Int. J. Heat Mass Transfer. Vol. 33, No. 2, pp. 359–366, 1990
Printed in Great Britain

0017-9310/90 $3.00 + 0.00
Pergamon Press plc

Susceptibility to drying of unsaturated soil near warm impermeable surfaces

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(*Received* 18 *January* 1989 *and in final form* 30 *May* 1989)

Abstract—Drained soil near warm impermeable surfaces heats up and may dry. It is proposed here, based on a theoretical study, that a soil property—critical temperature difference—is a measure of the susceptibility of soil to drying; near a surface of any shape or size, drying will take place if a temperature difference greater than the critical temperature difference is maintained between any two points in the soil. The design of an experiment to measure critical temperature difference is discussed.

INTRODUCTION

WHEN A temperature gradient exists within unsaturated soil, moisture tends to flow in the direction of decreasing temperature; soil near a warm impermeable surface therefore tends to dry creating a moisture distribution (with moisture content increasing with distance from the surface) which encourages a natural flow back towards the surface. The flows away from and towards the surface occur simultaneously and the resulting moisture distribution depends on the relative strengths of the flows. If the outward flow under the temperature gradient dominates the inward flow under the moisture gradient, soil in a region near the surface tends to dry to a very low moisture content. Since dry soil has a lower effective thermal conductivity (defined here as the ratio of heat flux to macroscopic temperature gradient) than moist soil, such a region of dry soil will tend to thermally insulate the surface; depending on the thermal characteristics of the surface, this insulation will either cause the surface heat flux to fall, or the surface temperature to rise, or both the surface heat flux to fall and the surface temperature to rise.

The natural development of a thermally insulating region of dry soil near a warm surface is sometimes an advantageous feature. One example is drying near underground pipes through which heat is transported. This is advantageous because the rate of loss of heat from the pipes and the rate of decay of the temperature and economic value of the transported heat will be reduced. The work presented here is not applicable only to buried pipes but is part of a wider study of the insulating properties of soil near buried pipes [1].

The natural development of a dry region near warm surfaces is not always advantageous. Buried electric power transmission cables and buried canisters of high-level nuclear waste emit heat. If drying takes place near such bodies, the efficiency with which they dissipate heat will be reduced and their temperatures will rise. They must therefore be designed with working temperatures high enough to dissipate heat through a dry region of soil or must be designed (with large surface area, for example) so the probability of drying is low.

Drying near buried cables and canisters has been studied by others. The aim has usually been to develop thermal design guides of which one part is the prediction of the conditions under which drying will take place. Drying near buried cables has been investigated in the field [2]; and much work has been carried out in an attempt to understand the physical processes involved. However, no concensus has yet been reached on the most important parameters. At a recent workshop [3], based on both theoretical and experimental studies, several different combinations of several parameters were proposed as being important in the prediction of drying near cables. The parameters were soil properties, ambient temperature, natural soil moisture content, cable temperature and the heat flux at the surface of the cable.

Some ideas developed here are similar to those developed by researchers considering drying near buried cables. The conclusions reached may be useful to specialists in cable design; however, they are not applicable only to cable design and they are not proposed as being the complete basis for a thermal design method for buried cables.

Drying of unsaturated geological media near buried canisters of high-level nuclear waste was studied by Doughty and Pruess [4]. They followed the analysis of Udell [5] and developed an expression, in terms of properties of the media and design parameters, for the conditions under which drying will take place. They considered canister temperatures well above the boiling temperature for the water in the geological media. Here the surface temperature is assumed to be below the boiling temperature. However, the approach adopted is similar to that of Doughty and Pruess in that it relies on an analysis of the distribution of moisture under steady conditions.

In this paper the aim is not to develop a guide for

NOMENCLATURE

a	radius of warm cylinder [m]
d	dry moisture content [1]
D_T	thermal moisture diffusivity [m^2 s^{-1} K^{-1}]
D_θ	isothermal moisture diffusivity [m^2 s^{-1}]
f	field capacity [1]
k	effective thermal conductivity [W m^{-1} K^{-1}]
L	latent heat of vaporization for soil water, 2.4×10^6 J kg^{-1}
q	net rate of moisture flow at the dry/moist boundary [kg s^{-1} m^{-1}]
Q	heat dissipation rate per unit length [W m^{-1}]
r	radius [m]
s_p	distance along path p [m]
T	temperature [K]
T_1	temperature at point 1 [K]
T_p	temperature along path p [K]
ΔT_c	critical temperature difference [K].

Greek symbols

θ	moisture content [1]
θ_1	moisture content at point 1 [1]
θ_p	moisture content along path p [1].

the thermal design of buried surfaces but to isolate the soil properties which describe the ease with which properly drained soils dry near warm impermeable surfaces. The theory and results are contributions towards a general method for the comparison of the properties of backfill soils.

Those soils which tend to dry under little thermal stress (heat flux, temperature, temperature gradient or other drying influence) can be said to be more susceptible to drying than soils which dry only under greater stress. It is found here that critical temperature difference (a soil property) is a measure of the susceptibility of soils to drying. The approach is not empirical; this result depends only on the assumptions made. The assumptions are therefore of primary importance so are discussed in detail as they are introduced. The basic assumption is that combined heat and moisture transfer in soil is well described by equations of the type developed by Philip and de Vries [6]. These equations have been widely and successfully tested for soil and other porous materials [7]. It is in effect shown here that critical temperature difference is a property of soils in which combined heat and moisture transfer is well described by equations of the Philip and de Vries type; and this property is, on its own, a measure of the susceptibility of soil to drying near warm impermeable surfaces.

The approach adopted is to consider the distribution of moisture under steady conditions. There are some similarities with the way in which Donazzi *et al.* [8] developed a method for the thermal design of buried electric cables. They assumed that drying will take place in the soil near a cable if the degree of saturation (the ratio of volumetric moisture content to porosity) of the soil falls below a particular value they call the critical degree of saturation. They then established a theoretical relationship between the temperature and moisture profiles under steady conditions. Their design method is based on the idea that the drop in degree of saturation near a cable can be predicted using this relationship; and drying is predicted if this drop is greater than the difference between the degree of saturation of the soil before heating and the critical degree of saturation.

Critical temperature difference is shown to be a property of soil by studying the theoretical relationship between moisture and temperature profiles under steady conditions. Donazzi *et al.* [8] took the first step along this route when they developed the relationship used in their thermal design guide. It was later noted by Germay [9] that the work of Donazzi *et al.* shows that "... the only possible critical value, if a critical value exists, is a gradient $T_{cr} - T_0$..." where T_{cr} is the critical temperature and T_0 the temperature at some distance from the cable. They stated that this critical value will depend on the natural moisture content of the soil. This result is extended and generalized here: critical temperature difference is a property of soil so it is independent of both the shape and size of the heated surface and the natural moisture content of the soil.

Degrees of saturation, temperatures and heat fluxes have all been proposed as parameters describing susceptibility to drying. Donazzi *et al.* [8] considered critical degree of saturation to be most important. However, although it may be a useful property in cable design, critical degree of saturation is not useful as a measure of susceptibility to drying: it does not give a direct measure of the thermal stress under which the soil will dry. In the theory developed here it is assumed that there is a low moisture content which characterizes the transition between (effectively) dry and moist soil. It is called the dry moisture content. It is assumed to be a property of soil but should not be confused with critical degree of saturation; it is not a property describing susceptibility to drying; it is simply the maximum value of moisture content at which the soil is, by definition, dry.

In cable design it is often assumed there is a critical temperature above which a soil dries out [10, 11]. This is consistent with there being a critical temperature difference: critical temperature is simply the sum of ambient temperature and critical temperature difference. Some approaches to the prediction of drying near buried electric cables are based on the maximum heat flux a soil can sustain without drying within a specified time [12]. This maximum heat flux is not a property of soil: it varies with the specified drying time and the initial moisture content of the heated sample of soil [12]; and will probably also vary with the shape of the heated surface. Therefore, although the maximum heat flux is an important parameter in the thermal design of buried electric cables, unlike critical temperature difference it is not a soil property describing susceptibility to drying of soil near warm surfaces.

Direct measurement as a spatial temperature difference is proposed as a method by which critical temperature difference could be determined for a soil for which it is known or is assumed that equations of the Philip and de Vries type are appropriate. The basic features of a suitable laboratory experiment are described in this paper. No experiments have yet been run specifically to measure critical temperature difference but an approximate value for a very susceptible soil (uniform medium sand) is calculated from existing experimental data.

THEORY OF SUSCEPTIBILITY TO DRYING

To be most useful, any theory of susceptibility to drying must reduce to a minimum the number of independent parameters involved in the prediction of drying. The theory developed here is based on an analysis of the resulting steady distributions when a surface has warmed and the temperature and moisture distributions in the surrounding soil are no longer changing with time. It is assumed that the parameters needed to predict the presence under these steady conditions of an infinitesimally small region of dry soil near the warm surface are identical to those needed to predict drying. The soil is assumed to be a continuum. This indirect approach leads to a method of prediction of drying involving the minimum possible number of independent parameters—one; this one parameter may therefore be said to be a measure of the susceptibility to drying.

A clear definition of the term drying is needed before susceptibility to drying can be investigated. Here it will be assumed that if drying has taken place the local moisture content at at least one point in the soil is the dry moisture content—a very low moisture content denoted by the letter d. (The practicability of this definition will be considered later.) It will also be assumed that all regions in which the moisture content is at or below the dry moisture content are near warm surfaces: the soil in regions beyond being moist. If the conditions under which dry soil is present are identical to those under which drying takes place, it may be concluded that the steady conditions under which the soil can simultaneously sustain (at different points) the dry moisture content and one higher moisture content are sufficient conditions for drying to take place. Here, in the development of a general theory of susceptibility to drying in drained soil, this higher moisture content is taken to be the highest sustainable moisture content—the field capacity.

To be most useful to an engineer designing a buried surface these sufficient conditions for drying must be related to the size, shape, and temperature of the surface and the heat flux normal to the surface. This is achieved by considering the constraints on the distribution of moisture and temperature implicit in the theory of moisture flow in unsaturated soil.

A commonly used theory of moisture flow is adopted here; it is assumed that the net rate of moisture flow at every point is directly proportional to a weighted sum of the local gradients of moisture content and temperature. This is the basic assumption made in the development of most theories of combined heat and moisture transfer in unsaturated soil and is usually supported by association with empirical linear laws: Fick's law of diffusion and Darcy's law of fluid flow in porous media. The most primitive (and arguably the most successful) use of this assumption is central in the theory of moisture flow developed by Philip and de Vries [6]. Using the nomenclature of Philip and de Vries, a vector equation may be written to describe, in mathematical terms, the assumption made about moisture flow. Under steady conditions there is no net flow at any point, therefore

$$D_\theta(\theta, T)\nabla\theta + D_T(\theta, T)\nabla T = \mathbf{0} \qquad (1)$$

where θ represents moisture content and T temperature. Philip and de Vries called the factors D_θ and D_T the isothermal and thermal moisture diffusivities, respectively. Although these names will be used here there is no implied association with the explicit equations developed by Philip and de Vries for the moisture diffusivities in terms of other soil properties and water properties. No knowledge is assumed of the functional relationship between the moisture diffusivities and values of moisture content and temperature other than that the diffusivities are always positive and the functions are well behaved. Hysteresis in moisture distribution, which would require modelling using multi-valued functions for the moisture diffusivities, is not considered.

No consideration was given above to the influence of the Earth's gravitational field on the distribution of moisture. As the soil is assumed to be properly drained, it will be assumed that the presence of the gravitational field simply limits—to the field capacity—the maximum sustainable moisture content at all points within the soil.

Unique values of moisture content and temperature are associated with each point in the soil; in mathematical language, moisture content and temperature are steady scalar quantities and their relationship with points in the soil define steady moisture content and temperature scalar fields. The gradient of such fields

[13] (denoted here by placing the symbol ∇ in front of the symbol for the scalar) is a vector field with direction at every point in the direction in which the scalar quantity changes most quickly with distance; at every point the magnitude of the gradient is equal to the rate of change of the scalar quantity with distance in the direction of the gradient. Provided, therefore, that there are no singularities in the temperature gradient field (associated for example with local maxima in temperature), a unique path through the soil can be associated with each point in the soil; the direction of this path is at all points in the direction of the temperature gradient. Starting at any point (temperature T_{l} and moisture content θ_{l}) the temperature distribution (T_{p}) along the path in the direction of monotonically decreasing temperature will be given by

$$T_{\mathrm{p}} = T_{\mathrm{l}} - \int_{0}^{s_{\mathrm{p}}} |\nabla T| \, \mathrm{d}s_{\mathrm{p}} \tag{2}$$

where s_{p} is the distance along the path and $\mathrm{d}s_{\mathrm{p}}$ a differential increment along the path. Equation (1) is a vector equation and must be satisfied for both magnitude and direction; it may therefore be deduced from equation (1) that the moisture gradient is at all points in the opposite direction to the temperature gradient; the path followed in equation (2) is therefore at all points in the direction of the local moisture content gradient. From equation (1)

$$|\nabla T| = \frac{D_\theta}{D_T} |\nabla \theta| \tag{3}$$

and on the path

$$|\nabla \theta| = \frac{\mathrm{d}\theta}{\mathrm{d}s_{\mathrm{p}}}. \tag{4}$$

Substituting these results into equation (2) gives the temperature distribution along the path in terms of the ratio of the moisture diffusivities

$$T_{\mathrm{p}} = T_{\mathrm{l}} - \int_{\theta_{\mathrm{l}}}^{\theta_{\mathrm{p}}} \frac{D_\theta}{D_T} \, \mathrm{d}\theta \tag{5}$$

where θ_{p} is the moisture content distribution along the path.

This equation is implicit in temperature as the ratio of the moisture diffusivities is temperature dependent.

Digressing from developing the theory of susceptibility for a moment, equation (5) is very useful in the analysis of combined heat and moisture transfer under steady conditions; it shows that there is similarity between moisture distributions in the soil near warm surfaces. The direction of the paths discussed earlier are locally in the direction of moisture and temperature gradient and will therefore (at least for isotropic soil) be locally in the direction of heat flow; the paths are therefore paths of heat flow. Equation (5) is independent of the geometry of the warm surface, the magnitude of heat flux, and of the thermal resistivity of the soil; it simply relates the temperature and moisture content distribution along paths of heat flow. This similarity between distributions may be used in the general study of steady conditions. One particular use is to relate the distributions seen at different physical scales for the same geometry of the warm surface. For example [14], distributions (given as functions of the scale $Q \ln (r/s)/2\pi$ where r is the radius, Q the radial heat dissipation rate per unit length of the warm surface, and s a reference radius) can be identified for temperature and moisture content near a buried warm cylinder.

The idea of similarity of moisture distributions can be used in the analysis of susceptibility to drying. From equation (5), each point in the soil at which the moisture content is the dry moisture content is uniquely associated (by being on the same heat flow path) with another point at which the moisture content is the field capacity. The temperature difference, ΔT_{c}, between all such pairs of points is given by

$$\Delta T_{\mathrm{c}} = \int_{d}^{f} \frac{D_\theta}{D_T} \, \mathrm{d}\theta. \tag{6}$$

It can be seen that the temperature difference ΔT_{c} only depends on three soil properties: dry moisture content, field capacity, and the temperature dependent ratio of the isothermal to thermal moisture diffusivities. The temperature difference is therefore a temperature dependent soil property; it will, through the general dependence of soil properties on degree of compaction, vary from sample to sample of a particular soil depending on the sample bulk dry density.

From equations (5) and (6), it can be deduced that if, under steady conditions, the temperature difference ΔT_{c} is exceeded between any two points in a sample of soil, regions must exist where the moisture content is less than the dry moisture content or greater than the field capacity; moisture contents greater than the field capacity cannot be sustained so there must be a dry region of finite thickness—the soil near the warm surface must be dry. The temperature difference ΔT_{c} is therefore proposed as a measure of the susceptibility of a drained soil to drying near a warm impermeable surface; it is called the critical temperature difference: if this or a larger temperature difference is maintained between any two points in a drained sample of soil near a warm impermeable surface of any size or shape, drying will take place irrespective of the temperature of the surface or of the heat flux normal to the surface.

Discussion

Critical temperature difference is a soil property in the same sense that field capacity is a soil property. They are not intrinsic properties: field capacity is only fully defined if some details of the way it is measured are specified [15]; and the same holds for critical temperature difference. (The design of an experiment to measure critical temperature difference is discussed in the next section.) Despite not being an intrinsic property, field capacity is a useful property: it is used widely in the comparison of the water holding quality of soils. It is proposed here that critical temperature difference is also useful; it can be used in the comparison of the susceptibility to drying near warm impermeable surfaces.

The theory of susceptibility to drying was based on sufficient conditions for drying to take place; it is therefore a sufficient condition for drying to (eventually) take place if the critical temperature difference is exceeded (for long enough) between any two points in the soil; it is not necessarily a necessary condition. It cannot therefore be assumed that drying will not take place if the critical temperature difference is not at any time exceeded between any two points in the soil.

The theory of susceptibility to drying was based on an analysis of the distribution of moisture under steady conditions. Under non-steady conditions, drying will tend to take place if the critical temperature difference of a soil is exceeded; and a dry region will (eventually) develop if a difference greater than the critical temperature difference is maintained. The time taken for a dry region to begin to develop near a cylindrical surface was measured by Martin *et al.* [12]. They defined drying time as the time elapsing between the surface first being heated (to emit constant heat flux) and the onset of drying; and showed that the drying time for Georgia clay soil varies both with the initial, unheated moisture content of the sample and the heat flux at the surface. Experiments on a very susceptible soil [1] (uniform medium sand, critical temperature difference about 0.7 K) have shown that once a dry region develops near a cylinder, its size increases with time such that

$$\frac{Lq}{Q} = 0.1 \tag{7}$$

where L is the latent heat of vaporization of soil water, Q the time varying rate of heat dissipation from the cylinder, and q the net rate of water mass flow at the boundary between the dry and moist soil.

Designers of buried electric cables face the unusual problem that the rate of dissipation of heat from the cable can vary greatly from day to day. It is argued by some (for example Martin *et al.* [12]) that a suitable guide to the drying of a soil near a cable is therefore best given in terms of drying time. A particular soil near a particular cable is defined as being thermally stable if its drying time under some specified maximum thermal stress is less than a fixed number of days (the typical time between rainfall may be applicable [12]). Since drying time varies with the initial moisture content of the soil and the heat flux at the surface of the cable, this leads to thermal design guides in which the important parameters in the prediction of drying are initial moisture content and the heat flux at the surface.

Hartley and Black [16] concluded from the results presented by Martin *et al.* [12] that the onset of drying does not correspond to a fixed surface temperature. Particular results were cited [16]. For Georgia clay soil at a moisture content of 0.145 by volume and a dry density of 1360 kg m^{-3}, the onset of drying corresponds to a surface temperature of 32°C for a surface heat dissipation rate of 10 W m^{-1} and 65°C for 50 W m^{-1}. This is not evidence against there being a critical temperature difference. Critical temperature difference is not the spatial temperature difference at the onset of drying. It is the minimum difference under which, if it is sustained long enough, drying can be guaranteed to take place.

A guide to the thermal design of buried surfaces is not being developed here. However, a few things can be concluded about the role critical temperature difference would play in such a guide. Critical temperature difference is a property of soil. It is a measure of the susceptibility of soil to drying and would be useful for comparing backfill soils to be placed near surfaces. For surfaces heated steadily, critical temperature difference is likely to be the most important parameter in the prediction of drying: it gives directly the spatial temperature difference which if exceeded within a sample of soil will be guaranteed to cause drying. For surfaces dissipating heat at a rate which varies with time, practical design guides may be based on drying time. These will incorporate (implicitly or explicitly) the spatial temperature difference a soil can sustain (without drying) for a specified time. Except for naturally dry soil, this difference is likely to be greater than the soil's critical temperature difference; how much greater it is will depend on the specified drying time.

Equation (6) gives the relationship between critical temperature difference and other soil properties: dry moisture content, field capacity, and the ratio of isothermal moisture diffusivity to thermal moisture diffusivity. The relation between susceptibility to drying and the ratio of the moisture diffusivities can be deduced from the equation: the lower the average ratio of the moisture diffusivities (averaged, that is, over the range of moisture content between the dry moisture content and the field capacity) the lower is the critical temperature difference and the greater the susceptibility to drying.

Equation (6) could be used in the calculation of a soil's critical temperature difference from measured values of other properties. In practice, however, this is not a good approach: the ratio of the moisture diffusivities is difficult to establish over the complete range of moisture content and there is no information on which to base the choice of the value taken for the dry moisture content. A better approach to the determination of a soil's critical temperature difference is direct measurement using temperature measuring equipment.

MEASURING CRITICAL TEMPERATURE DIFFERENCE

It is proposed that the critical temperature difference of a soil can be measured provided a suitable sample of the soil can be isolated or created in the laboratory. It has been shown that critical temperature difference is the temperature difference between two particular points on any steady heat flow path; at one point the local moisture content is the dry moisture content and at the other the local moisture content is the field capacity. The points mark the bounds of regions of moist soil; a suitable design of a laboratory experiment for the measurement of critical temperature difference is therefore one in which a full moist region is sustained under steady conditions and the temperature difference across the moist region can be measured along a heat flow path. It can be seen that this design does not directly constrain the choice of shape or size of the warm surface, the surface heating pattern (over time), the magnitude of surface temperature or heat flux, or the extent of drying that has taken place. However, steady heating (for example, surface heating at constant temperature or heat flux) will be required if moisture hysteresis effects are to be avoided; and any other choice made must be such that the extent of the moist region is detectable and the temperature difference across the region can be measured accurately.

Reports on laboratory experiments in which soil was heated have been reviewed [1]. Three types of experimental configuration were identified: soil in a container with two parallel plain ends, one of which is heated; soil packed around a heated cylinder; and soil packed around a heated sphere. The choice made for a study on the rate at which unsaturated sand dries near a warm cylinder [1] was a cylinder within cylinder configuration: soil was placed in the annular region between a warm cylindrical rod and a large diameter cylindrical container. The plain ends of the container were thermally insulated. Such a configuration is also suitable for the measurement of critical temperature difference: the heat flow paths are known—measurements of temperature taken along a radial at the longitudinal centre of the soil sample will be measurements taken along a heat flow path. The least appropriate experimental configuration is soil within a container with two parallel plain ends, one of which is heated; with such experiments heat flow paths are often distorted as some heat leaks through the (adiabatic) walls of the sample container [1].

In the introduction to this paper it was noted that dry soil has a lower effective thermal conductivity than moist soil; this, it was said, will lead to significant changes in heat flow when soil dries near a warm surface. It is these changes in the heat flow from the surface which are of interest to design engineers and not the moisture content distributions in the dry and moist soil; experimentally, it is therefore most appropriate to study drying by looking only at its influence on temperature distribution.

This approach has been followed successfully in the study of non-steady conditions [1]. Under conditions in which the radial heat dissipation rate (Q) varies little with radius, by Fourier's law the temperature distribution in the soil near a warm cylinder of radius a may be approximated by

$$\frac{\mathrm{d}T}{\mathrm{d}\ln(r/a)} = \frac{Q}{2\pi k(r)} \tag{8}$$

where k is the local effective thermal conductivity at radius r. From this equation it can be seen that the slope of a plot of temperature against $\ln(r/a)$ will be locally inversely proportional to effective thermal conductivity; dry regions will therefore be associated with steep slopes and moist regions with shallow slopes in such a plot. The dry region near the warm cylinder and the moist region beyond can be clearly seen in Fig. 1; in this plot of experimental data the boundary between the dry and moist regions is at the knee in the piecewise-linear curves.

For other soils there may not be such an obvious choice for the boundary between the regions of dry and moist soil. The boundary is the point where the local moisture content is the dry moisture content. If it is assumed that effective thermal conductivity is well approximated by a single valued function of moisture content, the boundary will have a unique value of effective thermal conductivity associated with it—the dry effective thermal conductivity. The position of the boundary may therefore be found directly from a temperature plot by finding the point where the slope corresponds to an effective thermal conductivity equal to the dry effective thermal conductivity. This approach is practicable for any type of soil.

No theoretical or experimental limitations have been set on the choice of dry effective thermal conductivity to be used in the determination of critical temperature difference; practical standards could be set at a fixed value (0.5 W m^{-1} K^{-1} for example) or as a fraction of the effective conductivity at saturation (0.3 for example). If (as in Fig. 1) there is a distinct knee in the temperature distribution. the measured value of critical temperature difference is insensitive to the choice of dry effective thermal conductivity: all

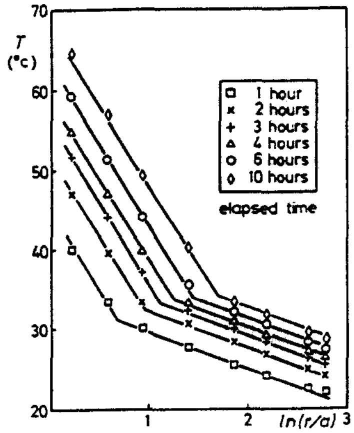

FIG. 1. Temperature in unsaturated medium sand near a 12.7 mm diameter heater emitting 53.8 W m^{-1}. Reproduced from ref. [1].

choices for dry effective thermal conductivity between the low effective thermal conductivity in the dry region ($0.42 \pm 1\%$ W m^{-1} K^{-1}, Fig. 1) and the high effective thermal conductivity in the moist region ($1.82 \pm 3\%$ W m^{-1} K^{-1}, Fig. 1) are associated with the knee.

The full moist region must be sustained in the laboratory experiment so the moisture content at the wall of the sample container must be the field capacity. In the non-steady experiments [1], the field capacity was naturally maintained at the surface of the sample container as excess moisture drained under gravity. The drained water collected at the bottom of the sample container but did not detectably affect the radial temperature distribution. However, it would probably be better to fit a drain (kept at a liquid pressure a few kilopascals below atmospheric pressure) in an experimental rig designed specifically for the measurement of critical temperature difference. Water collecting in the drain during an experiment is a sign that natural drainage is taking place and a full moist region is developing. Steady conditions can be taken to have been reached when the temperature of the soil is changing by less than a given amount per day or water has stopped draining from the sample. On a plot of the steady temperature distribution, the boundary between dry and moist soil can be detected and the critical temperature difference of the soil taken as the difference in temperature between the boundary and the inside wall of the sample container.

No experiments have yet been run specifically to measure critical temperature difference. However, a value for the critical temperature difference of a uniform medium sand has been calculated from published experimental data. The sand is Garside grade 21; it is very susceptible to drying and is ideal for use as backfill around pipes carrying heat. It is easily compacted to a dry density of 1580 kg m^{-3} at which its field capacity is approximately 0.05 by volume and its dry moisture content 0.003 by volume (corresponding to a dry thermal conductivity of 0.42 W m^{-1} K^{-1}) [1].

When heated by a cylinder emitting 53.8 W m^{-1}, the boundary between the dry and moist soil was found (by digging part of the sample out of the sample container) to be at a radius of 94 mm. The radius of the sample container was 109.8 mm. The steady heating conditions correspond to those for the non-steady heating shown in Fig. 1. Assuming the effective thermal conductivity in the moist soil under steady conditions is the same as that under non-steady conditions (1.82 W m^{-1} K^{-1}) all the data necessary for the calculation of critical temperature difference are available. The data were inserted in equation (8) (integrated across the moist region) and the critical temperature difference of Garside grade 21 medium sand calculated as 0.7 K.

CONCLUSIONS

It has been shown that it is a sufficient condition for drained unsaturated soil near a warm impermeable surface of any shape or size to dry if a temperature difference greater than the soil's critical temperature difference is maintained between any two points in the soil.

Steady moisture transfer in the soil was assumed to be well described by the model of Philip and de Vries [6]

$$D_\theta \nabla \theta + D_T \nabla T = 0 \tag{9}$$

where θ is the moisture content, T the temperature, and D_θ and D_T the isothermal and thermal moisture diffusivities, respectively. It was then shown that critical temperature difference (ΔT_c) is a temperature dependent soil property as it may be expressed as a function of soil properties, one of which is temperature dependent

$$\Delta T_c = \int_d^f \frac{D_\theta}{D_T} \, d\theta \tag{10}$$

where d and f are the dry moisture content and the field capacity of the soil, respectively. It is probable that critical temperature difference can be measured directly in the laboratory.

It is proposed that critical temperature difference is a measure of the susceptibility of soil to drying near warm impermeable surfaces; and comparisons of the susceptibility of soils may be made by comparing their critical temperature differences.

Acknowledgements—Part of this work was completed while I was a member of the Solar Energy Unit at University College, Cardiff, and funded by grant GR/D/69976 from the Science and Engineering Research Council.

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SUSCEPTIBILITE AU SECHAGE D'UN SOL NON SATURE PRES DES SURFACES IMPERMEABLES CHAUDES

Résumé—Un sol drainé près de surfaces imperméables chaudes se réchauffe et peut sécher. A partir d'une étude théorique, on propose qu'une propriété du sol, la différence de température critique, soit une mesure de la susceptibilité du sol au séchage : près d'une surface de taille ou de forme quelconque, le séchage peut prendre place si une différence de température critique est maintenue entre deux points qualconques du sol. On discute d'un protocole expérimental pour mesurer la différence de température critique.

ANFÄLLIGKEIT UNGESÄTTIGTER ERDE GEGENÜBER AUSTROCKNUNG AN WARMEN UNDURCHLÄSSIGEN OBERFLÄCHEN

Zusammenfassung—Entwässerte Erde heizt sich an warmen undurchlässigen Oberflächen auf und kann austrocknen. Hier wird, auf einer theoretischen Untersuchung basierend, eine Eigenschaft der Erde, nämlich die kritische Temperaturdifferenz, als Maß für die Anfälligkeit von Erde gegenüber Austrocknung vorgeschlagen; an einer Oberfläche irgendeiner Form oder Größe setzt Austrocknung dann ein, wenn zwischen 2 beliebigen Punkten in der Erde eine Temperaturdifferenz auftritt, die größer als die kritische Temperaturdifferenz ist. Es wird der Entwurf eines Versuchs zur Messung der kritischen Temperaturdifferenz erörtert.

ПРОЦЕСС ВЫСЫХАНИЯ НЕ НАСЫЩЕННОЙ ЖИДКОСТЬЮ ПОЧВЫ ВБЛИЗИ ТЕПЛЫХ НЕПРОНИЦАЕМЫХ ПОВЕРХНОСТЕЙ

Аннотация—Почва, осушаемая вблизи теплых непроницаемых поверхностей, нагревается, и может произойти ее высыхание. На основе теоретического исслеования сделано предположение, что мерой восприимчивости почвы к высыханию является такая ее характеристика, как критическая разность температур; высыхание вблизи поверхности любой формы и размера произойдет в том случае, если между двумя произовольными точками в почве будет поддерживаться разность температур, превышающая критическую. Обсуждается постановка опыта для измерения критической разности температур.