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Technical Note

Some Studies on Estimation of Soil Thermal Resistivity based on Transient Method

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Introduction

Thermal properties of materials are important for various civil and electrical engineering projects. Important amongst these are the thermal insulation of several man-made materials and natural geological materials viz. soils and rocks which are more significant for subsurface transmission of either heated fluids or high power currents. Soil thermal resistivity plays an important role in designing and laying of high voltage buried power cables (King and Halfter, 1982), oil and gas pipe lines (Slegel and Davis, 1977), nuclear waste disposal facilities (Davies and Banerjee, 1980), ground modification techniques (Slegel and Davis, 1977), employing heating and freezing (Thomas, 1985), etc. For such situations, it is essential to estimate the resistance offered by the soil mass in dissipating the heat generated.

Type of the soil is an important factor to determine its resistivity (Kerstan, 1949; Van Rooyen, 1958). Soil resistivity gets affected easily by the conditions in which it is formed and its location (Tagg, 1964). Since the conduction through soil is largely electrolytic, the amount of water present plays an important role in determining the resistivity (Van Rooyen, 1958). Normally, dry soils exhibit high resistivity because air, a poor conductor (resistivity equal to 4000°C-cm/W), separates the solid grains (resistivity equal to 4°C-cm/W) of the soil. If the moisture content of the soil increases, then the resistivity drops (Kerstan, 1949); because, water (resistivity equal to

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165°C-cm/W) is a good conductor. As such, a saturated soil has lower resistivity than dry soil. The resistivity, at first, falls rapidly as the moisture content is increased, but beyond certain moisture content, the rate of decrease becomes much less (Van Rooyen and Winterkorn, 1957).

The particle size and its distribution have an effect on the manner in which the moisture is held. With large sized grains, the pore space available will be more (due to the presence of air) resulting in higher resistivity or lower conductance. Also, if the size and shape of grains are such that they form a compact dense structure, then there will be a decrease in the thermal resistivity (Kerstan, 1949).

Various investigators have tried to develop relationships to estimate thermal resistivity of soils in dry and moist states. It has been noticed that, in general, these relationships are either empirical (Smith, 1942; Kerstan, 1949; Van Rooyen and Winterkorn, 1957) or theoretical equations (Mickley, 1951; Gemant, 1950 and 1952). The empirical equations are based on data obtained by measurement and analyzed by graphical or numerical techniques, while theoretical equations are based on some models wherein the actual soil structure is simplified in such a way so as to permit a mathematical analysis. However, these relationships have their limitations in terms of proper incorporation of various factors, as mentioned above, affecting such a complex phenomenon (Sinclair et al., 1960).

As such, it is important to detect and estimate the thermal resistivity of different geomaterials. This paper deals with details of the investigations carried out on various soils to estimate their thermal resistivity using a "Laboratory Thermal Needle" referred to as "Laboratory Thermal Probe". Based on the experimental observations, generalized equations have been developed for estimating thermal resistivity of different soils.

Principle of Transient Method

The temperature at any point in an infinite homogeneous medium, with a line heat source of constant strength, mainly depends on the duration of heating (time) and its thermal conductivity. In the mathematical form the same can be presented as (Hooper and Lepper, 1950; Mitchell and Kao, 1978)

$$\frac{\partial\theta}{\partial t} = \alpha\left(\frac{\partial^2\theta}{\partial r^2}+\frac{1}{r}\frac{\partial\theta}{\partial r}\right) \tag{1}$$

where θ = temperature of the soil mass,

t = time of heating,

α = thermal diffusivity constant (= $k/\gamma . C_p$),

k = corresponds to the thermal conductivity of the soil,

C_p = specific heat of the soil,

γ = unit weight of the soil, and

r = radial distance from the heat source.

Thus, the temperature rise, $\Delta\theta$, between the times t_1 and t_2 may be represented as

$$\Delta\theta = \left(\frac{Q}{4\pi k}\right)\log_e\left(\frac{t_2}{t_1}\right) \tag{2}$$

As such, a plot of temperature against log of time yields

$$\text{slope} = \frac{Q}{4\pi k} \tag{3}$$

where Q is the heat input per unit length of the heat source.

Experimental Investigations

In the initial stages, based on transient method principle, a study has been carried out using a bare heater wire made up of Nichrome (Resistivity = 0.1923 Ω/cm), which simulates a needle, and a thermocouple mounted on it to measure the change in temperatures (Fig. 1). However, this setup was not found to be efficient due to the problems associated with proper placement and deformation of the wire, during sample preparation.

This leads to adoption of a probe as shown in Fig. 2. The probe consists of insulated Nichrome heater wire, inserted in a 140 mm long copper tube with external diameter of 2.5 mm. A thermocouple is attached on the surface of the tube as shown in the figure. For the sake of completeness, the circuit diagram employed in the present study is depicted in Fig. 3.

The calibration of this probe has been done using a standard glycerol (with thermal resistivity equal to 349°C-cm/W) taken in a container and allowing the probe to achieve thermal equilibrium (which takes approximately 5 min). The power supply to the probe is switched on and the temperature of the probe is recorded as a function of time (for 20 min.) to compute the

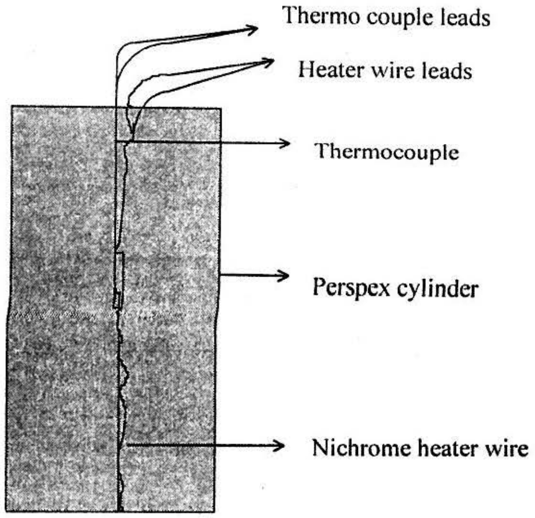

FIGURE 1 : Test Set-up with Heater Wire

thermal resistivity of the glycerol, using Eqns. 2 and 3. The thermal resistivity value of the glycerol, as measured by the probe, is 357.52°C-cm/W which deviates by only 2.4% as compared to its standard resistivity value.

A metal container (126 mm long and 101 mm diameter) is used to prepare the samples of soils corresponding to a particular dry density. A

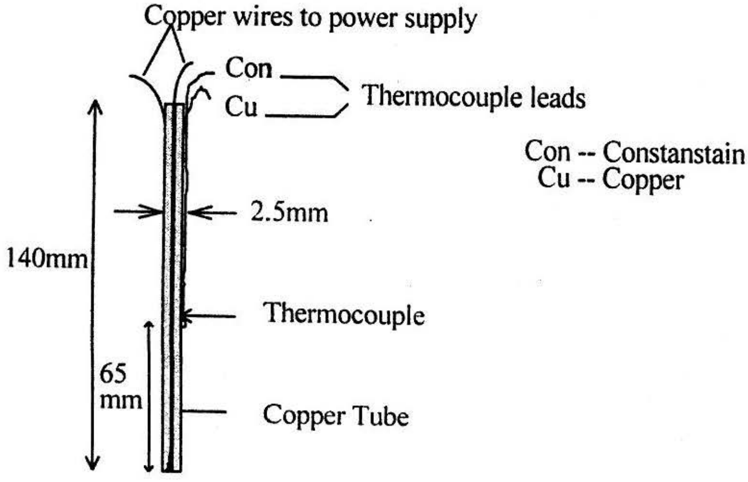

FIGURE 2 : Laboratory Thermal Probe

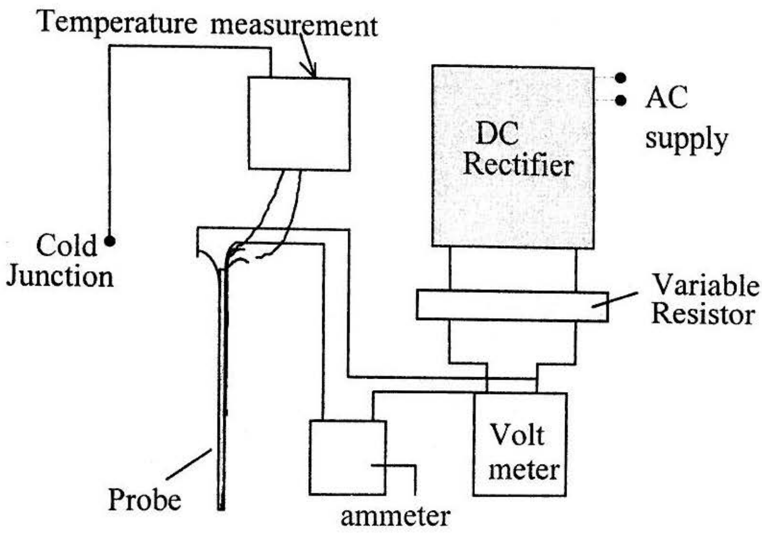

FIGURE 3 : Circuit Diagram

3 mm-diameter hole is drilled in the soil sample and the thermal probe is tightly fitted into it. The probe is allowed to achieve thermal equilibrium in the soil mass (which takes approximately 5 min). Then the power supply to the probe is switched on. The current is maintained constant at 0.5 A (i.e. a power input per unit length of the probe equal to 0.048 W/cm). The temperature of the probe is recorded (for 20 min.) as a function of time to compute soil thermal resistivity.

At the end of these tests, the moisture contents of the soil samples have been obtained and it is noticed that the moisture content of the samples practically remains constant. To demonstrate this, a typical black cotton soil sample (with initial moisture content of 25.43% compacted to a dry-density of 1.4 g/cc) has been considered. The sample has been cut in to small sections and for each of these sections, the moisture content has been obtained, as depicted in Fig. 4. From the figure, it can be noticed that locations in the vicinity of the thermal probe and the open side of the mould show a decrease in the moisture contents as compared to the closed boundaries where it increases. However, the observed decrease and increase in moisture contents is practically negligible.

Following this, the thermal resistivities of clay (black cotton soil), silt (fly ash), silty-sand, fine sand and coarse sand have been obtained. Black cotton soil, fly ash and the fine sand have been mixed (by their weight %) and five mixes (M1, M2, M3, M4 and M5) have also been tested for their thermal resistivity. The properties of these soils and mixes are presented in Tables 1 and 2. The gradational characteristics of these soils are depicted in

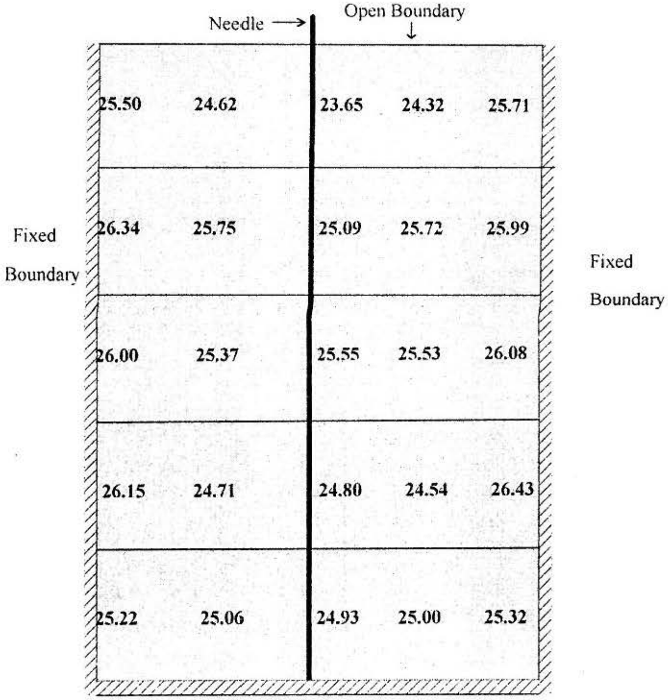

FIGURE 4 : State of Moisture in the Black Cotton Soil Sample

Table 1. Soil Properties of Various Soils

Soil Type	G	C_u	C_c	w_L(%)	w_P (%)
Clay (Black Cotton Soil)	2.72	-	-	67	34
Silt (Fly ash)	2.14	-	-	-	-
Silty sand	2.78	-	-	41	28
Fine sand	2.65	-	-	-	-
Coarse sand	2.63	-	-	-	-
M1	2.53	2.65	0.78	-	-
M2	2.55	30.69	5.92	-	-
M3	2.61	5.40	0.39	-	-
M4	2.55	9.53	1.35	-	-
M5	2.47	23.24	3.90	-	-

Table 2. Properties of Fine and Coarse Sand

Sand	Maximum Void ratio	Minimum Void ratio	Bulking Moisture (%)
Fine	0.782	0.54	4.0
Coarse	0.765	0.623	4.0

Figs. 5 and 6. For obtaining gradational characteristics of the black cotton soil, a laser particle size analyzer has been used.

Results and Discussions

Variation of thermal resistivity with moisture content for black cotton soil, fly ash, silty-sand, fine sand, coarse sand and mixes (M1, M2, M3, M4 and M5) have been obtained. In general, the resistivity is noticed to decrease with increasing moisture content for a given compaction state of the soil. Fig. 7 shows typical results, obtained for the black cotton soil compacted at different dry densities. For the sake of brevity, such relationships for other soil samples are not being presented herein. As water is added to the soil, it forms a thin film on the soil particles which eases the flow of heat. This

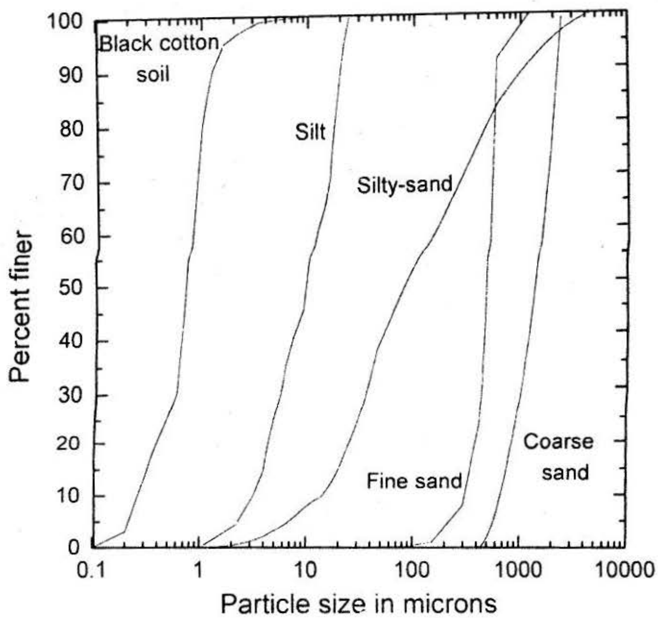

FIGURE 5 : Particle Size Distribution Curves for Single-phase Soils

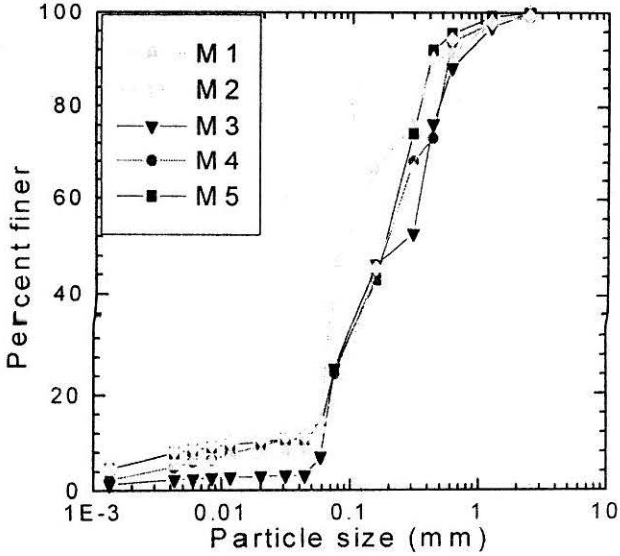

FIGURE 6 : Particle Size Distribution Curves for Multi-phase Soils

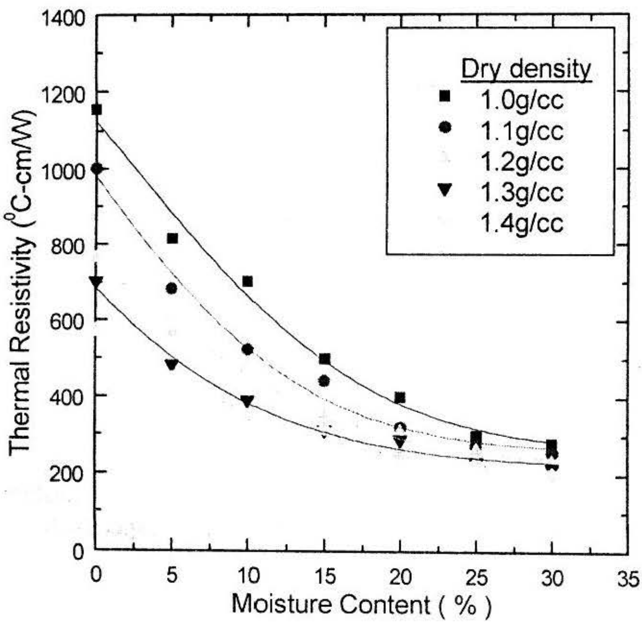

FIGURE 7 : Variation of Thermal Resistivity with Moisture Content for Black Cotton Soil (Clay)

may be attributed to the fact that the thermal resistivity of air is higher than that of water. Further, addition of moisture to the soils results in replacement of air in the voids (and hence the density increases) by water and in bringing down the thermal resistivity of the soil (Radhakrishna et al., 1980; Salomone and Kovacs, 1984).

Proposed Relationships for Estimating Soil Thermal Resistivity

Based on the experimental results the following empirical relations have been developed

Dry (single-phase) soils

For dry soils (single-phase) the following relationship to estimate soil resistivity is being proposed:

$$1/R = \left[a.10^{(0.6243\gamma_d - 3)}\right] \qquad (4)$$

Moist (single-phase) soils

(a) Clays and silts

To obtain resistivity of moist clays and silts (single-phase) the following relationships are being proposed

$$1/R = \left[b.10^{(0.6243\gamma_d - 3)}\right] \qquad (5)$$

$$1/R = \left[1.07\log(w) + c\right]\left[10^{(0.6243\gamma_d - 3)}\right] \qquad (6)$$

where R = soil thermal resistivity (°C-cm/W),

w = moisture content (%), and

γ_d = dry-density of the soil (g/cc).

Parameters a, b and c depend on the type of the soil and its moisture content and their values are presented in Tables 3, 4 ând 5 respectively.

(b) Silts and sands

Equation 6 can also be used to predict resistivity of silts and sands.

Table 3 Value of 'a' for Various Soils

Soil type	a
Clays Silts	0.219
Silty-sand	0.385
Fine sand	0.340
Coarse sand	0.480

Table 4 Value of 'b' for Clays and Silts

w (%)	Type of soil	b
$4 > w \geq 2$	Clays	0.243
	Silts	0.254
$5 \geq w \geq 4$	Clays	0.276
	Silts	0.302

Table 5 Value of 'c' for Various Soils

Soil type	c	w (%)
Clays	−0.73	≥ 5
Silt (Fly ash)	−0.54	
Silty sand	0.12	≥ 1
Fine sand	0.70	
Coarse sand	0.73	

In order to facilitate computation of thermal resistivity of a multi-phase soil system, a generalized method (algorithm DDTHERM) has been developed. It is assumed that the soil consists of five-phase system (clay, silts, silty-sand, fine-sand and coarse-sand). For a naturally occurring soil, the resistivity of different phases is calculated by using Equations 4, 5 and 6. These resistivity values are multiplied by certain weights, which can be computed on the basis of their phase fraction. The weights assigned to different single-phase soils can be obtained as follows:

For clay and silt phase:

$$\text{Weight} = (\text{phase }\%), \text{ when } 5 \geq w\,(\%) \geq 2 \tag{7}$$

$$\text{Weight} = \text{Minimum of the (Absolute c value or phase \%), when } w\,(\%) > 5 \tag{8}$$

Silty-sand, fine-sand and coarse-sand:

$$\text{Weight} = (\text{phase }\% \times c \text{ of the phase}) + \text{phase }\%, \text{ when } w\,(\%) > 1 \tag{9}$$

$$\text{Weight} = a \text{ of the phase, when } w\,(\%) < 1 \text{ (dry soils)} \tag{10}$$

However, if a certain phase is absent, the weight for the phase is assigned as zero. Sum of the resistivity values, so obtained, yields the thermal resistivity of the naturally occurring soil (or a soil mix).

Validation of 'DDTHERM'

To demonstrate utility and versatile nature of the algorithm DDTHERM for predicting soil thermal resistivity, the same has been tested against experimental observations for single-phase (black cotton soil, silty-sand, fine-sand, coarse-sand and fly ash) and multi-phase soils (M1, M2, M3, M4 and M5), as shown in Tables 6 and 7. These tables also present the absolute percentage difference of the obtained results with respect to the experimental results. It can be observed from these tables that the absolute percentage difference is less than 15 to 20, for most of the cases studied.

Further validation of DDTHERM has been done by comparing the obtained results with the experimental studies conducted by William et al. (1960) as shown in Table 8. From the table, it can be noticed that, for dry soils, DDTHERM predicts resistivity values which are very close to the experimental findings of William et al. (1960) and the difference between the two varies from 0.3 to 13.5%, only. At the same time, for the soil samples at their OMC, the difference between experimental values and DDTHERM is noticed to be too much (ranging from 61 to 77%). However, from Tables 6 and 7 the efficiency of DDTHERM in predicting resistivity values of the soils, corresponding to their OMC, can be easily noticed. The poor agreement between the experimental results of William et al. (1960) and DDTHERM can be attributed to the fact that the clay fraction has been specified as < 0.005 mm by William et al. (1960) which results in higher resistivity values when DDTHERM is used.

This method can be employed for estimation of thermal resistivity values

Table 6 : Summary of Resistivity Values (°C-cm/W) of Single-phase Soils

Soil type	Dry Density (g/cc)	Moisture Content (%)	Experimental Results	DDTHERM	Difference %
(1)	(2)	(3)	(4)	(5)	(6)
Clay (Black Cotton)	1.00	0.0	1157.420	1084.615	6.29
	1.00	5.0	816.070	860.619	5.45
	1.00	*10.0*	*700.620*	698.620	0.28
	1.00	15.0	499.400	449.513	9.98
	1.00	20.0	402.160	358.752	10.79
	1.00	25.0	300.780	310.175	3.12
	1.00	30.0	280.750	279.277	0.52
	1.10	0.0	1001.880	939.394	6.24
	1.10	5.0	681.00	745.388	9.45
	1.10	10.0	524.060	605.080	15.46
	1.10	15.0	442.650	389.327	12.04
	1.10	20.0	322.280	310.718	3.58
	1.10	25.0	275.810	268.645	2.59
	1.10	30.0	257.810	241.884	6.17
	1.20	0.0	762.270	813.616	6.73
	1.20	5.0	567.500	645.587	13.75
	1.20	10.0	480.620	524.064	9.04
	1.20	15.0	346.180	337.199	2.59
	1.20	20.0	306.870	269.115	12.30
	1.20	25.0	259.460	232.675	10.32
	1.20	30.0	231.200	209.497	9.38
	1.30	0.0	700.620	704.679	0.57
	1.30	5.0	482.380	559.148	15.91
	1.30	10.0	392.350	453.896	15.68
	1.30	15.0	314.500	292.050	7.13
	1.30	20.0	290.000	233.083	19.62
	1.30	25.0	233.810	201.522	13.80
	1.30	30.0	217.190	181.447	16.45
	1.40	0.0	574.510	610.328	6.23
	1.40	5.0	448.330	484.28	8.01
	1.40	10.0	340.500	393.123	15.45
	1.40	15.0	316.670	252.947	20.12
	1.40	20.0	246.620	201.875	18.14
	1.40	25.0	230.410	174.540	24.24
	1.40	30.0	203.180	157.153	22.65
Silty-sand	1.30	0.0	409.10	400.843	2.01
	1.30	7.0	288.890	150.670	47.84
	1.30	14.0	137.470	114.624	16.61

Table 6 : Continued ...

(1)	(2)	(3)	(4)	(5)	(6)
	1.30	22.0	96.890	99.155	2.33
	1.30	22.7	87.340	98.121	12.34
	1.30	32.2	86.900	88.978	2.39
	1.40	0.0	340.100	347.174	2.07
	1.40	5.0	249.230	154.006	38.20
	1.40	10.2	150.250	111.290	25.93
	1.40	15.0	99.980	96.967	3.01
	1.40	22.3	74.390	85.442	14.86
	1.40	30.4	74.040	78.296	5.74
Fine-sand	1.50	0.0	332.170	340.487	2.50
	1.50	2.0	93.780	113.262	20.77
	1.50	4.0	63.620	86.122	35.36
	1.50	6.0	70.310	75.534	7.42
	1.50	8.0	63.400	69.474	9.58
	1.60	0.0	265.850	294.898	10.92
	1.60	2.0	85.650	98.097	14.53
	1.60	4.0	58.260	74.591	28.03
	1.60	6.0	55.820	65.420	17.19
	1.60	8.0	48.240	60.172	24.73
	1.72	0.0	264.190	248.175	6.06
	1.72	2.0	76.970	82.555	7.25
	1.72	4.0	41.510	62.773	51.22
	1.72	7.0	37.980	52.597	38.48
	1.72	9.0	34.390	49.028	42.56
	1.72	11.0	38.420	46.508	21.05
Coarse-sand	1.50	0.0	263.480	241.178	8.46
	1.50	1.0	156.290	158.583	1.46
	1.50	2.0	149.900	110.032	26.59
	1.50	3.0	99.550	93.320	6.25
	1.50	4.0	82.720	84.242	1.83
	1.50	5.0	86.950	78.331	9.91
	1.50	6.0	79.990	74.084	7.38
	1.60	0.0	182.520	208.886	14.44
	1.60	1.0	138.130	137.350	0.56
	1.60	2.0	111.670	95.300	14.65
	1.60	3.0	81.700	80.825	1.07
	1.60	4.0	79.030	72.962	7.67
	1.60	5.0	80.800	67.843	16.03
	1.60	6.0	77.390	64.164	17.09
Fly ash	1.00	0.0	1104.360	1089.591	1.33
	1.00	5.0	749.100	786.526	4.99

Table 6 : Continued ...

(1)	(2)	(3)	(4)	(5)	(6)
	1.00	10.0	448.330	448.171	0.03
	1.00	15.0	412.010	330.630	19.75
	1.00	20.0	340.500	278.758	18.13
	1.00	25.0	254.240	248.516	2.25
	1.00	30.0	268.990	228.281	15.13
	1.00	35.0	242.890	213.577	12.06
	1.10	0.0	925.000	943.703	2.02
	1.10	5.0	610.630	681.216	11.55
	1.10	10.0	363.200	388.164	6.87
	1.10	15.0	326.880	286.361	12.39
	1.10	20.0	265.590	241.435	9.09
	1.10	25.0	246.300	215.241	12.61
	1.10	30.0	241.760	197.715	18.21

Table 7 : Summary of Thermal Resistivity Values (°C-cm/W) of Multi-phase Soils

Soil type (1)	Dry Density (g/cc) (2)	Moisture Content (%) (3)	Experimental Results (4)	DDTHERM (5)	Difference % (6)
M1	1.33	0.0	458.379	443.433	3.26
	1.33	5.0	407.448	310.757	23.73
	1.33	10.0	329.189	285.071	13.40
	1.33	15.0	279.180	209.794	24.85
	1.33	20.0	256.150	179.067	30.09
	1.33	25.0	223.330	161.517	27.67
	1.40	0.0	408.390	400.986	1.812
	1.40	5.0	358.420	281.009	21.59
	1.40	10.0	281.320	257.782	8.36
	1.40	15.0	246.450	189.712	23.02
	1.40	20.0	215.550	161.926	24.87
	1.40	25.0	195.890	146.056	25.43
M2	1.30	0.0	484.440	462.974	4.43
	1.30	5.0	365.759	306.331	16.24
	1.30	10.0	303.330	315.654	4.06
	1.30	20.0	212.4133	184.813	12.99
	1.30	25.0	196.430	164.699	16.15
	1.30	30.0	184.930	151.571	18.03
	1.38	0.0	413.520	412.681	0.20
	1.38	5.0	319.330	273.054	14.49

Table 7 : Continued ...

(1)	(2)	(3)	(4)	(5)	(6)
	1.38	10.0	280.170	281.097	0.33
	1.38	20.0	200.140	164.736	17.68
	1.38	25.0	188.310	146.807	22.03
	1.38	30.0	180.590	135.106	25.18
M3	1.43	0.0	369.570	384.061	3.92
	1.43	4.0	264.010	323.518	22.54
	1.43	6.0	234.197	282.100	20.45
	1.43	8.0	220.180	188.693	14.30
	1.43	10.0	210.310	160.174	23.83
	1.43	12.0	200.310	144.840	27.69
	1.43	15.0	196.526	130.949	33.36
	1.48	0.0	315.180	357.426	13.40
	1.48	4.0	240.110	301.082	25.39
	1.48	6.0	218.340	262.536	20.24
	1.48	8.0	211.330	175.607	16.90
	1.48	10.0	202.430	149.065	26.36
	1.48	12.0	195.310	134.795	30.98
	1.48	15.0	194.210	121.867	37.24
M4	1.31	10.0	305.466	340.985	11.62
	1.31	12.0	264.749	281.476	6.31
	1.31	15.0	229.470	233.519	1.76
	1.31	17.0	219.589	213.663	2.69
	1.31	20.0	219.589	192.790	12.20
	1.31	25.0	208.485	170.435	18.25
	1.40	10.0	258.380	299.606	15.95
	1.40	12.0	230.110	247.318	7.47
	1.40	15.0	220.330	205.181	6.87
	1.40	17.0	205.310	187.375	8.73
	1.40	20.0	195.320	169.394	13.27
	1.40	25.0	181.310	149.753	17.40
M5	1.20	8.0	402.560	454.288	12.84
	1.20	10.0	369.980	345.600	6.58
	1.20	12.0	321.120	292.486	8.91
	1.20	15.0	250.960	247.535	1.36
	1.20	20.0	194.580	208.285	7.04
	1.20	25.0	184.670	186.152	0.80
	1.30	8.0	344.980	393.462	14.05
	1.30	10.0	308.599	299.327	3.00
	1.30	12.0	277.841	253.064	8.91
	1.30	15.0	205.068	214.392	4.54
	1.30	20.0	184.340	180.397	2.13
	1.30	25.0	182.330	161.228	11.57

Table 8 : Thermal Resistivity (°C-cm/W) of Nine Soil Samples

Soil	Coarse Sand (%)	Fine Sand (%)	Silt (%)	Clay (%)	γ_d (g/cc)	OMC (%)	R_{Exp} (William et al., 1960)		$R_{DDTHERM}$	
							OMC	Dry	OMC	Dry
1	39.2	47.3	7.0	6.5	1.845	13.3	41.2	194	68.9	211
2	36.8	48.7	7.0	7.5	1.746	9.3	52.5	234	91.8	243
3	26.9	58.1	7.4	7.6	1.970	9.7	37.5	155	65.6	176
4	38.0	46.5	9.0	6.5	1.778	14.0	44.8	220	75.4	232
5	27.1	62.4	5.5	5.0	1.621	16.1	54.3	290	87.9	291
6	13.9	71.6	7.0	7.5	1.951	8.8	39.6	162	70.0	181
7	13.5	70.0	8.5	8.0	1.743	9.8	51.8	235	91.6	244
8	10.9	73.1	8.5	7.5	1.570	10.0	66.1	322	116.0	314
9	28.5	62.0	5.0	4.5	1.719	11.7	51.2	246	88.2	253

of wet or dry soil samples with equal precision. Also, the probe is compact and portable. It is relatively inexpensive to fabricate and operate. Another advantage is that the tests can be conducted in a short time, and the operator requires little skill or training. In addition to this, the required calculations are not complicated.

Conclusions

Based on the results and discussions presented above, following generalized conclusions can be made:

1. Thermal resistivity of different soils can be estimated, very efficiently, using a laboratory probe which works on the principle of transient method.

2. Test results indicate that the resistivity of a soil is strongly dependent on its type, dry-density and its moisture content.

3. It has been observed that resistivity of a soil decreases as its dry density increases.

4. It has also been noticed that, for a soil, the rate of decrease of resistivity is much more in the initial stages of moisture addition.

5. Relationships have been developed, to incorporate almost all possible states of the soils (i.e. dry as well as moist soil and single/multi-phase soils), for estimating soil resistivity. These equations are noticed to be quite efficient in predicting the soil resistivity.

Based on these relationships an algorithm (DDTHERM) has been developed which is found to be very efficient.

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Notation

a,b,c = parameters having dependence on type of the soil

C_p = specific heat of the soil

D_x = particle size finer than x percent

G = specific gravity of the soil

k	=	thermal conductivity of the soil
M	=	soil mix
P.I.	=	plasticity index of the soil
Q	=	heat input per unit length
R	=	soil thermal resistivity (= $1/k$)
r	=	radial distance from the heat source
t	=	time of heating
w	=	moisture content
w_L	=	liquid limit of the soil
w_P	=	plastic limit of the soil
θ	=	temperature of the soil mass
α	=	thermal diffusivity constant (= $k/\gamma.Cp$)
γ	=	unit weight of the soil
γ_d	=	dry-density of the soil