Indian Geotechnical Journal, 18 (2), 1988

An Instrument for In-Situ Measurement of Thermal Conductivity of Soils

by

C. Sudhindra*

V. M. Sharma**

A. K. Dhawan***

R. B. Gangadhar****

P.P. Singh*****

Introduction

Thermal conductivity of soils is of great importance to soil scientists, meteorologists, agronomists and engineers. It is of relevance to problems involving flow of heat through soils. From an engineering view point, the information is valuable in connection with buried cables, electrodes, road construction and related activities.

The thermal properties vary from place to place due to difference in soil constituents due to changes in temperature, moisture content etc. from time to time.

The present work on thermal properties of soil has been carried out for National HVDC Project involving transmission of power with return path through the earth. The project involves new technology which is being experimented in the country to reduce transmission losses. The investigation for soil thermal properties were conducted for the first time in the country for sites at Lower Sileru (A.P.) and Barsoor (M.P.). The work has recently been done for NTPC at Rihand and Delhi sites of Rihand—Delhi HVDC transmission project.

The paper describes the work of design and development of the instrument for in-situ measurement of thermal conductivity of soil by the "Transient method" and also the measurement of temperature of soil using the same instrument. The transient method for in-situ measurement of thermal conductivity of soil is advantageous as the water movement in response to temperature gradient is minimised and also a long wait for thermal gradient to stabilise is not required as in the case of steady state heat flow method.

*Director
**Joint Director
***Chief Research Officer
****Senior Research Officer
*****Research Assistant

Central Soil & Materials Research Station, Olof Plame Marg Hauz Khas, New Delhi-110016. INDIA

(*The modified paper was received in Feb* 88 *and is open for discussion till the end of July* 1988)

The development of thermal conductivity probe and the use of transient method for thermal conductivity of soil has been described by several workers e.g., Mason and Kurtz (1952), Rooyen and Winterkorn (1959), De Vries (1958), Woodside and Messmer (1961), Jackson and Taylor (1965), Baver, Gardner and Gardner (1972), Farouki (1986) etc.

Principle of the Method

The general equation of heat conduction is given by,

$$\partial T/\partial t = k\nabla^2 T \quad (1)$$

where 'T' is the temperature of soil at any point, 't' is time at which the temperature measurement is carried out, 'k' is thermal diffusivity of soil and '∇^2' is Laplacian operator.

For radial flow of heat, the governing equation of heat conduction is given by,

$$\partial T/\partial t = k[(\partial^2 T/\partial r^2) + (1/r)(\partial T/\partial r)] \quad (2)$$

where 'r' is the distance from a line source.

If an infinitely long line source of heat is embeded in an infinite homogeneous isotropic medium then the flow of heat away from the source is governed by equation (2). For thermal conductivity measurements, the infinite line source is approximated by a long electrically heated wire enclosed in a cylindrical probe. The probe is introduced into the soil. Heating current is supplied to the wire and the consequent rise of temperature is measured using suitable temperature sensors adjacent to the wire.

The temperature rise $T - T_o$ at a radial distance 'r' from the source is given by,

$$T - T_o = [q/(4\pi K)] \; [-Ei(-r^2/4kt)] \quad (3)$$

where 'q' is the heat produced per unit time per unit length of the source, 'K' is thermal conductivity of soil and 'T_o' is temperature at $t = 0$, and

$$-Ei(-r^2/4kt) = \int_{r^2/4kt}^{\infty} (1/u)\exp(-u)\,du$$

$$= -\gamma - \ln(r^2/4kt) + (r^2/4kt) - (r^2/4kt)^2/4 + \ldots$$

is approximately the exponential integral for small values of $r^2/4kt$.

Where, 'u' is a variable of integration and 'γ' is Euler's constant (0.5772......).

For $r^2/4kt \ll 1$, all terms after the logarithmic term may be neglected.

Thus

$$T - T_o = [q/(4\pi K)]\,[-\gamma - \ln(r^2/4kt)]$$
$$= [q/(4\pi K)]\,[c + \ln t] \qquad (4)$$

where 'c' is a constant,

Equation (4) may be rewritten as,

$$T = [q/(4\pi K)]\,[c + \ln t] + T_o$$
$$= [qc/(4\pi K)] + T_o + [q/4\pi K)]\ \ln t \qquad (5)$$
$$= [qc/(4\pi K)] + T_o + [2.303\ q/(4\pi K))\ Log_{10} t \qquad (6)$$

The plot between T and $Log_{10}t$ gives the straight line having a slope $2.303\ q/4\pi K$ and intercept $[qc/(4\pi K)] + T_o$.

The thermal conductivity of soil can be calculated by measuring this slope 'S', i.e.,

$$S = 2.303\ q/4\pi K$$

or thermal conductivity,

$$K = 2.303\ q/4\pi S$$

where 'q' is the heat introduced into the probe i.e., $q = I^2R$ or,

$$K = 0.1834\ I^2\ R/S \quad W/m^\circ C.$$

where 'I' is current in Amperes passing through the heater of the probe, 'R' is specific resistance of the heater in ohms/m.

Description of the Instrument

The instrument used for measurement consists of a probe, temperature indicator, constant current source, stop watch and drilling accessories which are described below.

The Probe

The probe has been designea to represent a line source of heat, i.e., the length of the source should be very large in comparison to its diameter. This is achieved in the present work by keeping its length 50 times of its diameter. The probe is made of Aluminium the specific heat of which is of the order of that of soil. Also its thermal conductivity is higher than that of soil.

The probe is made from 20mm diameter, one meter long Aluminium rod. A hole of 5 mm diameter has been drilled through the length of the rod at its centre along its axis. A heater of one meter length made of Nichrome wire with electrical insulating sleeves has been inserted into this hole. The heater has been terminated at the top for connection to the current source. A metallic cone has been fitted at the bottom of the probe for its easy insertion into the earth. The cone has been thermally insulated from the probe body. Three Platinum Resistance Temperature Detectors (PRTDs) have been fitted inside the rod towards its surface within slots at 20, 50 and 80 cms. distance from the top. The leads of the PRTDs have been taken to the terminals mounted in the top cap through a groove provided on the rod. The construction of the probe is given in Figure 1. These terminals have been used for connecting the detectors to the temperature indicator. Separate leads and suitable connectors have been used for probe heater and temperature detectors. The probe thus provides for a heater along its length and simultaneously temperature sensing at three different points along its length. The probe has been fabricated for rugged use without damage to sensors, heaters, terminals and leads during its insertion and use in the soil medium.

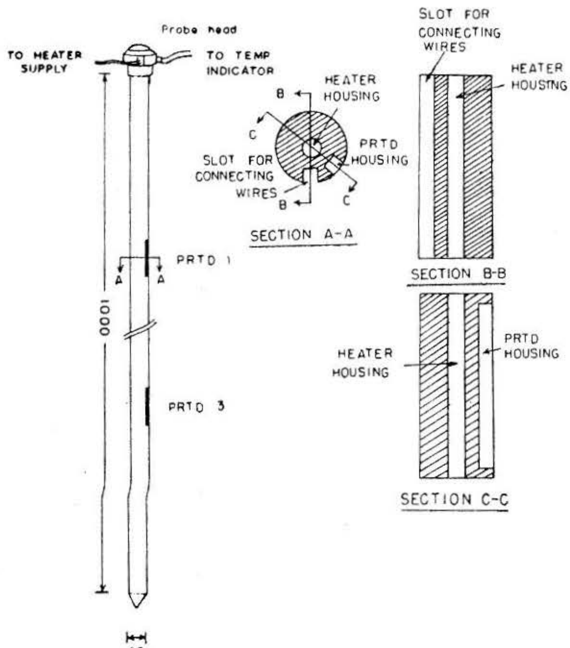

FIGURE 1 The Probe for measurement of Temperature and Thermal Conductivity of Soil.

Temperature Indicator

A digital temperature indicator (3-1/2 digit) suitable for use with PRTDs has been used for measurement of temperatures. The leads from the PRTDs have been connected to the temperature indicator through a three channel selector switch for taking observations at three different depths. The indicator has a resolution of 0.1°C.

Constant Current Source

A 12 volt lead acid battery has been used to supply current to the probe heater. The probe heater has been connected to the battery through an on-off switch and an Ammeter. An adjustable resistance has been used to keep the electric current constant throughout the test.

Stop Watch

A stop watch has been used for taking the temperature measurements at half and one minute intervals after switching on the current source.

Drilling Accessories

A MS pipe of 20 mm OD, 1.5 meter length with sharpened edge on one end, one 500 g hammer and one MS rod 5 mm diameter and 1.8 meters long are the drilling accessories used. These have been used for drilling holes for insertion of the probe.

Insertion of the Probe in Soil

The pipe is slowly hammered into the earth while rotating it simultaneously. The process is continued till the pipe drilled into the earth penetrates with ease. The pipe is pulled out and the soil collected is removed using the MS rod. The pipe is again inserted, hammered and rotated slowly and the process is repeated till one meter hole has been made. The probe is then inserted gently into the hole by pushing and rotating it.

The Temperature Measurement

The probe inserted into the hole is left for some time (say 10 to 15 minutes) so that it acquires the temperature of the soil. The depth of PRTDs from ground level is noted. The temperature readings are noted from the digital temperature indicator for the three different depths using the selector switch. The constant reading attained for each depth and for each location is noted and recorded.

Thermal Conductivity

After 10 to 15 minutes of probe insertion into soil, the three temperature sensors selected by the selector switch indicate a constant temperature of soil. Now, the heater and stop watch are switched on simultaneously. The adjustable resistance is used for providing a constant current throughout the measurement. The heater current value is chosen to give a temperature rise of soil of about 10°C in 30 minutes. The PRTDs are connected in turns to the temperature indicator using the selector awitch and the temperature at different depths is noted at 30 seconds interval and later at one minute intervals.

Calculations

The rise in temperature is plotted against time on semilog paper. A straight line is observed. The slope 'S' of the line for one time cycle (3-30 minutes typical) is taken. Computer software has been developed for processing the field data, graphical presentation and tabulation of results. A typical computerised plot between temperature and time is shown in Figure 2.

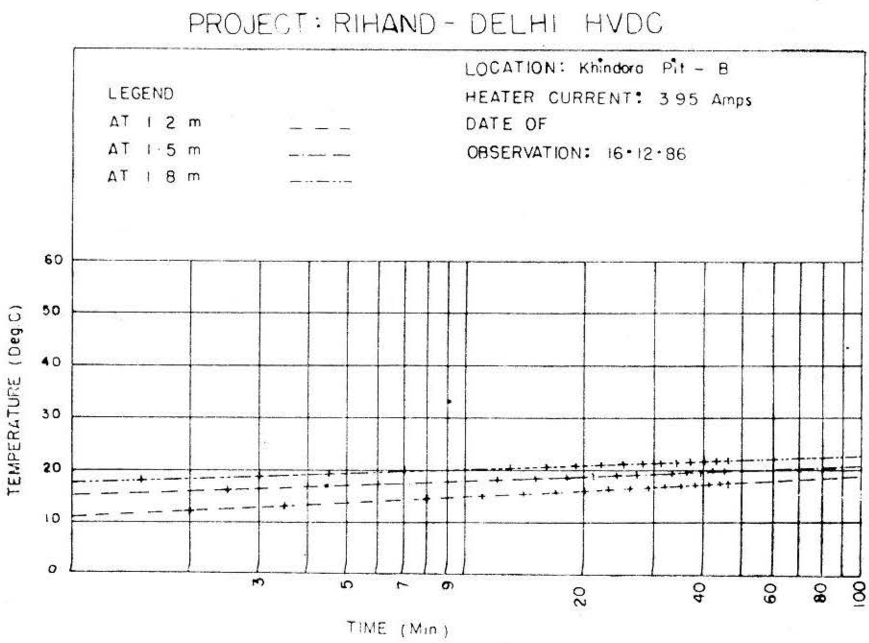

FIGURE 2 Temperature Vs Time Plot

The heater resistance is measured with a sensitive ohm-meter and the resistance per unit length ot the probe is evaluated.

The thermal conductivity of the soil is calculated by,

$$K = 0.1834\ I^2R/S \qquad \text{Watts/m}^\circ\text{C}$$

Thus we get thermal conductivity values for each depth of PRTDs.

Field Work

The present work was done for earth electrode sites each of 400 m × 400 m for National HVDC Project at Lower Sileru, (A.P.) and Barsoor, (M.P.) and Rihand-Delhi HVDC Project at Rihand Nagar (U.P.) and Delhi terminal. Five locations were selected for each site; four at corners of 200 m × 200 m square and one at the centre, representing the entire site.

Measurements of soil temperature and thermal conductivity were carried out at three different depths (ranging from 0.2 to 1.8 m) simultaneously for each location.

Thermal properties viz. temperature and thermal conductivity are measured for three depths and different locations. The values are averaged to ascertain the suitability of the particular site.

For National HVDC project, tests were conducted at Lower Sileru (A.P.) and Barsoor (M.P.) for two different seasons, namely, rainy and summer. The values obtained are shown in Table 1.

TABLE 1

Typical In-situ Thermal Conductivity Values

Name of the Site	Thermal Conductivity W/m°C Summer	Rain
Lower Sileru (A.P.)	1.04	1.77
Barsoor (M.P.)	1.12	1.79

Later on, tests were also conducted for Rihand — Delhi HVDC project at Ashnahar, Pokhara and Chapaki sites (Rihand terminal) and Khindora and Surana sites (Delhi terminal). The values obtained for the above five sites were 1.02, 0.77, 1.20, 1.58 and 1.54 W/m°C respectively.

Based on the work carried out at site and evaluation of test data the final location of earth electrodes had been recommended.

Conclusions and Scope of Work

The above work of measurement of thermal properties of soil viz., in-situ temperature and thermal conductivity had been done for earth electrodes of HVDC Transmission Projects.

The probe in particular has been designed to be rugged enough to stand the wear and tear during its usage inside soil. The instrument is designed for ease and simplicity of operation and maintenance. Several field trials have been made and it has been found that it gives reliable and accurate measurements.

The instrument can be used for measurement of temperature and evaluation of thermal conductivity of soil at three different depths with a single set of measurements in a short period of time, say, about 45 minutes. The probe has been used to about 2 meters inside the earth.

The thermal properties of soil depend upon several factors such as soil constituents, moisture content etc. While temperature and moisture content change from time to time, the soil constituents have large variations from place to place. Hence, a considerable work is required to be carried out on various types of soils and moisture contents under different natural conditions to understand the effect of different parameters on the thermal properties. The thermal conductivity measurements are proposed to be carried out with sensors placed away from the heat source.

The work of modification of the instrument for measurement of thermal properties in other media viz., rock, concrete etc. is being taken up.

References

BAVER, L.D., GARDNER, W.H. and GARDNER, W.R., (1972) : "Soil Physics" *Wiley Eastern Ltd.*, New Delhi, 266-275.

DE VRIES, D.A. and PECK, A.J., (1958) : "On the cylinderical probe method of measuring thermal conductivity with special reference to soils", *Australian Journal of Physics*, 11 : 225-271.

FAROUKI, O.T., (1986): "Thermal properties of Soils", *Trans Tech Publications*, 91-101.

JACKSON, R.D. and TAYLOR, S.A., (1965) : "Methods of Soil Analysis", *Agronomy Monograph*, No. 9, Pt. I, Academic Press, 349-360.

MASON, V.V. and KURTZ, M., (1952) : "Rapid measurement of thermal resistivity of soils", *American Institute of Electrical Engineers Transactions*, 71 : 570-577.

ROOYEN, M.V. and WINTERKOREN, H.P., (1957) : "Theoretical and Practical aspects of thermal conductivity of soils and similar granular systems", *Highway Research Board*, Bulletin 168, 143-205.

WOODSIDE, W. and MESSMER, J.M., (1961) : "Thermal conductivity of porous media", *Journal of Applied Physics*, 32 : 9 : 1688-1706.