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THERMAL PROPERTIES OF SOME SOILS FROM LOWER AUSTRIA, CENTRAL BOHEMIA AND LUBLIN UPLAND

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A b s t r a c t. The paper presents a method for the determination of thermal properties of soil, and the results and analysis of thermal properties of selected soils of Austria, the Czech Republic, Poland. The measurements of the physicochemical properties of soils, calculations, data processing and analysis of results were performed within the framework of the multilateral project of cooperation between Austria, the Czech Republic, Hungary, Poland and the Slovak Republic on 'Assessment of Soil Structure in Agricultural Soils'.

K e y w o r d s: thermal properties of soils, heat capacity, thermal conductivity, thermal diffusivity

INTRODUCTION

The basic thermal properties of soil, characterizing the soil with respect to its ability to conduct and accumulate heat, are the thermal conductivity and the heat capacity of the soil. The thermal diffusivity of soil, which is the quotient of thermal conductivity and heat capacity per unit of soil volume, is a secondary value which determines the ability of the soil to equalize temperature at all the points within the soil.

Heat capacity of soil

The heat capacity of soil - C - is the amount of heat which has to be supplied to (or removed from) the soil for its temperature to increase (or decrease) by 1 K, and it is expressed in (J/K). The heat capacity of soil per unit of soil volume - C_v (J/m^{3}K) - depends on the heat capacity per unit of volume of the particular components of the solid phase (particles of various minerals and organic matter), the liquid phase (free and bound water), the gaseous phase (soil air), and the proportions of those components in the soil. C_v values are calculated from the formula:

$$C_v = \sum_{i=1}^{n} x_{si} C_{si} + x_w C_x + x_a C_a \qquad (1)$$

where x_{si}, x_w, x_a - component content per unit of volume, of solid phase, liquid phase and gaseous phase respectively; C_{si}, C_w, C_a - heat capacity per unit of volume of the components of the solid, liquid, and gaseous phases.

The following relation occurs between the specific heat - c_i (J kg K^{-1}) of the particular components of soil and their heat capacity per unit of volume:

$$C_{vi} = c_i \rho_i \qquad (2)$$

where ρ_i (Mg m^{-3}) - density of the soil components.

The volumetric heat capacity - C_v (J m^{-3}K^{-1}) was calculated according to de Vries [1]:

$$C_v = (2.0\, x_m + 2.51\, x_o + 4.19\, \theta_v) \cdot 10^6 \qquad (3)$$

where x_m, x_o, θ_v (m^{3}m^{-3}) - content of mineral part, organic matter, and water in a unit of soil volume.

Thermal conductivity of soil

Thermal conductivity is a phenomenon consisting in automatic equalization of temperature within the medium under study with no macroscopic motions. From the microscopic point of view, thermal conductivity consists in the equalization of the mean energy of thermal motions through impacts among particles. The measure of the rate of thermal conductivity is the coefficient of thermal conductivity - λ (W $m^{-1}K^{-1}$). Numerically, it is equal to the amount of energy Q (J) passing in a unit of time t (s) through a unit of surface area S (m^2) at a temperature gradient grad T (K m^{-1}) equal to one:

$$\lambda = \frac{Q}{t\,S\,\nabla T} \tag{4}$$

The thermal conductivity of soil - λ (W $m^{-1}K^{-1}$) was calculated according to a statistical-physical model expressed by means of the following mathematic formula [5,6]:

$$\lambda = \frac{4\,\pi}{m\,(\theta_v, \Phi, T, r, u) \cdot u} \tag{5}$$

where: θ_v (m^3m^{-3}) - water content in a unit of soil volume, Φ (m^3m^{-3}) - total porosity of the soil, T (°C) - soil temperature, r - equivalent radius of soil particles considered as spheres, u - number of parallel connections between soil particles considered as thermal resistors, m - expected value calculated from the formula:

$$m = \sum_{j=1}^{K} \frac{P\,(x_{1\alpha}, x_{2\alpha}, \dots x_{k\omega})}{x_{1j}\lambda_{1j}\,(T)\,r_{1j} + \dots + x_{kj}\,\lambda_{kj}\,(T) r_{kj}} \tag{6}$$

where K is the number of all possible combinations of particle arrangement, P - probability of occurrence of a given combination of soil particle configuration, with $\sum P = 1, x_1, x_2, \dots, x_k$ - number of particles of particular soil components of thermal conductivity $\lambda_1, \lambda_2, \dots, \lambda_k$ and particle radius $r_1, r_2, \dots, r_k$, while $x_1 + x_2 + \dots x_k = u$.

The probability of occurrence of all possible configurations of particles x_{ij} participating in thermal conductivity ($i = 1, 2, \dots, k, j = \alpha, \beta, \dots, \omega$, where $\alpha, \beta, \dots, \omega$ assume values from the range of 0, 1, ..., u) is calculated from the polynomial distribution:

$$P\,(x_{1\alpha}, x_{2\beta}, \dots, x_{k\omega}) = \frac{u!}{x_{1\alpha}!\,x_{2\beta}! \dots x_{k\omega}!}\, f_1^{x_{1\alpha}} f_2^{x_{2\beta}} \dots f_k^{x_{k\omega}} \tag{7}$$

where: $f_1, f_2, \dots, f_k$ is the content of particular minerals, organic matter, water and air in a unit of soil volume and is considered as the probability of obtaining a type 'i' result in a single test.

In the calculation of thermal conductivity, model identification is performed using the empirically determined characteristics of the number of parallel connections between the soil particles with relation to the degree of the soil saturation with water, as well as the empirically determined values of the equivalent radii of particle spheres for mineral soils (0.044) and for organic soils (0.08), [4,5].

In data pertaining to a specific soil, five main components were distinguished, of the following values of thermal conductivity: quartz (λ_q), other minerals (λ_m), organic matter (λ_o), water (λ_w), and air (λ_a). These thermal conductivity values are used in practice in the calculation of the thermal conductivity of the soil.

The theory presented in the paper permits the determination of all the basic thermal characteristics of the soil with relation to soil moisture (θ_v), soil density (ρ), soil temperature (T), mineralogical composition (f_i), soil water potential (ψ), and barometric pressure (P), salinity (G), [8].

Practical realization of the theoretical foundations of the determination of the thermal properties of soil consists in the measurement of the basic physical properties of the soil and performing calculations according to the algorithm representing the statistical-physical model of thermal conductivity of the soil, and the mathematical formula for the heat capacity and thermal diffusivity of the soil [5].

MATERIALS AND METHODS

Examples of characteristics of the thermal properties of soils have been prepared for soils from Austria (profiles Wiselburg and Fuchsenbigl), the Czech Republic (profiles T11, T12 and T13), and Poland (profiles: Forest, Private Farm, State Farm), [3]. All the data used for the determination of the thermal properties of the soils originate from the Final Report, Multilateral Project of Cooperation between Austria, the Czech Republic, Hungary, Poland, and the Slovak Republic, in 'Assessment of Soil Structure in Agricultural Soils' [2]. The mineralogical composition and the solid phase density of soils are the basic data for the determination of the thermal properties of soils. The calculations were performed using the soil thermal properties software package (public domain), Copyright 1992, Institute of Agrophysics, Polish Academy of Sciences, Lublin [7]. The results of measurements of the mineralogical composition and the basic physical properties of the soils are presented in Table 1. All the values of the thermal properties of soils were calculated for a soil temperature of 10^{o} C.

Sample calculations of the thermal properties of soil were performed for the following horizons: profiles Wiselburg and Fuchsenbigl (Austria) - horizons Ap (0-20) and Ap (0-15); profiles T11 (15-20), T12 (10-20) and T13 (15-20) (Czech Republic); and profiles forest and state farm, Czesławice (Poland) - Ah (3-8) and Ap (3-8), at soil densities 1.0, 1.2, 1.4, 1.6 and 1.8 Mg m^{-3}. Values of the solid phase density and organic matter content were taken from Table 1. Soil moisture varied from 0 to full saturation with water, with a 2 % step.

RESULTS

The results of the calculations are presented in Fig. 1-3. The thermal conductivity of soil (Fig. 1) increases with increasing soil moisture and density, and the increase is faster in soils of higher quartz content. For example, with soil density of 1.8 Mg m^{-3}, a soil of 75 % quartz content has its maximum thermal conductivity higher by over 1 W $m^{-1}K^{-1}$ than a soil of 24 % quartz content. The latter soil, at that density, has its maximum thermal conductivity equal to 1.5 W $m^{-1}K^{-1}$. The other components of the solid phase have a smaller effect on the thermal conductivity of soils. Organic matter content at a level of several percent in a mineral soil does not contribute much towards the total thermal conductivity of the soil; it is above the level of a dozen percent that organic matter content begins to have a significant decreasing effect on the thermal conductivity of the soil. The relation of the thermal conductivity to the moisture content of the soil is non-linear, and the form of the non-linearity is affected by the soil density, while the inclination of the thermal conductivity characteristic of the soil in the function of its moisture content is considerably affected by the quartz content of the soil.

The characteristics of heat capacity of soil in the function of moisture content (Fig. 2) are linear. The greatest effect on the heat capacity of soil is that of its moisture. Soil density has a smaller effect on the heat capacity. An increase in soil density causes a parallel translocation of the characteristics of thermal capacity towards its higher values. Under the conditions of soil saturation with water, an increase in the content of solid phase in a unit of soil volume causes a decrease in the water content in a unit of soil volume. This results in a decrease in the thermal capacity of the soil, and conversely - when the content of solid phase in a unit of soil volume decreases and is replaced with water, the thermal capacity of the soil increases. Changes in the organic matter content in the soil have only a slight effect on the thermal capacity of the soil - the thermal capacity increases with increasing organic matter content.

The thermal diffusivity of soil displays characteristic extremes (Fig. 3). The new element - extreme - which appears in the characteristics of thermal diffusivity of soils, is the result of changes in the intensity of the thermal conductivity of soils with changes in their moisture and density. The heat capacity of soil has a constant intensity and does not affect the shape of the characteristics, though it can

Table 1. Semiquantitative mineralogical composition of the profiles studied, in terms of weight percentages, bulk density (ρ_b), particle density (ρ_s), organic matter content (O.M.)

Horizon (cm)	Mineralogical composition, %					ρ_b	ρ_s	O.M.
	Quartz	Layer silicates	Felspars	Calcite	Dolomite	(Mgm^{-3})		(%)
				Wiselburg - (PW)				
Ap (0 - 20)	42	48	10	0	0	1.46	2.65	2.2
AB (20 - 40)	44	41	15	0	0	1.55	2.70	2.0
Bv (40 - 80)	44	39	15	0	2	1.49	2.69	1.2
BC (80 - 95)	33	32	6	12	17	1.53	2.74	0.7
C (95 +)	33	28	4	17	18	1.54	2.74	0.5
				Fuchsenbigl - (PF)				
Ap (0 - 20)	24	31	15	20	10	1.34	2.69	2.5
AB (20 - 40)	30	34	8	18	10	1.45	2.69	2.7
Bv (40 - 80)	20	34	6	26	14	1.41	2.76	1.0
BC (80 - 95)	35	23	11	13	18	1.42	2.78	0.5
C (95 +)	38	18	20	8	16	1.43	2.78	1.0
	Tl1							
(15 - 20)	73	22	2	3	0	1.59	2.64	3.6
(35 - 40)								2.2
55 - 60)						1.56	2.64	1.2
(80 -)								-
	Tl2							
(10 - 20)	58	37	0	7	0	1.64	2.63	3.6
(50)						1.44	2.65	2.7
(100)								1.9
	Tl3							
(15 - 20)	75	18	3	4	0	1.59	2.60	3.2
(45)						1.24	2.63	1.2
(65)						1.33	2.64	-
				Forest - (PFC)				
Ah (3 - 8)	68	0	32	0	0	1.03	2.50	1.9
E (11 - 16)						1.35	2.64	0.7
E-Bt1 (28-33)	71	0	29	0	0	1.36	2.65	-
Bt1 (42-47)	58	39	3	0	0	1.45	2.68	0.3
Bt2 (72 - 77)	71	22	7	0	0	1.48	2.66	0.1
BC (112 - 117)	61	31	8	0	0	1.43	2.64	0.1
Ck (142 - 147)	59	20	10	7	4	1.51	2.63	0.1
				Private farm - (PPFC)				
Ap (2 - 7)	68	0	32	0	0	1.23	2.62	1.4
E (12 - 30)	71	0	29	0	0	1.48	2.65	0.4
Bt1 (45 - 50)	58	39	3	0	0	1.49	2.67	0.4
Bt1 (85 - 90)	71	22	7	0	0	1.57	2.66	0.1
				State farm - (PSFC)				
Ap (3 - 8)	68	0	32	0	0	1.39	2.61	1.5
Ap-E (26 - 31)	71	0	29	0	0	1.48	2.65	-
E (30 - 35)						1.41	2.66	0.3
Bt1 (41 - 46)	58	39	3	0	0	1.49	2.67	0.1
Bt1 (56 - 61)						1.55	2.68	-
Bt2 (82 - 87)	71	22	7	0	0	1.56	2.64	0.1
BC (136 - 141)	61	31	8	0	0	1.47	2.62	0.1
Ck (150 - 155)	59	20	10	7	4		2.67	0.1

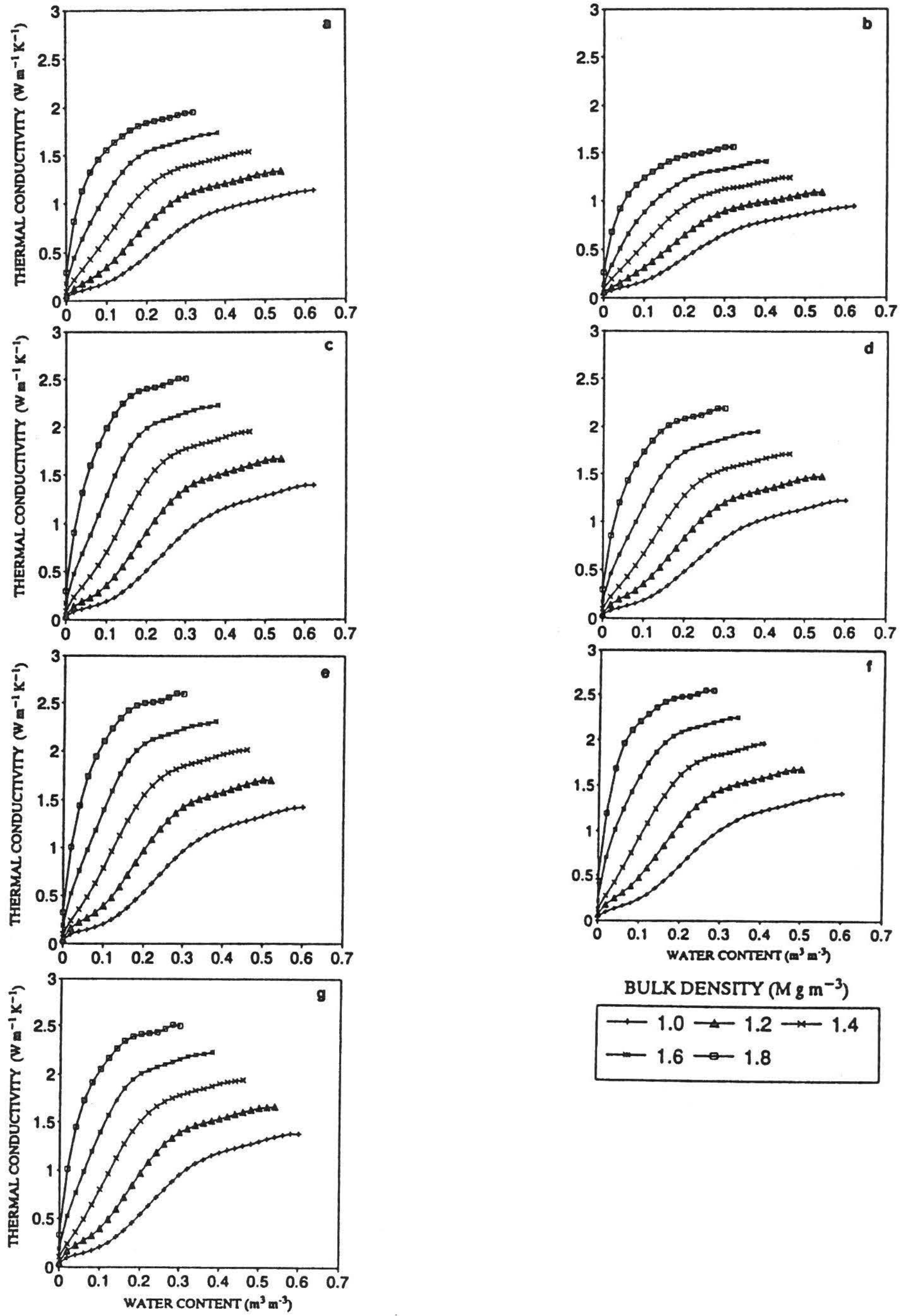

Fig. 1. Heat conductivity of soil in the function of soil moisture. Austria: a) profile Wiselburg, b) profile Fuchsenbigl; Czech Republic: c) profile T11P, d) profile T12P, e) profile T13P; Poland: f) profile Forest, g) profile State farm.

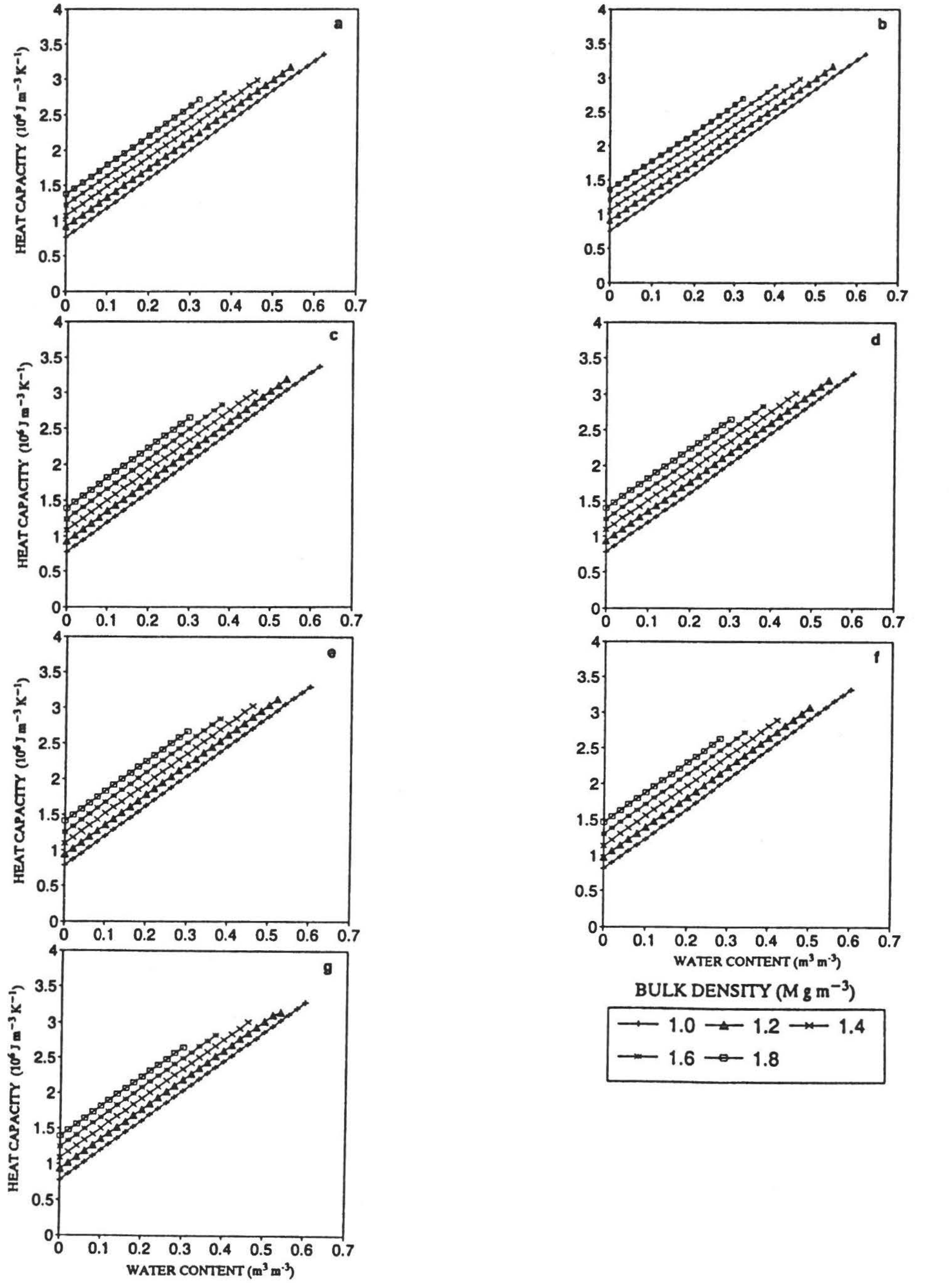

Fig. 2. Thermal capacity of soil in the function of soil moisture. Austria: a) profile Wiselburg, b) profile Fuchsenbigl; Czech Republic: c) profile T11P, d) profile T12P, e) profile T13P; Poland: f) profile Forest, g) profile State farm.

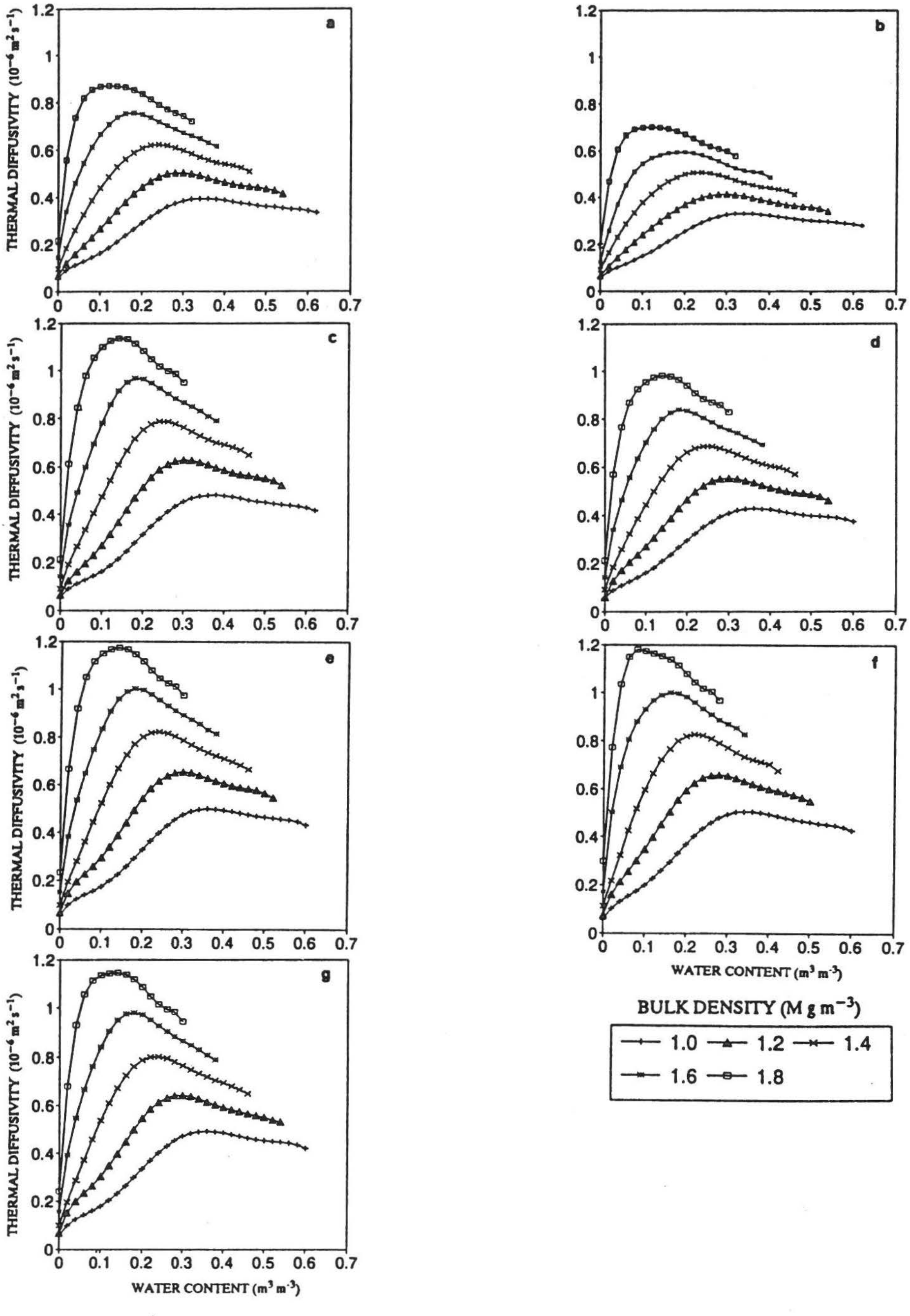

Fig. 3. Thermal diffusivity of soil in the function of soil moisture. Austria: a) profile Wiselburg, b) profile Fuchsenbigl; Czech Republic: c) profile TI1P, d) profile TI2P, e) profile TI3P; Poland: f) profile Forest, g) profile State farm.

translocate them towards higher or lower thermal diffusivity values. The values of thermal diffusivity are very strongly affected by the quartz content. Like in the case of thermal conductivity, a soil of 75 % quartz content has maximum thermal diffusivity values nearly twice as high as a soil of 24 % quartz content. The thermal diffusivity of soil of the same moisture content is higher at higher soil density values, while maxima of thermal diffusivity of soils display a tendency to move towards lower values of moisture content and higher densities. Maxima of thermal diffusivity of soil in the function of soil moisture, as well as trend equation of moisture in the function of soil density and their numerical values, are presented in Fig. 4 and Table 2. The trend equations are described by the linear equation:

$$\theta = a\rho + b \tag{8}$$

where θ - soil moisture, ρ - soil density, a and b - parameters of the equation.

The coefficients of inclination of the lines for the soils presented here varied from -0.27 to -0.32, while their translocations varied from 0.610 to 0.668.

These extremes are characteristics in that they determine values of soil moisture and density at which the temperature wave propagation in the soil is the fastest. The characteristics of thermal diffusivity of soil in the function of soil moisture and density presented here have a practical significance, as they permit the determination of such moisture-density conditions in the soil which maximize, minimize, or optimize the rate of its warming up or cooling down.

CONCLUSION

The theory presented in the paper permits the determination of all the basic thermal characteristics of the soil with relation to soil moisture (θ_v), soil density (ρ), soil temperature (T), mineralogical composition (f_i),

Table 2. Parameters of the equation of moisture in the function of soil density, at which the thermal diffusivity reaches maximum values for the soil of Austria, Czech Republic, and Poland

Parameter	Profiles							Global for all soils
	PW	PF	T11	T12	T13	PSFC	PPFC	
a	-0.27	-0.27	-0.30	-0.28	-0.28	-0.32	-0.28	-0.286
b	0.610	0.618	0.668	0.636	0.636	0.664	0.636	0.638

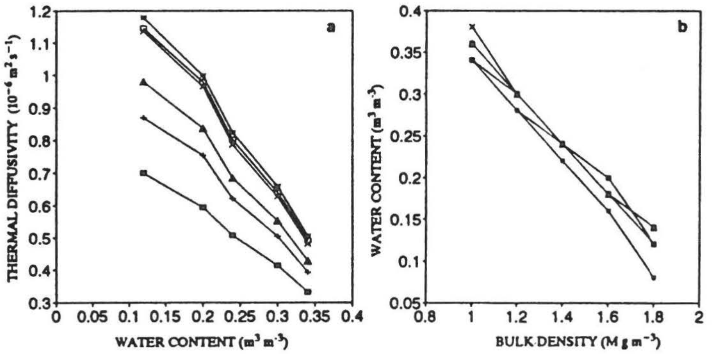

Fig. 4. a) Maximum values of thermal diffusivity of soil in the function of soil moisture at various soil density values (from the left to the right side of the graph soil density varied from 1.8 to 1.0 Mg m^{-3} with a step of 0.2); b) Soil moisture in the function of soil density, at which the thermal diffusivity of soil reaches its maximum. Symbols: full square - profile Fuchsenbigl, cross - profile Wiselburg, x - profile T11P, full triangle - profile T12P, empty square - profile Forest, asterisk - profile State farm.

soil water potential (ψ), and barometric pressure (P), salinity (G). The method utilizes elementary physical values of soil, thanks to which it allows for rapid determination of the characteristics of the thermal properties of soil, or their distribution in the soil profile.

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