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A THEORETICAL APPROACH FOR EVALUATING EVAPORATIVE FLUXES FROM UNSATURATED SOIL SURFACES IN GEOTECHNICAL ENGINEERING

G.W. Wilson, D.G. Fredlund, S.L. Barbour

Unsaturated Soils Group, Department of Civil Engineering
University of Saskatchewan. Saskatoon, Saskatchewan

ABSTRACT

Evaluation of the flux boundary condition at the soil-atmosphere boundary is an essential component in the analysis of many problems in geotechnical engineering. For example, the analysis of pore-water pressures for slope stability analysis, and the prediction of volume change in expansive soils requires accurate prediction of moisture fluxes between the soil surface and the atmosphere. The flow of water across the ground surface is also important for problems in geo-environmental engineering such as the design of soil cover systems for waste management facilities.

The flow of water across the soil-atmosphere boundary occurs as two separate processes. Liquid water due to precipitation enters the soil below the ground surface through the process of infiltration. Alternately, water vapour leaves the ground surface through the process of evaporation. The physics of liquid flow during infiltration has been widely discussed in the literature and many suitable methods of analysis are available. However, the physical processes which govern evaporation from soil surfaces are poorly understood. Extreme difficulties are encountered when attempting to predict evaporation from unsaturated soil surfaces.

This paper presents a theoretical model for predicting the rate of evaporation from unsaturated soil surfaces. The theory is founded on the well-known principles of Darcy's Law and Fick's Law to describe the flow of liquid water and water vapour in the soil below the soil-atmosphere boundary. Dalton's Law and a modified Penman formulation are used to describe water vapour transfer above the soil-atmosphere boundary.

A column evaporation test was carried out in the laboratory. The laboratory test results show that evaporative fluxes from a soil surface are controlled by the soil suction at and below the soil-atmosphere boundary. Furthermore, soil evaporative fluxes are also strongly dependent on groundwater conditions and the flow properties of the soil.

The theoretical model for soil evaporation was used to simulate the evaporative fluxes measured from the soil columns during the laboratory evaporation test. The theoretical model provided good agreement with the evaporative fluxes measured in the laboratory over the 6-week period of the test.

INTRODUCTION

The exchange of water between the atmosphere and soil surface is an important component of the hydrologic cycle. Water enters and leaves the soil surface through the processes of infiltration and evaporation (and evapotranspiration). Predicting the actual rate of the flow of water across the soil-atmosphere boundary is an important issue for many problems. Hydrologists and agricultural scientists have great historical interest in this subject. However, geotechnical engineers are increasingly required to address flux boundary problems for many analytical and practical problems.

The evaluation of the flux boundary condition with respect to moisture flow across the soil-atmosphere boundary is paramount for numerous problems in geotechnical engineering. These problems may be classified into two general groups; namely, soil behavior analysis and groundwater analysis.

The flow of water across the soil surface is important for problems in soil behavior and classical soil mechanics. Expansive soils occur in many areas of the world. Shallow foundations and pavement structures frequently experience extensive heave and/or settlement depending on changes in climatic conditions (Sattler and Fredlund, 1991; Silvestri et al., 1990). Furthermore, the bearing capacity of pavement structures depends on pore-water pressures and values of matric suction (Oloo, 1994). The stability of natural and man-made slopes also depends on pore-water pressures along the slip surface. Ng (1988) showed the factor of safety of a potential slip surface to be strongly dependent on the flux boundary condition with respect to water flow across the surface of the slope. In summary, an accurate prediction of the flow of water across the soil-atmosphere boundary is essential for many problems in classical geotechnical engineering.

Problems in groundwater analysis occur at both a regional and local level. For example, the recharge of groundwater to a large aquifer depends on the net flow of water across the soil-atmosphere boundary at a regional scale (Freeze and Cherry, 1979). Alternately, the local flow of water through the soil cover at a hazardous waste site controls the rate at which water flows through the waste fill and contaminates the local groundwater system (Healy, 1989). The performance of soil covers with respect to soil-atmosphere moisture flow is also important when the cover is designed as an oxygen barrier for long-term closure of sulphitic mine tailings (Collin and Rasmuson, 1990).

The exchange of moisture across the soil-atmosphere boundary occurs through two primary processes. Water enters the soil surface as liquid through the process of infiltration. Alternately, water exfiltrates from the soil surface as vapour through the processes of evaporation and evapotranspiration. The mechanics of flow governing infiltration are reasonably well understood and widely discussed in the literature (Horton, 1933; Philip and de Vries, 1957; Freeze 1969; Freeze and Banner, 1970; Dunin, 1976; Eagleson, 1978; and Milly 1986). In contrast, the processes which control exfiltration are not well understood. The ability of engineers to predict evaporative fluxes from a free water or saturated surface such as a lake or an irrigated field is in most cases quite satisfactory. However, extreme difficulties are encountered for unsaturated soil surfaces. This presents a serious obstacle in the analysis of many problems in geotechnical engineering. For example, in areas such as western Canada, fully saturated conditions occur only for a brief period of time following precipitation events. The flux boundary condition at the ground surface is generally dominated by evaporation from an unsaturated soil surface. Conventional methods of predicting evaporation and evapotranspiration from saturated surfaces are not suitable for unsaturated surfaces and often over-estimate actual evaporation.

POTENTIAL AND ACTUAL EVAPORATION

The widely used terms "Potential Evaporation" and "Potential Evapotranspiration" have been in use by hydrologists and engineers for more than 40 years (Thornthwaite, 1948; Penman, 1948). The International Glossary of Hydrology WMO (1974) defines potential evaporation as: "The quantity of water vapour which could be emitted by a surface of pure water per unit surface area and unit time under the existing atmosphere conditions". In simple terms, potential evaporation determines the upper limit or the maximum possible rate of evaporation.

The actual rate of evaporation from a soil surface depends on the availability of water (Thornthwaite, 1948; Penman, 1948; Holmes, 1961; Bouchet, 1963; Priestley and Taylor, 1972; Brutsaert, 1982; and Morton; 1985). The maximum potential rate occurs only when the soil surface is fully saturated and water is present on the ground surface. The actual rate of evaporation begins to decline once the soil surface becomes unsaturated. The rate of evaporation continues to decline as the soil surface continues to desiccate. Hillel (1980) showed typical curves for evaporation rates versus drying time for soil (Figure 1).

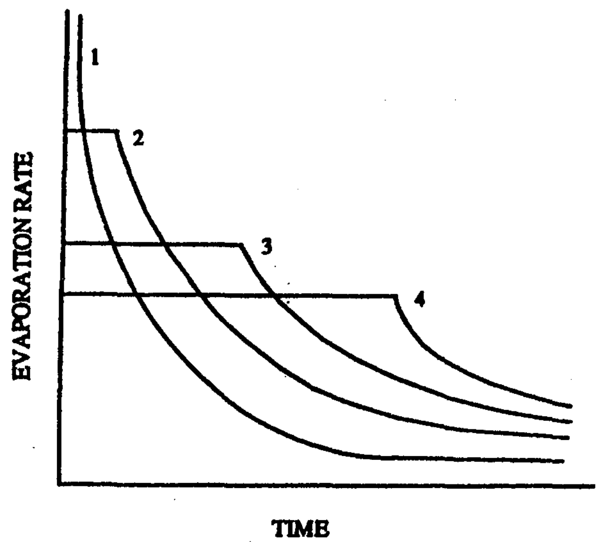

Figure 1 Typical Curves for Evaporation Versus Time for Soil. (after Hillel, 1980)

The different initial upper limits for each curve represent the maximum potential rates under various climatic conditions. For example, curve No. 2 is the measured evaporation rate from an initially saturated soil surface in a hot arid climate. Curve No. 4 is the measured rate of evaporation from an identical soil surface in a cool, moist climate. All curves show the actual rate of evaporation suddenly drops below the upper potential rate after some period of drying. These breaks in the evaporation rates indicate the transition of the soil surfaces from saturated to unsaturated conditions.

METHODS OF PREDICTING EVAPORATION

The potential rate of evaporation as described above may be computed using the simple mass transfer equation (Gray, 1970) as follows:

$$E = f(u)\,(P_{sv} - P_a) \qquad [1]$$

where:

E = vertical evaporative flux in mm/day.

$f(u)$ = a function dependent on wind speed, surface roughness and eddy diffusion.

P_{sv} = vapour pressure of the saturated evaporating surface.

P_a = the vapour pressure in the air above the evaporating surface.

This simple mass transfer approach is widely accepted and has deep historical roots which extend back to Dalton during the nineteenth century (Gray, 1970; Rosenberg et al., 1983). In general terms, the evaporative flux is a function of the vapour pressure gradient between the saturated surface and the overlying air. The vapour pressure at the surface is known if the surface is saturated and its temperature is known. The vapour pressure in the air is determined on the basis of air temperature and relative humidity. The function, f(u), may be evaluated on the basis of turbulent mixing theory or by using empirical relationships. The mass transfer approach has been applied to free-water surfaces, bare soil and vegetated surfaces (Conaway and van Bavel, 1967; Brutsaert, 1982; and Rosenberg, et al., 1983).

Numerous other methods of evaluating evaporation may be found in the literature. Some of the most common methods are:

1. The Thornthwaite Method
2. The Penman Method
3. The Priestly-Taylor Model
4. The Complimentary Relationship

Thornthwaite (1948) proposed a method of estimating potential evapotranspiration as a guide for the classification of regional climates. The method is empirical and is based on mean monthly air temperatures. The method has been used frequently over the years simply because it does not require detailed and sophisticated data. In general, the Thornthwaite method has proven satisfactory for some applications (Sattler, 1989).

Penman (1948) developed a method of calculating potential evaporation through the simultaneous combination of the mass transfer equation with the energy budget at the soil surface. The equation presented by Penman (1948) is written as follows:

$$E = \frac{\Gamma Q + vE_a}{\Gamma + v} \qquad [2]$$

where:

E = potential evaporation per unit time, in mm/day.

E_a = $f(u)\,(P_{sa} - P_a)$.

P_{sa} = saturation vapour pressure of the mean air temperature, usually mm-Hg.

$f(u)$ = $0.35\,[1 + u_a\,(0.146)]$

u_a = wind speed, km/hr.

Q = heat budget or all net radiation, Qn, mm/day.

Γ = slope of the saturation vapour pressure versus temperature curve at the mean temperature of the air.

v = psychometric constant.

The Penman Method of calculating potential evaporation has become the most popular and widely adopted combination approach (Rosenberg et al, 1983). The Penman Method requires only routine weather parameters such as relative humidity, air temperature and wind velocity. The energy budget may be estimated on the basis of solar radiation charts and empirical formula. The Penman formulation is most correctly applied to open water surfaces. Penman (1948), however, extended the method to include ground surfaces such as bare soil and turf (grass).

Priestley and Taylor (1972) provided a method of calculating potential evapotranspiration on the basis of the combined latent and sensible heat fluxes. In other words, potential evapotranspiration is evaluated solely on the basis of available energy. The Priestley-Taylor (1972) formula is written as follows:

$$ET_p = \alpha \frac{\Gamma}{\Gamma + v}(Q_e + Q_h) = \alpha \frac{\Gamma}{\Gamma + v}(Q_n + Q_g) \qquad [3]$$

where:

ET_p = potential evaporation, mm/day.

Q_e = latent heat flux, mm/day.

Q_h = sensible heat flux, mm/day.

Q_n = all net radiation, mm/day.

Q_g = subsurface heat flux, mm/day.

α = an empirical constant

This method has been found to give reasonable estimates of evaporation in humid regions but has not been widely tested in arid regions (Rosenberg et al., 1983).

All the methods of estimating evaporation or evapotranspiration discussed thus far provide an estimate of potential evapotranspiration or the maximum possible rate of evaporation. The availability of water to the evaporating ground surface is assumed unlimited. However, the actual rate of evaporation falls below the maximum potential rate once the ground surface becomes unsaturated. Figure 2 shows how both the Priestley-Taylor Model and the Penman Method overestimate actual evaporation from an unsaturated soil surface. The Penman Method in particular, often over-estimates actual evapotranspiration when applied to dry regions (Morton, 1975, 1985).

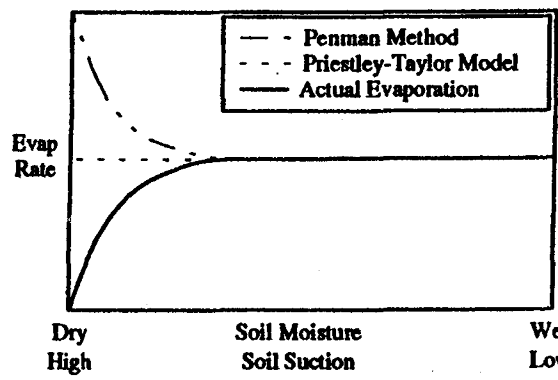

Figure 2 Comparison of Potential Evaporation to Actual Evaporation from an Unsaturated Soil Surface.

The actual rate of evapotranspiration may be estimated by the complementary relationship proposed by Bouchet (1963). The relationship is based on what Brutsaert (1982) described as "heuristic arguments" since the fundamental assumptions and principles are difficult to verify. In simple terms however, the complementary relationship states that there is a relationship between potential evapotranspiration and actual regional evapotranspirations which may be written as follows:

$$ETP + ETR = 2ETP_O \qquad [4]$$

where:

ETP = potential evapotranspiration which would occur under the given atmospheric conditions if available energy is the only limiting factor.

ETR = actual evapotranspiration within the region, having a characteristic scale in the order of 1 to 10 m

ETP_O = rate of evapotranspiration when the actual regional evapotranspiration is equal to the potential evapotranspiration (i.e., a wet environment).

In general, the complementary relationship shown in equation 4 may be evaluated by setting ETP equal to the potential rate given by the Penman Method and ETP_O equal to the potential rate computed using the Priestly-Taylor formula. Hence, the calculation of the actual evapotranspiration, ETR, becomes elementary. Brutsaert and Stricker (1979) and Morton (1982) have found there to be a good correlation between the actual regional evapotranspiration, ETR, computed using the complementary relationship and actual measured values determined on the basis of measured energy and water budgets. In spite of the apparent theoretical deficiencies which may be identified, the complementary relationship may be considered useful from an empirical point of view.

All of the most common methods described for the evaluation of potential or actual evaporation, are suitable for some applications. Indeed, the engineering community has been relying on and applying these methods for a number of decades. However, none of these methods permit the calculation of an actual evaporation rate versus time curve such as those shown in Figure 1. The fundamental assumption which is required for the application of any of the previous methods is that the soil at the ground surface is saturated. In other words, the relative humidity of the soil surface is assumed to be 100 percent. The calculation of the actual evaporation rate of an unsaturated surface is much more difficult because the relative humidity is less than unity. The analysis actually becomes indeterminate since there are more unknowns than unique equations. The solution to this problem requires the availability of more physical relationships to render the calculation determinant.

The solution to the problem of indeterminacy for calculating actual evaporation from an unsaturated ground surface, can be resolved by introducing relationships which describe the properties or characteristics of the soil at ground surface. The soil surface and microclimate above the soil-atmosphere boundary function as a coupled system. The response of the soil surface to the atmosphere depends not only on the climatic conditions but also on its own properties such as soil water potential, vegetation type, subsurface water availability, soil texture, hydraulic conductivity and porosity. The flow of water from an evaporating unsaturated soil surface using a coupled soil-atmosphere approach will subsequently be discussed.

COLUMN EVAPORATION TEST

A column evaporation test was conducted under controlled laboratory conditions to observe the process of evaporation from a soil surface. Two identical columns of soil, approximately 170 mm in diameter and 300 mm in height, were installed in an environmentally controlled chamber. The columns were filled with a saturated, fine, uniform, aeolian sand and placed on electronic scales. The actual rate of evaporation was determined by the change in column mass on a continuous basis. Figure 3 shows the laboratory apparatus for the column drying test which is described in more detail by Wilson (1990).

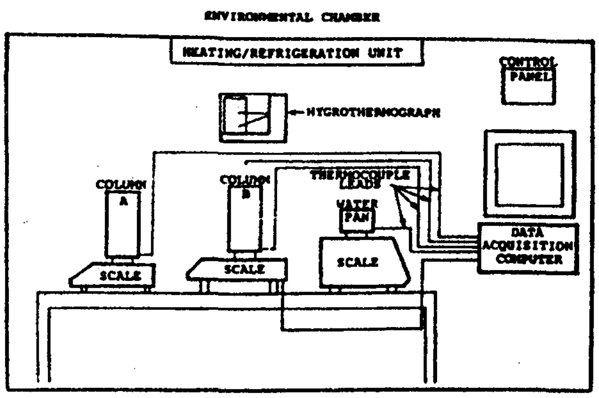

Figure 3 Column Evaporation Test Apparatus.

The vertical walls and base of the columns were constructed using high density PVC plastic to restrict moisture migration. The columns were filled to the top with sand and leveled to form a flat, uniform, evaporative surface. A pan of water with identical surface geometry, diameter and area as the sand surfaces was installed adjacent to the columns as a control to establish the potential evaporation rate. The temperature within the environmental chamber was maintained at a constant value of 40°C with a low relative humidity of approximately 10 percent. This resulted in a nearly constant potential evaporation rate of approximately 8 mm/day which is typical for the Saskatoon area during the mid-summer period.

Both sand columns were identical and were tested simultaneously. The sand surfaces and the underlying profiles were at or near the state of saturation at the start of the evaporation test. The change in moisture content of the sand surfaces and down the vertical profiles of the columns were monitored on a regular basis. Small sand samples were retrieved as described by Wilson (1990) through sampling ports installed in the walls of the PVC columns. The evaporation test was conducted for a period of 42 days without interruption.

Figure 4, after Wilson (1990), shows the results of the evaporation test. The line identified as potential evaporation is the evaporation rate measured from the control evaporation pan. The measured rates of evaporation from both columns A and B are nearly identical which provides a good measure of assurance with respect to reproducibility and accuracy. The rate of evaporation from each column is approximately equal to the potential evaporation rate during the first 4 days of the test and then begins to decline rapidly.

The rate of evaporation from the initially saturated sand surfaces should be the same as that for the free water surface. However, the difference in the thermal conductivity between the sand and the water caused a slightly lower vapour pressure for the saturated sand surfaces compared to the water

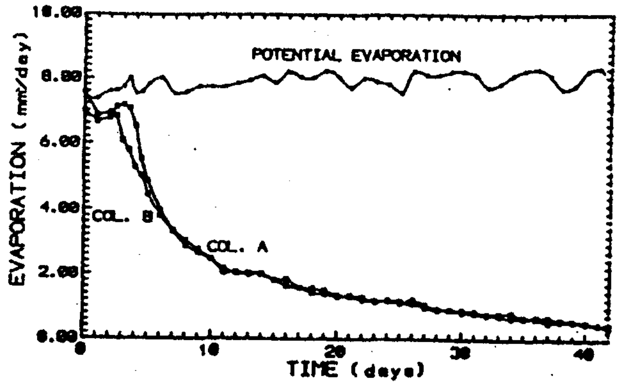

Figure 4 Observed Potential and Actual Evaporation Rates Versus Time for the Water Filled Evaporation Pan and Columns A and B.

surface resulting in a slightly depressed potential evaporation rate.

The rate of evaporation from both sand columns suddenly declines after approximately 4 days of drying. The actual rate of evaporation falls rapidly between days 4 and 11 and continues to decrease over the remaining 31 days, however, at a slower rate. It is interesting to note that the observed patterns of evaporation from the soil surfaces were similar to the typical curves shown in Figure 1 after Hillel (1980). Figure 5 shows the measured water content profiles in columns A and B over the 42 day test. The sand surfaces were visually wet during the period of high rate or potential evaporation. Measured water contents were below the saturation level but were still within a range which would be described as moist to wet. In general terms, the saturated water content of the sand was approximately 23 percent. The sand maintained a wet to very wet consistency with water contents between 10 and 23 percent and remained moist for water contents well below 10 percent. The sand did not appear dry until the water content fell below approximately 2 percent. The sudden decline in the evaporation rate corresponds to the time at which the sand surfaces became visually dry.

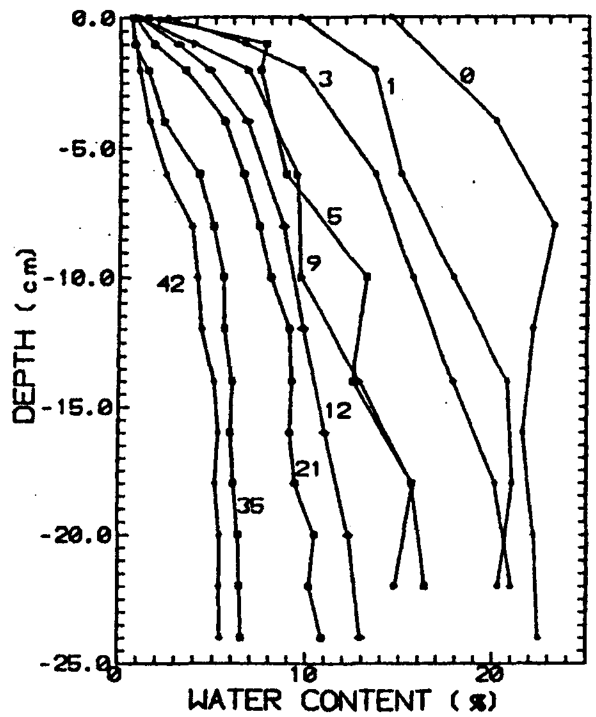

Figure 5 Measured Water Content Versus Depth in the Columns after 0, 1, 3, 5, 9, 12, 21, 35, and 42 Days of Evaporation.

A thin dry skin of sand with a gravimetric water content of less than 2 percent formed on both sand surfaces after 4 days of drying. However, the sand immediately below the dry skin remained quite moist. For example, Figure 5 shows the water content to be approximately 2 percent at the surface and 6 percent just 1 cm below the surface on day 5 of the evaporation test. The thickness of the dry layer increased as the evaporation test continued. The measured evaporation rate continued to decline as the thickness of the drying front increased. After 4 weeks of evaporation, the surficial moisture content decreased to less than 1 percent and the drying front had advanced to a depth of 2 cm. The evaporation rate on day 28 was approximately 1 mm/day compared to the initial potential rate of 8 mm/day. The evaporation rate continued to decrease to less than 0.4 mm/day after 42 days of continuous drying. As well, the drying front had advanced to a depth of 8 cm by the end of the evaporation test.

THE SOIL-ATMOSPHERE FLUX BOUNDARY MODEL

A theoretical soil-atmosphere flux model for predicting the rate of evaporation from saturated and unsaturated soil surfaces was developed by Wilson (1990). The model computes the moisture flux across the soil-atmosphere boundary using a coupled system of equations which describe heat and mass transfer in a porous soil media. The equations for the transfer processes in the soil are as follows:

For mass flux,

$$\frac{\partial h_w}{\partial t} = c_w^1 \frac{\partial}{\partial y}\left(k_w \frac{\partial h_w}{\partial y}\right) + c_w^2 \frac{\partial}{\partial y}\left(D_v \frac{\partial P_v}{\partial y}\right) \quad [5]$$

where:

h_w = total hydraulic head, m.

P_v = the partial pressure due to water vapour, kPa.

k_w = the coefficient of permeability as a function of matric suction, m/sec.

D_v = the diffusion coefficient of the water vapour through the soil, kg•m/kN/sec.

c_w^1 = the coefficient of consolidation with respect to the water phase, $\frac{1}{\gamma_w m_2^w}$

c_w^2 = the coefficient of consolidation with respect to the water vapour phase, $\frac{P+P_v}{P}\frac{1}{\rho_w \gamma_w m_2^w}$

m_2^w = the slope of the moisture retention curve, 1/kPa.

γ_w = unit weight and mass density of water, kN/m^3.

ρ_w = mass density of water, kg/m^3.

P = total gas pressure in the air phase, kPa.

t = time

For heat flux,

$$C_v \rho_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) - L_v\left(\frac{P+P_v}{P}\right)\frac{\partial}{\partial y}\left(D_v \frac{\partial P_v}{\partial y}\right) \quad [6]$$

where:

T = temperature, °C.

$C_v \rho_s$ = volumetric specific heat of the soil as a function of water content, J/m^3/°C.

λ = thermal conductivity of the soil as a function of water content, W/m/°C.

L_v = latent heat of vapourization of water, J/kg.

Equation 5 was developed on the basis of Darcy's Law and Fick's Law to describe the transfer of liquid water and water vapour respectively (Wilson, 1990). The variables of hydraulic head and vapour pressure in Equation 5 are related to one another by assuming the Gibbs Free Energy of the two phases are in equilibrium. Equations 5 and 6 are similar to those proposed by Dakshanamurthy and Fredlund (1981) for describing heat and mass transfer in porous media. A source term, S, may be included in Equation 5 to account for the uptake of water by roots should the soil surface be vegetated.

The evaporative flux in the soil-atmosphere model is computed by combining Equation 1 for mass transfer in the atmosphere with Equations 5 and 6 and solving all three equations simultaneously. More specifically, the term for vapour pressure at the soil surface, P_V, is common to all three equations (i.e., P_V replaces P_{SV} in Equation 1).

MODEL SIMULATIONS AND THE MECHANISM OF EVAPORATION FROM SOIL

Evaporative fluxes from the sand columns were calculated using the soil-atmosphere flux boundary model. The material coefficients for Equations 5 and 6 such as, k_W, c^1_w, c^2_w, etc., were evaluated on the basis of the soil-water characteristic curve for the sand shown in Figure 6.

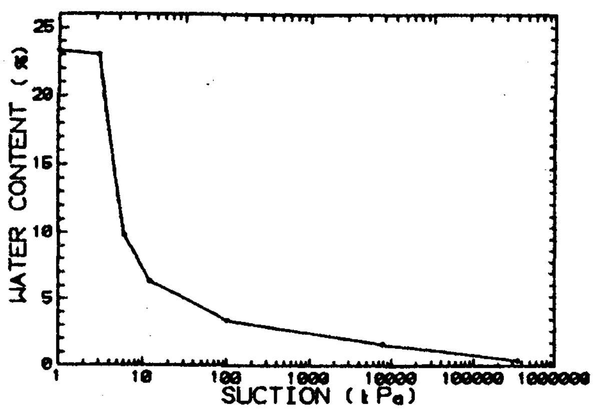

Figure 6 Soil-water Characteristic Curve for the Sand.

The relationship between the coefficient of permeability, kw, and the matric suction for the sand was evaluated using the method described by Laliberte et al (1968) and is shown in Figure 7. The thermal conductivity and volumetric specific heat of the sand were computed using the method described by de Vries (1963).

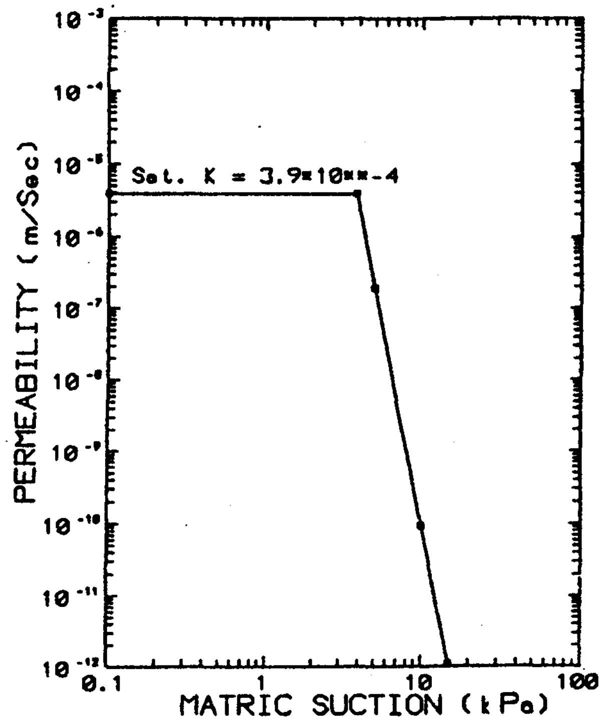

Figure 7 The Coefficient of Permeability Versus Matric Suction for the Sand.

The results of the model simulation are shown in Figure 8. The evaporative flux computed by the soil-atmosphere flux model compares well with the measured fluxes from both columns A and B. The model computed a similar period of high rate or potential evaporation of approximately 7 mm/day with a sudden decline occurring after 4 days. The computed rate of evaporation continues to fall similar to the measured rates and falls to the same slow residual rate of 0.4 mm/day after 42 days.

Figure 9 shows the measured and computed water contents for the columns after 0, 1, 5, 21, and 42 days of evaporation. The computed water contents compare well to the measured water contents. The model simulation also indicates that a thin dry skin with a low water content below 2 percent develops after 5 days. The computed water content of the soil below this dry layer is considerably wetter. The thickness of the dry layer continues to increase with time which corresponds to the progressive decline in the computed evaporation rate. The computed drying front advances to approximately 10 cm after 42 days similar to the measured drying front of 8 cm.

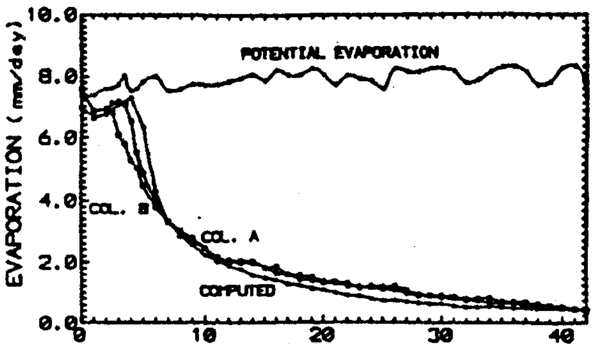

Figure 8 Computed and Measured Rates of Evaporation for the Column Evaporation Test.

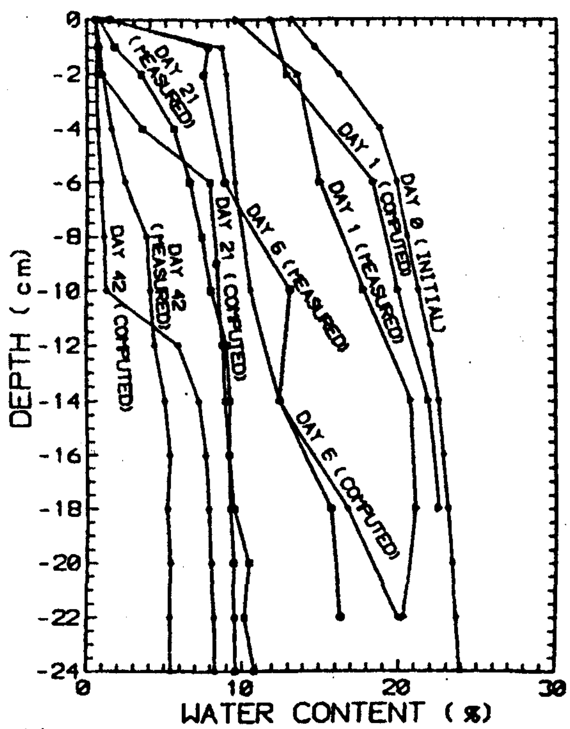

Figure 9 Computed and Measured Water Contents Versus Depth for the Columns after 1, 5, 21, and 42 Days of Evaporation.

The turbulent mixing parameter, f(u), in Equation 1 used in the model simulation was determined on the basis of the measured rate of evaporation from the free water surface in the control pan. The calculation of this term was simple since all the other terms were measured or calculated directly. For example, E equals the measured potential evaporation, P_{SV} equals the saturated vapour pressure of the free water surface at the measured temperature during the test and P_a equals the vapour pressure in the environmental chamber computed on the basis of the measured relative humidity and temperature of the air. The calculated value of f(u) is substituted along with the vapour pressure, P_a, in the chamber into Equation 5 for computing the evaporative flux from the sand columns. The only variable which changes when computing the evaporation rate from the sand compared to the free water surface evaporation rate is the surface vapour pressure, P_V. The vapour pressure of the water remains constant at the saturated value (i.e., relative humidity of 100 percent). The vapour pressure of the sand surface is initially equal to the saturated value; however, it falls below this value once the water content of the sand decreases sufficiently. The decline in vapour pressure of the sand surface results in the decreased rate of evaporation.

The vapour pressure in the sand was calculated on the basis of the total suction and the Gibbs Free Energy using the relationship proposed by Edlefsen and Anderson (1943) as follows:

$$P_V = P_{SV} \cdot h_r \qquad [7]$$

where:

P_v = the actual vapour pressure within the soil.

P_{sv} = the saturation vapour pressure of the soil water at its temperature, T.

h_r = relative humidity as a function of total suction and temperature,

$$= \frac{\Psi g W_v}{e^{RT}}$$

Ψ = total suction in the soil, m.

W_v = molecular weight of water, 0.18 kg/mole.

R = universal gas constant, 8.314 J/mole•K.

T = absolute temperature, °K.

g = acceleration due to gravity, m/sec^2.

Figure 10 shows the relationship between relative humidity and total suction as given by Equation 7. The relative humidity remains high at approximately 100 percent for values of total suction less than about 1000 kPa. The soil-water characteristic curve in Figure 6 shows that the water content of the sand used in the evaporation test is approximately 2 percent at a suction of 3000 kPa. This corresponds to the water content of the sand surface at which the decline in measured and computed rates of actual evaporation were observed. From Figure 10 it is also shown that the relative humidity and vapour pressure falls rapidly once the total suction exceeds 5000 kPa. An increase in total suction from 3000 kPa to 5000 kPa corresponds to a slight decrease in the water content of the sand from 2.0 to 1.8 percent. This explains the rapid decline in evaporation rate once the water content of the sand surface decreased below 2 percent. The measured and computed rates of evaporation continued to decrease during the test as the surfaces of the sand became progressively drier.

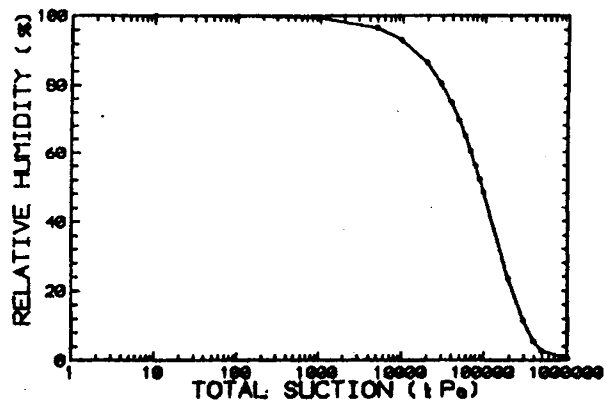

Figure 10 Relative Humidity Versus Total Suction in the Air Phase of Unsaturated Soil.

The lowest rate of evaporation occurred at the end of the test when the sand surface was essentially dry. The measured and computed water contents of the sand surfaces of the columns were approximately 0.6 percent on day 42 of the test. This corresponded to a total suction of about 200,000 kPa and a relative humidity of only 20 percent. The reduction in the actual and computed evaporation rates from the sand surfaces occurred as a function of increasing total suction in the pore-water of the sand surface.

In summary, the rate of evaporation from the sand surface is approximately equal to the potential rate of evaporation provided the total suction at the sand surface is less than 1000 kPa. The evaporation rate is rapidly suppressed once the total suction exceeds 3000 to 5000 kPa. Extremely high suctions (i.e., 200,000 kPa) developed at the sand surface as the drying continued. In the case of the column drying tests, the actual and computed rates of evaporation decreased from the high potential rate of approximately 7 mm/day to

0.4 mm/day as a result of the development of high total suctions at the sand surface.

A MODIFIED PENMAN FORMULATION

The soil-atmosphere model developed for the simulation of the column drying test is not suitable for application to practical problems in nature. The computation of the evaporative flux from a soil surface using Equation 1 requires the evaluation of the parameter, f(u). This was straight forward in the case of the column test because it was possible to use the control evaporation pan. Detailed information regarding surface roughness, wind speed and atmospheric stability are required in order to evaluate f(u) for a field problem. An even more serious difficulty occurs because the surface temperature must be known in order to apply Equation 1. Gray (1970) states this is an extremely difficult parameter to determine for actual field problems.

The method proposed by Penman (1948) overcomes the problem of evaluating surface temperature by combining Equation 1 with the energy balance at the ground. Penman (1948) formulated his approach for the evaluation of potential evaporation from saturated surfaces. However, the formulation may be extended to unsaturated surfaces if the vapour pressure or relative humidity of the surface is known (Wilson, 1990).

Wilson (1990) provides a modified Penman formulation which may be applied to evaporation from unsaturated soil surfaces as follows:

$$E = \frac{\Gamma Q + vE_a}{\Gamma + Av} \qquad [8]$$

where:

E_a = f(u) Pa (B - A)

B = the inverse of the relative humidity of the air

$A = \frac{1}{h_r}$

h_r = relative humidity at the soil surface, Eq. 7

Equation 8 can be incorporated into the soil-atmosphere model for simulating evaporative fluxes in actual field problems. Gray (1970) presents an example calculation of potential evaporation from a saturated surface for Saskatoon, Saskatchewan in July. A potential rate of evaporation was equal to 7.7 mm/day based on typical climatic data. Wilson (1990) used the modified Penman Method to compute evaporative fluxes from the soil surface assuming the same soil properties as the sand used in the column drying test and the identical climatic conditions used by Gray (1970).

Figure 11 shows the results of the soil-atmosphere model simulations using the modified Penman formulation. Simulations were carried out with the water table at various depths below the surface. Curve No. 1 shows the evaporation rate with the water table positioned just below the soil surface. The high potential rate of evaporation of 7.7 mm/day was constantly maintained for the entire 10 days of the simulation. This occurred because the phreatic surface was sufficiently close to the ground surface to maintain low suctions and near saturated conditions at the soil surface. Curve No. 2 shows the effect of lowering the water table to 0.75 m below the surface. In this simulation, the initially saturated sand surface quickly desaturates and surface suctions increase resulting in a decrease in the evaporation rate from 7.7 mm/day to 2.1 mm/day. Upward flow from the water table is insufficient to maintain the high evaporative flux from the surface. Lowering the water to 1.0 m below the surface reduces the evaporative flux further to approximately 0.4 mm/day, 10 days after initial saturation as shown by curve No. 3.

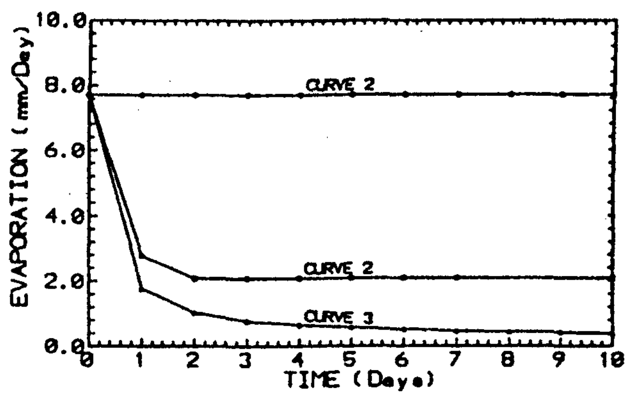

Figure 11 Evaporation Rate Versus Time Using the Modified Penman Formulation with the Water Table 0.5 m (Curve 1), 0.75 m (Curve 2), and 1.0 m (Curve 3) below the Surface of the Sand.

Large values of total suction were computed at, and near the sand surface for the simulations with the water table 0.75 m and 1.00 m below the surface. A drying front developed at the surface and the thickness of the drying front controlled the evaporative flux. The computed water content of the sand became so low that the coefficient of permeability with respect to the water phase approached zero.

In general terms, when large values of total suction exist at a soil surface and a drying front develops, the liquid water phase becomes discontinuous, if not absent. The upward flux of water from the water table proceeds only a short distance as liquid in the unsaturated porous media and then changes phase to water vapour. Vapour diffusion through the surficial dry soil layer at the ground surface becomes the dominate process which controls evaporation from the dry, unsaturated soil surface.

SUMMARY AND CONCLUSIONS

The results of the column evaporation test show that the rate of evaporation from a soil surface depends on the availability of water. The rate of evaporation from the saturated sand surface is approximately equal to the potential evaporation rate from a free-water surface. The actual rate of evaporation declines as the sand surface becomes unsaturated and as the total suction exceeds approximately 3000 kPa. Evaporative fluxes from the soil surface are dependent on total suction and decrease as suctions increase. In addition to total suction values at the ground surface, long-term evaporation rates depend on groundwater levels and the flow properties of the soil beneath the surface.

The proposed soil-atmosphere flux boundary model predicted actual evaporation from a desiccating column of sand reasonably well. The model can be extended for field applications using a modified Penman formulation. Model simulations show that groundwater levels are an important factor with respect to predicting actual evaporative fluxes.

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