depth of soil cover may determine the possible configuration of the ground coil. If bedrock is within 1.5 m of the surface or there are large boulders, it may not be possible to install a horizontal ground loop. For a vertical borehole the depth of soil will influence the cost as, in general, it is more expensive and time consuming to drill through overburden than rock as the borehole has to be cased.

Figure-4. Single-needle sensors for thermal conductivity and resistivity measurements (6 cm) for liquids

The temperature difference between the ground and the fluid in the ground heat exchanger drives the heat transfer so it is important to determine the ground temperature. At depths of less than 2 m, the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperature at the surface. At a depth of about 1.5 m, the time lag is approximately one month. Below 10 m the ground temperature remains effectively constant at approximately the annual average air temperature (i.e., between 10°C and 14°C in the UK depending on local geology and soil conditions). The annual variation in ground temperatures at a depth of 1.7 m compared to the daily average air temperature measured at the site. It also shows the ground temperature at a depth of 75 m.

The need for alternative low-cost energy resources has given rise to the development of DX-GSHPs for space cooling and heating. The performance of the heat pump depends on the performance of the ground loop and vice versa. It is therefore essential to design them together. Closed-loop GSHP systems will not normally require permissions/authorisations from the environment agencies. However, the agency can provide comment on proposed schemes with a view to reducing the risk of groundwater pollution or derogation that might result. The main concerns are:

- Risk of the underground pipes/boreholes creating undesirable hydraulic connections between different water bearing strata.
- Undesirable temperature changes in the aquifer that may result from the operation of a GSHP.
- Pollution of groundwater that might occur from leakage of additive chemicals used in the system.

Figure-5. Extended single-needle sensors for thermal conductivity and resistivity measurements (10 cm) for use in hard materials

In order to determine the length of heat exchanger needed to meet a given load the thermal properties of the ground will be needed. The most important difference is between soil and rock as rocks have significantly higher values for thermal conductivity. The moisture content of the soil also has a significant effect as dry loose soil traps air and has a lower thermal conductivity than moist packed soil. Low-conductivity soil may require as much as 50% more collector loop than highly conductive soil. Water movement across a particular site will also have a significant impact on heat transfer through the ground and can result in a smaller ground heat exchanger.

A geotechnical survey can be used to reduce the uncertainty associated with the ground thermal properties. More accurate information could result in a reduction in design loop length and easier loop installation. For large schemes where multiple boreholes are required, a trial borehole and/or a thermal properties field test may be appropriate (Fournier and Potter, 1979).

Figure-6. Dual-needle sensors for volumetric specific heat capacity and diffusivity measurements (30 mm)

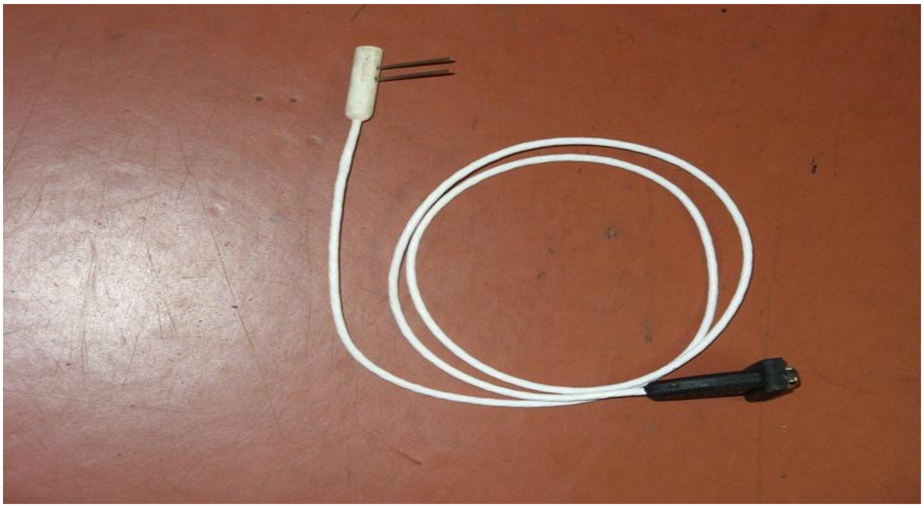


Table-1. Typical thermal properties of soil

Material	Conductivity (Wm^{-1}K^{-1})	Specific heat (kJkg^{-1}K^{-1})	Density (kgm^{-3})	Diffusivity (m^{2}d^{-1})
Granite	2.1-4.5	0.84	2640	0.078-0.18
Limestone	1.4-5.2	0.88	2480	0.056-0.20
Marble	2.1-5.5	0.80	2560	0.084-0.23
Sandstone				
Dry	1.4-5.2	0.71	2240	0.074-0.28
Wet	2.1-5.2			0.11-0.28
Clay				
Damp	1.4-1.7	1.3-1.7		0.046-0.056
Wet	1.7-2.4	1.7-1.9	1440-1920	0.056-0.074
Sand				
Damp		1.3-1.7		0.037-0.046
Wet*	2.1-26	1.7-1.9	1440-1920	0.065-0.084

* Water movement will substantially improve thermal properties

The ground temperature is important, as it is the difference between this and the temperature of the fluid circulating in the heat exchanger that drives the heat transfer. At depths of less than 2 m, the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases, the seasonal swing in temperature reduces and the maximum and minimum soil temperatures begin to lag the temperatures at the surface (e.g., a time lag of approximately one month at 1.5 m, two months at 4 m). The two rock/soil properties that most affect the design of a heat pump system are the thermal conductivity (k) and the thermal diffusivity (D). The thermal properties of common ground types are given in Table 1. The most important difference is between soil and rock because rocks have significantly higher values for thermal conductivity and diffusivity.

The main consideration with installation of the ground coil is to ensure good long-term thermal contact. Only standard construction equipment is needed to install horizontal ground heat exchanger i.e., bulldozers or backhoes and chain trenchers. In larger installation in Europe, track type machines have been used to plough in and backfill around the pipe in continuous operation. Drilling is necessary for most vertical heat exchanger installations. The drilling equipment required is considerably simpler than the conventional equipment for drilling water wells. Drilling methods commonly used are listed in Table 2.

Table-2. Drilling methods for the installation of vertical collectors (Kluitenberg *et al.*)

Ground	Method	Remarks
Soft, sand	Auger	Sometimes temporary casing required
Gravel	Rotary	Temporary casing or mud additives required
Soft, silt/clay	Auger	Usually the best choice
	Rotary	Temporary casing or mud additives required
Medium	Rotary	Roller bit, sometimes mud additives required
	DTH*	Large compressor required
Hard	Rotary	Button bit, very slow
	DTH	Large compressor required
	Top hammer	Special equipment
Very hard	DTH	Large compressor required
	Top hammer	Special equipment
Hard under soft	ODEX#	In combination with DTH

* Down-the-hole-hammer

\# Overburden drilling equipment (Atlas Copco, Sweden)

For the design of thermally efficient and economically sized borehole heat exchanger systems the soil thermal characteristics, especially the thermal conductivity, borehole resistance and undisturbed ground temperature are essential parameters (Table 3). The design and economic feasibility of these systems critically depend upon the estimate of the ground thermal conductivity.

Efficiencies for the GSHPs can be high because the ground maintains a relatively stable temperature allowing the heat pump to operate close to its optimal design point. Efficiencies are inherently higher than for air source heat pumps because the air temperature varies both throughout the day and seasonally such that air temperatures, and therefore efficiencies, are lowest at times of peak heating demand.

6. SOIL THERMAL HEAT PROPERTIES

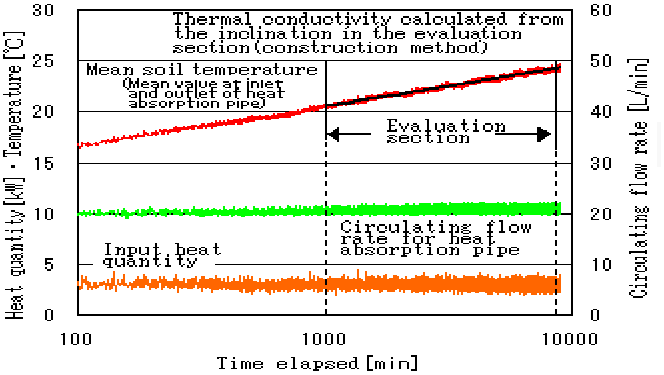
The ground source heat pump system, which uses a ground source with a smaller annual temperature variation for heating and cooling systems, has increasingly attracted market attention due to lower expenses to mine for installing underground heat absorption pipes and lower costs of dedicated heat pumps, supported by environmentally oriented policies (Fetter, 1981).

The theme undertakes an evaluation of heat absorption properties in the soil, and carries out a performance test for a unit heat pump and a simulated operation test for the system. In fact, these policies are necessary for identifying operational performance suitable for heating and hot water supply, in order to obtain technical data on the heat pump system for its dissemination and maintain the system in an effort of electrification. In these circumstances, the study estimated the heat properties of the soil in the city of Nottingham and measured thermal conductivity for the soil at some points in this city, aimed at identifying applicable areas for ground source heat pump system.

Table-3. Actual values of thermal conductivity

Case number	Simulation duration (hr)	Ground thermal conductivity predicted by numerical model (Austin *et al.*, 2000; Rybach and Sanner, 2000) (W/m°C)
1	50	1.11
2	50	1.12
3	50	1.26
4	50	1.98
5	50	6.33
6	50	10.51
7	168	1.08
8	168	1.20
9	168	1.66
10	168	3.89
11	168	14.24
12	168	26.14

Figure-7. Thermo response test



Based on existing information regarding Sapporo's subsurface geology (using geologic columnar section, etc.), thermal properties (thermal conductivity, heat capacity, etc.) for the soil, which is typically found 0 to 30 m deep underground, were estimated (Table 4).

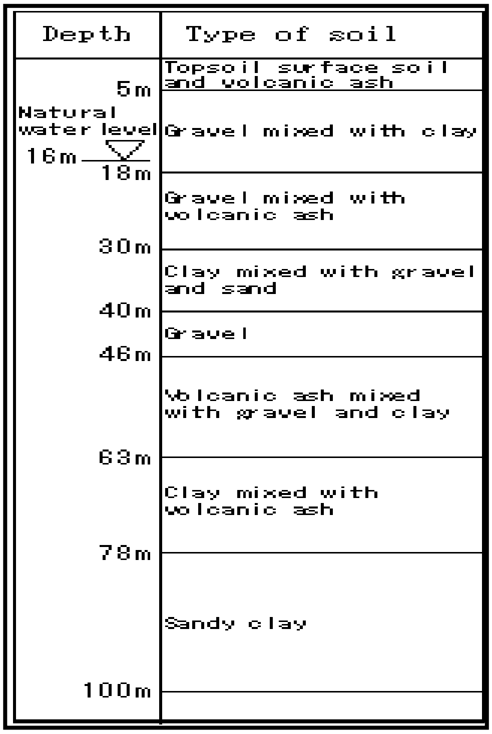
Table-4. Observed value and estimated value of soil thermal conductivity

Evaluation method	Thermal conductivity ($Wm^{-1}K^{-1}$)
Observed value by thermo response test	1.37
Estimation value by geologic columnar section	1.27

6.1. Test of Soil Thermal Conductivity

The sample soil thermal conductivity-measuring instrument was produced to measure the soil thermal conductivity from rises in underground temperature (Figure 7). Thermo response test when a certain amount of heat was conducted into heat absorption soil. According to the measurement result (Table 4), the soil thermal conductivity was observed slightly higher than the thermal conductivity estimated by the geologic columnar section (Figure 8). The future plan is to predict system operational performance at each observation point, based on the relationship between estimated soil thermal property and measured soil thermal conductivity. Figures 9-10 show the examples of measured and predicted soil temperatures.

Figure-8. Geologic columnar sections



Depth	Type of soil
5m	Topsoil surface soil and volcanic ash
Natural water level 16m 18m	Gravel mixed with clay
30m	Gravel mixed with volcanic ash
40m	Clay mixed with gravel and sand
46m	Gravel
63m	Volcanic ash mixed with gravel and clay
78m	Clay mixed with volcanic ash
100m	Sandy clay

It is seen from the figures that temperature drops much faster for granite and slower for the coarse graveled soil either in the soil. This is mainly due to the fact coarse graveled material has a higher thermal storage capacity or lower thermal diffusivity than granite. Therefore, the high thermal energy stored found in the coarse graveled can provide longer heat extraction as shown in Figure 11. Figures 12-15 show summary of the soil thermal properties. The temperature difference between the ground and the fluid in the ground heat exchanger drives the heat transfer so it is important to determine the ground temperature.

Figure- 9. Measured and predicted data of the soil thermal diffusivity

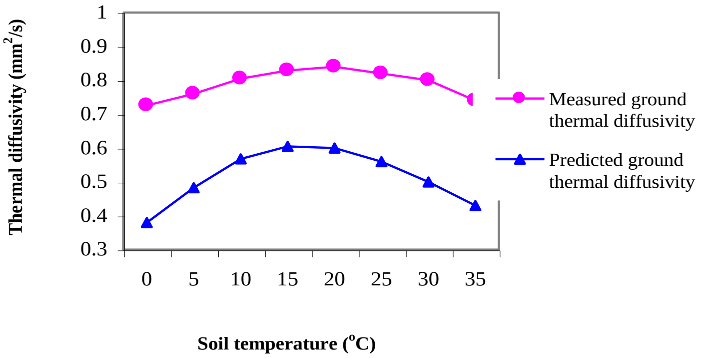
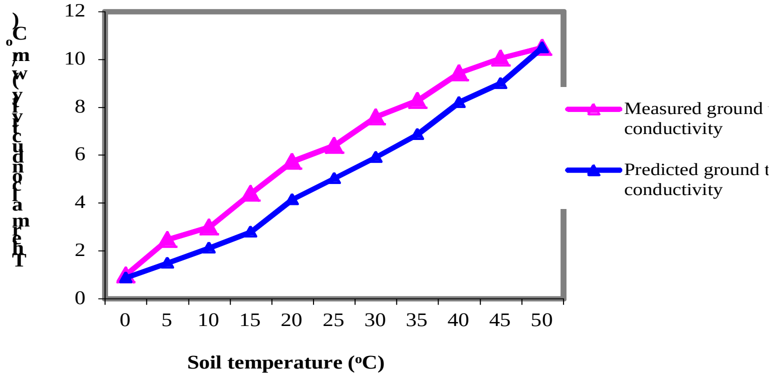


Figure- 10. Measured and predicted data of soil thermal conductivity



At depths of less than 2 m, the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperature at the surface. At a depth of about 1.5 m, the time lag is approximately one month. Below 10 m the ground temperature remains effectively constant at approximately the annual average air temperature (i.e., between 10°C and 14°C depending on local geology and soil conditions). The annual variation in ground temperatures at a depth of 1.7 m compared to the daily average air temperature measured at the site. It also shows the ground temperature at a depth of 75m.

Figure- 11. Comparison of thermal conductivity for different soils

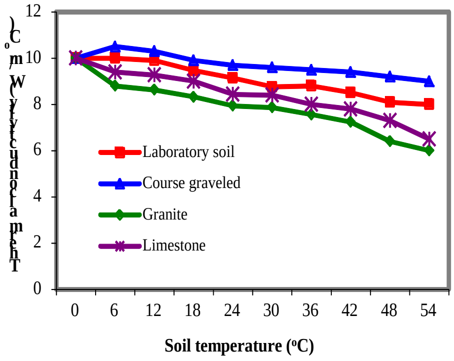
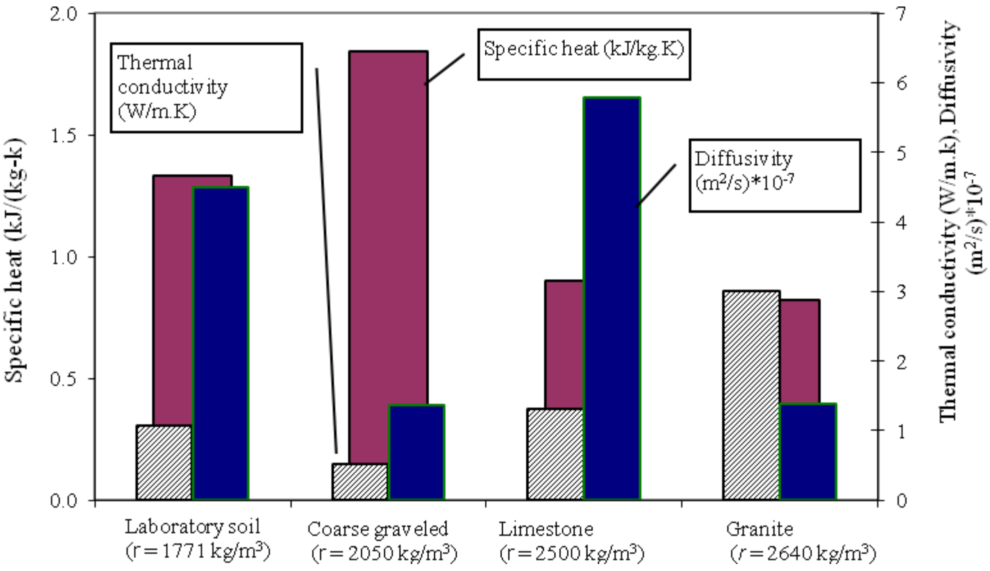


Figure- 12. Thermal properties for different soils



6.1. Ground Temperature

The temperature difference between the ground and the circulating fluid in the heat exchanger drives the heat transfer. So it is important to know the ground temperature. Figure 16 shows the profile of soil temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperatures at the surface. An empirical formula suggested by Eggen (1990) is:

$$T_m = T_o + 0.02 \qquad (14)$$

Where:

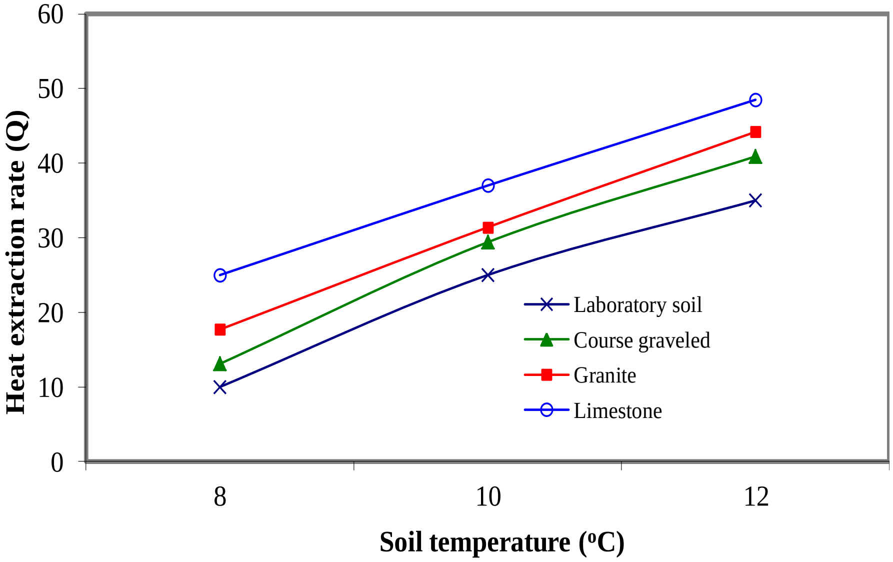
Tm is the mean ground temperature (°C)

To is the annual mean air temperature (°C)

H is the depth below the ground surface (m)

The temperature variation disappears at lower depth and below 10 m the temperature remains effectively constant at approximately the annual mean air temperature (Austin *et al.*, 2000).

Figure-13. Heat extraction rate for 4 types of soils



The heat transfer between the GSHP and its surrounding soil affected by a number of factors such as working fluid properties (e.g., 20% glycol) and its flow conditions, soil thermal properties, soil moisture content and groundwater velocity and properties, etc. GSHP has a great potential to be one of the main energy sources in the future as it can be tapped in a number of different ways and can be used to produce hot water as well as electricity. It has a large spatial distribution with almost all countries having at least low enthalpy resources available (less than 125°C) and many countries around the world in both developing and developed countries are already harnessing it.

Figure-14. Variation of soil temperature ground depth

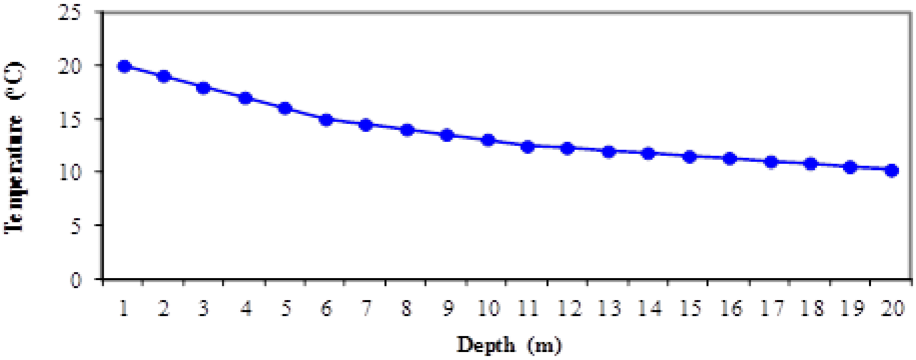


Figure-15. Effect of soil properties on ground water temperatures

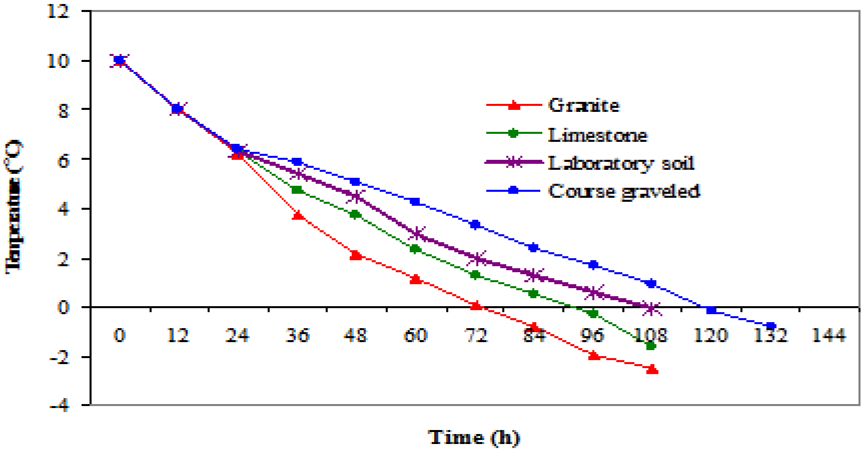
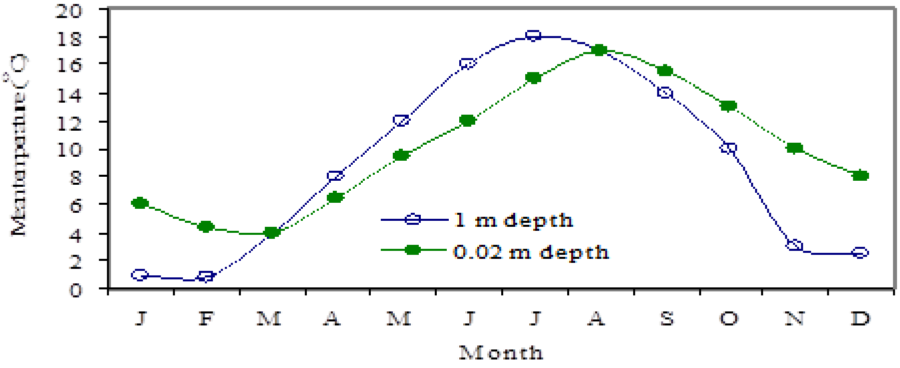


Figure-16. Seasonal variation of soil temperature at depths of 0.02 m and 1 m



It is important to maximise the efficiency of a heat pump when providing heating, not only to have a low heating distribution temperature but also to have as high a source temperature as possible. Overall efficiencies for the GSHPs are inherently higher than for air source heat pumps because ground temperatures are higher than the mean air temperature in winter and lower than the mean air temperature in summer. The ground temperature also remains relatively stable allowing the heat pump to operate close to its optimal design point whereas air temperatures vary both throughout the day and seasonally and are lowest at times of peak heating demand. For heat pumps using ambient air as the source, the evaporator coil is also likely to need defrosting at low temperatures. It is important to determine the depth of soil cover, the type of soil or rock and the ground temperature. The depth of soil cover may determine the possible configuration of the ground coil. In order to determine the length of heat exchanger needed to meet a given load the thermal properties of the ground will be needed. The most important difference is between soil and rock as rocks have significantly higher values for thermal conductivity (Table 5). The moisture content of the soil also has a significant effect as dry loose soil traps air and has a lower thermal conductivity than moist packed soil. Low-conductivity soil may require as much as 50% more collector loop than highly conductive soil. Water movement across a particular site will also have a significant impact on heat transfer through the ground and can result in a smaller ground heat exchanger. This study urges the need for GSHP to be considered much more strongly than it currently is in environmental policies as it has been overlooked as a main alternative to fossil fuels and other forms of renewable energies.

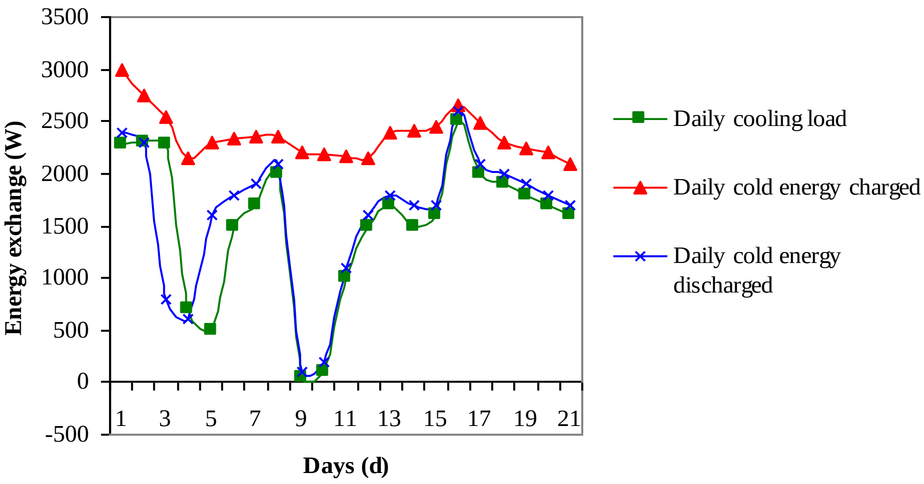
Table-5. Peclet numbers corresponding to typical values of thermal properties of soils and rocks

Porous medium	Peclet number L= a typical borehole spacing of (4.5 m)
Soil	
Gravel	5.72E+02
Sand (coarse)	1.34E+01
Sand (fine)	1.15E+00
Silt	1.28E-02
Clay	3.2E-05
Rocks	
Limestone, Dolomite	5.92E-03
Karst limestone	5.28E+00
Sandstone	1.77E-03
Shale	1.05E-06
Fractured igneous and metamorphic	6.32E-02
Unfractured igneous and metamorphic	1.00E-07

7. CONCLUSIONS

Geothermal energy and the other renewable energy sources are becoming attractive solutions for clean and sustainable energy needs. Being environmentally friendly and with the potential of energy-efficiency, GSHP systems are widely used. Also, the need for alternative low-cost energy resources has given rise to the development of GSHP systems for space cooling and heating in residential and commercial buildings. GSHP systems work with the environment to provide clean, efficient and energy-saving heating and cooling the year round. GSHP systems use less energy than alternative heating and cooling systems, helping to conserve the natural resources. The heat transfer between the GSHP and its surrounding soil affected by a number of factors such as working fluid properties (e.g., 20% glycol) and its flow conditions, soil thermal properties, soil moisture content and groundwater velocity and properties, etc. Soil was a homogeneous porous medium, with its mass force, heat radiation effect and viscosity dissipation neglected. The local temperature of groundwater and soil arrived at a thermal equilibrium instantly. The thermal and physical properties of soil and its temperature at the far-field boundary remained constant. Heat transfer between a GSHP and its surrounding soil illustrated in Figure 17, which shows the daily cold energy charged to and discharged from its surrounding soil using DX-GSHP at different days. The daily cold energy charged in the initial pre-cooling period sharply decreased, while during the normal operating period, it increased gradually, and the building cooling load although is not big. The direct expansion (DX) ground source heat pump (GSHP) systems have been identified as one of the best sustainable energy technologies for space heating and cooling in residential and commercial buildings. The GSHPs for building heating and cooling are extendable to more comprehensive applications and can be combined with the ground heat exchanger in foundation piles as ell as seasonal thermal energy storage from solar thermal collectors. Heat pump technology can be used for heating only, or for cooling only, or be 'reversible' and used for heating and cooling depending on the demand. Reversible heat pumps generally have lower COPs than heating only heat pumps.

Figure-17. Simulation results in summer



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Appendix-1. Types of thermo/hygrometer and air current measurement devices

Device Type	Name of equipment	Images
Thermometer / Hygrometer	Thermal recorder TR-72U T&D Corp. Japan	
Air current Measuring device	Velocity calculator TSI Inc. USA	
Thermometer of surface area	testo 925 Testo AG Germany