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# THE USE OF GROUND SURFACE MOISTURE FLUX BOUNDARY CONDITIONS IN GEOTECHNICAL ENGINEERING

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# The use of ground surface moisture flux boundary conditions in geotechnical engineering

## Prise en considération des conditions aux limites du flux d'humidification de la surface du sol en géotechnique

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ABSTRACT: The need to evaluate ground surface moisture flux boundary conditions is of paramount importance for geotechnical problems. These problems may range from the estimation of pore-water pressures for a slope stability problem to the design of covers for wastes from mining operations.

The primary hindrance in the evaluation of ground surface moisture fluxes is related to the prediction of actual evaporation (and evapotranspiration) from the ground surface. This paper presents a coupled heat and mass flow theory for the soil-atmosphere zone. Laboratory results are presented to confirm the theory. The theory is then applied to a cover system built and instrumented in a humid alpine environment of central British Columbia, Canada.

RÉSUMÉ: Le besoin d'évaluer les conditions limites du mouvement de l'humidité à la surface du sol est de grande importance pour les problèmes géotechniques. Ces problèmes peuvent varier de l'estimation des pressions pore-eau lors d'un probleme de stabilité de pente au design de couverture pour déchets originant des opérations minières.

La principale difficulté dans l'évaluation du mouvement de l'humidité à la surface du sol est reliée à la prédiction de l'évaporation réelle (et l'évapotranspiration) de la surface du sol. Cet article présente une théorie d'écoulement de chaleur et masse couplées pour la zone sol-atmosphère. Des résultats obtenus en laboratoire sont présentés de façon à confirmer la théorie. La théorie est ensuite appliquée à un système de couverture construit et instrumenté dans un environnement alpin humide du centre de la Colombie Britannique, Canada.

## 1 INTRODUCTION

Classical soil mechanics has addressed problems which have head type boundary conditions and problems involving impervious boundaries (or zero flux). However, the ground surface constitutes a "real world" moisture flux boundary which interacts with the atmospheric environment. This boundary is continuously subjected to either an upward moisture flux related to evaporation (or evapotranspiration) or a downward moisture flux due to precipitation. The upward flux has proven to be difficult to quantify.

The upward moisture flux associated with evaporation from the soil surface is influenced by the state of stress in the water in the soil. If the soil surface is extremely wet (i.e., near zero suction), the rate of evaporation from the ground surface is equal to the potential evaporation (*PE*). If the soil is quite dry, (i.e., high soil suction), the actual rate of evaporation from the ground surface is greatly reduced from the potential evaporation. It is the actual evaporation (*AE*), that is required for engineering modelling.

The actual evaporation, *AE*, rate can be computed through the use of a coupled heat and mass transport analysis for the liquid and vapour flow of water from the soil (Wilson et el, 1994). The soil-water characteristic curve (SWCC) of the soil becomes the primary soil property function required for a solution of the coupled heat and mass transport formulation.

There are numerous geotechnical problems which can be studied if the ground surface moisture flux can be estimated. These problems may range from the consideration of the stability of a slope to the design of cover systems for waste materials. In the first case, it is the prediction of pore-water pressures which is of importance while in the second case, it is the prediction of the moisture flux through the cover which is of importance. The pore-water pressures in both the saturated and unsaturated soils comprising the slope, control the shear strength of the soil. The pore-water pressures are controlled by the flux of water entering and leaving the surface of the soil. On the other hand, the moisture flux through a cover system over mine wastes may control the rate of acid rock drainage (ARD).

The paper presents a theoretical and experimental study of the prediction of the actual evaporation, *AE*, from a soil surface and then applies the theory to the evaluation of a cover sytem located in the central region of British Columbia, Canada. The objective of the cover system was to limit the entrance of water and oxygen to the underlying waste rocks.

## 2 THEORY AND NUMERICAL MODELLING

The prediction of the moisture flux boundary condition at the soil surface depends on a knowledge of the rate of infiltration during precipitation events and the rate of evaporation during subsequent dry periods. The rate of potential evaporation depends on climatic factors such as solar radiation, relative humidity, temperature and wind speed. Potential evaporation from a water surface is computed from the mass transfer equation first proposed by Dalton in 1802 as a function of the difference in vapour pressure between the water surface and the overlying air

$$PE = f(u)\,(e_s - e_a) \qquad [1]$$

where *PE* is the rate of potential evaporation (mm/day), $e_s$ is the saturation vapour pressure at the water surface temperature (kPa), $e_a$ is the vapour pressure of the air in the atmosphere above the water (kPa), $f(u)$ is an empirical transmission function depending on the mixing characteristics of the air above the evaporating surface (Gray, 1970).

The actual evaporation from an unsaturated soil surface can be computed using the following modified Penman formulation developed by Wilson (1990).

$$AE = \frac{\Gamma Q + \eta E}{\Gamma + \eta A} \qquad [2]$$

where *AE* is the actual evaporative flux, $\Gamma$ is the slope of the saturation vapor pressure versus temperature curve at the temperature of the air, $Q$ is the net radiation, $\eta$ is the psychrometric constant, $E$ is equal to $f(u)\, e_a\, (B - A)$ where $f(u)$ is a function of the wind speed, surface roughness and eddy diffusion, $e_a$ is the vapour pressure in the air above the soil surface, $B$ is the inverse of the relative humidity of the air, and $A$ is the inverse of the relative humidity of the soil surface.

An alternative method for determining actual evaporation can be developed as follows. The relative humidity in the soil at the ground surface is related to the suction in the soil (Edlefsen and Anderson, 1943).

$$h_r = e^{-\frac{\psi g W_v}{RT}} \qquad [3]$$

where $h_r$ is the relative humidity in the soil voids, $\psi$ is the soil suction in the liquid water phase expressed in terms of pressure head (m), $W_w$ is the molecular weight of water (0.018 kg/mol), $g$ is the acceleration due to gravity (9.81 m/s$^2$), $R$ is the universal gas constant (8.314 J/mole-K) and $T$ is the absolute temperature (K).

The ratio of the actual evaporative flux to the potential evaporative flux, *AE/PE*, can be obtained by combining Dalton's equation (i.e., [1]) with the relationship between relative humidity and soil suction (i.e., [3]). The empirical transmission function, *f(u)* in [1] is assumed to be the same for both the soil surface and the water surface.

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

where $e_o$ is actual vapor pressure of soil surface.

When the numerator and the denominator in [4] is divided by the saturated vapour pressure, [4] can be written in terms of relative humidities.

$$\frac{AE}{PE} = \frac{(h_r - h_a)}{(1 - h_a)} \qquad [5]$$

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

The relative humidity in the soil at ground surface is computed on the basis of the heat and mass equations (Wilson et al, 1994). Substituting [3] into [5] gives the following equation.

$$\frac{AE}{PE} = \frac{\left(e^{-\frac{\psi g W_v}{RT}} - h_a\right)}{(1 - h_a)} \qquad [6]$$

The actual rate of evaporation is only equal to the potential rate of evaporation if water is freely available. Experimental data (Wilson et al, 1996) show that the rate of actual evaporation relative to the potential evaporation is a function of the suction in the soil (Fig. 1). The ratio of the actual evaporative flux to the potential evaporative flux, *AE/PE*, was found to be the same for three soils ranging from a sand to a highly plastic clay. The rate of actual evaporation decreases as soil suction increases when the soil surface dries. Hence, the use of the potential evaporation during prolonged dry periods may give inaccurate estimates of the actual rate of evaporation.

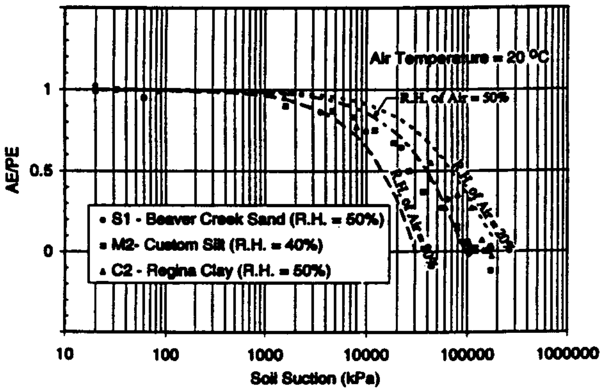

Figure 1. The AE/ PE ratio versus soil suction for Beaver Creek sand, Custom silt and Regina clay, with contours for AE/PE for environments at various relative humidities.

The ratio of the actual evaporative flux to the potential evaporative flux is dependent upon the relative humidity of the air above the soil. Contour lines of AE/PE ratio for several values of relative humidity for the air above the soil are shown in Fig. 1, along with the experimental data of the three soils.

## 3 DESCRIPTION OF THE FIELD SITE

Three waste rock dumps totalling about 85 Mt of soils and rocks were deposited in central British Columbia, Canada. The mean annual precipitation for the humid alpine environment is approximately 710 mm, 43% of which occurs as rainfall while 57% occurs as snow. The total annual potential evaporation varies between 300 mm and 500 mm per year. Thus, the annual evaporation is well below the annual precipitation.

The average monthly temperature is below zero from November to March. Snowpack accumulation can exceed 350 mm (water equivalent), and the majority of the snow melts in May. A maximum average temperature of 20.3 deg. C occurs in June. Average wind speed varies between 6 and 8 km/hour throughout the year while average monthly relative humidity ranges between 43% and 80%.

The waste rock materials is estimated to contain between 2 to 3 percent pyrite. Acidic drainage is collected and treated with lime. Progressive construction of a 0.8 m thick till cover began in 1990 and was completed in 1994. Seeding with clover and grasses has been completed and vegetative stands are developing well.

The satisfactory performance of the cover requires that a saturated zone is maintained at all times. This limits the diffusion of atmospheric oxygen to the underlying waste rocks and minimizes the oxidation of pyrite and associated production of acid drainage. Analysis for the prediction of cover performance requires accurate evaluation of the flux boundary condition at the cover/atmosphere boundary.

## 4 APPLICATION TO THE DESIGN OF A COVER SYSTEM

Numerical modelling of the water and heat flow through the cover system was carried out using the software called SoilCover (Version 1.0; MEND, 1993). The computer program solves the equations for one-dimensional, transient, coupled heat and mass transfer through the soil cover in response to the ground surface moisture flux.

The theoretical model for predicting evaporation was applied to the soil cover system shown in Fig. 2. Thermal conductivity sensors were installed to measure soil suction and temperature during a six-month period in 1993. Hourly values for precipitation, net radiation, temperature and wind speed were recorded together with the measurements for suction in the soil cover.

The soil-water characteristic curves for the cover materials and waste rocks are shown in Fig. 3. The associated hydraulic conductivities as a function of soil suction are shown in Fig. 4. The coefficient of permeability functions were calculated using the software KCAL (Geo-Slope International Ltd., 1993).

The measured climatic data was used in the theoretical model to predict the values of soil suction in the cover profile. The hydraulic conductivity properties for the soil system were also required in order to solve for the coefficients of permeability and the volume of water flow. Figure 5 shows the cumulative fluxes for the six-month period. The values of precipitation are specified on the basis of measured precipitation. The amount of runoff is computed on the basis of the infiltration rate for the soil during each precipitation event.

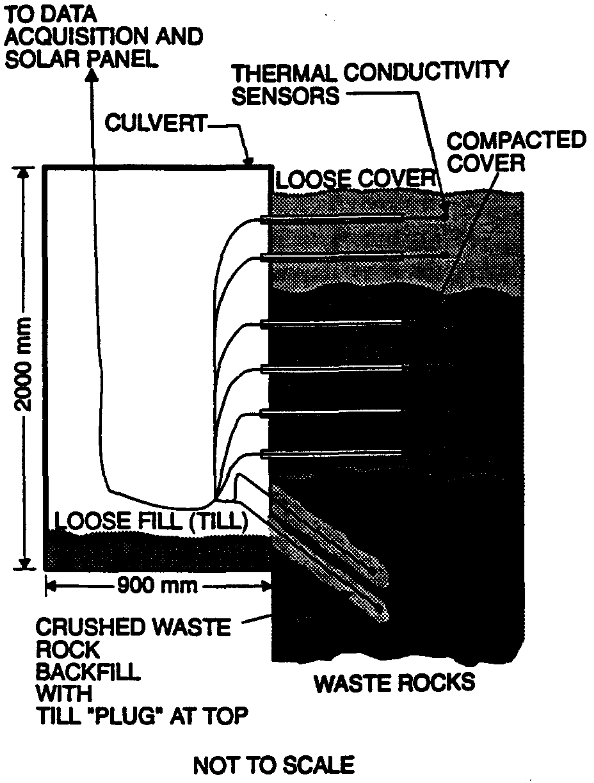

Figure 2. Cross-section of the instrumentation station and sensor installations at Site 1 (after O'Kane, 1995).

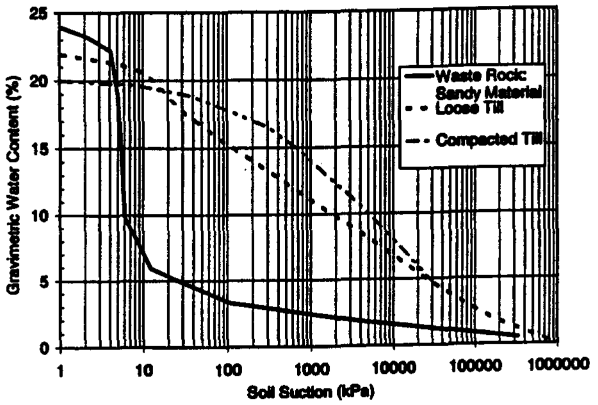

Figure 3. Soil-water characteristic for the uncompacted till, the compacted till and the waste rock (after Swanson, 1995).

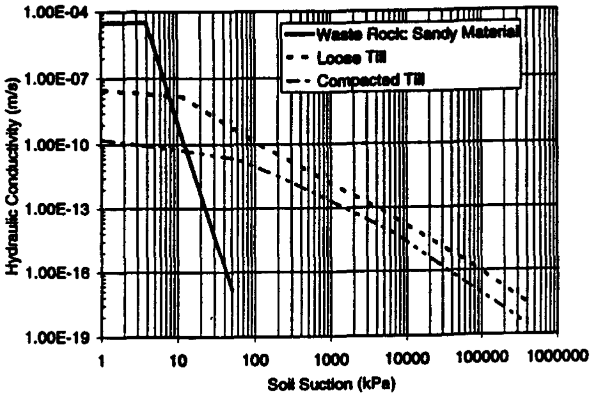

Figure 4. Unsaturated hydraulic conductivity versus matric suction for the cover materials and waste rock (after Swanson, 1995).

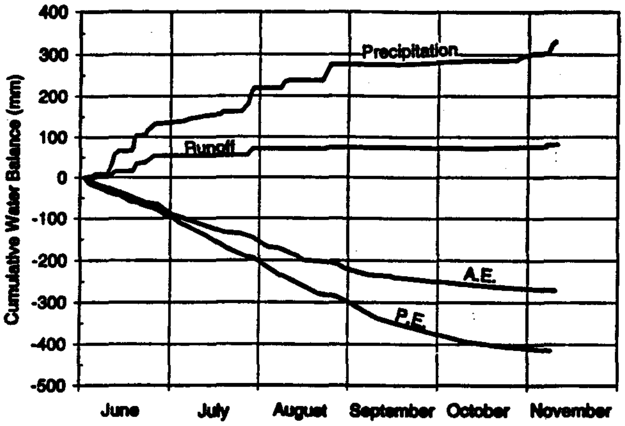

Figure 5. Surface flux boundary conditions for Site 1 (after Swanson, 1995).

Potential evaporation was computed on the basis of the Penman method and measured climatic conditions. The cumulative actual rate of evaporation was computed using the method given by Eq. [2]. The calculated rate of actual evaporation, *AE*, was found to be approximately the same as the potential rate during the first month when precipitation was sufficiently high to maintain a wet soil surface. The rate of actual evaporation decreases below the potential rate (i.e., August to October) when the amount of precipitation is low.

The actual rate of evaporation from the soil surface was not measured directly. However, the values of the computed suctions in the soil can be compared to measured values. The agreement between the computed and measured values (Fig. 6) appears to be quite acceptable. There is also a consistency between the results in Fig. 5 and Fig. 6. For example, during May, the actual evaporation is approximately equal to the potential evaporation because of the high precipitation and the measured and computed values of soil suction are low (Fig. 6) which is consistent with high precipitation. With continued evaporation and lack of rainfall the suctions increase (i.e., August and September) and the actual rate of evaporation decreases (Fig. 5). Once again, the measured soil suctions are close to the computed values.

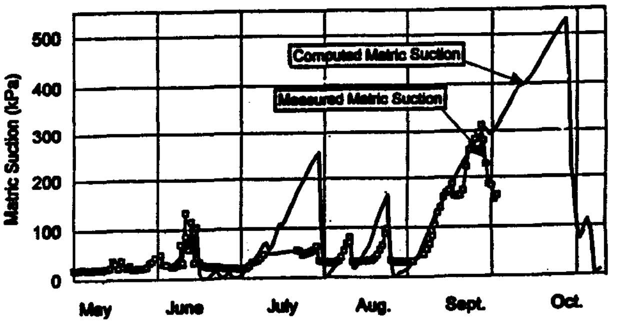

Figure 6. Measured and computed values of matric suction versus time at 13 cm depth in the soil cover at Site 1 (after Swanson, 1995).

## 5 SUMMARY AND CONCLUSIONS

The results of the field measurements at the waste rock site, illustrate that the climatic conditions can be used to predict the actual evaporation from the surface of a soil cover. The computed values can be used as a moisture flux boundary condition to predict the soil suctions throughout the soil cover.

The instrumented soil cover system showed that a fine grained cover material can successfully reduce the liquid water flow to the underlying waste rock. The analysis showed that the liquid water flow was reduced to between 1% and 5% of precipitation from approximately 70% when a soil cover was not used.

It is important that actual evaporation be used for the boundary condition for the predictive model for soil suction. There is need for further studies to be performed at other sites with differing climatic conditions.

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