

# The prediction of evaporative fluxes from unsaturated soil surfaces

## Prédiction des flux d'évaporation des surfaces de sol non-saturé

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**ABSTRACT:** The analysis of problems such as volume change in expansive soils or groundwater flow through saturated/unsaturated soils requires an evaluation of the flow of moisture between the soil surface and the atmosphere. This paper presents a theoretical approach for the prediction of evaporative fluxes from unsaturated soil surfaces. Soil evaporation tests were conducted in the laboratory for sand, silt and highly plastic clay. The actual rate of evaporation was found to be a function of total suction for all three soil types. A theoretical approach is proposed for the evaluation of soil evaporative fluxes on the basis of potential evaporation and total suction at the soil surface.

**RESUME :** L'analyse de problèmes comme la variation de volume dans les sols gonflants ou le transit d'eau à travers des sols saturés et non saturés nécessite l'évaluation du flux de l'eau entre la surface du sol et l'atmosphère. Cet article présente une approche théorique pour la prédiction des flux d'évaporation pour les surfaces de sol non saturé. Les essais d'évaporation ont été réalisés au laboratoire sur du sable, du silt et de l'argile très plastique. La vitesse d'évaporation a été trouvée fonction de la succion totale pour ces trois types de sol. Une approche théorique est proposée pour l'évaluation des flux d'évaporation sur la base du potentiel d'évaporation et de la succion totale à la surface du sol.

### 1. INTRODUCTION

The need to predict the flux of water across the soil/atmosphere boundary can be found in several areas of Geotechnical Engineering. Silvestri et al (1990) showed that settlement problems in a lightweight building founded on Champlain clays around Montreal, Quebec occurred when the accumulated rate of potential evapotranspiration exceeded precipitation by 170 mm (i.e., rainfall deficit). Other applications include the design of soil cover systems for waste management facilities, the prediction of contaminant migration in

unsaturated/saturated flow systems, and the analyses of the stability of slopes in wet versus dry seasons.

Evaporation plays a major role in determining the mass flux of water across the soil/atmosphere boundary. Prolonged periods of evaporation occur between precipitation events in many regions of the world, particularly those in arid regions. Actual evaporation rates (AE) from soil surfaces are controlled by both atmospheric demand quantified as potential evaporation (PE), and by the availability of water at the soil surface. Figure 1 shows typical relationships for the

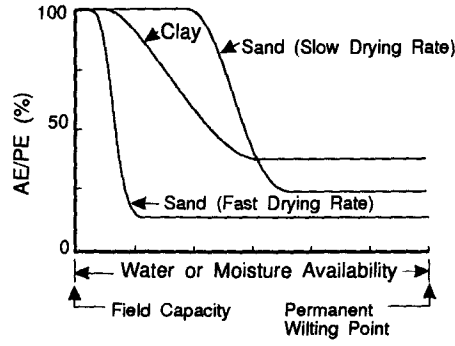


Figure 1: AE/PE versus soil water content (after Holmes, 1961).

normalized evaporation AE/PE and soil water availability for clay and sand. These empirical relationships suggest that evaporation from soils is a function of water content, suction, soil type and evaporation rate. No single variable is clearly identified. This paper presents a theoretical approach for the prediction of evaporation from soil surfaces.

## 2. THEORY

The term potential evaporation has been used for almost 50 years (Thornthwaite, 1948). Potential evaporation is the quantity of water per unit time which is removed from a free surface of water by the atmosphere. The rate of potential evaporation, PE, may be computed by the well known equation for mass transfer given by Dalton in 1802 (Gray, 1970):

$$PE = f(u) (e_s - e_a) \quad (1)$$

where  $f(u)$  is a turbulent exchange function which depends on the mixing characteristics of the air above the evaporating surface,  $e_s$  is the saturation vapour pressure of water at the temperature of the surface, and  $e_a$  is the vapour pressure of the air in the atmosphere above the water surface. Equation 1 shows that evaporation is controlled by the vapour pressure at the surface, given constant atmospheric conditions (i.e.,  $f(u)$  and  $e_a$ ). It is known that a saturated soil surface evaporates

at the same rate as a free water surface; however, as evaporation continues and the soil becomes unsaturated, the rate of evaporation falls below PE rates. Predicting the actual rate of evaporation, AE, requires the ability to evaluate the vapour pressure at the soil surface.

Wilson et al (1994) proposed a system of coupled heat and mass transfer equations for the evaluation of the vapour pressure at a soil surface. The flow of liquid water and water vapour is calculated as follows:

$$\frac{\delta h_w}{\delta t} = C_w^1 \frac{\delta}{\delta y} [k_w \frac{\delta h_w}{\delta y}] + C_w^2 \frac{\delta}{\delta y} [D_v \frac{\delta P_v}{\delta y}] \quad (2)$$

where  $h_w$  is total head,  $t$  is time,  $C_w^1$  is the modulus of volume change with respect to the liquid water phase,  $y$  is position,  $k_w$  is hydraulic conductivity,  $C_w^2$  is the modulus of volume change with respect to the water vapour phase,  $D_v$  is the diffusion coefficient of water vapour through the soil, and  $P_v$  is the actual vapour pressure within the unsaturated soil voids. Vapour pressure is calculated using total suction,  $\Psi$ , in the liquid phase as:

$$P_v = e \frac{\Psi g W_v}{RT} P_{sv} \quad (3)$$

where  $g$  is acceleration due to gravity,  $W_v$  is the molecular weight of water,  $R$  is the universal gas constant,  $T$  is temperature, and  $P_{sv}$  is the saturation vapour pressure at temperature  $T$ . The mass transfer equation given by Equation 2 is coupled with the heat flow equation shown below:

$$C_h \frac{\delta T}{\delta t} = \frac{\delta}{\delta y} (\lambda \frac{\delta T}{\delta y}) - L_v \left( \frac{P + P_v}{P} \right) \frac{\delta}{\delta y} (D_v \frac{\delta P_v}{\delta y}) \quad (4)$$

where  $C_h$  is the volumetric specific heat of the soil as a function of water content,  $\lambda$  is the thermal conductivity of the soil as a function of water content,  $L_v$  is the latent heat of

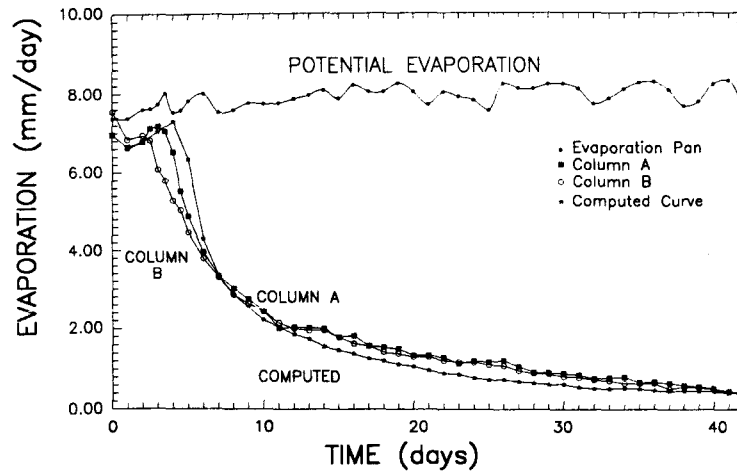


Figure 2: Measured and computed values of AE/PE for Beaver Creek sand.

vaporization, and  $P$  is the total gas pressure in the air phase of the soil.

The upper boundary condition in Equation 2 for evaporation is defined by Equation 1 by replacing the value of saturated vapour pressure,  $e_s$ , with the value of actual vapour pressure,  $P_v$ , at the soil surface.

### 3. LABORATORY TESTS

Wilson et al (1994) carried out a laboratory test to check the accuracy of the proposed system of equations. Two 169 mm diameter, 300 mm high columns of initially saturated Beaver Creek sand were allowed to evaporate over a 42 day period. The rate of evaporation from the sand columns was compared to the rate of evaporation from an identical surface of free water. The results of the evaporation tests are presented in Figure 2. The rate of evaporation for columns A and B was found to be approximately equal to the potential rate of evaporation when the sand surfaces were wet. However, as drying continued, the evaporation rates declined similar to those shown in Figure 1.

The actual rate of evaporation from the sand surfaces was computed using the coupled system of Equations 1 through 4. Wilson et al (1994) describes the material properties of the

sand and details of the calculations. The computed rate of evaporation is shown in Figure 2. A good correlation between the computed and measured values of evaporation from the surface of the sand is apparent.

The results of the column evaporation test described above show that actual soil evaporation is computed on the basis of solving for the actual vapor pressure at the soil surface; however, this has only been demonstrated for a single soil type (i.e., fine, uniform sand). Figure 1 suggests that soil texture may also play a significant role. In order to test the influence of soil type on evaporative fluxes, evaporation tests were performed using a custom silt and highly plastic Regina clay in addition to the sand described above. The evaporation tests were carried out using thin sections of soil (i.e., 0.2 to 0.7 mm thick and 258 mm in diameter). The soil samples were initially saturated and then allowed to evaporate to a completely air dried state at room air conditions of 20°C temperature and 50% relative humidity. Evaporation was also measured from a dimensionally identical surface of free water to establish PE. Figure 3 shows the results of the evaporation tests for the three soil types. Wilson (1990) describes the specific details of the tests and the analytical procedures.

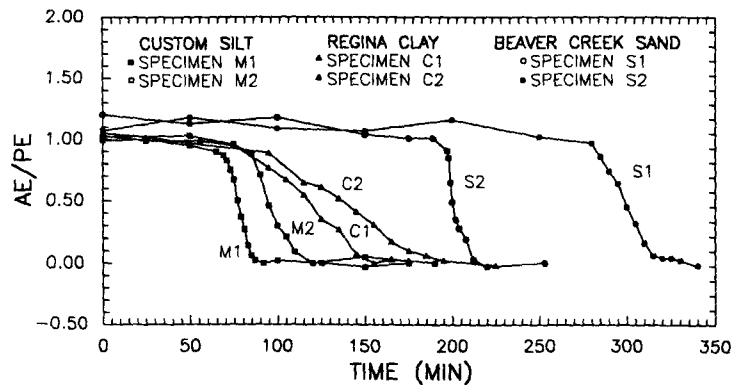


Figure 3: AE/PE versus time for the thin section drying tests.

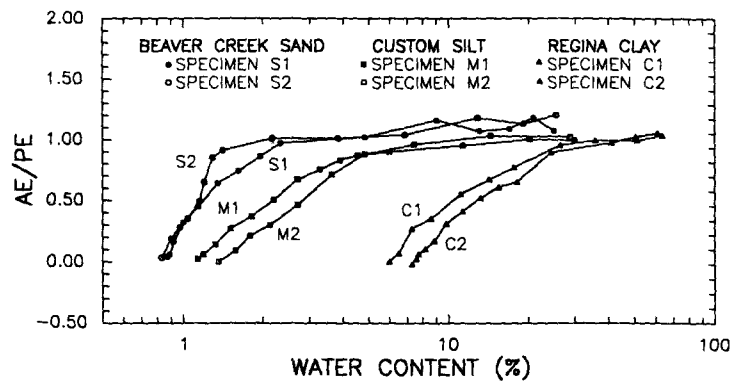


Figure 4: AE/PE versus water content for the thin section drying test.

#### 4. ANALYSIS

Figure 3 shows the decline in evaporative fluxes with respect to time. The decline in AE for each test corresponds to the decreasing water content in the soil. A decrease in water content corresponds to an increase in total suction (i.e., matric plus osmotic). Since the mass of the evaporating samples was continuously measured, the water contents were determined at various times and at corresponding values of AE/PE. Figure 4 shows the relationship between water content and AE/PE for each test. The corresponding value of suction may be determined on the basis of the water content if the soil water characteristic curve is known.

The soil water characteristic curves for the

Beaver Creek sand, Custom silt and Regina clay are shown in Figures 5 through 7. These curves were determined using the pressure plate and osmotic desiccator methods (Fredlund, 1964). The curves were established for temperatures of 5°C, 20°C and 50°C. A slight downward shift in the curves can be noted as temperature increases. The curves at 20°C were used to compute the values of total suction corresponding to the water content values shown in Figure 4.

Figure 8 shows the values of AE/PE versus suction plotted on the basis of the soil water characteristic curves for the Beaver Creek sand, Custom silt and Regina clay. A consistent relationship can be seen for all three soil types with respect to values of suction. The AE/PE is approximately equal to unity

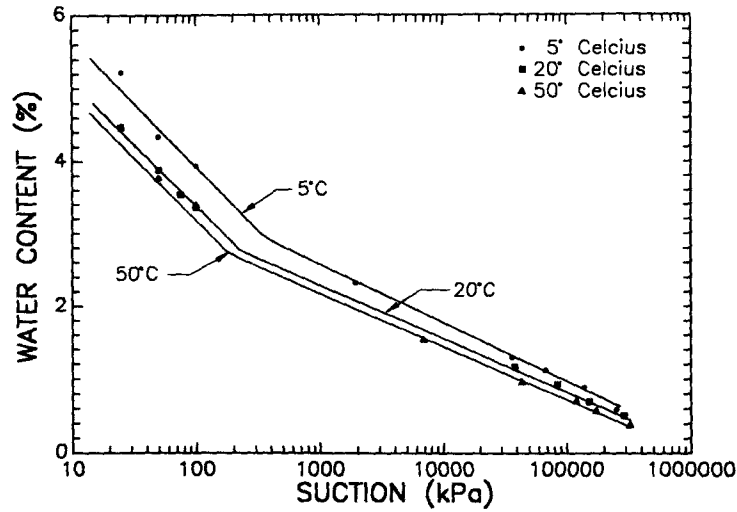


Figure 5: Soil water characteristic curves at 5°C, 20°C and 50°C for Beaver Creek sand.

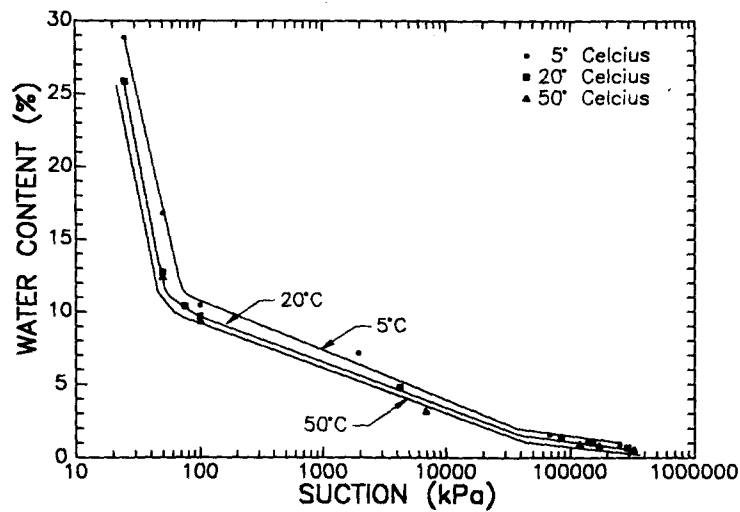


Figure 6: Soil water characteristic curves at 5°C, 20°C and 50°C for Custom silt.

until the value of suction reaches about 3000 kPa. AE/PE values then continue to decline and reach zero at approximately 100 000 kPa.

The relationship between AE/PE and suction shown in Figure 8 may be explained by considering Equation 3. Equation 3 can be used to compute the relative humidity in a soil (i.e.,  $P_v/P_{sv}$ ) as a function of suction. Figure 9 shows a plot of the relative humidity versus

suction at 20°C using Equation 3. The relative humidity remains approximately equal to 100% until the value of suction increases to about 3000 kPa. As the value of suction increases above 3000 kPa, the relative humidity declines quickly and reaches a value approaching zero at approximately 100 000 kPa.

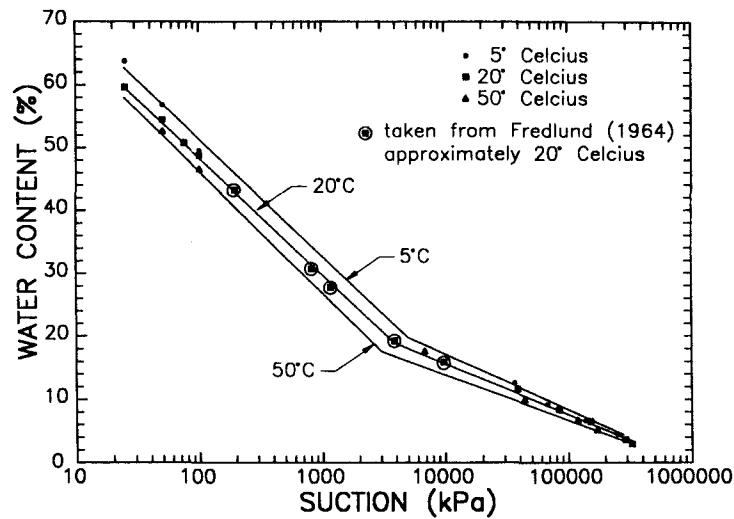


Figure 7: Soil water characteristic curves at 5°C, 20°C and 50°C for Regina clay.

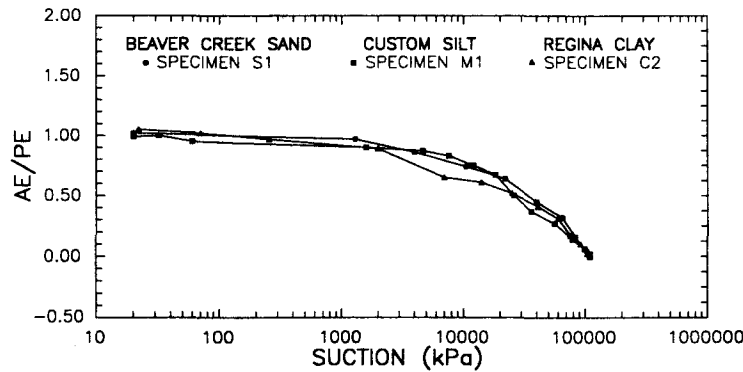


Figure 8: AE/PE versus suction for Beaver Creek sand, Custom silt and Regina clay.

The value of AE/PE shown in Figure 8 begins to decline when the suction exceeds 3000 kPa because the vapour pressure at the soil surface begins to fall below the saturated vapour pressure. The actual vapour pressure in the soil is equal to the product of the saturation vapour pressure (i.e.,  $e_s$ ) and the relative humidity which is a function of suction. Figure 9 shows that the relative humidity begins to decline when suctions exceed 3000 kPa, hence, the actual vapour pressure in the soil must decrease. As the value of suction increases, the relative humidity continues to decrease along with the

actual vapour pressure of the soil. The value of AE/PE (or AE, since PE is constant) continues to decline as suctions increase, and reaches zero at a value of suction equal to approximately 100 000 kPa. This corresponds to a relative humidity of about 50% which was the relative humidity of the air in the room for the evaporation tests. It can be seen in Figure 9 that a relative humidity of 50% corresponds to a value of suction equal to approximately 100 000 kPa. Hence, evaporation ceased when the actual vapour pressure in the soil equalized with the vapour pressure in the air above.

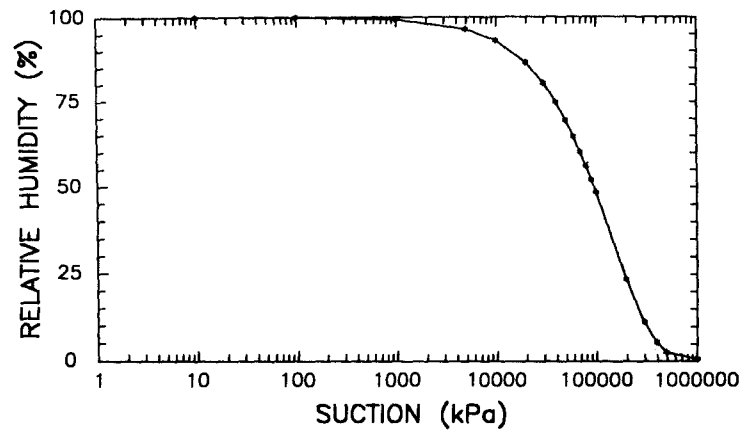


Figure 9: Relative humidity versus total suction computed on the basis of Equation 3.

In summary, the decrease in AE/PE at suctions greater than 3000 kPa, as shown in Figure 8, appears to be consistent with the decrease in relative humidity as a function of suction shown in Figure 9 (i.e., Equation 3).

## 5. CONCLUSIONS

The actual rate of evaporation from unsaturated soils is a function of total suction. Saturated soil surfaces evaporate at a rate approximately equal to the potential rate. The rate of evaporation begins to decrease when the values of suction exceed approximately 3000 kPa and the rate continues to decrease as suctions increase. The relationship between actual soil evaporation and suction appears to be applicable to a variety of soil types including sand, silt and clay. This suggests that the theoretical method of computing evaporation (i.e., Equations 1 through 4) for the columns of Beaver Creek sand can be used for other soil types such as silt and highly plastic clay.

## 6. REFERENCES

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