Measuring and analysing the underground temperature and heat flux changes for the local assessment of the shallow geothermal potential

László Merényi[1], Péter Szilágyi[1]

[1] Geological and Geophysical Institute of Hungary, Stefánia út 14., H-1143 Budapest, Hungary

merenyi.laszlo@mfgi.hu

Keywords: shallow geothermal potential, thermal diffusivity, temperature profile.

ABSTRACT

The surface temperature changes due to meteorological reasons induce downward propagating temperature signal in the soil. The two major components of the underground temperature signal are the daily and annual changes, but other long or short term components can also be present. While a temperature signal propagates downward, its amplitude is attenuating and its phase shifts is increasing. By continuously measuring the natural temperature and/or heat flux variations at different depths, we can derive relevant information about the medium's thermal property and some information about the heat transport processes. Such measurements can be considered as a thermal test method for shallow depths that is similar but not identical to the more frequently used active test measurements in shallow and deeper depths, employing known heat sources.

In this paper we discuss the shallow temperature and heat flux measurements and analysis as a potential tool for the local assessment of the shallow geothermal potential. We share some practical aspects of the application of the method. We notice the importance of the calculated apparent thermal diffusivity. We present our measurements done with common temperature sensors and with special high sensitivity heat flux sensors. We processed the temperature and heat flux recordings with different methods to find the phase shift of daily and annual signals measured at different depths and then to get the apparent thermal diffusivity for the sections between the depths. Through a presented example we show the results got from a shallow temperate and a deeper heat flux measurements from the same station. Finally we make suggestion to include the intensity of the atmosphere-ground thermal interactions into the value of shallow geothermal potential.

1. INTRODUCTION

The knowledge of the ground thermal properties and the underground heat and mass transport processes is essential for the right evaluation of the feasibility and sustainability of ground source heat pump systems (GSHP), and for the safe and optimal sizing of ground heat exchangers (GHE). In addition, the knowledge of the thermal interactions between the atmosphere and the underlying surface is also very important in case of very shallow GHEs or energy piles installed into one or several meter depths.

Information about these influencing factors can be obtained in different ways and for different scales, depths and accuracies. Geological, pedological, hydrogeological maps together with meteorological data can be integrated and processed to create large and medium scale maps presenting one or more elements of the influencing factors (Bertermann et al 2015). A typical displayed value is the average ground thermal conductivity for a representative depth or for a given depth interval. However, the shallow geothermal potential is also affected by other parameters, like heat capacity, permeability and groundwater flow.

Especially in case of shallow and very shallow systems and in case of urban environment, the local geothermal conditions can vary within very short distances, and maps cannot generally supply accurate information for local installations. In such cases site specific assessments have to be accomplished. This process typically starts by gathering information about the local ground type and underground water tables. Ground thermal properties then can be estimated from tables, based on the obtained geological and pedological information. The thermal parameters derived in this way contain some uncertainties. The possible errors in the estimations can be compensated by oversizing the GHE length. The level of uncertainty, and consequently the oversizing length can be reduced if one or more parameters are determined by specific test measurements. In case of borehole heat exchangers a frequently employed method is the so called thermal response test (TRT). During a TRT, a known amount of heating or cooling power is applied to an installed GHE for several days, and the temperature response is measured and then analysed to get borehole resistance and ground apparent thermal conductivity. TRT can determine the apparent thermal conductivity precisely for the desired dimension; however the method requires the installation of a GHE and a high power testing apparatus. There are some standardized methods for measuring soil thermal conductivity and heat capacity on smaller volumes of samples. These measurements can be realized samples taken to laboratory or sometimes directly on the site. However, mainly due to soils micro-scale heterogeneity and to some problems in the sample preparation (like keeping original moisture content and consistency), the results of these measurements are often subject for bigger deviation and error.

Another potential tool for the assessment of thermal properties and heat flow processes in shallow depths is the measurement and analysis of natural or induced temperature changes over a period, at two or more adjacent points, generally in a vertical arrangement. By determining phase shift and/or amplitude attenuation of diurnal and/or annual temperature waves propagating downward in the soil, the apparent average thermal diffusivity for the layers between the points can be easily obtained. This method has been used for long time for the geothermal (Lovering and Gode 1963, Zhang et al 1995, Verhoef et al 1996, Gao et al 2008, Evstatiev 2013) and other applications (for example: Smerdon et al 2003). However in shallow geothermal exploration its practical usage is still rare. It is important to note that in addition to the determination of the thermal diffusivity (and its temporal changes), the measurements could produce some other important results. It is possible, for example, to detect thermal anomalies due to non-conductive forms of heat transfers, e.g. due to groundwater flow or to considerable lateral heat flow. The measurements can be realized near working GHEs or energy piles, to monitor the heat extraction and injection, the ground temperature depletion and to determine ground thermal parameter at the same time. In our paper, we discuss some practical aspects, some possible applications and extensions of this method. For example, we show that continuous heat flux measurements can be used similarly to temperature measurements for the analysis. We present an example from our measurements and results. We processed a temperature recording taken at shallower depth than 1 meter, to calculate the apparent thermal diffusivity from the phase delay between the diurnal temperature waves. Specifically, we calculated the temporal change of the value of apparent thermal diffusivity that can be due to the soil humidity variations and to some changing non-conductive forms of heat transfer. We also show the results for a 7 meter deep heat flux measurements from the same site. Finally, we make a suggestion to extend the method in order to easily classify the intensity of air-ground heat exchange that can be an important factor for very shallow geothermal systems.

2. THERMAL CHARACTERIZATION OF THE GROUND

2.1 Thermal conductivity

One dimensional vertical heat transfer through conduction can be described from Fourier's law:

$$Q = \lambda \frac{\partial T}{\partial z}, \qquad [1]$$

where Q is the heat flux (W m^{-2}), λ is thermal conductivity (W m^{-1} K^{-1}) and $\partial T/\partial z$ (K m^{-1}) is the vertical temperature gradient. In the non-steady state heat flux in the soil is described by equation:

$$C_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right), \qquad [2]$$

where C_v (J m^3 K^{-1}) is the volumetric heat capacity and t (s) is the time.

2.2 Apparent thermal conductivity

In addition to pure heat conduction, other forms of heat transfer can also appear in the ground, such as advection through groundwater flow in saturated layers, or sensible or latent heat changes in unsaturated layers. For practical reasons, one or more elements of these non-conductive forms can be included – with more or less limitations – in the value of apparent thermal conductivity. As we discuss below, an apparent (or averaged) value can also be used to describe a larger volume of the ground that is subject for inhomogeneity, and/or to account for the temporal variability of the parameters.

2.3 Heat capacity and thermal diffusivity

It is common to classify the shallow geothermal potential based on the apparent thermal conductivity value. The other basic thermal parameter is the volumetric heat capacity that is also an important factor in the point of view of GHE operation. The typical values of volumetric heat capacities of different types of grounds fall within a narrower range than heat conductivity values, and it is less frequently used for ranking geothermal potential. The ratio of thermal conductivity to the volumetric heat capacity is the thermal diffusivity:

$$\alpha = \frac{\lambda}{C_v}. \qquad [3]$$

The primary outcome of the method described in this paper is the thermal diffusivity. The thermal diffusivity, similarly to thermal conductivity, can be used as an indicator value for the shallow geothermal potential. Moreover, similarly to apparent thermal conductivity, the apparent thermal diffusivity can account – with limitations – for non-conductive heat transfer forms and for material inhomogeneity and temporal variations. The thermal conductivity value, if required, can be calculated from the determined thermal diffusivity value and from measured or estimated volumetric heat capacity value.

2.4 Spatial and temporal variation of the thermal parameters

A difficulty to classify the shallow geothermal potential with thermal property values comes from the possible spatial and temporal variation of the basic thermal properties. Vertical and lateral inhomogeneity of the ground can be handled by making the test measurements in similar scales and by expressing the parameters for similar scales than the size of the installed BHE. Especially in the temporary or permanently unsaturated layers, the changing water content can result in changes in the effective thermal conductivity and volumetric heat capacity values (Eppelbaum et al 2014). Thermal parameters depend also on the absolute temperature, but this dependence is considerable in only the ground's top section, where the temperature variations have higher amplitudes. If the ambient temperature can fall below freezing point in winter, then snow-melting and soil freezing-thawing processes can considerably change heat transfer on the top section (Smerdon et al 2003). These processes can be still included in seasonal averaged value of thermal diffusivity. Snow cover has also important influence for the surface-ground interaction. In the point of view of heating dominated utilization of shallow GHEs, the thermal isolation due to snow cover can be beneficial.

3. UNDERGROUND TEMPERATURE SIGNALS

The surface temperature changes due to meteorological reasons induce downward propagating temperature signal in the soil. The two major components of the underground temperature signal are the daily and annual changes, but other long or short term components are also present. While this multicomponent temperature signal propagates downward, the amplitude of the changes is attenuating while the phase shift is increasing. The daily variations can be measured up to several meters and the annual changes up to about 15-18 meters.

If we assume homogeneous medium, harmonic temperature signal and only heat conduction, then the phase shift and logarithm of then amplitude attenuation of the fixed frequency (daily and annual) signals are directly related to the thermal diffusivity of the medium. From the steady state analytic solution for one-dimensional heat conduction in case of harmonic surface signal (see for example: Carslaw and Jaeger 1959) the temperature $T(h,t)$ at t(s) time and h(m) depth can be get as:

$$T(h,t) = T_0 + T_a \cdot e^{-2\pi\frac{h}{l}} \cdot \sin\left[2\pi\left(\frac{t}{\tau} - \frac{h}{l}\right)\right], \quad [4]$$

where T_0 (K) is the temperature at the surface at t=0 s time, T_a (K) is the amplitude of the harmonic temperature signal at the surface, l (m) is the wavelength and τ (s) is the signal period (1 day or 1 year in this application). The wavelength is a function of the thermal diffusivity:

$$l = 2\sqrt{\pi a \tau} \,. \quad [5]$$

These equations offer the possibility to determine the wavelength and consequently the thermal diffusivity from temperature profile time series with two methods: from the experimented logarithm of amplitude attenuation or from the experimented phase shift.

The temperature effect of a heating or cooling BHE measured at a sufficient distance can also be considered as a harmonic annual wave. Consequently, measurement with more sensors in horizontal radial arrangement near a working BHE can produce similar results.

Differentiating equation [4] with respect to depth, we obtain the following formula that can be used to process temperature gradient (heat flux) measurements:

$$\frac{\partial T}{\partial h}(h,t) = \sqrt{2}T_a\left(\frac{-2\pi}{l}\right) \cdot e^{-2\pi\frac{h}{l}} \cdot \sin\left[2\pi\left(\frac{t}{\tau} - \frac{h}{l}\right) + \frac{\pi}{4}\right]. \quad [6]$$

4. MEASUREMENTS

4.1 Temperature sensors

In our test measurements we use Pt100 resistance temperature sensors and LM35/LM335 integrated circuit type sensors, but underground temperature recordings can also be realized by using other common types of temperature probes. In a measurement point two or more sensors are installed vertically, at different depths. Because of the fact that amplitudes of the thermal waves are very low at deeper measuring points and because of the difficulties to obtain amplitudes accurately from measurements having lower and/higher frequency signals (noises), we do not use the amplitudes in the calculations. Instead, we examined only the phase shifts between the temperature waves, recorded at different depths. As the determination of the phase shift is possible from relative temperature changes, ensuring good absolute accuracy with calibrations and ensuring long term stability of the sensors are not critical. This is an important advantage of the phase shift based data processing.

4.2 Heat flux sensors

The direct measurement of underground heat flux can be accomplished with soil heat flux sensors or plates. These sensors generally consist of a thermopile, measuring temperature difference that is converted to heat flux value using the thermal conductivity of the material. The commercially available heat flux plates are generally designed for near surface measurements, and their sensitivity is not enough to detect variations below several tens of centimetres. For deeper measurements we manufactured heat flux sensors in which the distance between the thermocouple junctions are bigger, to get a higher sensitivity (around 1 mW m^{-2}). The analytical formula of equation [6] can be used to process measured data, on condition that the sensor length (the distance between the junction points) is small compared to the measurement depth. For deeper measurements (below 5-10 meters), it is possible to use long (10-20 cm) sensors, supporting very high sensitivity. Moreover, if using equation [6], there is no need to convert the measured temperature difference into heat flux value, which conversion otherwise can be inaccurate due to the difference between the thermal conductivity of ground and the probe. In addition, similarly to the temperature data, only the relative changes are important to determine phase shifts. All these considerations simplify the realization of the measurement. We also note that it is possible to process temperature and heat flux (actually temperature-difference) recordings together. At a given depth, the heat flux has a constant $\pi/4$ phase shift compared to the temperature.

4.3 Data acquisition, sampling

Continuous digital data acquisition of the temperature sensors and heat flux sensors can be easily realized using commercial products. Special care should to be taken for temperature dependence of the sampling A/D converter (and for the current generator in case of Pt100 sensor). If the A/D converter is operated in a room where the temperature can change during days and over seasons, then the temperature sensitivity can add a noise to the measurement at the signals frequency (daily and annual waves). This type of error has to be checked, and if possible, has to be decreased, e.g. by continuous self-calibration.

To get high resolution data, we are sampling with relatively high rates (1 Hz or 30 Hz depending on the A/D converter), and using medium or high resolution A/D converters (16-bit and 23-bit). Raw data are filtered to lower data rates, to remove high frequency noise and quantization noise. We can eventually use the dithering effect to increase the resolution. We found that with this type of sampling, 0.001°C resolution can be easily achieved in time series filtered to one or several minute intervals.

4.4 Test stations

We conduct continuous underground temperature and heat flux recordings in three sites in Hungary: (1) near an office building in Budapest, XIVth district, (2) in Tihany Geophysical Observatory and (3) in Papsziget (Szentendre) geothermal monitoring station. Table 1 summarizes primal information of the stations. All of the measurements are done in urban environment, near buildings, in partially disturbed soils. The location of Papsziget station is special as it is at the riverside of Danube.

Table 1: Underground temperature and heat flux measurement test stations

Stations	Soil texture	Temperature recordings depths (m)	Heat flux recording depths (m)
Buda-pest	Sandy clay loam	0.23, 0.43, 0.63	7, 4*
Tihany	Clay with geyserite pieces	0.02, 0.20, 0.60	-
Papsziget	Sandy loam	0.10, 0.30, 0.50 and 0.10, 0.25, 0.40	7.5, 14.5

* heat flux measurements started at 2003 and stopped in the beginning of 2006 in Budapest.

5. RESULTS

We processed the temperature and heat flux recordings with different methods to find the phase shift between different depths. Here we present only the results for Budapest temperature recordings for a shorter period that is covered by a continuous data set and for the 7 m deep heat flux recording.

We used 1 minute record interval data for calculations with diurnal temperature signal. The 1 minute samples were aggregated to 10 minute when analysing the annual temperature signal.

We tried out several mathematical methods to find the phase shift. These methods included minimum-maximum search, sinusoidal curve fitting, Fourier transformation and cross-correlation. We applied these calculations not for the whole data set, instead we selected a smaller calculation period (a calculation window) and run this window through the entire data set and calculated results for each step. In this way we were able to get temporal changes of the phase shift. The result for a calculation window is related to the center-time of that window. The calculation window sizes were selected to 5-30 days when analysing diurnal signal, and 1-2 years when analysing annual signal.

When analysing diurnal signals, we found that data have to be first band-pass filtered, to get reliable results with all the above methods. We employed frequency-domain filtering with FFT then applied an inverse FFT. This type of filtering successfully removed all the lower and higher frequency signals and noises. After filtering, all the methods outputted very similar results. When analysing the annual signal, we found the sinusoidal curve fitting method the best. It performed well even without band-pass filtering the data for the annual frequency. This can be a practical advantage when working with data sets containing bigger data gaps (that cannot be fixed by interpolation), because the difficulties of the application of band-pass filtering in that case.

At the end of procession, we calculated the thermal diffusivity from the phase shift.

Figure 1 shows the measured data and the results for Budapest temperature recordings for about one and a half year. Thermal diffusivity values are presented for the three possible combinations of the three measuring depths (0.23 - 0.43 m, 0.23 - 0.63 m and 0.43 – 0.63 m) on the bottom plot. Here the thin curves represent the results got with diurnal waves, using 20 day window, while thick curves represents the results got with annual waves, using 1 year window. The latter curve is much narrower, that is due to the wider, one-year calculation window size (curve has half year margins at both sides). On the middle plot we present the 1-day band-pass filtered version of the bottom (0.63 m) data set. According to this plot, the amplitude of the bottom temperature signal is sometimes getting very low, especially during winter. The time average thermal diffusivity is about $0.65 \cdot 10^{-6}$ m^{2}s^{-1} for all three depths combinations. The thermal diffusivities calculated for the top layer (0.23 – 0.43 m) are within a small range all along the examined period. We accept this results, and we due the seen variations mainly to real changes in thermal diffusivities, coming from water content and absolute temperature changes. For other depth combinations, the curves show higher variation and they eventually go out of presented range. We relate these unstable periods to the calculation errors coming from the very low amplitudes of the bottom recording. The results from the annual signals does not really fit the results from diurnal signals (especially in case of the top layer), however they are in the same order of magnitude. Probably the one year period is not enough to get the accurate phase shift from the shallow depth temperature records, containing higher frequency signals with high amplitudes.

Earlier, in 2003, at the same station we started a 7 m and 4 m deep recording with an own made heat flux sensor. Due to some reconstruction on the site, these measurements stopped after several years. For the 7 m measurement, the phase of the heat flux sensor recordings and ambient air temperature had been determined by fitting sinusoidal function (Merényi 2005). The recordings together with fitted sinusoidal functions are presented in figure 2. There are gaps in the data, and also some small jumps that can be due to groundwater flow or to measurement errors, but the fitting was still possible with acceptable accuracy.

In the plot we present the direct voltage output of the heat flux sensor (in μV), as for the phase shift based analysis there is no need to convert it either to temperature difference nor to real heat flux value. Because of the lack of shallow temperature recordings at that time, we consider the ambient air annual variation as an h=0 m ground temperature (GST) variation. According to Smerdon et al (2003), the phase difference is negligible between the GST and SAT annual time series. The determined phase shift between the annual signals of the heat flux sensor output and the ambient air temperature is 101.6 days. Comparing equation [4] and equation [6] shows that correcting this phase shift with $\pi/4$ (365/8 days), we can get the phase shift of a similar temperature measurement. Thus we can process this data similarly to the temperature data. The corrected 147.2 days phase shift correspond to a thermal diffusivity value of $0.76\cdot10^{-6}$ m^2s^{-1}. This result is slightly higher than the average value ($0.65\cdot10^{-6}$ m^2s^{-1}) got from shallow temperature recordings. This increase can easily be explained by effect of the saturated zone that is already involved in the 7 meter deep measurement's result.

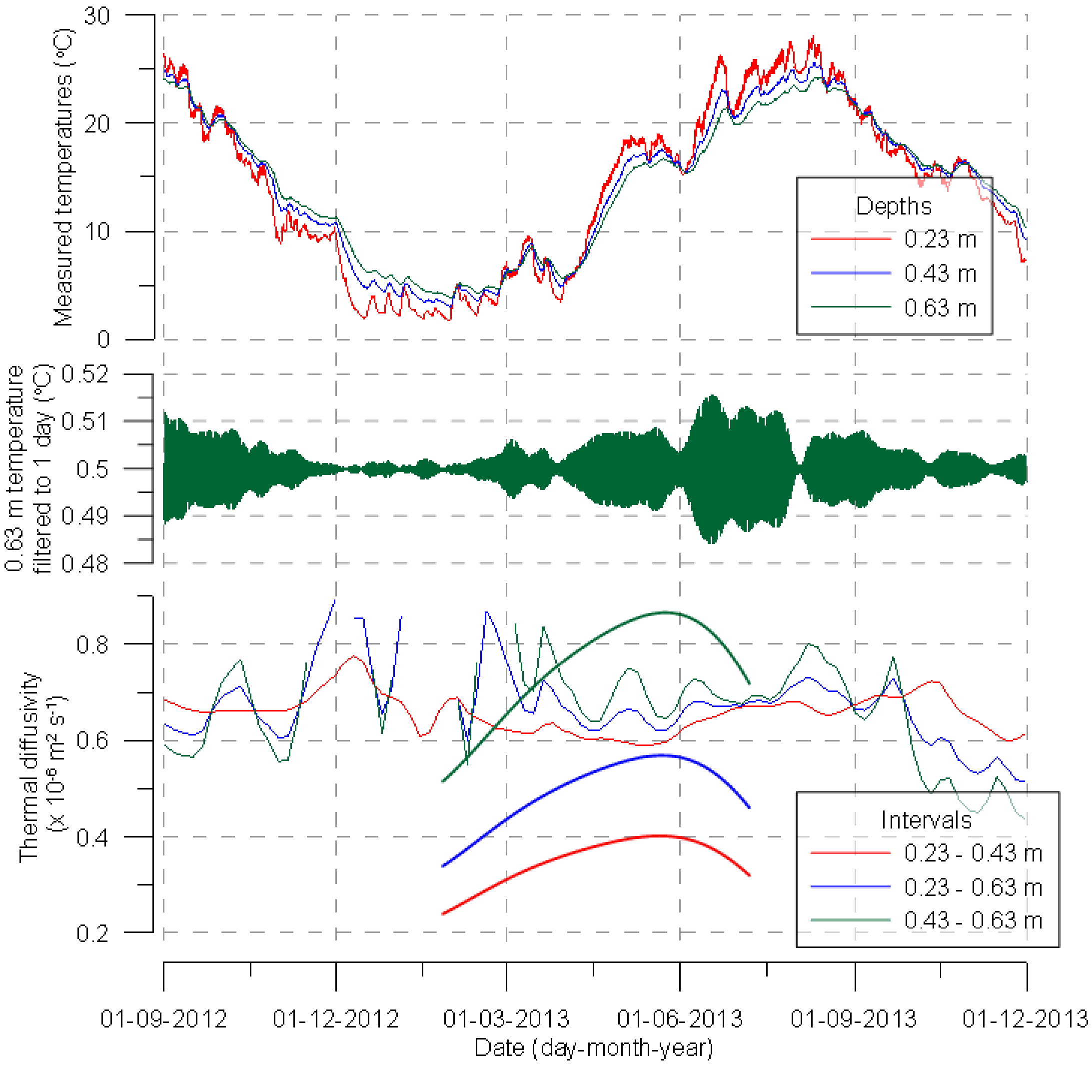

Figure 1: The measured temperatures (top plot), temperatures filtered for 1-day interval at the 0.63 m measurement point (middle plot) and the calculated thermal diffusivities (bottom plot), for the Budapest station. Thick curves represent the results got with annual waves.

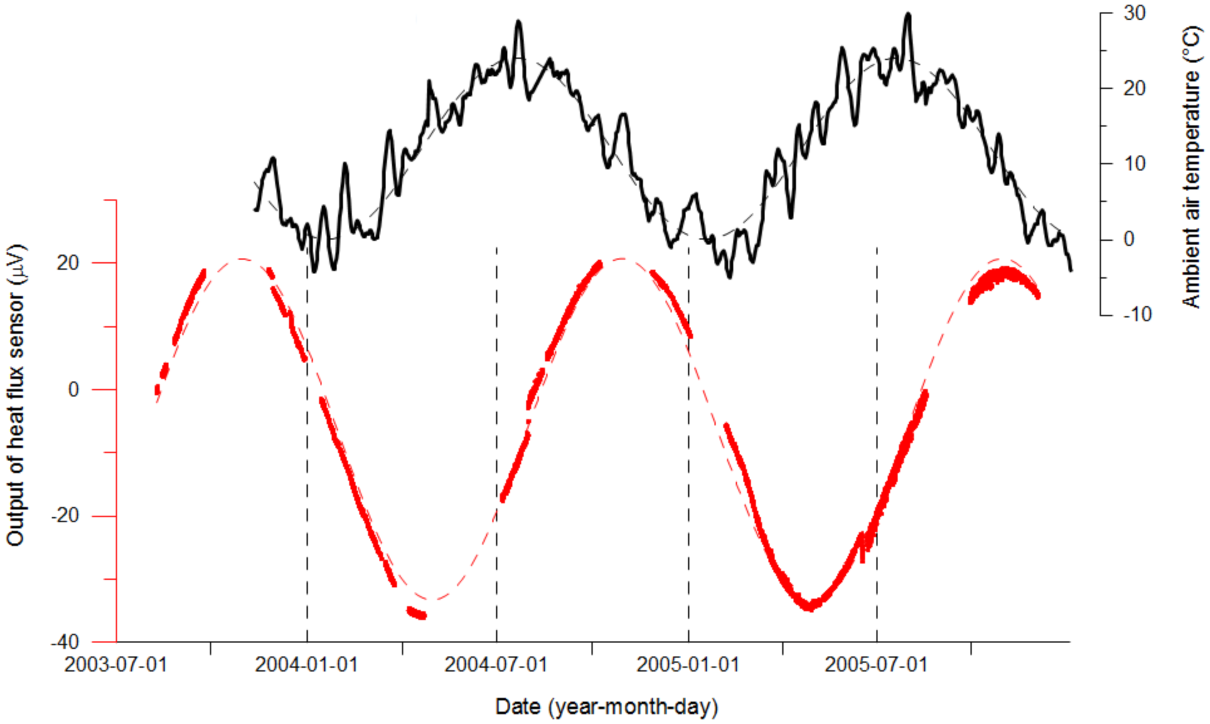

Figure 2: The measured voltage output of heat flux sensor at 7 meter depth (red curve) and daily averages of ambient air temperatures (black curve). Dashed curves represent the fitted sinusoidal functions.

6. SHALLOW GEOTHERMAL POTENTIAL

The influence of the different ground thermal and hydrogeological properties and the existing underground heat and mass transport processes for the performance the GSHP systems can be summarized in the term of shallow geothermal potential. Because of the complexity and heterogeneity of the influencing factors, the definition of the shallow geothermal potential value is not obvious. A simple approach for GHE based system is to define the potential based on the ground basic thermal properties, especially on the thermal conductivity. For a more detailed expression, other parameters like porosity, permeability, natural groundwater flow should also be included. In addition, for very shallow systems (up to about several meters), the intensity of ground–atmosphere thermal interaction is also an important factor that should to be taken into account. The ground- atmosphere thermal interaction is determined again by many different physical and biological processes (adsorption/radiation, evapotranspiration, freezing-thawing, etc.). Furthermore, the intensity of these processes can considerably vary between seasons and even over decades, due to vegetation changes, to built environment changes and to long term meteorological changes, especially the winter meteorological conditions (Smerdon et al 2003). By extending calibrated near surface temperature measurements with surface meteorological measurements, valuable quantitative information could be get both on the ground's apparent thermal property and on the ground-surface thermal interaction. A simple approach of the calculation can be the determination of the difference between the amplitudes of the diurnal or annual surface air temperature (SAT) and ground surface temperature (GST) series. This difference can be a measure of the intensity of soil-air heat exchange rate. In the analysis, the special thermoinsulation effects of winter conditions should be separately taken into account. GST can be estimated by extrapolating the logarithm of the amplitude of diurnal/annual temperature signals determined for two or more depths to the surface (Smerdon et al 2003).

7. CONCLUSIONS

We presented some practical aspects of the underground temperature profile measurements as a tool for the determination of the ground thermal diffusivity, and as a potential tool for the assessment of the shallow geothermal potential. We showed the possible application of heat flux (or temperature difference) measurement for the same reason. We briefly presented the processing steps and the results for a shallow temperature profile recording and for a deeper heat flux recording from one of our measurements stations.

From the presented results and from some other results not presented here we draw some conclusions on the limits of the method. The maximum measurement depth and the minimum measurement time depend on the soil thermal diffusivity and on the sensors' sensitivity. In case of the diurnal signals, the depth and time also strongly depends on the actual metrological conditions (amplitude of temperature variations at the surface). For working with diurnal signals, it is suggested to use at least 10-20 days of continuous measurements. Below 0.5 meter depth the strong amplitude attenuation can result in inaccuracy. However, by increasing the measurement's resolution, the bottom limit can be extended. Filtering data is necessary to get reliable results. Annual signals should be measured preferably below 0.5 meter. We presume that with special high resolution measurements, the annual signal can be still caught at 15-18 meter depths on sedimentary layers. Depending on the quality of the measurement, one or several years long time series is required for the analysis.

REFERENCES

Bertermann, D., Klug, H. and Morper-Busch, L.: A pan-European planning basis for estimating the very shallow geothermal energy potentials, *Renewable Energy*, 75, (2015), 335–347.

Lovering, T. S. and Gode H. D..: Measuring Geothermal Gradients in Drill Holes Less Than 60 Feet Deep East Tintic District, Utah, Geological Survey Bulletin 1172, *United States Government Printing Office*, Washington, (1963).

Zhang, T. and Osterkamp, T. E.: Considerations in determining thermal diffusivity from temperature time series using finite difference method, *Cold Regions Science and Technology*, 23, (1995), 333-341.

Verhoef, A., van den Hurk, B. J. J. M., Jacobs, A. F. G. and Heusinkveld, B. G.: Thermal soil properties for vineyard (EFEDA-I) and savannah (HAPEX-Sahel) sites, *Agricultural and Forest Meteorology*, 78, (1996), 1-18.

Gao, Z., Lenschow, D. H., Horton, R., Zhou, M., Wang, L. and Wen, J.: Comparison of two soil temperature algorithms for a bare ground site on the Loess Plateau in China, *J. Geophys. Res.*, 113, (2008).

Evstatiev, B.: Evlauation of thermal diffusivity of soil near the surface: methods and results, *Bulgarian Journal of Agricultural Academy*, 19 (No 3), (2013), 467-471.

Smerdon, J. E., Pollack, H. N., Enz, J. W and Lewis, M. J.: Conduction-dominated heat transport of the annual temperature signal in soil, *J. Geophys. Res.*, 108(B9), (2003).

Eppelbaum, L., Kutasov, I. and Pilchin, A.: Thermal Properties of Rocks and Density of Fluids, in: Applied Geothermics, Lecture Notes in Earth System Sciences, 99-149, *Springer*, (2014).

Carslaw, H.S. and Jaeger, J.E.: Conduction of Heat in Solids, 2nd Edition. *Oxford University Press*, New York, (1959).

Merényi, L.: Geotermikus Kutatások - Jelentés a 2005. évi tevékenységről (Report in Hungarian). *Eötvös Lorand Geophysical Institute*, Budapest, Hungary (2005).