JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY **5**, 041809 (2013)

Assessments about soil temperature variation under censored data and importance for geothermal energy applications. Illustration with Romanian data

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(Received 18 November 2012; accepted 15 March 2013; published online 8 July 2013)

The study presents an experimental research carried out to study the natural soil temperature variations and to determine the soil thermal diffusivity based solely on temperature measurements. The research was conducted for two locations in Romania: Cluj-Napoca on bare clay soil and Reghin on grass covered clay soil. It was proved that the design and methodology of the research can be successfully applied in any location. Based on a statistical analysis of the experimental data, a simple and precise mathematical model for natural temperature variation was identified for each location. An important particularity of the models is that for each parameter are presented specific ranges of variation and confidence intervals. To the best knowledge of the authors, this approach is unique in the scientific literature. Another particularity of the models is that it was obtained under censored data. The presented models are generally suitable for any depth up to 10 m. For both locations the soil thermal diffusivity was calculated with specific ranges of variation and confidence interval. The obtained results are of utmost importance for the evaluation of local soil thermal potential for geothermal energy applications. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4812655]

I. INTRODUCTION

Results of soil temperature monitoring for long time periods were previously reported in Refs. 1–17 and others.

Some studies on soil thermal properties are presenting correlations between soil water content, texture, and thermal properties without involving temperature measurements.[18–20]

Influence of soil composition on the soil thermal properties together with soil temperature measurements, but without long term monitoring are presented in Refs. 21 and 22.

Many previous studies concerning soil temperature measurements, indicated in Table I, deal with ambient parameters, soil composition, and soil thermal properties. The considered ambient parameters are air temperature (ta), solar radiation (sr), wind speed (w), relative humidity (rh), precipitation (p), heat flux through the soil (h), and snow cover (s). The soil composition refers to water content, mechanical, and chemical structure or porosity. The considered soil thermal properties are density (ρ), thermal conductivity (λ), specific heat (or thermal capacity) (c_p), and thermal diffusivity (α).

All the elements presented in Table I are important for the study of operation conditions of many thermal systems, based on the use of heat accumulated in ground, as potential source of

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TABLE I. Ground level atmospheric parameters and soil thermal properties related with soil temperature.

		Ground level atmospheric parameters								Soil thermal properties			
Reference	ts	ta	sr	w	rh	p	s	h	cpw	ρ	λ	c_p	α
18									✓	✓	=	✓	✓
1	✓	✓	✓	✓				✓		=	✓	✓	✓
2	✓												✓
23	✓	✓						✓		✓	✓	✓	=
3	✓	✓	✓	✓	✓	✓	✓						
4	✓	✓									✓		✓
5	✓										✓		
21	✓								✓	=	✓	✓	✓
6	✓							✓	✓				✓
7	✓	✓						✓	✓	=	✓	✓	✓
8	✓	✓	✓	✓	✓								✓
9	✓												✓
20									✓	✓	✓	✓	✓
10	✓	✓	✓			✓		✓	✓	=	✓	✓	✓
11	✓	✓									✓		
12	✓		✓	✓	✓				✓		✓		
13	✓		✓		✓			✓					✓
14	✓									✓	✓	✓	=
24									✓	✓	✓	✓	✓
15	✓							✓			✓		✓
16	✓	✓	✓						✓		✓		✓
22	✓								✓	=	✓	✓	✓
19		✓				✓			✓	=	✓	✓	✓
17	✓		✓			✓			✓	=	✓	✓	✓
Our study	✓												✓

ts—soil temperature.
Ambient parameters.
ta—air temperature; sr—solar radiation; w—wind speed.
rh—relative humidity; p—precipitation; s—snow cover; h—heat flux through the soil.
cpw—soil composition (water content, texture and porosity).
Soil thermal properties.
ρ—density; λ—thermal conductivity; c_p—specific heat (or thermal capacity); α—thermal diffusivity.
✓ the sign is indicating that mentioned parameter is referred in the paper.
= the sign is indicating that mentioned parameter is not referred in the paper, but it can be determined since the thermal parameters are related ($\alpha = \lambda/\rho c_p$) —the definition of thermal diffusivity.

renewable energy. Such technical systems are geothermal heat pumps and ground/air heat exchangers.

One of the most important parameters characterizing the heat transfer into the ground is the thermal diffusivity. This parameter is indispensable while designing the mentioned systems and the paper will, therefore, focus mainly on this parameter.

The soils considered in the present study are of clay types.

Novelty elements of the paper are as follows: (1) the proposed models are suitable for depths up to 10 m, representing a larger limit that found in literature; (2) each parameter of the models are provided with specific ranges of variation and confidence intervals; (3) the soil thermal diffusivity was calculated only from temperature measurements.

The aim of the paper was to obtain both a good model for the estimation of natural temperature variation as well as a good estimation of the soil thermal diffusivity which was obtained from the temperature measurements.

II. GEOGRAPHICAL LOCATIONS

The study was conducted in two locations in central Transilvania, Romania: between 1 May 2009 and 8 October 2010 in Cluj-Napoca (CJ) on bare clay soil and between 17 October 2009 and 26 June 2010 in Reghin (RG) on grass covered clay soil. The geographic coordinates where the measurements were carried out are in CJ: N: 46° 45′ 35″; E: 23° 34′ 19″ at 379 m of altitude and in RG: N: 46°46′12″; E: 24°41′28″ at 390 m of altitude.

The two measurements locations are presented on an Eastern Europe map, in Figure 1.

The geographic region of measurements (central Transylvania or Transylvania plane) is characterized by a temperate continental climate, according to the Köppen-Geiger climate classification.[25] This climate is highly dynamic, ranging from hot and dry summers to cold and moist winters. The southern part is dryer with steppe vegetation and the northern part is more humid. Information on soil temperatures of the region are very limited.[26]

The central Transylvania region has a relief of rolling hills with 300–450 m in south and 550–600 m in north. The soil is of marine origin and consists mainly of marl, clay marl, sand, and sandy clay complexes. The predominant soils are Mollisols 40%, Alfisols 22%, and Entisols 25%.[27] These types of soil are associated with the "clay."[28]

The soil bulk density evaluation procedure, at depth of 10 cm and of 30 cm, based on measurements of 40 probes, is presented in Ref. 27. The obtained soil bulk density in central Transylvania was ranged between 0.83 and 1.50 kg/m^3, with an average of 1.29 kg/m^3.

III. MEASUREMENT SYSTEM

The evaluation of soil temperature variation is a key issue in soil thermal engineering, proved by the great number of reported monitoring systems with different characteristics, as indicated in Table II. The characteristics of the monitoring systems presented in this paper are also indicated.

A monitoring system based on a wireless soil temperature and moisture measurement station was used in both locations to collect the experimental data.

Four pairs of temperature and relative humidity sensors were mounted in the soil at different depths of up to 2 m following a geometrical distribution: 0.18 m, 0.40 m, 0.89 m, and 2.00 m. The geometrical distribution was chosen to be correlated with the exponential soil temperature variation with depth. The characteristics of the sensors are presented in manufacturer technical documentations.[29,30]

FIG. 1. Measurements locations on the Eastern Europe map (from Google Earth Copyright 2013 Google) Cluj-Napoca (N: 46° 45′ 35″; E: 23° 34′ 19″); Reghin (N: 46°46′12″; E: 24°41′28″).

TABLE II. Characteristics of different reported soil temperature measurement systems.

Reference[a]	H	T	D	ST	S	N
1	0–0.5 m	1 s/15 min[b]	10 days	clay	bare	2
2	0–5 m	…	"long term"	clay/sandy	bare	20
3	0–1 m	30 s/5 min[b]	360 days	clay	grass	1
4	0–0.6 m	1 min	360 + days	clay	grass	1
5	0–900 m	…	250 years	different	…	15
6	0–0.1 m	…	5 days	clay/sandy	…	2
7	0–0.5 m	3 h	360 days	laterite	…	1
8	0–2 m	30 min	360 days	clay	…	1
10	0–0.8 m	30 s	2 years	loess	…	1
9	0–5 m	24 h	20 years	different	…	322
11	0–600	…	100 years	different	…	35
12	0–1.2 m	3 times in 24 h	10 years	…	bare/grass	2
13	0–1.2 m	…	10 years	…	bare/grass	2
14	0–4 m	…	360 days	…	bare/glass	1
15	1–14 m	1 week	588 days	…	bare/grass	2
16	0–100 m	10 min	20 years	different	…	28
17	0–0.8 m	5 s	750 + days	clay	…	1
27	0.5 m	…	360 days	different	…	20
Our study CJ	*0–2 m*	*1 min*	*530 + days*	*clay*	*bare*	*1*
Our study RG	*0–2 m*	*1 min*	*250 + days*	*clay*	*grass*	*1*

H—Depths of temperature measurements; T—Time step of measurement systems; D—total duration of the experiment; ST—Soil type; S—Type of ground covering surface layer; N—Number of measurement locations.
[a]Only the first author is indicated.
[b]Measurements are realized at each indicated number of seconds, but only averaged data are stored at each indicated number of minutes.

The components of the experimental setup are presented in Figure 2.

The measurement station (1) transmits via the wireless system (2) to a console (3). A data logger (4) is connected to both the console (3) and a local computer (5) with Internet connection (6). Home-made software is used to transfer the data into a database located on the web server (7). The measured data were recorded at 1 min intervals.

The soil stations measurement systems (1)–(4) and the local computers (5) are located in CJ at the University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca and in RG at a small private farm.

The web server (7) is located at the Technical University of Cluj-Napoca.

The data acquisition systems used in this study, operated continuously in both locations, more than 530 days in CJ and more than 250 days in RG, except for some interruptions mainly caused by electric network breakdowns. In CJ the total length of interruptions was of about 60 days representing 11% of the total experiment period and in RG the total length of interruptions was of about 140 days representing 56% of the total experiment period. Considering these particular conditions, the study was classified as "under censored data."

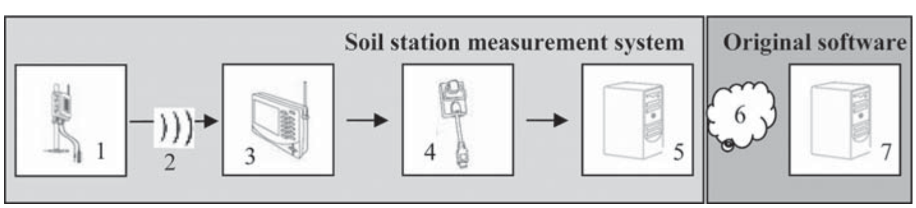

FIG. 2. Schematic configuration of the measurement system 1: Soil station; 2: Wireless radio communication; 3: Console; 4: Data logger; 5: Local PC; 6: Internet connection; 7: Server.

IV. THEORETICAL MODELING

The natural undisturbed ground temperature variation t(z,τ) (°C) can be calculated according to Refs. 21, 31, and 32 as

$$t(z,\tau) = t_{avg}(z) - t_{amp}\exp\left(-z\sqrt{\frac{\pi}{d\alpha}}\right)\cos\left(\frac{2\pi}{d}\tau - \frac{2\pi}{d}\tau_0 - z\sqrt{\frac{\pi}{d\alpha}}\right), \quad (1)$$

where z (m) is the depth where the temperature is calculated, τ (s) is the moment for which the temperature is calculated, $t_{avg}(z)$ (°C) is the yearly soil average temperature at given depth (z), t_{amp} (°C) is the yearly amplitude of soil temperature variation at the surface, d (s) is the length (duration) of the year: d = 365 243 600 = 31 536 000 s/year, τ_0 (s) is a phase constant, α (m^2/s) is the soil thermal diffusivity: $\alpha = \frac{\lambda}{\rho \cdot c_p}$, λ (W/mK) is the soil thermal conductivity, ρ (kg/m^3) is the density of the soil, and c_p (J/kgK) is the specific heat of the soil.

The mathematical model, presented in Eq. (1), is covering the yearly natural soil temperature variation. In order to determine the parameters of the model, needed for the real time design of geothermal energy systems, such a long period of time for measurements and soil thermal potential evaluation is undesirable. From this point of view, the validation under censored data, presented in the study, is important and prove the stability of the model even under conditions of considerably shorter periods of time with available data.

The following notations were recorded for Eq. (1):

$$a_1 = \pm t_{amp}\exp\left(-z\sqrt{\frac{\pi}{d\alpha}}\right)[°C]; \quad a_2 = \frac{2\pi}{d}\tau_0 + z\sqrt{\frac{\pi}{d\alpha}}. \quad (2)$$

Based on these notations and on ($2\cdot\pi/d \approx 1.992 \times 10^{-7}$ s^{-1}), Eq. (1) became

$$t(z,\tau) = t_{avg}(z) + a_1(z)\cdot\cos(1.992\times10^{-7}\cdot\tau - a_2(z)). \quad (3)$$

In Eq. (3), modeling the yearly soil temperature variation, the recorded values of time were converted in number of seconds since the Unix Epoch (January 1 1970 00:00:00 GMT).

The coefficients of Eq. (3) were established to best fit a set of measured temperatures, selected with a one-hour time interval. These temperatures correspond to the exact value of "00" min.

Equation (3) was implemented in the SLIDEWRITE software, which displays powerful curve-fitting and data analysis functions.[33]

The following notations were used for coefficients a_1 and a_2:

$$a_1 = \pm t_{amp}\exp\left(-z\sqrt{\frac{\pi}{d\alpha}}\right) = b_1\exp(-z\, b_2), \quad (4)$$

$$a_2 = \frac{2\pi}{d}\tau_0 + z\sqrt{\frac{\pi}{d\alpha}} = b_3 + z\, b_2, \quad (5)$$

where

$$b_1 = t_{amp}[°C];\ b_2 = \sqrt{\frac{\pi}{d\alpha}}[m];\ b_3 = \frac{2\pi}{d}\tau_0[-]. \quad (6)$$

Equations (2)–(5) together with obtained values of the coefficients b_1, b_2, and b_3 represent a simple and precise mathematical model for natural temperature variation at any depth and at any given moment up to 10 m (Refs. 2 and 15).

The obtained mathematical model was validated according to the procedure presented in Figure 3.

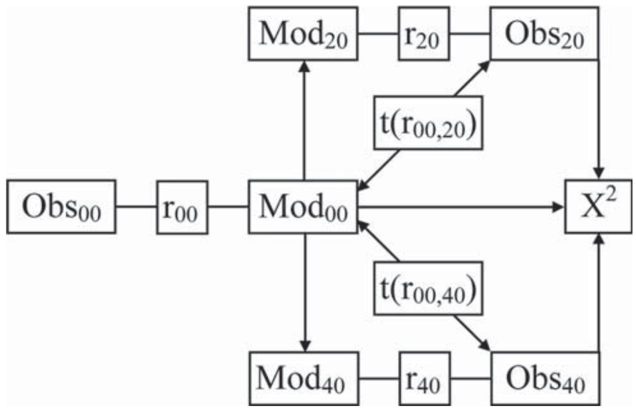

FIG. 3. Scheme of mathematical model testing (validation) procedure. Obs_{00}, Obs_{20}, Obs_{40}—Sets of observed data at the exact value of "00," "20," and "40" min; Mod_{00}, Mod_{20}, Mod_{40}—Sets of calculated data for the exact value of "00," "20," and "40" min; r_{00}, r_{20}, r_{40}—Correlation coefficient value between Obs_{00}—Mod_{00}, Obs_{20}—Mod_{20}, and Obs_{40}—Mod_{40}; $t(r_{00},_{20})$, $t(r_{00},_{20})$—Student t-test for Mod_{00}—Obs_{20} and Mod_{00}—Obs_{40}; X^2—Chi square test involving all observed and calculated data.

All the Obs and Mod sets of measured and calculated data refer to the four depths where the sensors were mounted. Each set of measured temperatures (Obs_{00}, Obs_{20}, and Obs_{40}) consists of 8599 values for each of the four depths selected at a one-hour time interval.

The first step was to obtain the mathematical model based on Obs_{00} together with the physical significance of coefficients. The Mod_{00} were calculated and correlated with Obs_{00} based on the obtained mathematical model. The correlation coefficient r_{00} was also obtained. Next, the mathematical model was applied and the calculated Mod_{20} and Mod_{40} data were correlated with the Obs_{20} and Obs_{40} sets of data. The r_{20} and r_{40} correlation coefficients were also obtained.

The Student test[34] and the Pearson's chi square test[35] were applied on the obtained correlation coefficients (r_{00}, r_{20}, and r_{40}) in order to prove that there were no significant differences between measured and calculated data.

The Fisher's Z transformation[36] was used in both tests.

V. RESULTS AND DISCUSSIONS

The obtained values of coefficients from Eq. (2) with range of variation and the determination coefficient (r^2) are presented in Table III. These values are coefficients obtained in the grid of observation points at different depth. Values presented in each line were obtained from the series of data (temperature, time) of the corresponding depth.

TABLE III. Values of coefficients from equation (2) and the determination coefficient (r^2).

Location	Depth (m)	$t_{avg}(z)$ (°C)[a]	a_1 (°C)[a]	a_2 (-)[a]	r^2
CJ	0.18	11.915 ± 0.040	10.705 ± 0.059	1.935 ± 0.005	0.938116
	0.40	12.045 ± 0.032	10.285 ± 0.047	2.007 ± 0.004	0.956489
	0.89	11.819 ± 0.017	8.185 ± 0.026	2.215 ± 0.003	0.978673
	2.00	11.639 ± 0.007	4.836 ± 0.011	2.723 ± 0.002	0.988780
RG	0.18	11.451 ± 0.085	9.565 ± 0.120	0.490 ± 0.012	0.935264
	0.40	11.457 ± 0.050	8.566 ± 0.074	0.625 ± 0.008	0.968133
	0.89	11.628 ± 0.036	6.617 ± 0.055	0.885 ± 0.007	0.969332
	2.00	11.131 ± 0.013	3.959 ± 0.020	1.366 ± 0.004	0.988333

[a]± Constants of 95% confidence interval.

TABLE IV. Values of coefficients b_1–b_3 and derived values.

	Coefficients			Derived values	
Location	b_1 (°C)	b_2 (m)	b_3 (-)	α (m^2/s)	τ_0
CJ	$11.94^{+1.52}_{-1.35}$	0.444 ± 0.02	1.835 ± 0.06	$5.05^{+0.49}_{-0.79} \cdot 10^{-7}$	$92\,10067 \pm 30\,1146$ s = 106.6 ± 3.5 days
RG	$10.318^{+0.288}_{-0.280}$	0.480 ± 0.025	0.425 ± 0.027	$(4.36 \pm 0.45)\times 10^{-7}$	2 153 198 s = 25 days

Our model generated four values of $t_{avg}(z)$, one for each of the four depths within an interval of $\approx 0.4\,°C$ for CJ and of $\approx 0.5\,°C$ for RG. This may be caused by model imperfections, especially at the soil surface. Important factors influencing soil temperature are wind, solar radiation, rain, etc. In order to establish the single and constant average soil temperature (t_{avg}), the arithmetic mean of the $t_{avg}(z)$ values was considered. Therefore, the $t_{avg} \approx 11.85\,°C$ was obtained for CJ and $t_{avg} \approx 11.42\,°C$ was obtained for RG.

Table IV is presenting the values of coefficients b_1–b_3 and the derived values of thermal diffusivity and τ_0.

Values of correlation coefficients and Fisher's Z transformation are presented in Table V.

The values of Student statistics (t_{val}) and the associated probability (p) were calculated by applying the formulas presented in Refs. 34 and 37.

The values of Pearson's chi square test (X^2) and associated probability (p) were calculated by applying the formulas presented in Refs. 35 and 38.

The results of applied statistics are presented in Table VI.

Temperature is one of the most important parameters in the evaluation of soil thermal potential.

The measured temperature variations are presented in Figure 4 for CJ and Figure 5 for RG, together with the calculated temperature variation for different depths.

The following parameters of temperature variation at different depths were determined based on our mathematical model: one year average temperature (t_{avg}), highest temperature (t_{max}), lowest temperature (t_{min}), and yearly amplitude of temperature variation (t_{amp}). These values are showed in Table VII, together with the dates when highest, lowest and average temperatures are reached at different depths.

In both measurement location sites, in the winter of 2009/2010, the layer of snow that covered the ground was large enough to prevent the soil freezing even at the surface. In the absence of snow, soil freezing can appear in periods with ambient temperature below 0 °C.

The analysis of the results presented in Table VII revealed the following:

- The average soil temperature (t_{avg}) calculated at any depth was constant ($t_{avg} \approx 11.85\,°C$ at CJ and $t_{avg} \approx 11.42\,°C$ at RG).
- The amplitude of surface temperature variation ($t_{amp} \approx 11.89\,°C$ at CJ and $t_{amp} \approx 10.41\,°C$ at RG) is identical with the calculated coefficient b_1 from Eq. (6), and anyway it is in the estimated range of variation for this parameter.
- The highest temperature (t_{max}) decreased with depth as expected.
- The lowest temperature (t_{min}) increased with depth as expected.
- The yearly amplitude of temperature variation (t_{amp}) decreased with depth as expected.

TABLE V. Values of correlation coefficients and Fisher's Z transformation.

Correlated series	Correlation coefficient (r)	Fisher's Z transformation Z(r)
$Obs_{00} - Mod_{00}$	$r_{00} = 0.977115925$	2.229476605
$Obs_{20} - Mod_{20}$	$r_{20} = 0.977103974$	2.229212533
$Obs_{40} - Mod_{40}$	$r_{40} = 0.977137347$	2.229950288

TABLE VI. Results of the applied statistics.

Statistics	Values	Interpretation
diffZ($r_{00,20}$); t($r_{00,20}$); p_t(t,n-3)	2.641×10^{-4}; 3.46×10^{-2}; 0.972	(1)
diffZ($r_{00,40}$); t($r_{00,40}$); p_t(t,n-3)	4.737×10^{-4}; 6.21×10^{-2}; 0.950	(2)
$\bar{Z}$; $\sum (Z-\bar{Z})^2$; X^2; $p_{\chi 2}(X^2,2)$	2.229546476; $2.795 \cdot 10^{-7}$; 9.61×10^{-3}; 0.995	(3)

In the hypothesis of random errors:
(1) Over 97% of correlations are not statistically different than it was experimentally observed; Accordingly, the hypothesis that Mod_{20} is not the evolution model of Obs_{20} failed to be rejected at a significance level of 5%.
(2) Over 95% of correlations are not statistically different than it was experimentally observed; Accordingly, the hypothesis that Mod_{40} is not the evolution model of Obs_{40} failed to be rejected at a significance level of 5%.
(3) Over 99% of correlations are not statistically different than it was experimentally observed when the correlations r(Mod_{00},Obs_{00}), r(Mod_{20},Obs_{20}), and r(Mod_{40},Obs_{40}) were investigated; Accordingly, the hypothesis that observations are significantly different by each other failed to be rejected at a significance level of 5%.

The temperature variations at several depths of up to 10 m were calculated using our mathematical model. The results of this simulation are presented in Figures 6 for CJ and Figure 7 for RG.

The diagrams of temperature variation with depth are presented in Figure 8 for CJ and Figure 9 for RG, each curve being represented for the 15th day of each month.

Soil temperatures proved to vary around the same average value at any depth of up to 10 m, where it became almost constant with a very light fluctuation as can be seen in Table VII and both Figures 8 and 9.

The method of analysis presented in the paper was used to calculate the thermal diffusivity, based only on temperature measurements, was applied for two different locations in Romania: CJ and RG. In both locations, long time experimental measurements were realized.

Figure 10 indicates the dispersion of soil's thermal diffusivity for the two locations. The values range between the limits reported in previous studies concerning clay soil.

It can be observed that reported values of thermal diffusivity for clay soils, are situated in a very large interval of variation: (1.7–13.5) $\times$ 10^{-7} m^2/s. This large range of variation is not

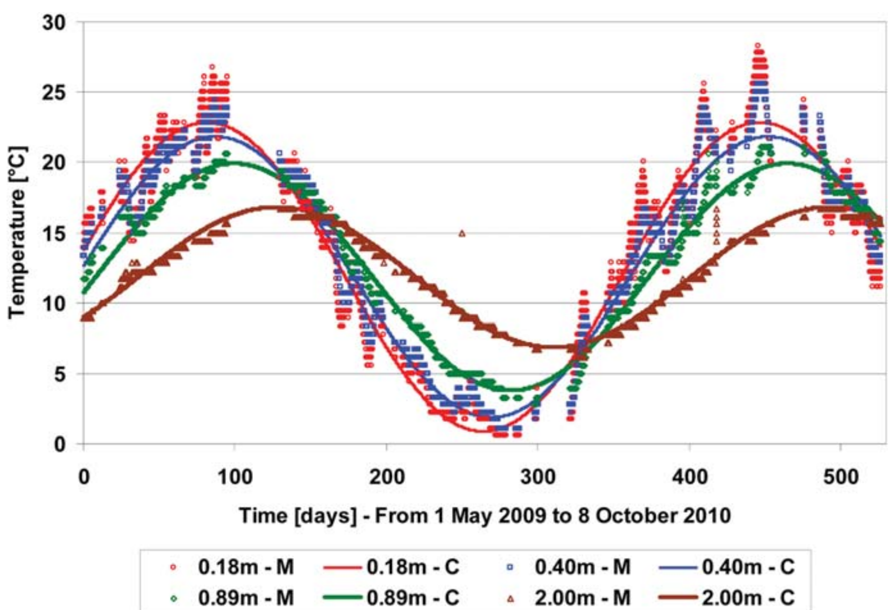

FIG. 4. Calculated (C) and measured (M) temperature variation at CJ.

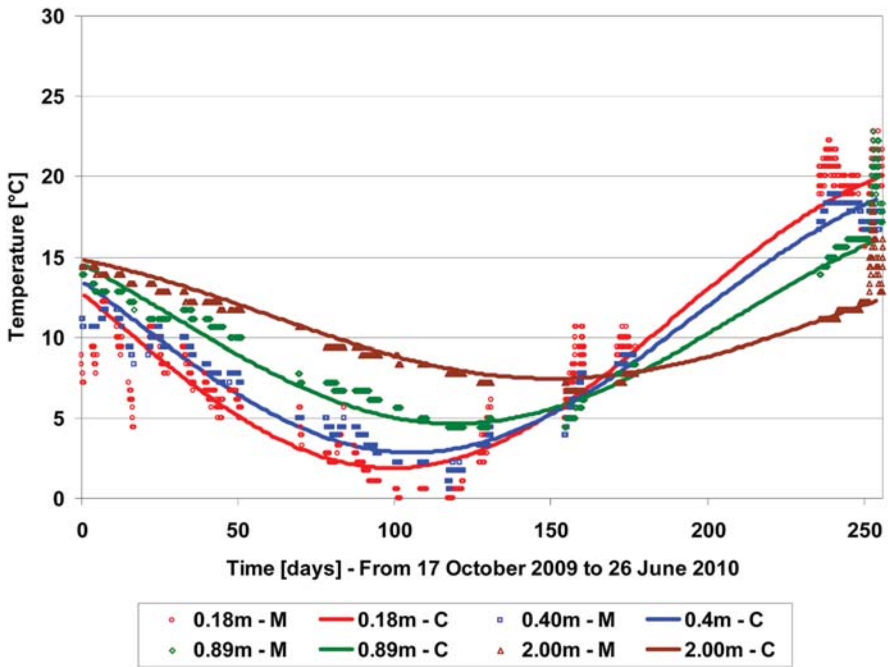

FIG. 5. Calculated (C) and measured (M) temperature variation at RG.

useful for the design of geothermal applications, where a more precise evaluation of thermal diffusivity is desired, for optimal thermal dimensioning of the equipment.

The current focus on the extended use of renewable energies justifies the detailed experimental research on the thermal potential of the soil and its particular behavior in CJ and RG, Romania.

The presented experimental study can be compared with Ref. 8 at the following criteria: same maxim depth (2 m), same type of soil (clay), and same number of locations (one) and

TABLE VII. Parameters of soil temperature variation, at different depths.

		Depth (m)						
Location	Temperature type	0.00	0.5	1.00	1.5	2.00	5.00	10
CJ	Average (t_{avg}) (°C)	11.85	11.85	11.85	11.85	11.85	11.85	11.85
	Highest (t_{max}) (°C)	23.74	21.41	19.54	18.03	16.82	13.19	12.00
	Lowest (t_{min}) (°C)	−0.04	2.29	4.16	5.67	6.88	10.51	11.70
	Amplitude (t_{amp}) (°C)	11.89	9.56	7.69	6.18	4.97	1.35	0.15
	Date of highest temperature	16.07	29.07	10.08	23.08	05.09	20.11	26.03
	Date of lowest temperature	15.01	27.01	09.02	22.02	06.03	20.05	25.09
	Date of average temperature	16.04	26.04	08.05	24.05	05.06	19.02	26.06
		15.10	28.10	10.11	22.11	05.12	20.08	26.12
RG	Average (t_{avg}) (°C)	11.42	11.42	11.42	11.42	11.42	11.42	11.42
	Highest (t_{max}) (°C)	21.83	19.60	17.84	16.47	15.38	12.35	11.50
	Lowest (t_{min}) (°C)	1.01	3.24	5.00	6.37	7.46	10.49	11.34
	Amplitude (t_{amp}) (°C)	10.41	8.18	6.42	5.05	3.96	0.93	0.08
	Date of highest temperature	20.07	03.08	17.08	31.08	14.09	07.12	26.04
	Date of lowest temperature	18.01	01.02	15.02	01.03	15.03	08.06	26.10
	Date of average temperature	20.04	03.05	18.05	01.06	15.06	08.03	27.01
		19.10	02.11	16.11	30.11	14.12	07.09	26.07

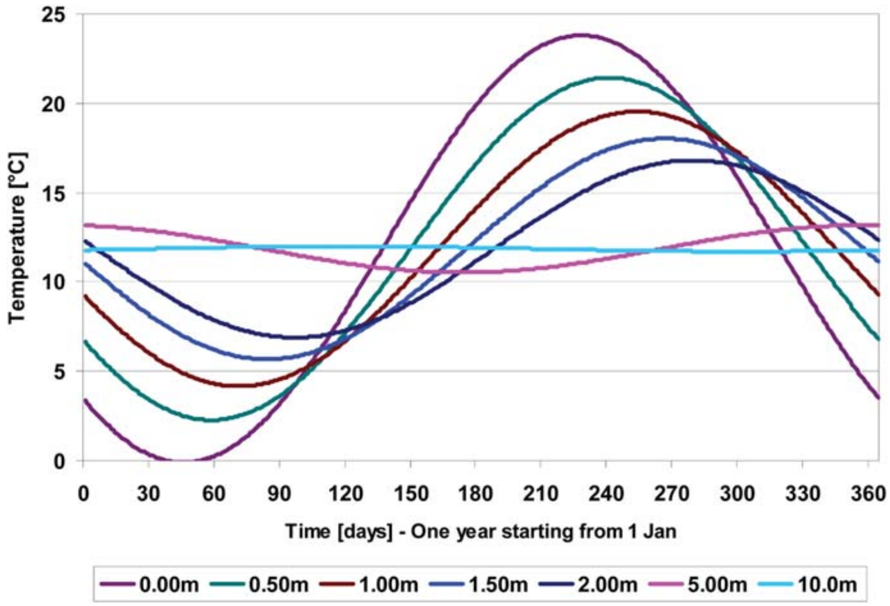

FIG. 6. Simulated one year temperature variations at CJ for depths between 0 and 10 m.

also with Ref. 4 at the following criteria: same data recording time step (1 min), same type of soil (clay), and same number of locations (one). Comparing with Ref. 8, this study has a shorter data recording time step (1 min, comparing to 30 min) and a comparative total duration of the experiment (530/250 days, comparing to 360 days). Comparing with Ref. 4, our study has a higher total depth of temperature measurements (2 m, comparing with 0.6 m) and a comparative total duration of the experiment (530/250 days, comparing to 360 + days). The only data concerning soil temperature variation in the central Transylvania region was reported in Ref. 27, but only at the depth of 0.5 m.

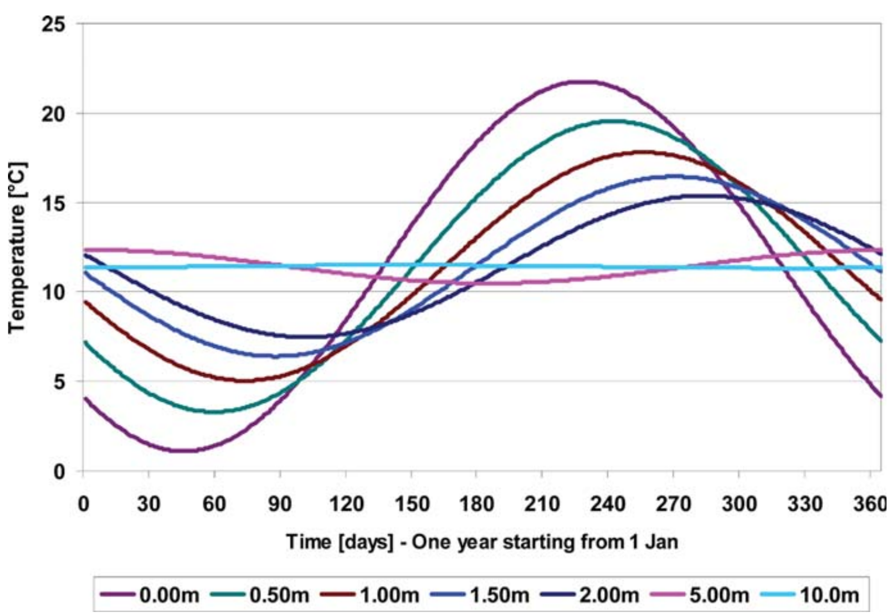

FIG. 7. Simulated one year temperature variations at RG for depths between 0 and 10 m.

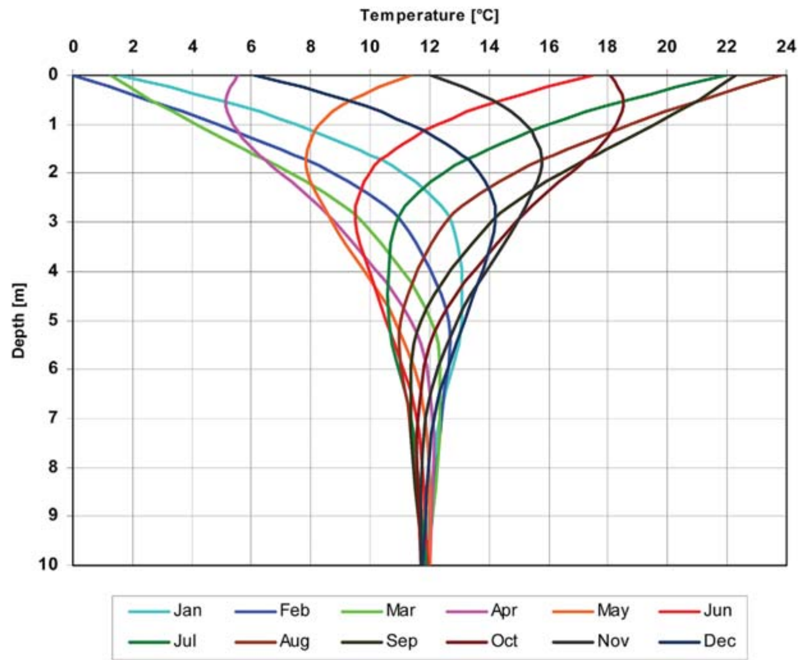

FIG. 8. Simulated temperature variation with depth during the year in each 15th day of month, for CJ.

Normal values of average underground temperatures are situated between 2 and 9 °C in Scandinavia, 9 and 11 °C in Germany, or 13 and 17 °C in Italy.[39] The obtained average values of 11.85 °C for the average bare clay soil temperature in CJ and of 11.89 °C for average grass covered clay soil in RG are situated between the normal values of average soil temperatures in Germany and Italy. This conclusion is reasonable, taking into account the geographic location of the three countries.

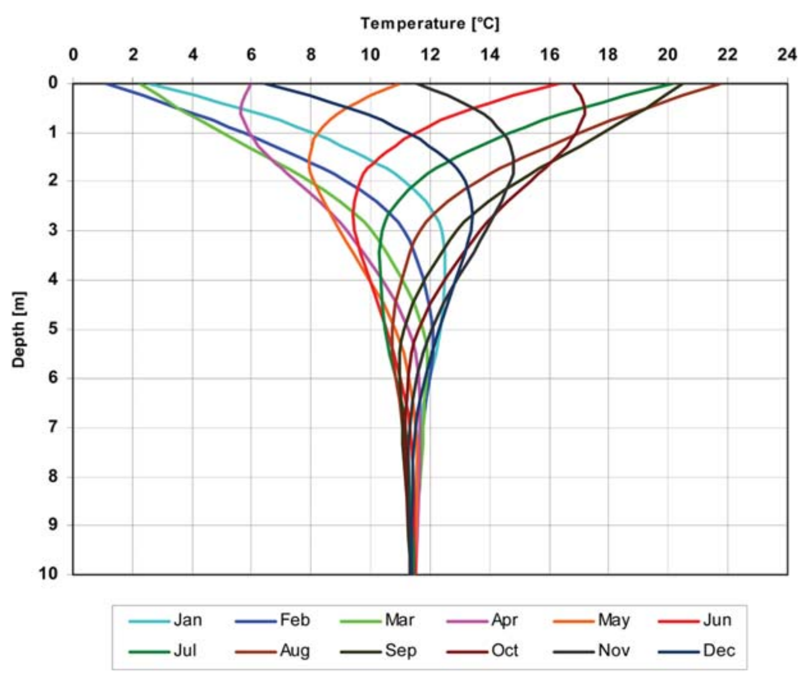

FIG. 9. Simulated temperature variation with depth during the year in each 15th day of month, for RG.

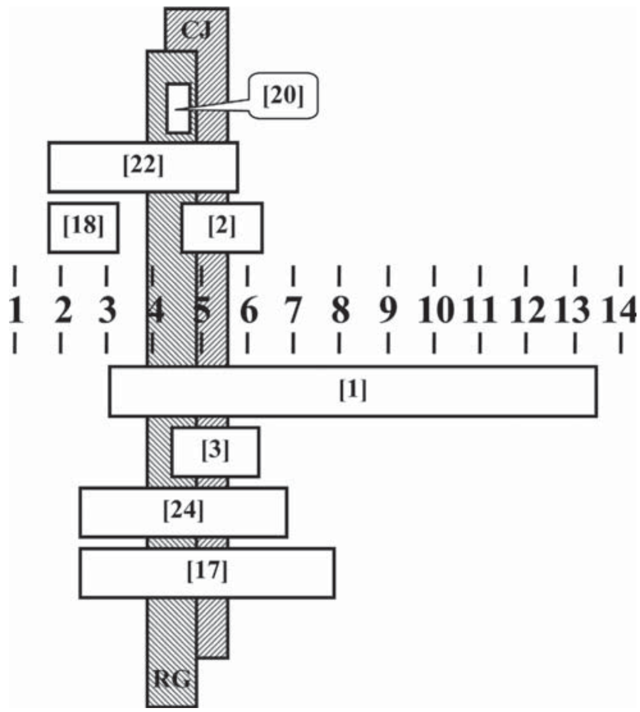

FIG. 10. Reported values of thermal diffusivity ($\times 10^{-7}$ m^2/s) for clay soils, compared with the ones from this study: CJ and RG.

The mathematical model identified in this study will be further investigated in technical applications, such as ground heat pumps and passive ground heating/cooling systems with underground heat exchangers, as well as in agricultural and horticultural applications.

VI. CONCLUSIONS

A simple mathematical model for natural soil temperature variation was identified and validated as an analysis tool for soil temperature variation. This model proved to perform correctly for two data sets, other than the one used to identify the model.

The coefficients of the mathematical model were determined together with precisely indicated range of variations at 95% confidence. On authors knowledge no other available mathematical models for natural temperature variation is providing values of coefficients together with both ranges of variation and confidence level.

Local soil temperature variation was measured and simulated at different depths, in one location within more than one-year interval and in the other one within more than 9 month interval. The highest, lowest, and average estimated temperatures were provided for different depths. The estimated dates when these particular temperatures should be reached were also estimated.

The amplitudes of temperature variations were estimated at different depths up to 10 m.

The local thermal diffusivity of the soil together with the range of variation at 95% confidence was calculated based on temperature variations only. This parameter is important for all types of soil heat transfer applications. Our results refer to data measured from near surface up to 2 m and calculated from surface up to 10 m. It was highlighted that our results are extremely important in renewable energy applications such as ground heat pumps or passive ground heating/cooling systems using underground heat exchanger.

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