

The effect of soil suction on evaporative fluxes from soil surfaces

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

Abstract: This paper presents a theoretical approach in which a Dalton-type mass transfer equation is used to predict the evaporative fluxes from nonvegetated soil surfaces. Soil evaporation tests were conducted in the laboratory on three different soil samples of Beaver Creek sand, Custom silt, and Regina clay. The soil surfaces were saturated and allowed to evaporate to a completely air-dried state. The actual evaporation rate for each soil surface was measured along with the potential evaporation rate for an adjacent water surface. The ratio of actual evaporation to potential evaporation or normalized soil evaporation was then evaluated with respect to drying time, soil-water content, and soil suction. The value of the normalized soil evaporation was found to be approximately equal to unity for all soils until the total suction in the soil surfaces reached approximately 3000 kPa. The rate of actual soil evaporation was observed to decline when the total suction exceeded 3000 kPa. A relationship between the actual evaporation rate and total suction was found to exist for all three soil types which appears to be unique and independent of soil texture, drying time, and water content.

Key words: actual evaporation, potential evaporation, soil suction.

Résumé : Cet article présente une approche théorique dans laquelle une équation de transfert de masse de type Dalton a été utilisée pour prédire les flux d'évaporation des surfaces de sol non couvertes de végétation. Des essais d'évaporation des sols ont été faits en laboratoire sur trois échantillons de sols différents, soit un sable de Beaver Creek, un silt Custom, et une argile de Regina. Les surfaces du sol ont été saturées et soumises à une évaporation jusqu'à un état de sécheresse complète à l'air. La vitesse réelle d'évaporation pour chaque surface de sol a été mesurée en même temps que la vitesse d'évaporation potentielle d'une surface d'eau adjacente. Le rapport de l'évaporation réelle sur l'évaporation potentielle, ou l'évaporation normalisée du sol, était alors évalué par rapport au temps de séchage, de la teneur en eau et de la succion du sol. L'on a trouvé que la valeur de l'évaporation normalisée du sol était approximativement égale à l'unité pour tous les sols jusqu'à ce que la succion totale dans les surfaces de sol atteignent approximativement 3000 kPa. L'on a observé que la vitesse de l'évaporation réelle du sol diminue lorsque la succion totale dépasse 3000 kPa. Il existe une relation entre la vitesse d'évaporation réelle et la succion totale pour les trois types de sol qui semble être unique et indépendante de la texture du sol, du temps de séchage, et de la teneur en eau.

Mots clés: évaporation réelle, évaporation potentielle, succion du sol.

[Traduit par la rédaction]

Introduction

Engineered soil covers cannot be designed without evaluating the evaporative fluxes at the soil surface. The purpose of any soil cover system is to control the mass flux of water entering the underlying waste materials. Net water fluxes are a function of the infiltration entering the soil cover due to precipitation and exfiltration leaving the soil cover due to atmospheric evaporation. A clear rationale for predicting infiltration is available. However, a suitable methodology for evaluating soil evaporation has yet to be demonstrated. The need for the development of an appropriate technique is great, since geotechnical engineers in many regions of the world find that the frequency and duration of evaporative events greatly exceed that for infiltration events.

Recent studies have illustrated the need for predictive techniques to evaluate evaporation rates from soil surfaces. Yanful

et al. (1993) provides design criteria and performance modeling for a composite soil cover system constructed on an acid-generating waste rock dump in New Brunswick. The cover was designed to minimize water and oxygen fluxes to the underlying waste rock. Cover efficiency with respect to oxygen fluxes depended on maintaining high saturation, since moisture losses due to evaporation may have led to failure. Laboratory tests were required in order to estimate the appropriate evaporation function for the cover.

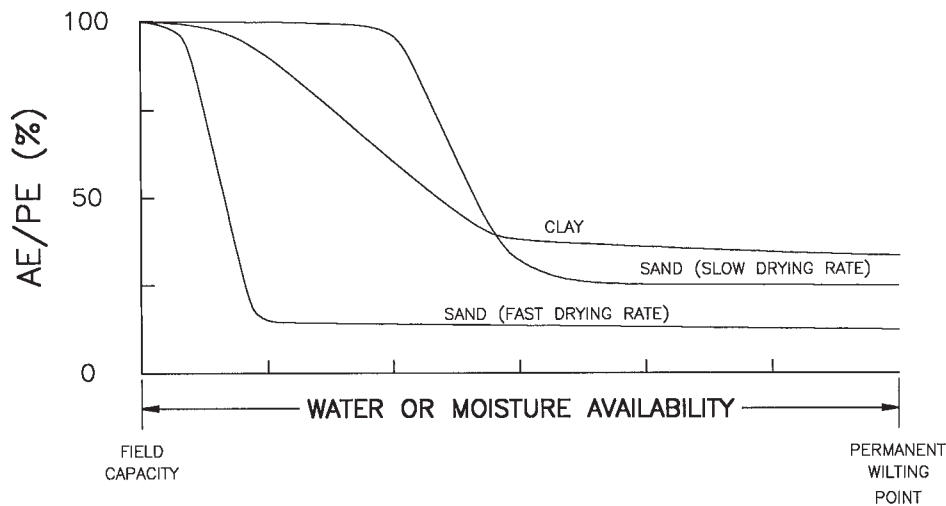
Barbour et al. (1993) evaluated the saturated-unsaturated groundwater conditions of a sulphide-rich thickened tailings deposit in Ontario. Oxidation of the tailings at the surface is known to increase as the degree of saturation decreases. The analysis showed that increased evaporative fluxes during the summer months decreased the thickness of the tension-saturated zone above the water table resulting in the increased potential for desaturation of the tailings surface. The evaporative fluxes used for the analysis were assumed on the basis of observed pan evaporation rates. Since actual evaporative fluxes were not evaluated, the accuracy of the analysis can be questioned.

Other applications exist for which geotechnical engineers must evaluate evaporative fluxes at the soil surface. Silvestri et al. (1990) showed settlement problems in lightweight structures

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Fig. 1. Typical drying curves for sand and clay showing actual evaporation, AE, as a percentage of potential evaporation, PE, versus water availability (after Holmes 1961).



founded on Champlain clays in Montréal to be strongly controlled by potential evapotranspiration and associated rainfall deficits. Sattler and Fredlund (1989) demonstrated how heave and settlement for expansive clay soils are influenced by evaporation.

Most of the previous work describing evaporation is found outside the traditional area of geotechnical engineering in disciplines such as hydrology and soil science. In response to the need to develop a clear rationale for geotechnical applications, this paper reviews the necessary background for evaluating evaporation found in these other disciplines. Laboratory data are presented where actual evaporation rates from initially saturated soil surfaces of sand, silt, and clay were measured. A simple theoretical approach for the prediction of evaporation from soils is presented and comparisons are made with measured values.

Definitions

The concept of potential evaporation (PE) has been used in engineering practice for nearly 50 years (Thorntwaite 1948). In the most simple terms, PE is considered to be an upper limit or maximum rate of evaporation. The International Glossary of Hydrology (World Meteorological Organization 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 atmospheric conditions."

Evaporation from a water surface may be computed by the simple and well-known equation for mass transfer first given by Dalton in 1802 (Gray 1970):

$$[1] \quad E = f(u) (e_s - e_a)$$

where E is the rate of evaporation (mm/day), e_s is the saturation vapour pressure at the temperature of the water surface (kPa), e_a is the vapour pressure of the air in the atmosphere above the water surface (kPa), and $f(u)$ is a transmission function that depends on the mixing characteristics of the air above the evaporating surface. The transmission function $f(u)$ may be established empirically (Gray 1970).

Many contemporary mass transfer equations in use take the same basic form as Dalton's equation with the function $f(u)$

evaluated on the basis of the aerodynamic profile and eddy diffusion similarity theory.

In simple terms, the mass transfer equation given in [1] describes evaporation as a function of the difference in vapour pressure between the water surface and overlying air. The vapour pressure of the evaporating water surface, e_s , is the saturation vapour pressure of the water given by the Clausius-Clapeyron equation, which is a function of temperature (Brutsaert 1982). The vapour pressure in the air above the water, e_a , is determined on the basis of the saturated vapour pressure at the measured air temperature and relative humidity. Determining the surface temperature of the water can be extremely difficult (Gray 1970), and as a result, [1] often becomes indeterminate. Penman (1948) rendered the problem determinant by incorporating the energy balance and net radiation available to the evaporating water surface.

The actual rate of evaporation from vegetated and bare soil surfaces is stated to be approximately equal to the rate of evaporation from an open or free water surface (i.e., PE), provided that the supply or availability of water to the surface is unlimited (Penman 1948). This suggests that the rate of evaporation from a wet soil surface can be evaluated using the same techniques as used for free water surfaces. However, the approach becomes inaccurate once the soil surface begins to dry and becomes unsaturated. As a result, traditional methods for predicting potential evaporation from saturated surfaces, such as the Penman method, provide overestimates of evaporation for unsaturated soil surfaces (Morton 1985; Granger 1989a).

Literature review

Hydrologists, soil scientists, and engineers have been attempting to evaluate evaporation from unsaturated soils for a number of decades. Figure 1, after Holmes (1961) and Gray (1970), shows the relationship between potential evaporation, PE, from a free water surface and actual evaporation, AE, for typical sand and clay soil surfaces that are allowed to evaporate from initially wet or nearly saturated states. Holmes (1961) showed that the AE is equal to the PE (i.e., AE/PE equals unity) for both the sand and clay soils when the water content

Table 1. Summary of material properties used for each soil type in the evaporation tests.

Item	Beaver Creek sand	Custom silt	Regina clay
Description	Fine, uniform clean sand; aeolian	Coarse to medium clean silt; laboratory produced	Highly plastic clay; lacustrine
Texture	98.0% sand 2.0% silt and clay	7.0% sand 84.0% silt 9.0% clay	8.0% sand 41.0% silt 51.0% clay
Atterberg limits	Nonplastic	Plastic	Plastic
Liquid limit	—	26.8%	75.5%
Plastic limit	—	25.4%	24.9%
Plasticity index	—	1.4%	50.6%
USCS ^a	SP	ML	CH
Specific gravity	2.67	Not measured – 2.72 estimated	2.83
Void ratio at 100 kPa suction	0.63	0.85	1.34

^aUnified Soil Classification System.

is high or near the field capacity. The ratio of AE/PE for each soil type begins to decline as the availability of water decreases to the permanent wilting point for plants. Holmes (1961) and Gray (1970) do not explicitly state the units of water or moisture availability, but the limit of the permanent wilting point (i.e., approximately equal to 15 atmospheres of suction) implies that the soil has large negative pore-water pressures or suction.

Figure 1 shows that as water becomes less available, the decline in the ratio AE/PE varies significantly depending on the soil texture and drying rate. For example, the ratio AE/PE for the sand undergoing rapid drying is significantly less than that for the slow drying sand when the water availability is at the mid-point between the field capacity and the permanent wilt point. The curve for the clay indicates a higher rate of actual evaporation than either the fast or slow drying sand as the water availability approaches the permanent wilt point. In summary, Fig. 1 indicates that the actual evaporation rate from soil surfaces relative to the potential evaporation rate is a function of water availability, soil texture, and drying rate. No single variable or soil property appears to control the evaporation rate from the soils.

The difficulty with respect to defining the soil properties that control evaporation from unsaturated soil surfaces has resulted in the development of empirical methods. For example, Hillel (1980) suggests the drying of a soil surface may be simulated using square-root time relations. The function is purely empirical, and the actual mechanisms that control soil evaporation are not identified. Yanful et al. (1993) essentially adopted an empirical approach for evaluating the performance of a soil cover system for acid-generating waste rock.

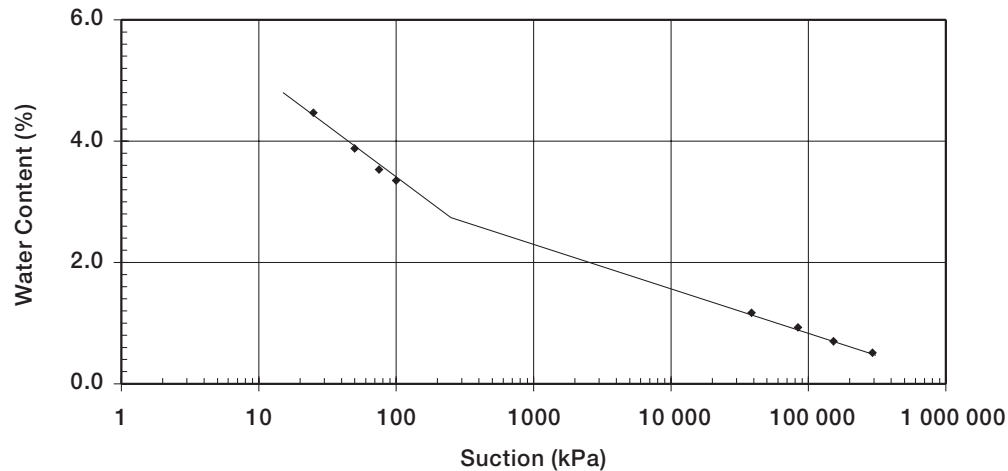
A few attempts have been made to define the dependent variables that control evaporation from unsaturated soil. Barton (1979) suggested soil evaporation may be estimated on the basis of the humidity and water content of the near surface soil. Hammel et al. (1981) also described actual evaporation from soil as a function of soil-water content and included water flow processes in the soil with combined moisture and temperature

gradients. Granger (1989b) stated that evaporation from unsaturated soil surfaces is a function of the actual vapour pressure at the soil surface. This behavior is in agreement with [1]. The actual vapour pressure for unsaturated soil surfaces is less than the vapour pressure that would occur at full saturation of the soil, hence, evaporation is suppressed. However, Granger (1989b) did not provide a means for evaluating the actual vapour pressure at the unsaturated soil surface.

Wilson et al. (1994) developed a coupled soil-atmosphere model for soil evaporation. The model solved for evaporation using [1] with the vapour pressure at the soil surface determined on the basis of solving coupled heat and mass transfer equations for the soil profile below the surface. Model predictions for a sand profile were compared to laboratory measurements with good correlations. However, the laboratory tests were conducted using a column of ideal cohesionless uniform sand. The suitability of the theoretical model for other soils such as a fine-grained silt or cohesive clay was not demonstrated.

In general, the work described above shows that for given climatic conditions, the evaporation rate from unsaturated soils is less than the evaporation rate from saturated soils or water. The mass transfer equation, [1], which defines evaporation, indicates that a reduction in the evaporation rate from a soil surface that is drying from an initial state of saturation under constant climate conditions will occur only if the vapour pressure at the soil surface, e_s , decreases during drying. However, this basic principle has not been clearly demonstrated. Instead, the decline in evaporation rates for unsaturated soil surfaces has been explained on the basis of a variety of other factors such as soil water availability or water content, soil texture, drying rate, and drying time.

The present work evaluates the process of evaporation from soil surfaces composed of various soil types that were allowed to evaporate under controlled laboratory conditions. The laboratory testing program carried out used two identical evaporation pans. One pan contained water to measure the potential evaporation rate and the second pan contained soil to measure

Fig. 2. Water-content characteristic curves for Beaver Creek sand at 20°C.**Table 2.** Summary of saturated salt solutions, activity coefficients, and osmotic suctions used for the vacuum desiccators at 20°C.

Salt solution	Activity coefficient	Osmotic suction (kPa × 10 ³)
Lithium chloride [LiCl H ₂ O] and [LiCl 2H ₂ O]	0.115	292.4
Magnesium chloride [MgCl ₂ 6H ₂ O]	0.330	152.4
Magnesium nitrate [Mg(NO ₃) ₂ 6H ₂ O]	0.543	84.0
Sodium chloride [NaCl]	0.755	38.6
Potassium sulphate [K ₂ SO ₄]	0.970	4.19

the actual soil evaporation rate. The simultaneously measured actual and potential evaporation rates were compared as the soil surfaces desiccated from wet to dry. The influence of soil parameters such as texture, drying time, water content, and soil suction were also evaluated.

Laboratory test program

Evaporation tests were carried out using three texturally distinct soil types selected to represent the clay, silt, and sand soil groups. They were as follows: (1) Beaver Creek sand; (2) Custom silt; and (3) Regina clay.

The Beaver Creek sand was a fine, uniform, natural aeoline soil consisting of 98% sand and 2% silt and clay. This material was selected to represent granular, cohesionless soils. Regina clay, which is a highly plastic lacustrine deposit, was the natural soil selected to represent fine-grained, cohesive soils. A silt material was also included to represent a fine-grained cohesionless soil intermediate to the extremes of a clean sand and a highly plastic clay. The silt was a custom material containing 84% silt produced in the laboratory. A summary of the soil properties for each soil type are presented in Table 1.

Water-retention characteristics

The soil-water characteristic curves were determined for each of the selected soil types. The soil-water characteristic curve of a soil is a measure of the availability of water since it provides a relationship between water content and suction. The soil-water characteristic curves for the Beaver Creek sand, Custom silt, and Regina clay were evaluated using pressure plates and glass desiccators containing electrolyte solutions.

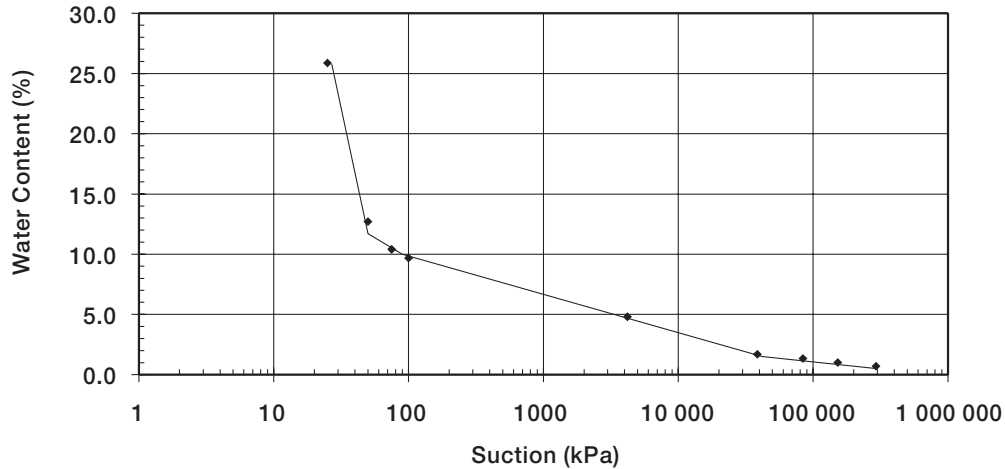
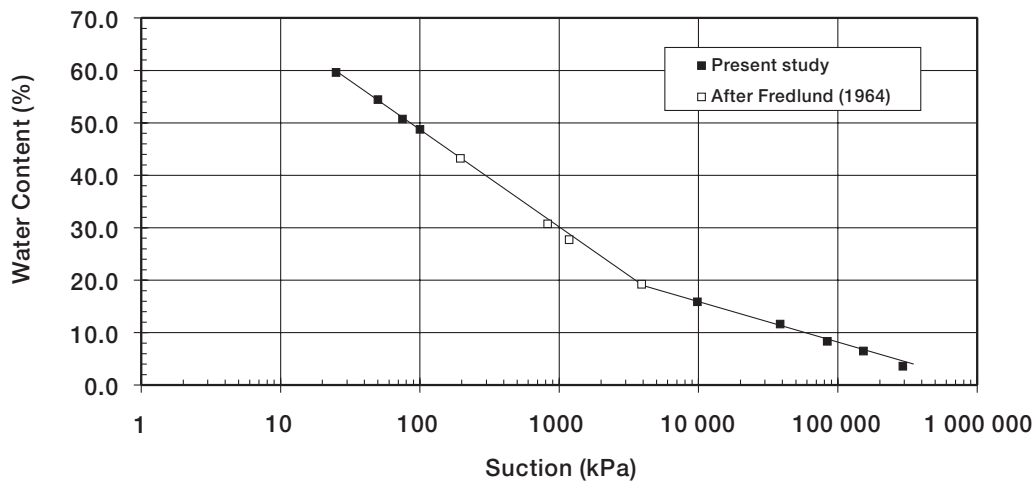
Pressure plates were used to determine soil-water contents at various values of matric suction between 0 and 100 kPa. Soil-water contents for high values of suction were determined using osmotic pressures induced by electrolyte solutions. The osmotic pressure of the electrolyte solutions in the glass desiccators was calculated using the well-known expression for thermodynamic equilibria of solvents given by Robinson and Stokes (1955) as follows:

$$[2] \quad \pi = \frac{RT}{V_A} \ln a_w$$

where π is osmotic pressure or suction (kPa), R is the universal gas constant (8.314 J/(mol·K)), T is absolute temperature (K), V_A is molar volume, and a_w is the activity of water for the aqueous solution.

Five aqueous solutions were selected to give a suitable range of osmotic suction. Table 2 provides a summary of the salt solutions used and the corresponding values of osmotic suction.

Each soil type was slurried with distilled water and placed into the pressure plate in a saturated state. The air pressure in the pressure plate was increased by increments of 25 kPa allowing the samples to reach an equilibrium water content for each increment of matric suction to a maximum of 100 kPa. Small soil samples were then removed from the pressure plate at the end of the procedure, as described by Wilson (1990). These samples were placed directly into each of the five glass desiccators, and the soil-water contents were allowed to come to equilibrium with the osmotic suction established in the desiccators. The samples were separated from the electrolyte solutions in the reservoirs of the glass desiccators by an air space that functioned as a semi-permeable membrane. The temperature was maintained at 20°C for the samples in the pressure plate and glass desiccators. Figures 2, 3, and 4 show the measured

Fig. 3. Water-content characteristic curves for Custom silt at 20°C.**Fig. 4.** Water-content characteristic curves for Regina clay at 20°C.

soil-water characteristic curves for the Beaver Creek sand, Custom silt, and Regina clay, respectively, for suctions ranging from 25 kPa to approximately 300 000 kPa.

The soil-water characteristic curve for the Regina clay at 20°C (Fig. 4) was established using several additional values of water content and corresponding values of suction obtained from Fredlund (1964). Fredlund determined these points by the pressure plate and glass desiccator methods as described above. The properties of the Regina clay samples used by Fredlund (1964) with respect to texture and plasticity are similar to those reported in Table 1.

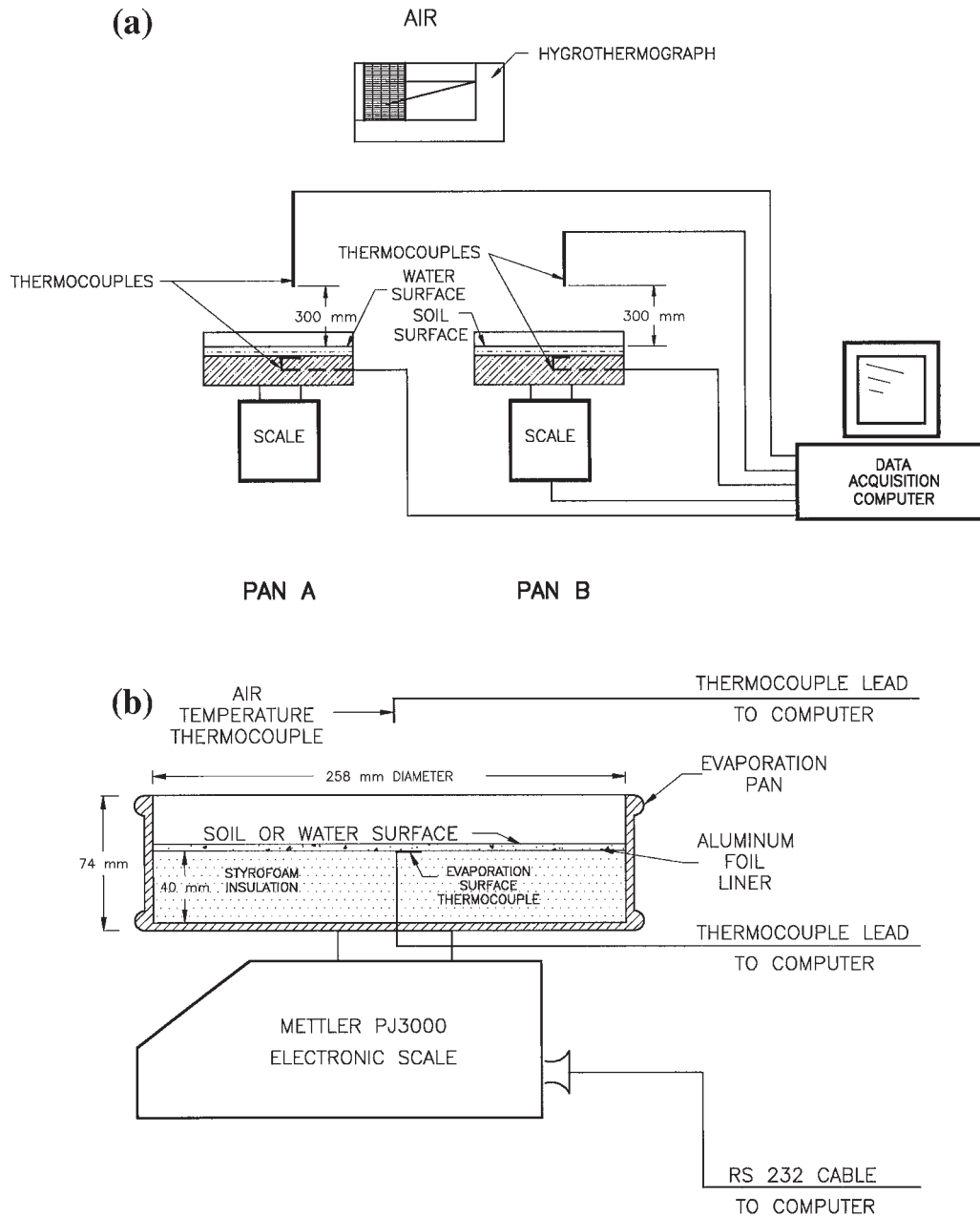
Evaporation tests

The second stage of the testing program was to conduct evaporation tests using specimens of each soil type. Thin soil sections were selected in order to minimize the influence of soil water below the evaporating soil surface. Hillel (1980) states: “the actual evaporation rate is determined either by external evaporativity or by the soil’s own ability to deliver water, whichever is the lesser (and hence the limiting factor).” The objective of the test procedure described here was to determine

the soil properties at the soil surface or the soil boundary layer that control evaporation. The soil sections were therefore made as thin as possible to minimize potential flow processes in the soil below the surface from influencing the rate of evaporation from the surface of the soil.

The thin soil section evaporation tests were conducted such that the AE from the soil surfaces was continually measured as drying took place from an initially saturated state to a completely air-dried state. The thin soil sections were artificially formed on a circular, 258 mm diameter, evaporation pan, as shown in Figs. 5a and 5b. Each evaporation test was carried out using two identical evaporation pans. One pan contained the thin section of soil surface to determine the AE, while the second identical pan contained distilled water which provided the reference for the PE. The mass and change in mass of each pan was continually monitored to determine the rate of evaporation from the pans. The water contents of the soil specimens at various times during each test were determined using the final mass of dry soil and water at the end of the test plus the instantaneous masses measured during the test. The temperature of the soil surfaces, the water surface, and the air was also monitored continuously along with the relative humidity of the

Fig. 5. (a) Thin soil section drying test apparatus. (b) Detailed section of the evaporation pan used for the thin soil section evaporation test.



air above the evaporating surfaces. All tests were conducted at room temperature in the geotechnical laboratory at the University of Saskatchewan.

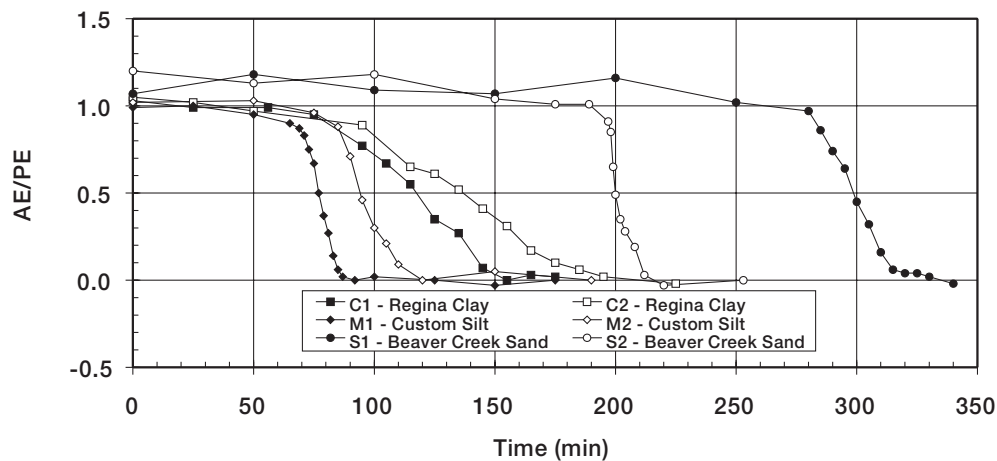
Two thin section drying tests were completed for each soil type (i.e., sand, silt and clay). Numerous attempts were required in order to develop a procedure that provided a thin layer of soil with a uniform thickness and an initial target water content. The thin soil sections were prepared by gently dusting a layer of soil onto the pan using a hand-held sieve filled with powdered dry soil. An 850 μm sieve was used to apply the Beaver Creek sand, while a 425 μm sieve was used to apply the Custom silt and Regina clay. The dusted soil layers were applied uniformly until a thickness just adequate to visually cover the aluminum surface of the pan was achieved. The final layer thickness for the two Beaver Creek sand specimens were

0.5 mm and 0.7 mm, while the final layer thicknesses for the two Custom silt and one of the Regina clay surfaces was 0.3 mm. A layer thickness of 0.2 mm was used for the second Regina clay sample.

The dry soil layers were wetted to saturation using a fine uniform mist of distilled water. The mass of the soil specimens were then monitored while evaporating to an air-dry state. Table 3 provides a summary of the six thin soil section drying tests. Figure 6 shows the normalized evaporation, AE/PE , obtained for the soil and water surfaces measured with respect to time for the Beaver Creek sand, Custom silt, and Regina clay. The normalized evaporation parameter is selected for convenience, since the term PE is controlled primarily by atmospheric conditions and surface temperature, which are the same for both the water and soil surfaces during each evaporation test.

Table 3. Summary of thin soil section evaporation tests.

Specimen No.	Soil type	Sample thickness (mm)	Initial water content (%)	Test duration (min)	Mean room air temperature (°C)	Mean relative humidity of air (%)	Mean water pan evaporation (mm/day)
S1	Beaver Creek sand	0.7	25.0	330	23.1	53	1.31
S2	Beaver Creek sand	0.5	25.5	250	22.7	44	1.40
M1	Custom silt	0.3	30.0	125	22.5	39	1.71
M2	Custom silt	0.3	28.8	190	23.0	62	1.16
C1	Regina clay	0.3	63.5	195	22.8	35	1.54
C2	Regina clay	0.2	61.2	225	25.5	50	1.29

Fig. 6. The ratio of actual evaporation and potential evaporation, AE/PE, versus drying time for the Beaver Creek sand, Custom silt, and Regina clay.

Discussion and analysis

The soil-water characteristic curves for each soil are shown in Figs. 2, 3, and 4. These drying curves are important in geotechnical engineering because they show the amount of water retained in the soil over the total range of soil suction. Wetting the soils from a dry state to a wet state (i.e., high suction to low suction) would result in slightly different curves due to the effects of hysteresis. The drying curves shown are most applicable to the thin soil section evaporation test.

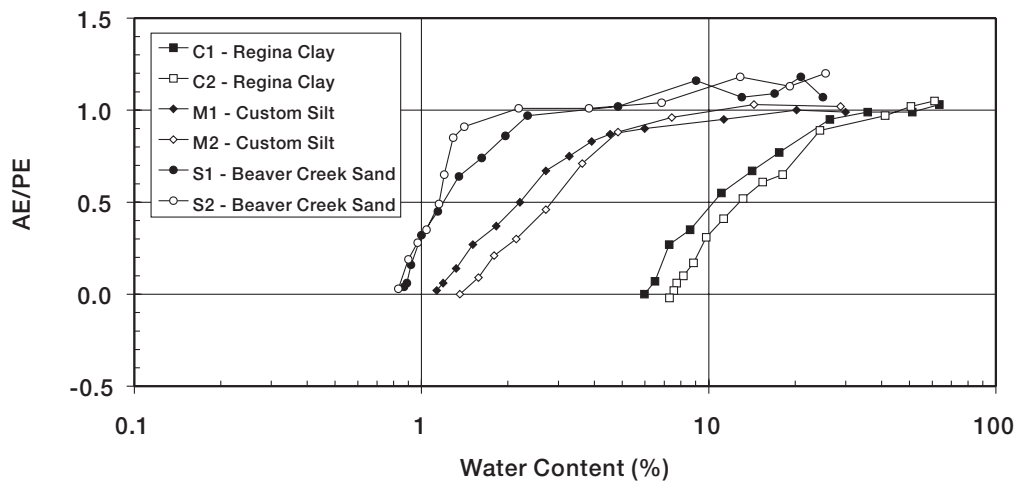
Geotechnical engineers are most familiar with soil suctions that are relatively low when compared with those shown in Figs. 2, 3, and 4. The unsaturated soils dealt with usually have values of matric suction that do not exceed 500 kPa. In nature, however, soils at the ground surface commonly have extremely high values of suction. The permanent wilting point of plants found in semi-arid climates is commonly reported to be 15 bar (Hillel 1980) or approximately 1500 kPa. Even at large values of suction, considerable water may still be present in the soil. For example, in Fig. 4, Regina clay has a water content of approximately 25% at 1500 kPa of suction. This corresponds approximately to the water content at the plastic limit. Natural soils commonly reach a completely air-dried state at the ground surface. This would be the case for the exposed soil surface of a cover for a municipal landfill after several days of continuous drying without precipitation. The water content for Regina clay, for example, may be as low as 6% at the ground surface. Figure 4 shows that this water content

would correspond to a value of total suction of approximately 200 000 kPa. Oven drying at a temperature of 105°C results in a suction approaching 1 000 000 kPa. Although the physical properties of soil water at extremely high values of suction are not yet fully explained (Fredlund 1991), it can be argued that understanding the behaviour of natural soils at and near the ground surface requires the acceptance of soil suctions far in excess of 500 kPa.

It should be noted that a distinction has been made between matric suction and total suction in Figs. 2, 3, and 4. The suctions established using the pressure plate method correspond to values of matric suctions (i.e., $u_a - u_w$). Osmotic suction due to the presence of dissolved solids is not included. Distilled water was used for all test procedures, therefore, the value of osmotic suction for the Beaver Creek sand and Custom silt may be assumed to be relatively small. This assumption may not, however, be true for the Regina clay because of its geochemical nature. Krahn (1970) showed osmotic suction to be approximately 200 kPa for Regina clay having a water content of 30%. This indicated that a high level of dissolved solids was present in the clay. The use of distilled water during sample preparation dilutes but does not remove the salts. In summary, the values of matric suction established by the pressure plate method for the Regina clay may underestimate total suction.

The soil-water contents shown in Figs. 2, 3, and 4 that correspond to high values of suction (i.e., greater than 1500 kPa) were established in the desiccators through vapour equilibrium

Fig. 7. The ratio of actual evaporation and potential evaporation, AE/PE, versus water content for the Beaver Creek sand, Custom silt, and Regina clay.



with the osmotic suction of the electrolyte solutions. The soil-water contents actually correspond to total suction, which includes both matric and osmotic suction. It is difficult to establish the relative components of matric and osmotic suction at such high values of total suction, but it is reasonable to assume that the magnitude of osmotic suction will increase at lower water contents, since the mass of dissolved solids remains constant.

Figure 6 shows the ratio of AE/PE versus time for each sample of Beaver Creek sand, Custom silt, and Regina clay. The curves are similar to those given by Holmes (1961) in Fig. 1, except that the AE/PE ratio is plotted as a function of time rather than water availability. Time zero in Fig. 6 corresponds to a nearly saturated state (or a high water availability), which is similar to the field capacity in Fig. 1. The normalized evaporation, AE/PE, is approximately unity for all specimens at the start of the evaporation test. It can be seen that the ratio is slightly greater than 1.0 for the Beaver Creek sand specimens S1 and S2. This deviation can be attributed to slight variations in the aerodynamic resistance in the air spaces above the water and soil evaporation pans, as well as the surface temperatures at the time of the tests. All specimens continue to evaporate at a near potential rate and then begin to decline after a period of time. The rate of evaporation decreases first for the silt, followed by the clay, and finally the sand. The evaporation rate for all soils falls to zero after each soil specimen reaches an air-dry state. It is difficult to understand and compare all of the controlling variables for Fig. 6, since each soil type has a different initial water content, sample thickness, and volume of water available for evaporation.

Figure 7 shows a plot of the AE/PE ratio versus water content for each specimen. The break or decline in evaporation rate occurs at a specific water content for each soil type. For example, the decline in evaporation for Regina clay specimens C1 and C2 occurs at a water content of approximately 20%. The Custom silt and Beaver Creek sand have a break in the evaporation rate at water contents of 5 and 2%, respectively. When the plots for the clay specimens C1 and C2, and for the silt specimens M1 and M2, are compared, they show slight variations. Specimens C1 and M1 reach zero evaporation at slightly lower water contents than specimens C2 and M2. This

slight variation can be attributed to a difference in the relative humidity of the air at the time of each test, since relative humidity control in the test area was not available. Table 3 shows the relative humidity in the air at the time of each test, and it can be seen that tests C1 and M1 were performed at significantly lower relative humidities than tests C2 and M2. Hence, the air-dried soils for tests C1 and M1 have less hygroscopic moisture. Tests S1 and S2 were performed with similar humidities and therefore show closer agreement for the final water content corresponding to zero evaporation (or an AE/PE ratio equal to zero).

The data shown in Fig. 7 suggest that the water content of the soil influences the rate of evaporation for each soil type. However, water content alone cannot be identified as the unique independent variable controlling the actual rate of evaporation for all soil types. Soil texture must also be taken into consideration. Water content may, however, be used to determine the value of total suction in the soil. The soil-water characteristic curves shown in Figs. 2, 3, and 4 were used to determine corresponding values of total suction at each measured water content during the evaporation tests. Figure 8 shows a plot of the AE/PE ratio versus total suction for the Beaver Creek sand specimen S1, Custom silt specimen M1, and Regina clay specimen C2. The tests for specimens S1 and C2 were conducted at a relative air humidity of approximately 50% while the test for specimen M1 was performed at a lower relative air humidity of approximately 40%.

Figure 8 shows a reasonably good correlation between the ratio of AE/PE and total suction. This correlation is independent of time, water content, and soil texture. The ratio of AE/PE is approximately constant and equal to unity for values of total suction less than approximately 3000 kPa. The actual rate of evaporation begins to decline once the value of the total suction exceeds approximately 3000 kPa. The rate of actual evaporation continues to decrease as the value of total suction increases. The AE/PE ratio then falls to zero for the three soil types at values of total suctions slightly larger than 100 000 kPa.

The relationship between total suction and AE/PE can be explained by considering the relationship between relative humidity and total suction given by Edlefsen and Anderson (1943):

Fig. 8. The ratio of actual evaporation and potential evaporation, AE/PE, versus total suction for the Beaver Creek sand, Custom silt, and Regina clay.

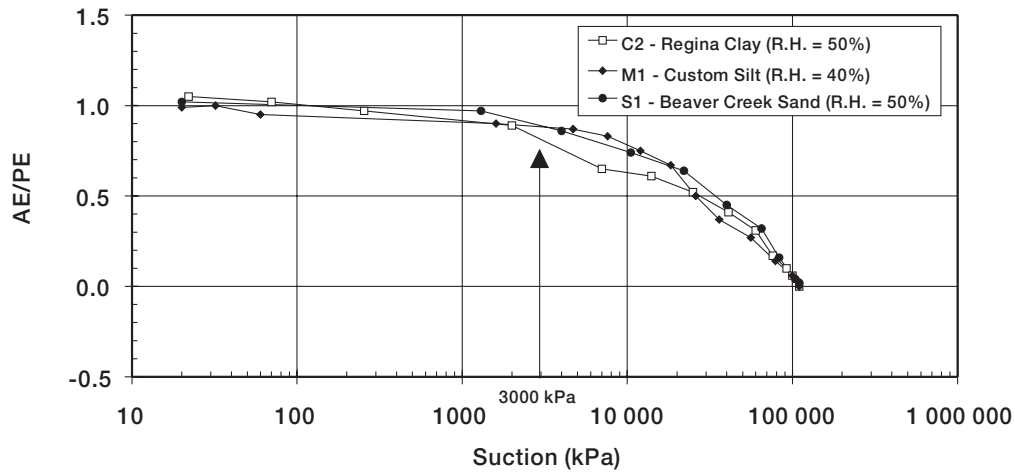
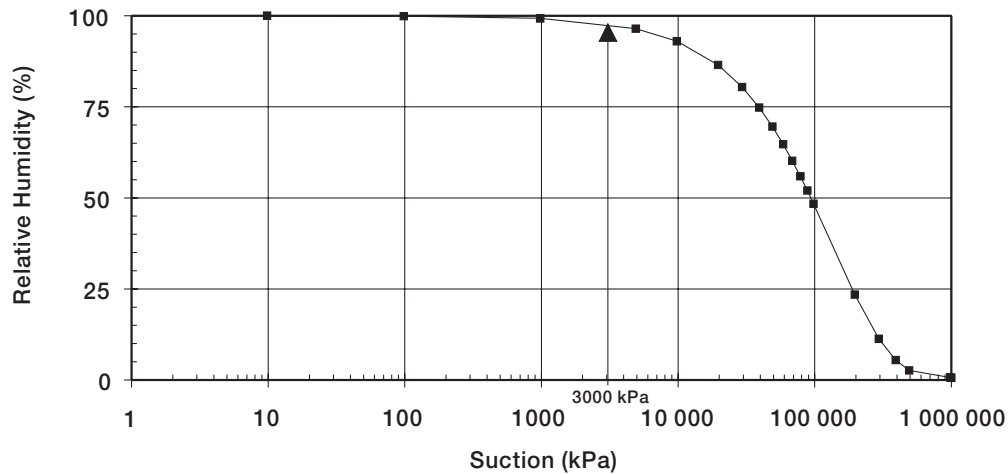


Fig. 9. Relative humidity versus total suction calculated on the basis of eq. [3] (20°C).



$$[3] \quad h_r = \exp\left(\frac{\Psi g W_v}{RT}\right)$$

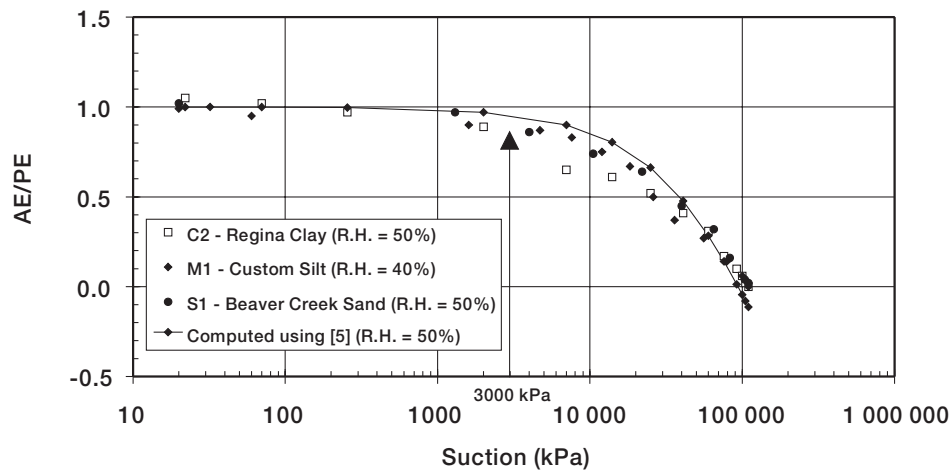
where h_r is relative humidity in the unsaturated soil voids (i.e., actual vapour pressure divided by saturation vapour pressure), Ψ is the total suction in the liquid water phase expressed as equivalent matric suction and as a negative value (m), W_v is the molecular weight of water (0.018 kg/mol) and g is acceleration (m/s^2).

Figure 9 shows this relationship graphically on a log–arithmetic plot. Relative humidity is an exponential function of total suction, and the decline in relative humidity with increasing suction is initially small. A substantial decrease in the relative humidity occurs only after the value of total suction exceeds 2000 to 3000 kPa (i.e., 3000 kPa of total suction corresponds to a relative humidity of approximately 98%). The suppression of relative humidity results in an equivalent decline in the absolute vapour pressure at the soil surface. Since [1] shows the rate of evaporation to be a function of the vapour pressure at the evaporating surface, the rationale which suggests that the actual rate of evaporation depends on the total suction at the soil surface appears valid.

Figure 8 has illustrated that the AE/PE ratio is equal to zero for a value of total suction slightly greater than 100 000 kPa. This point of zero evaporation is controlled by the relative humidity in the air. The evaporating soil surface dries to a point that is in equilibrium with the air. For example, test C2 was performed with a room air relative humidity of 50%. As shown in Fig. 9, this corresponds to a total suction of approximately 100 000 kPa. Soil evaporation should cease when the relative humidity in the soil reaches equilibrium with the relative humidity of the air above the soil. Hence, zero evaporation should correspond to a suction of 100 000 kPa, as shown in Fig. 8. Alternately, evaporation would have continued to a higher value of total suction if the humidity in the air were less. A room air relative humidity of 20% would have resulted in a total suction of approximately 200 000 kPa for the soil surface to reach air-dry equilibrium.

The relationship between actual soil evaporative fluxes and total suction in the soil is important to geotechnical engineers, since it forms the basis for the prediction of actual evaporative fluxes. Predicting the values of AE/PE as a function of total suction shown in Fig. 8 can be achieved by combining [1] and

Fig. 10. Comparison of the measured AE/PE versus total suction for the Beaver Creek sand, Custom silt, and Regina clay to the curve computed using eq. [5].



[3]. Using [1] and assuming $f(u)$ is the same for both the soil surface and the water surface gives

$$[4] \quad \frac{AE}{PE} = \frac{(e_o - e_a)}{(e_s - e_a)}$$

where e_o is the actual vapour pressure of the soil surface equal to the product of h_r and e_s (kPa); e_s is defined by the temperature of the soil, water, and air; and e_a is equal to the product of the relative humidity measured in the air (i.e., Table 3) and e_s .

Assuming the air, water, and soil are at approximately the same temperature so that e_s cancels out and substituting [3] into [4] gives

$$[5] \quad \frac{AE}{PE} = \left[\frac{\exp\left(\frac{\Psi_g W_v}{RT}\right) - h_a}{1 - h_a} \right]$$

where h_a is the relative humidity of the air above the evaporating soil and water surfaces.

It is important to note that should the soil, water, and air temperatures not be equal, [3] and [4] must be solved using the saturated vapour pressure corresponding to each temperature.

Equation [5] provides the value of AE/PE as a function of total suction at the soil surface. The accuracy of the functional relationship can be tested through comparison with the experimental data. Figure 10 shows the curve for AE/PE as a function of total suction computed using [5], along with the values measured for the sand, silt, and clay surface. It can be seen that the predicted curve compares reasonably well to the measured values. The predicted curve is least reliable for the Regina clay. This may be attributed to a nonuniform water content across the thickness of the soil specimen during the evaporation test, since the particle size of the clay is much smaller than the thickness of the thin soil section (i.e., 0.2 to 0.3 mm). In general, however, the principle that soil suction controls the normalized evaporation for a soil surface appears valid. Furthermore, this principle is independent of other soil properties such as moisture content, texture, and mineralogy.

It should be noted that this discussion has addressed only the properties of soil surfaces that control evaporative fluxes into the atmosphere. The soil evaporation tests considered only thin soil sections in the absence of the influence due to soil

water below the surface. Increasing the thickness of the soil layers would greatly influence evaporative fluxes, as deeper soil water would be available as recharge to the desiccating soil surfaces. The analysis of this more complex problem would require a theoretical approach that includes the influence of flow processes below the soil surface.

Summary and conclusions

Many problems in geotechnical engineering require that the exchange of water between the atmosphere and ground surface be known. The process of evaporation from soil surfaces in particular has not been clearly defined in the past. This study has found that a relationship between the actual or normalized evaporation rate and total suction does exist for three different soil types.

Evaporation from a soil surface is a function of the vapour pressure gradient between the soil surface and the ambient atmosphere. The mass transfer equation, [1], initially proposed by Dalton for evaluating evaporation from water surfaces, can be modified and applied to soil surfaces. Saturated and nearly saturated soil surfaces evaporate at a potential rate approximately equal to the evaporation rate from free water surfaces. It has been found that the actual rate of evaporation from a soil surface falls below this potential rate of evaporation once the soil becomes unsaturated and the value of total suction exceeds a value of approximately 3000 kPa. This relationship occurs independently of water content. The rate of evaporation continues to decline as the total suction increases. In general, total suction (i.e., matric suction plus osmotic suction) appears to be a suitable state variable for describing soil atmosphere evaporative fluxes. This is consistent with the stress-state variables generally used in unsaturated soil mechanics.

In summary, evaporative fluxes from soil surfaces can be evaluated on the basis of easily measured soil properties. The measured water content can be used in conjunction with the soil-water characteristic curve for total suction to calculate the vapour pressure at the soil surface. Evaporative fluxes from unsaturated soil surfaces at high values of suction are less than those from saturated surfaces under identical climatic conditions. This is an important consideration with respect to the design, for example, of soil cover systems for the control of

water fluxes into underlying waste materials. In such an application, the geotechnical engineer could use a conventional method for evaluating the potential rate of evaporation (i.e., the Penman method) and modify it to obtain the actual evaporation for unsaturated conditions using [5].

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