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Heat conduction and moisture migration in unsaturated soils under temperature gradients

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Abstract. An experimental study has been done to investigate the heat conduction and moisture distribution through the different layers of unsaturated soil. The soil is taken in the form of cylindrical columns in vertical and horizontal positions. The two ends of the cylindrical column were maintained at different constant temperature. The effective thermal conductivity was measured by dynamical method after achieving steady state. The distribution of moisture in the soil column was determined by gravimetric technique. The effective thermal conductivity (ETC) has also been predicted by temperature dependent model developed by Singh *et al* (1988). A close agreement has been found in experimental and predicted values of ETC.

Keywords. Moisture migration; vapour condensation; steady state.

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1. Introduction

Heat flow and moisture migration has received a great importance in recent times. Its study is important for development of a cheaper insulating material for solar thermal energy storage devices, buildings and earth sheltered structures. The study is also important for successful storage and utilization of solar or geothermal energy in soil.

In many other situations heat transfer is generally associated with the moisture migration (Philip and De Vries 1957; Huang 1979; Reddy and Mulligan 1987). Therefore, it becomes essential to know the mechanism of heat transfer in soils with distribution of moisture content, its effect on ETC and diffusion coefficients. In general, if the temperature gradient exists, the vapour diffuses from the zones of higher temperature and condenses in the colder regions. Thus, the amount of moisture becomes low towards the higher temperature side and gradually increases as we move towards the low temperature end. Thus a moisture gradient is established. The moisture gradient in the soil is effected by the presence of salts, porosity, gravity, temperature gradient and the solid soil material phase structure (De Vries 1975; Hadas 1977). An incorporation of all these factors makes the problem much complex.

In the past studies, either a constant value of thermal conductivity was assumed (Szydolowski and Kuehn 1980; Wang and Frang 1984) or a seasonal variation of effective thermal conductivity has been taken. The present study gives a more detailed information about variation of ETC with moisture and temperature. It has been observed that migration of soil water and vapour diffusion through the pores increase the ETC more than five times at half saturation to its value in dry state. The moisture in the soil has a strong influence on temperature gradient and heat transfer. To evaluate the effectiveness of the soil to control the heat transfer in related applications, the study of moisture and temperature gradient on ETC is to be dealt carefully.

Although many workers have developed models (Brailsford and Major 1964; Chang 1983; Okazaki *et al* 1982; Crane and Vachon 1977), no one predicts the ETC of moist soils satisfactorily. In the present endeavour the moisture and temperature gradient is established in the soil and its ETC is determined by the transient probe method.

2. Experimental arrangement and measurements

The experimental arrangement is shown in figure 1. The sample container was fabricated from cylindrical PVC pipe having a diameter of 15·0 cm and length of 27·0 cm. Flat cylindrical boxes made up from copper sheet were fitted at the two ends of the pipe. The terminal ends of the boxes were made up of bakelite sheets. Liquid at different constant temperatures was circulated through the two boxes.

To begin with the cylindrical container was filled by sandy soil of particle size 106–150 μm. The solid density and moisture were predetermined. The two ends of the column were maintained at different constant temperatures by circulating water through the hollow space in the boxes. This caused a distribution of temperature gradient through the cylindrical column of soil. Thermal probes at interval of 2·0 cm were placed through the holes drilled in the pipe along its length. The ETC and temperature at different layers were measured with the help of probes itself. The body of column was surrounded by wool for better insulation.

The apparatus was placed in vertical as well as horizontal position. The hot and cold ends were kept at 55°C and 25°C respectively. When steady state is reached, the ETC was determined by the probes. At the end of experiment, the probes were removed and the sample was taken from each position in vicinity of probes with the help of hollow brass tubes. Determination of moisture content was done by weighing sample specimen before and after drying. The drying was done in an oven at a

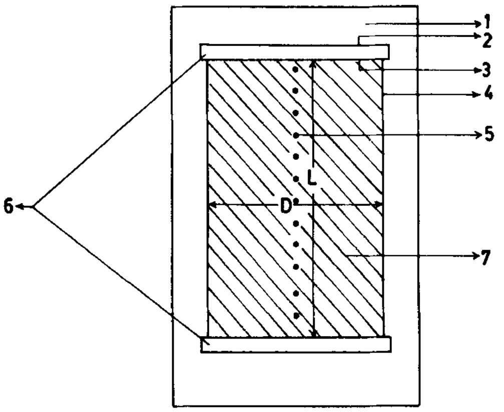

Figure 1. Schematic illustration of experimental arrangement. 1. Cotton wool insulation 2. bakelite 3. copper plate 4. PVC pive 5. thermal probe 6. hollow cylindrical plate 7. moist soil and 8. $D = 0{\cdot}15\,m$, $L = 0{\cdot}27\,m$.

temperature of 105°C for 24 h. The net amount of water was determined and expressed as the percentage of moisture content of the soil relative to dry soil weight.

The expression used (Carslaw and Jaeger 1959) for the calculation of ETC of moist soil by a thermal probe is

$$\lambda_e = \frac{Q}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \tag{9}$$

where T_2 and T_1 are two values of temperature at time t_2 and t_1 respectively and Q is power per unit length supplied to the probe.

3. Theory

The temperature dependency of ETC was incorporated by Singh *et al* (1988) in the model and the model was further modified to account ETC of moist soils. A brief outline of the expression used is presented here.

The effective continuous media (ECM) of a material is defined as a system, made of equal volume fractions of solid and air phase. Dry natural soil may be thought as formed by introducing a small relevant dispersion of solid or air in ECM. In moist sample a further dispersion of third phase (water) in dry soil takes place. We consider n successive small dispersion of value $\delta\psi_g$ of gas phase in continuous solid phase ψ_s. Under the condition $n\delta\psi_g \to 0{\cdot}5$, the ETC of ECM become (Pande *et al* 1984)

$$\lambda_{en} = \lambda_{\mathrm{ECM}}(1 + 3{\cdot}844\,\xi_s^{2/3}) \quad \text{for}\, 0 < \xi_s = \psi_s - 0{\cdot}5 \tag{1}$$

$$\lambda_{en} = \lambda_{\mathrm{ECM}}(1 - 1{\cdot}1545\,\xi_g^{2/3}) \quad \text{for}\, 0 < \xi_g = \psi_g - 0{\cdot}5. \tag{2}$$

Where ξ_s and ξ_g stand for small dispersions of solid and gas phase respectively in ECM and ψ_s, ψ_g are volume fractions of solid and gas phases. From (1) and (2), the thermal conductivity of ECM

$$\lambda_{\mathrm{ECM}} = 1{\cdot}092(\lambda_g \lambda_s)^{1/2}. \tag{3}$$

Where λ_s and λ_g are thermal conductivity values of solid and gas phase respectively. An addition of water replace the air in void spaces of the sample. As a consequence the thermal conductivity of moist air within the pore is given by

$$\lambda_{\mathrm{ma}} = \lambda_a[1 + 3{\cdot}844[(\lambda_w - \lambda_a)/(\lambda_w + 2\lambda_a)]\psi_{\mathrm{ma}}^{3/2}] \quad \text{for}\, 0 < \psi_{\mathrm{ma}} < 0{\cdot}5. \tag{4}$$

At saturation, air is completely replaced, thus $\psi_{\mathrm{ma}} = \psi_w$ and $\lambda_{\mathrm{ma}} \to \lambda_w$. When ψ_{ma} lies between 0·5 and 1·0 i.e. for $0{\cdot}5 < \psi_{\mathrm{ma}} < 1{\cdot}0$

$$\lambda_{\mathrm{ma}} = \lambda_w[1 + 3{\cdot}844[(\lambda_a - \lambda_w)/(\lambda_a + 2\lambda_w)](1 - \psi_{\mathrm{ma}}^{2/3})]. \tag{5}$$

If ψ_m be the volume fraction of moisture and ψ_a that of air then ψ_{ma}, volume fraction of moisture with respect to air can be expressed as

$$\psi_{\mathrm{ma}} = [\psi_m/\psi_a] \quad \text{where}\, \psi_m = (m/M)\psi_a \tag{6}$$

m and M represents the existing varying moisture content and the moisture content at saturation respectively in weight per cent relative to dry soil weight.

The temperature dependency of λ_a and λ_w is expressed as (De Vries 1974)

$$\lambda_w = 0{\cdot}55 + 2{\cdot}34 \times 10^{-3}\,T - 1{\cdot}1 \times 10^{-5}\,T^2$$

and

$$\lambda_a = 0{\cdot}0237 + 6{\cdot}41 \times 10^{-5}\,T. \tag{7}$$

Here T is temperature in °C and by using these calculated values of λ_{ma} from (4) and (5) and on replacing λ_g by λ_{ma} in (3), λ_{ECM} can be calculated. If the porosity, thermal conductivity of solid of soil and moisture content are known, the ETC of soil can be obtained from (8) for $\psi_s > 0{\cdot}5$

$$\lambda_e = \lambda_{\mathrm{ECM}}[1 + 3{\cdot}844[(\lambda_s - \lambda_{\mathrm{ECM}})/(\lambda_s + 2\lambda_{\mathrm{ECM}})]\,\xi_s^{2/3}] \tag{8}$$

where

$$\xi_s = \psi_s - 0{\cdot}5.$$

And for the values $\psi_s < 0{\cdot}5$ one replaces $\xi_s^{2/3}$ in (8) by $(0{\cdot}5 - \psi_s)^{2/3}$.

4. Comparison with experimental results and discussion

An analysis of results is shown in figures 2–6. Measurement of temperature was done along the axis of column at each probe position in steady state as well as in transient state. However the transient temperatures are not depicted in the figures for simplicity. A close agreement between the predicted and experimental values of ETC

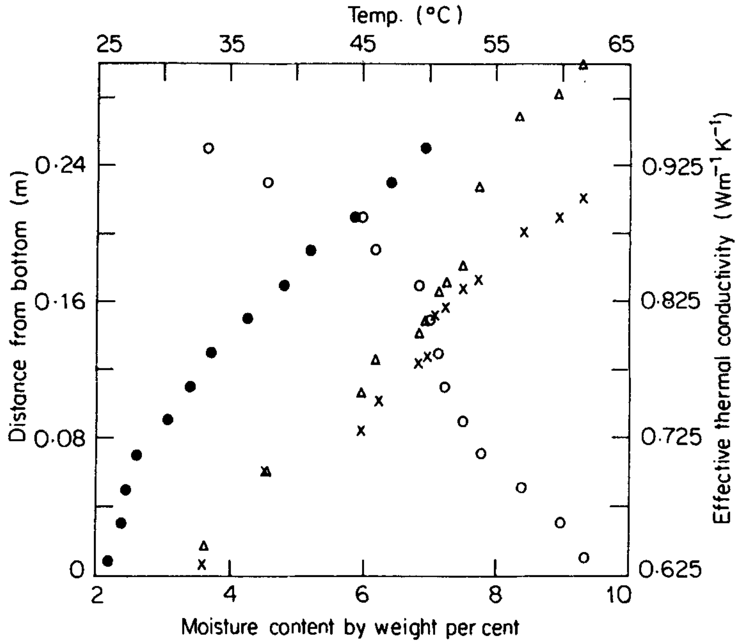

Figure 2. Variation of effective thermal conductivity with moisture content (initial moisture content by weight per cent = 7·16, top temperature = 55°C and bottom temperature = 25°C) (△ △) experimental curve; (×) theoretical curve; ● distribution of temperature with distance from bottom (m); ○ distribution of moisture with distance from bottom (m).

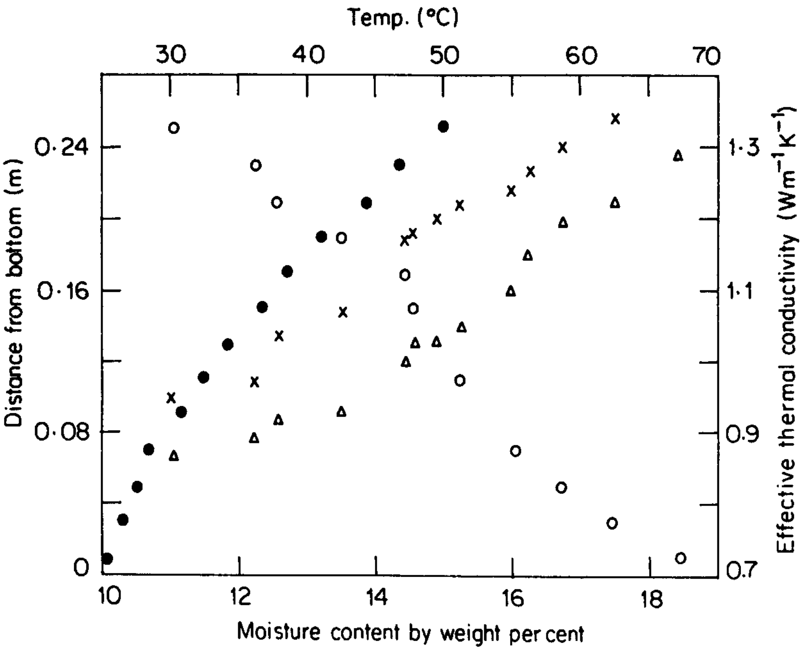

Figure 3. Variation of effective thermal conductivity with moisture content (initial moisture content by weight per cent = 14·62, top temperature = 55°C and bottom temperature = 25°C), (symbols are same as used in figure 2).

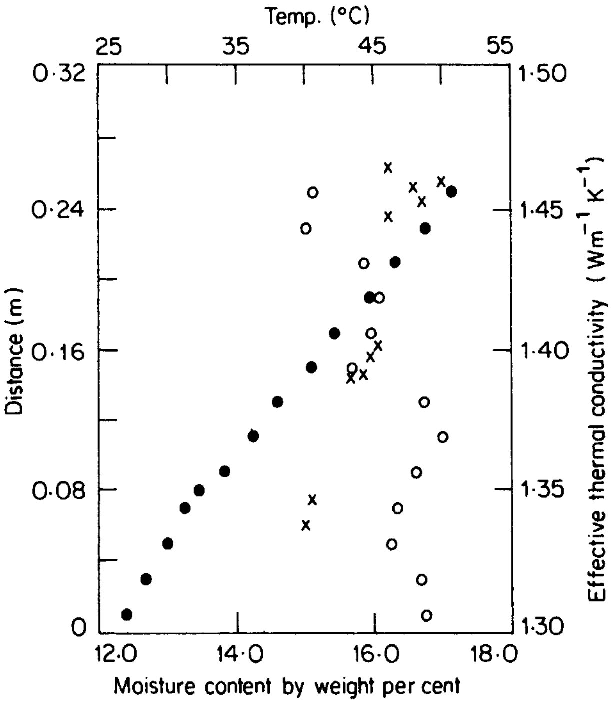

Figure 4. Variation of effective thermal conductivity with moisture content for horizontal position (initial moisture content by weight per cent = 15·97, one end temperature = 55°C and another end temperature = 25°C) (symbols are same as used in figure 2).

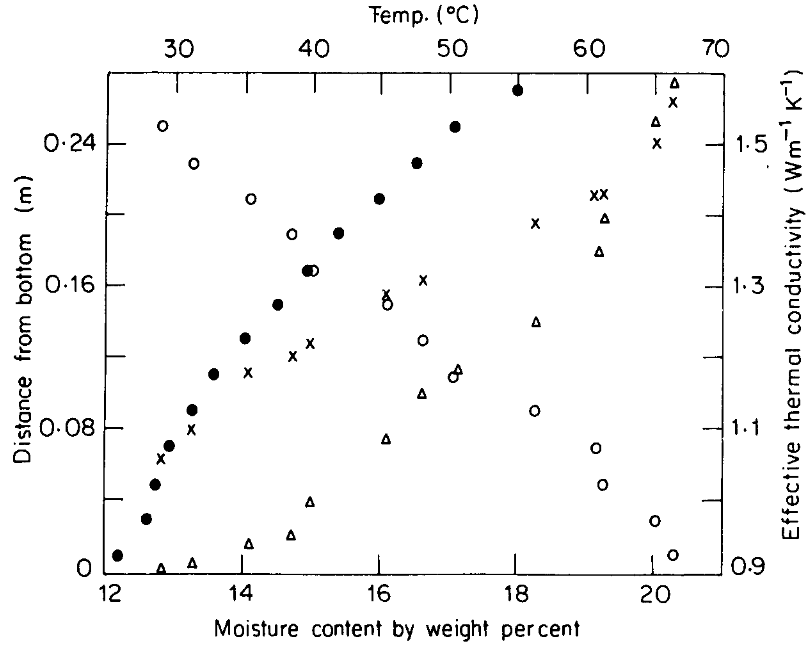

Figure 5. Variation of effective thermal conductivity with moisture content (initial moisture content by weight percent = 16·50, top temperature = 55°C and bottom temperature = 25°C) (symbols are same as used in figure 2).

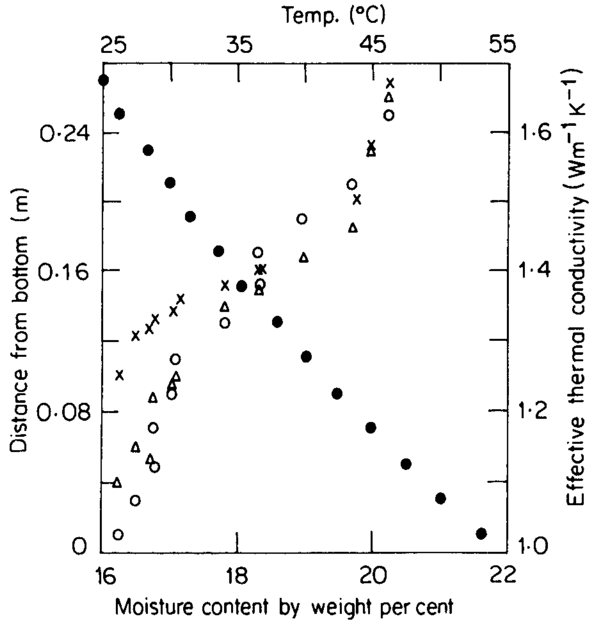

Figure 6. Variation of effective thermal conductivity with moisture content (initial moisture content by weight per cent = 20·50, top temperature = 25°C and bottom temperature = 55°C) (symbols are same as used in figure 2).

was found. The thermal conductivity (λs) of solid phase was taken 3·35 $W/m\,K$ (Singh *et al* 1988).

No experimental values of effective thermal conductivity are reported for horizontal position of soil column and only calculated values are presented in figure 4 because the system takes longer time to reach the steady state. However the transient record of temperatures shows the existence of a steady temperature gradient although it is not shown. But, the moisture record with position (figure 4) shows that the moisture gradient has not been fully developed.

The observations on moisture study show that there is moisture transfer from the warm to the cold end of the sample. Because temperature gradient water begins to evaporate in the warm region and migrate towards the cooler region where condensation of vapour takes place. Although some water is also held on the warmer side in small films around the solid grains of sand due to adhesion. Increasing trend in ETC with increase of moisture can be explained by formation of wedges around solid particles at their contact points. As the moisture increases the area of contact between sand grains increases which results in an increase of ETC.

Conclusions

1. The present study shows that ETC, largely depends upon the moisture content and temperature of the specimen and increases with the increase in both the parameters.
2. For moist soils the ECM model yields close prediction of ETC.
3. For moist soils the convective transfer of thermal energy due to fluid flow is appreciable. One can utilize the investigation in the study of heat losses from thermal energy storage devices and earth sheltered structures from the viewpoint of energy economics.
4. Probes can be calibrated for direct measurement of moisture content or ETC. Such calibrated probes are useful for transient study of mass transport and energy transfer in soils.

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