Measurements of Ground Temperature at Various Depths

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ABSTRACT: Information on ground temperatures is necessary for many construction projects. These include the calculations of heat losses of buildings to the ground and the design of thermal energy storage equipment. With the growing need for conservation of energy, information on ground temperature is also important for the possible use of the ground as a source for heat pump applications. Engineers and architects concerned with these problems require knowledge of the factors that determine ground temperatures as well as an understanding of how these temperatures vary with time and depth from the surface. The earth temperature beyond a depth of 1 meter is usually insensitive to the diurnal cycle of air temperature and solar radiation and the annual fluctuation of the earth temperature extends to a depth of 9 to 12 meters. This study discusses the factors affecting ground temperature and the winter temperature variation with depth. Temperatures were measured in Nicosia, Cyprus, with thermocouples inserted in the ground at a depth of 0m to 50m. It was found that the short-period temperature variations in winter, are prominent to a depth of approximately 0.5m. The temperature measurements are compared to the calculated values resulting from the use of the Kasuda formula adopted by the TRNSYS type 501, with the results showing good agreement within about 0.5°C for a depth greater than 2 meters.

Keywords: Ground temperature, Kasuda formula, TRNSYS

1. INTRODUCTION

Measurements show that the ground temperature below a certain depth remains relatively constant throughout the year. This is due to the fact that because of the high thermal inertia of the soil the temperature fluctuations at the surface of the ground are diminished as the depth of the ground increases. Also, there is a time lag between the temperature fluctuations at the surface and in the ground. Therefore, at a sufficient depth, the ground temperature is always higher than that of the outside air in winter and is lower in summer. This difference in temperature can be utilised as a preheating means in winter and pre-cooling in summer by operating an earth heat exchanger. Also, because of the higher efficiency of a heat pump than conventional natural gas or oil heating systems, a heat pump may be used in winter to extract heat from the relatively warm ground and pump it into the conditioned space. In summer, the process may be reversed and the heat pump may extract heat from the conditioned space and send it out to an earth heat exchanger that warms the relatively cool ground.

This study presents the temperatures measured in a borehole in Nicosia, Cyprus, during the months of December 2003 to March of 2004 in an ongoing project and compares these values with the calculated ones using the Kasuda formula.

2. GROUND THERMAL BEHAVIOUR

The use of direct or indirect earth-coupling techniques for buildings and agricultural greenhouses requires knowledge of the ground temperature profile. The ambient climatic conditions affect the temperature profile below the ground surface (Fig. 1) and need to be considered when designing a ground heat exchanger. Actually the ground temperature distribution is affected by the structure and physical properties of the ground, the ground surface cover (e.g. bare ground, lawn, snow etc), the climate interaction (i.e. boundary conditions) determined by air temperature, wind, solar radiation, air humidity and rainfall. The above daily variations can affect the ground temperature to a depth of approximately one meter. According to the ASHRAE Handbook of HVAC Applications [1], the earth temperature beyond a depth of 1 meter is usually insensitive to the diurnal cycle of air temperature and solar radiation and the annual fluctuation of the earth temperature extends to a depth of 9 to 12 meters. In deeper layers, the temperature distribution remains unchanged throughout the year with the temperature increasing with depth by an average gradient of about 30 °C/km. The geothermal gradient deviations from the average value are, in part, related to the type of rocks present in each section.

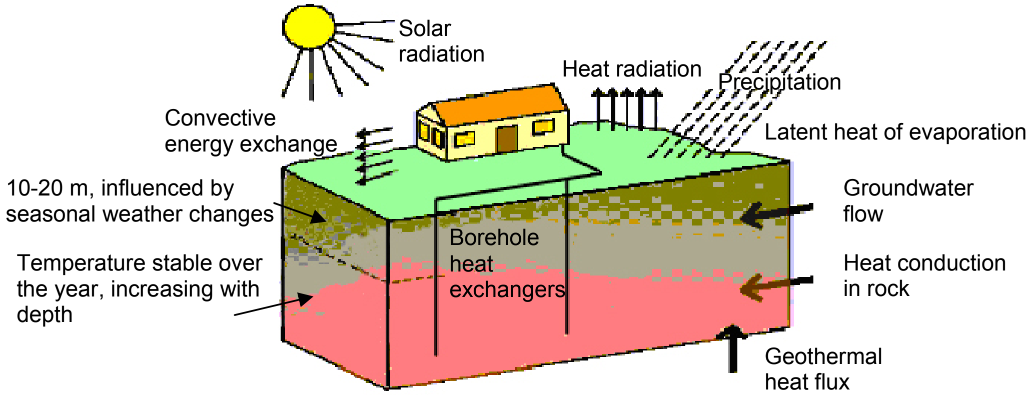

Figure 1: Energy flows in ground.

Heat flow, which is a measure of the amount of thermal energy coming out of the earth, is calculated by multiplying the geothermal gradient by the thermal conductivity. Each rock type has a different thermal conductivity, which is a measure of the ability of a material to conduct heat. Rocks that are rich in quartz, like sandstone, have a high thermal conductivity, indicating that heat readily passes through them. Rocks that are rich in clay or organic material, like shale and coal, have low thermal conductivity, meaning that heat passes less readily through these layers. If the heat flow is constant throughout a drill hole (i.e., water is not flowing up or down the hole), then it stands to reason that low-conductivity shale layers will have a higher geothermal gradient compared to high-conductivity sandstone layers [2].

A complete model for the prediction of the daily and annual variation of ground surface temperature is presented by Mihalakakou et al. [3]. This model uses a transient heat conduction differential equation and an energy balance equation at the ground surface to predict the ground surface temperature. The energy balance equation involves the convective energy exchange between air and soil, the solar radiation absorbed by the ground surface, the latent heat flux due to evaporation at the ground surface as well as the long-wave radiation. The model is validated against 10 years of hourly measured temperatures for bare and short-grass covered soil in Athens and Dublin. The results are compared with the corresponding results of models using Fourier analysis. Furthermore, a sensitivity investigation is performed to investigate the influence of various factors involved in the energy balance equation at the ground surface on the soil temperature profile. As it is demonstrated, an increase of the wind speed leads to a reduction of the ground surface temperature, mainly caused by the heat transfer by convection between the ground surface and the air and also by the latent heat flux due to evaporation. An increase of the soil absorptivity leads to higher ground surface temperatures. Also, an increase of the air relative humidity results in increased ground surface temperatures.

Popiel et al. [4], present the temperature distributions measured in the ground for the period between summer 1999 to spring 2001. The investigation was carried out in Poznan, Poland, for two differently covered ground surfaces, a bare surface and a surface covered with short grass. Temperatures were measured with thermocouples distributed in the ground at a depth from 0 to 7 m (bare surface) and from 0 to 17 m (short grass). It was found that the short-period temperature variations reached a depth of approximately 1 m. From July to the end of September from the surface region at ground depth (below about 1.5 m) a heat flux of 3.6 W/m^2 was transferred. Usually the recommended depth for horizontal ground heat exchangers is from 1.5 to 2 m. The measurements also show that during the summer period the ground temperature under the bare surface below 1 m was about 4°C higher in comparison to the temperature of the ground covered with short grass. Therefore for the ground "cold" source, e.g. for the air conditioning application the surface covered with short grass is recommended. However, in winter, the temperature distributions were almost the same. A comparison of the Buggs's formula for the ground temperature distribution adapted to the region of Poznan shows a good agreement with the experimental data.

From the point of view of the temperature distribution three ground zones are distinguished [4]:

1. *Surface zone* reaching a depth of about 1m, in which the ground temperature is very sensitive to short time changes of weather conditions.
2. *Shallow zone* extending from the depth of about 1-8 m (for dry light soils) or 20 m (for moist heavy sandy soils) where the ground temperature is almost constant and close to the average annual air temperature; in this zone the ground temperature distributions depend mainly on the seasonal cycle weather conditions and
3. *Deep zone* (below about 8-20 m), where the ground temperature is practically constant (and very slowly rising with depth according to the geothermal gradient).

Williams and Gold [5], present a table showing approximate values for the depth of penetration for different types of ground and moisture content. By defining the "penetration depth" as the depth at which the amplitude of a temperature variation is reduced to 0.01 of its amplitude at the surface, the depth of penetration of the daily cycle can be calculated to be 7.64 k/c_v and that of the annual wave 19.1 times this value. The conclusion drawn from Table I is that the presence of water deepens the effect of both the daily cycle and that of the annual wave.

Table I: Depth of Penetration of Diurnal and Annual Temperature Cycles.

Types of Ground	Thermal diffusivity of the ground (soil) $\alpha = k/c_v$ (cm²/sec)	Penetration Depth of Cycle	
		Diurnal (m)	Annual (m)
Rock	0.020	1.10	20.5
Dry sand	0.001	0.30	4.5
Wet sand	0.010	0.80	14.5
Dry clay	0.002	0.40	6.5
Wet clay	0.015	0.95	18.0

In Cyprus, there are no studies undertaken so far related to the efficiency and cost estimation of ground heat exchanger systems and it is of interest to examine such systems in this environment. For this purpose we have recently installed a 50 m deep U-tube, 40mm polyethylene heat exchanger, equipped with 20 thermocouples, which are installed at various depths, for recording the ground temperature and exploiting the possibilities for using this type of systems. The lithology and temperature measurements obtained so far are indicated in the following sections.

3. LITHOLOGY OF THE BOREHOLE AREA

The lithology prevailing over the site of the borehole is the Nicosia-Athalassa formation and is represented by the calcareous sandstone and the in situ mari. In detail the geological formation is shown in Table II.

The water level is at about 15 meters. The discharge rate is estimated between 2 to 3 m^3/h. The water conductivity is about 2250 ms/cm.

4. TEMPERATURE MEASUREMENTS

Preliminary temperature measurements for the whole depth of the borehole have shown that the annual temperature cycle had penetrated to a depth of 12-15 meters as shown in Fig. 2. The temperature measurements were taken on the 23rd of December, 2003. The temperature between 15 and 50 meters remains relatively constant at about 22.5 °C, since the water present in these ground layers smoothens any variations.

Table II: Geological details of the Nicosia-Athalassa formation.

Depth (m)	Type of material	Density ρ (kg/m^3)	Thermal Conductivity k (W/m-K)	Observations
0-1	Fill material such as gravels, sands and silt	1950	0.255	Measured values for undisturbed soil
1-15	Yellowish-creamy, fine to coarse grained weak to moderately cemented, calcareous sandstone. According to sieve analysis the results are 15-30% silt and the rest sand	1660	0.237	Measured values for dry soil
15-21	Khaki, marly calcarenite grading to calcarenitic marl (clay 15-20%, silt 45-50%, sand 30-40%)			Water table starts at this level
21-24	Fine grained moderately cemented calcareous sandstone			
24-29	Khaki, marly calcarenite grading to calcarenitic marl (clay 15-25 %, silt 45 50%, sand 30-40%)			
29-32	Khaki, sandy marl (fine sand 5-10%, clay 25-30%, silt 60-65%)			
32-50	Grayish marl (fine sand 5-10%, clay 30-40%, silt 50-65%)	1400	0.225	Measured values for dry soil
		1560	0.285	Measured values for soil with 12% water

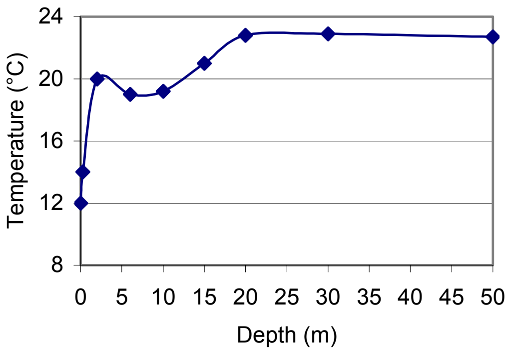

Figure 2: Temperature variation with depth for December 2003 (preliminary results).

Measurements taken during January to March 2004, show that the ground to a depth of about 2 meters becomes colder at about mid February and then it gets warmer. For a depth between 2 to 3 meters the ground continues to cool from January to the end of March (Fig. 3 and 4).

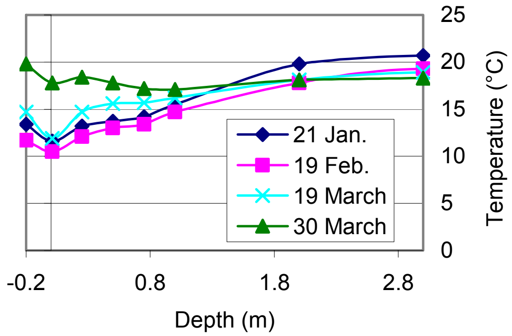

Figure 3: Temperature variation with depth for various dates, at 6 a.m. which is the coldest hour of the day. (Depth at -0,2m corresponds to ambient temperature)

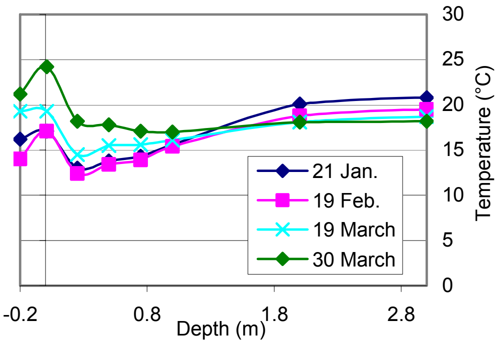

Figure 4: Temperature variation with depth for various dates at 12 noon (Depth at -0,2m corresponds to ambient temperature).

Temperature variation with depth for a continuous time span, for 12 noon on the 18th to12 noon on the 19th March 2004, (Fig. 5), shows that the depth of penetration of the daily cycle is prominent to a depth of about 0.5m. This depth depends greatly on the thermal conductivity of the top soil which in this case is low (see Table II) therefore the penetration depth is not expected to be large.

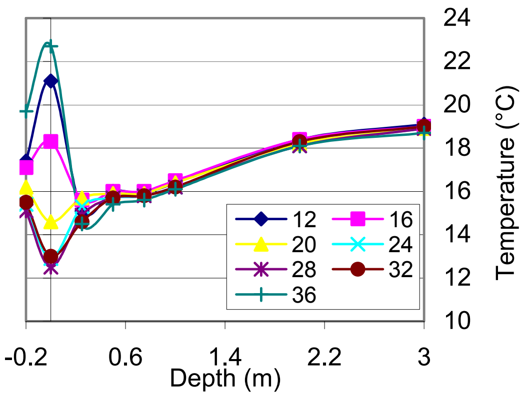

Figure 5: Temperature variation with depth for a continuous time span, for 12 noon on the 18th to12 noon on the 19th March 2004. (Depth at -0,2m corresponds to ambient temperature)

Figure 6 shows the time lag which is observed between the temperature fluctuations at the surface and in the ground during a sunny day. Because of the solar radiation falling on the ground and the higher capacity of the soil relative to the ambient air, the temperature of the soil just below the surface starts getting hot at about 8 a.m. and is heated at a higher rate than the ambient air. Because of the high thermal inertia of the soil, the temperature fluctuations at the surface of the ground are diminished as the depth of the ground increases and the temperature at 0.25 meters depth gets its highest value of the day at about 7 p.m., with a time lag of five hours compared to the maximum temperature at the depth of 0.1 meters. The daily variation below the depth of 0.25 meters is nearly negligible in this case.

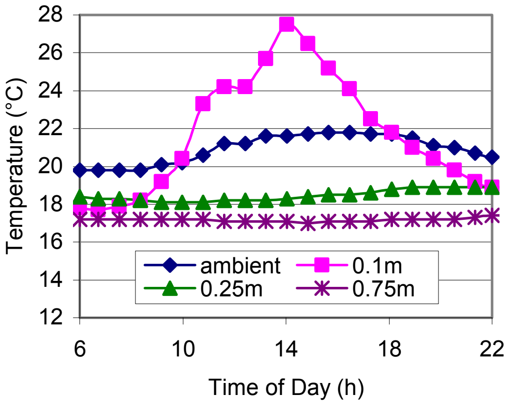

Figure 6: Time lag observed in temperature penetration for 30 March 2004.

5. NUMERICAL SIMULATION

For the numerical simulation, a program like TRNSYS can be utilized [6]. This program, developed by the University of Wisconsin, consists of many subroutines that model subsystem components. The mathematical models for the sub-system components are given in terms of their ordinary differential or algebraic equations. The program has the capability of interconnecting system components in any desired manner, solving differential equations and facilitating information output. For the present study, TRNSYS Type 501 library component is used, developed by the Thermal Energy System Specialists (TESS). This subroutine models the vertical temperature distribution of the ground and is based on the method developed by Kasuda [7]. Kasuda found that the temperature of the ground is a function of the time of year and the depth below the surface and could be described by the following correlation:

$$T = T_{mean} - T_{amp} * \exp\left(-Z * \sqrt{\frac{\pi}{365 * \alpha}}\right) * \cos\left(\frac{2\pi}{365} * \left[t_{year} - t_{shift} - \frac{Z}{2} * \sqrt{\frac{365}{\pi * \alpha}}\right]\right) \tag{1}$$

where:

T	Temperature of soil
T_{mean}	Mean surface temperature (average air temperature). The temperature of the ground at an infinite depth will be this temperature
T_{amp}	Amplitude of surface temperature (The maximum surface temperature will be $T_{mean}+T_{amp}$ *and the minimum value will be* $T_{mean}-T_{amp}$)
Z	Depth below the surface
α	Thermal diffusivity of the ground (soil)
t_{year}	current time (day)
t_{shift}	day of the year of the minimum surface temperature

To apply the above equation the weather variables for Nicosia-Cyprus are needed. For this purpose the Typical Meteorological Year (TMY) data for Nicosia, Cyprus, developed by Petrakis et al. [8] are used. These have been generated from hourly measurements, for a seven-year period, from 1986 to 1992. The data were collected by the Meteorological Service of the Ministry of Agriculture and Natural Resources of Cyprus, at the Athalassa region, where the borehole is drilled. According to these data the time shift is 35 days, the mean surface temperature is 18.5°C, the amplitude of the surface temperature is 21°C with the maximum air temperature being 42°C and a minimum 0°C. These data show that there is a discrepancy between the mean surface temperature and the Amplitude of surface temperature, since 21°C added to18.5°C is not 42°C.

Figure 7 shows the distribution of temperature with respect to time for different values of soil depth for Nicosia, Cyprus.

Comparing the above results with the measured values (Fig. 8) it is shown that the values obtained for the depths of 2 and 3 meters are very close. The values though, for the one meter depth vary considerably. This is due to the fact that the variation of the temperature depends greatly on the actual weather conditions which are affected by the diurnal cycle. Also, the results of the numerical simulation of the ground temperature distributions may not be reliable, mainly because of difficulties in determining precisely the physical properties of the undisturbed ground.

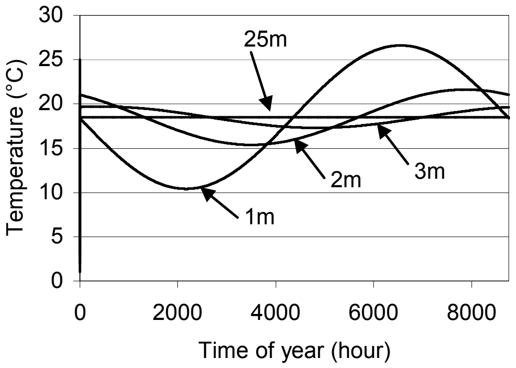

Figure 7: Results obtained for a typical year, by using the Kasuda formula for various depths.

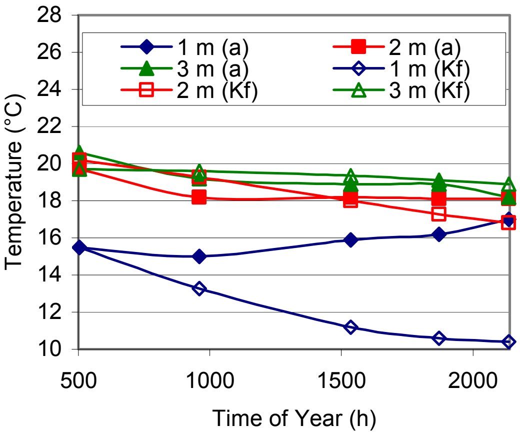

Figure 8: Comparison of results obtained using the Kasuda formula (Kf) and actual measurements (a) at various depths.

6. CONCLUSIONS

This study discusses the factors affecting ground temperature and the winter temperature variation with depth. It was found that the short-period temperature variations in winter are prominent to a depth of approximately 0.5 m. Because of the high thermal inertia of the soil, the temperature fluctuations at the surface of the ground are diminished as the depth of the ground increases and the temperature at 0.25 meters depth gets its highest value of the day with a time lag of five hours compared to the maximum temperature at the depth of 0.1m. In this particular case, for winter, the daily variation below the depth of 0.25 meters is small.

The temperature measurements are compared to the calculated values resulting from the use of the Kasuda formula adopted by the TRNSYS program, type 501, with the results showing good agreement within about 0.5°C for a depth greater than 2m. However the comparison between the model and measurements at a depth of 1m vary considerably. This is due to the fact that the variation of the temperature depends greatly on the actual weather conditions which are affected by the diurnal cycle. Also, the results of the numerical simulation of the ground temperature distributions may not be reliable, mainly because of difficulties of the precise determination of the physical properties of the undisturbed ground.

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