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SOILCOVER, A NEW COMPUTER MODEL TO AID IN THE DESIGN OF SOIL COVER SYSTEMS FOR ACID GENERATING WASTE ROCK AND TAILINGS

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ABSTRACT

Evaluation of the flow of water across the soil atmosphere boundary is an essential component in the design of soil cover systems. The design of soil cover systems as oxygen barriers for the long term closure of sulphitic tailings and waste rock requires the accurate prediction of moisture fluxes between the cover surface and the atmosphere.

SoilCover is a new software package which uses a theoretical method for predicting the exchange of water between the atmosphere and a soil surface. The theory is based on the well known principles of Darcy's Law and Pick's Law to describe the flow of liquid water and water vapour in the soil profile below the soil atmosphere boundary. A modified Penman formulation is used to compute the rate of evaporation to the atmosphere above the soil atmosphere boundary.

SoilCover predicts the actual rate of evaporation from both saturated and unsaturated soil surfaces. The model accounts for atmospheric conditions, soil properties, and the effects of vegetation. In addition, SoilCover performs a water balance on the basis of infiltration, evapotranspiration, surface runoff, surface ponding, and the soil profile. The change in water content, suction, vapour pressure, temperature, and hydraulic conductivity with respect to time and depth within the soil profile are also calculated.

SoilCover provides a one dimensional transient analysis which can be used interactively with other commercially available software packages for modelling groundwater flow in mine tailings and waste rock. The two dimensional flow system is modelled using the transient flux boundary conditions at the soil cover atmosphere boundary predicted by SoilCover.

INTRODUCTION

Correct evaluation of the flow of water across the soil atmosphere is an essential part of predicting the long term performance of soil cover systems. SoilCover can be used as an engineering tool to aid in the design of soil cover systems as oxygen barriers for the long term closure of sulphitic tailings and waste rock dumps.

The flow of moisture between the soil and the atmosphere is a complex process in which three important factors dominate (Wilson, 1990). The factors do not function as independent variables, but rather as a closely coupled system. The first factor is the supply and demand of water imposed on the soil by atmospheric conditions such as total precipitation, all net radiation, wind speed, and air temperature. The secondly factor is the ability of the soil surface to transmit water which in turn is a function of the hydraulic conductivity and storage characteristics of the soil. The final factor involves the influence of vegetation. The type and density of vegetation effects not only the consumption of water through root uptake but also ground cover and canopy effects. The accurate prediction of the flux boundary condition with respect to water at the soil surface requires a comprehensive and rigorous method which addresses the entire system.

SoilCover is a one dimensional transient analysis program which can be used in tandem with other commercially available software packages to model the flow of water across the soil atmosphere boundary. Similar models are currently being used to make these predictions. For example, the Hydrogeologic Evaluation of Landfill Performance (HELP) computer program is a quasi-two-dimensional hydrologic model of water movement across, into, through, and out of landfills (Schroeder et al, 1984). The HELP model accepts climatologic, soil and design data and utilizes a solution technique that accounts for the effects of surface storage, runoff, infiltration, percolation, evapotranspiration, soil moisture storage, and lateral drainage. HELP is a useful tool for comparing alternative cover designs when dealing with large periods of climatogical data, but absolute results are questionable when the model's assumptions and limits of calibration are not met (Schruben & Bone, 1984). A number of simplifying assumptions are made in the analysis to allow for rapid evaluation of alternative cover designs. These basic assumptions must be met to ensure that the flux boundary condition predicted by HELP are reliable.

The HELP computer program can be used to analyze a cover design when dealing with climatological data that covers a large time frame. For example, Environment Canada supplies precipitation and temperature data for specific locations dating back 50 years and in some cases even further. Computer simulation runs can be made with HELP to identify periods of concern with regards to dry years (in terms of total precipitation), wet years, and mean years. SoilCover can then be used to evaluate alternative cover designs for these periods of concern. For example, SoilCover can be used to study the effect of zero precipitation throughout a growing season on alternative cover design systems. By initially using HELP to identify periods of concern, SoilCover can then be used to accurately predict flux boundary conditions with respect to the flow of water across the soil atmosphere boundary.

SEEP/W is a finite element software product that predicts the flow of water in saturated and unsaturated porous materials such as soil and rock. The comprehensive formulation makes it possible to analyze both simple and highly complex seepage problems (Geo-Slope International Ltd., 1991). SEEP/W requires the specification of a flux boundary at the ground surface. The flux boundary conditions predicted by SoilCover can be used as input into SEEP/W. For example, SoilCover may be used to predict the flux boundary conditions over a given period of time. The computed flux boundary condition is then specified as the upper flux boundary condition to the two dimensional flow system. In this way two dimensional flow systems may be modelled utilizing the correct flux boundary conditions with respect to the flow of water across the soil atmosphere boundary.

THEORY

The one dimensional transient flow equations for coupled heat and mass transfer in the soil cover profile are derived by Wilson (1990). Joshi (1993) provides the finite element formulation for these coupled nonlinear equations. The flow of water vapour and liquid water are described on the basis of Pick's Law and Darcy's Law as follows:

$$\frac{\delta h_w}{\delta t} = C_w^1 \frac{\delta}{\delta y}(k_w \frac{\delta h_w}{\delta y}) + C_w^2 \frac{\delta}{\delta y}(D_v \frac{\delta P_v}{\delta y}) - S \qquad (1)$$

where:

h_w = Total head (m)
t = Time (s)
C_w^1 = Coefficient of consolidation with respect to the liquid water phase (m)
$= \frac{1}{\rho_w \, g \, m_2^w}$
ρ_w = Mass density of water (kg/m^3)
g = Acceleration due to gravity (m/s^2)
m_2^w = Slope of the moisture retention curve (1/kPa)
y = Position (m)
k_w = Hydraulic conductivity (m/s)
C_w^2 = Coefficient of consolidation with respect to the water vapour phase (m^4/Mg)
$= \frac{(P + P_v)}{P \, \rho_w{}^2 \, g \, m_2^w}$
P = Total gas pressure in the air phase (kPa)
P_v = The partial pressure due to water vapour (kPa)
D_v = Diffusion coefficient of water vapour through the soil (kg m/ kN/s)
$= \alpha\beta(D_{vap} \frac{W_v}{RT})$
α = Tortuosity factor of soil
$= \beta^{2/3}$
β = Cross sectional area of soil available for vapour flow
D_{vap} = Molecular diffusivity of water vapour in air (m^2/s)
$= 0.229 \times 10^{-4} (1 + \frac{T}{273.15})^{1.75}$
T = Temperature (K)
W_v = Molecular weight of water (0.18 kg/kmole)
R = Universal gas constant (8.314 J/mole/K)
S = A source term to account for the uptake of water by roots should the soil surface be vegetated

The vapour pressure in the soil is calculated on the basis of the total suction in the liquid phase using the following relationship (Edlefsen & Anderson, 1943):

$$P_v = P_{sv}\, h_r \qquad (2)$$

where:

P_v = Actual vapour pressure within the soil
P_{sv} = Saturation vapour pressure of the soil at it's temperature, T
h_r = Relative humidity of the soil surface as a function of total suction and temperature
$= e^{(\frac{\Psi g W_v}{RT})}$
Ψ = Total suction in the soil (m)

Temperature is evaluated on the basis of conductive and latent heat as transfer as follows:

$$C_h \frac{\delta T}{\delta t} = \frac{\delta}{\delta y}(\frac{\lambda \delta T}{\delta y}) - L_v\,(\frac{(P + P_v)}{P})\frac{\delta}{\delta y}(D_v \frac{\delta P_v}{\delta y}) \qquad (3)$$

where:

T = Temperature (^0C)
C_h = Volumetric specific heat of the soil as a function of water content ($J/m^3/^0C$)
$= C_v \rho_s$
C_v = Specific heat of the soil ($J/kg/^0C$)
ρ_s = Mass density of the soil (kg/m^3)
λ = Thermal conductivity of the soil ($W/m/^0C$)
L_v = Latent heat of vapourization of water (J/kg)

Soil evaporative fluxes are calculated on the basis of the vapour pressure gradient between the cover surface and the atmosphere above. A modified Penman formulation (Wilson, 1990) is utilized and may be written as follows:

$$E = \frac{\Gamma Q + \nu E_a}{\Gamma + A\nu} \qquad (4)$$

where:

E = Vertical evaporative flux (mm/day)
Γ = Slope of the saturation vapour pressure versus temperature curve at the mean temperature of the air
Q = Net radiant energy available at the surface (mm/day)
ν = Psychromatic constant
E_a = $f(u)P_a(B - A)$
$f(u)$ = Function dependent on wind speed, surface roughness, and eddy diffusion
$= 0.35(1 + 0.15U_a)$
U_a = Wind speed (km/hr)
P_a = Vapour pressure in the air above the evaporating surface
B = Inverse of the relative humidity of the air
A = Inverse of the relative humidity at the soil surface $= \frac{1}{h_r}$

Equation 4 describes evaporation from a soil surface on the basis of net radiation, wind speed, and the relative humidities of the air and the soil surface. This expression reduces to the conventional Penman formulation (Penman, 1948) when A = unity (i.e., relative humidity of 100 percent for a saturated surface). The relative humidity of the soil surface is evaluated by solving the moisture flow equation and the modified Penman formulation simultaneously. Infiltrative fluxes due to precipitation are also specified as an upper boundary condition for the moisture flow equation while the water table defines the lower boundary condition. Temperatures within the soil profile are required for the solution of the moisture flow equation, hence the heat flow equation must also be solved simultaneously.

MODEL PARAMETERS

Three areas of model parameters must be determined to accurately predict the flux boundary condition with respect to water at the soil atmosphere boundary. Soil parameters for each soil layer in the one dimensional soil profile must be determined. Climatic parameters for the location of the study area must also be determined. Finally, vegetation parameters must be determined if a vegetative surface is to be modelled.

Soil Parameters

The soil parameters for each of the soils in the one dimensional soil profile must be determined during a laboratory investigation. Laboratory tests can include:

1) Grain size analysis
2) Moisture retention characteristics
3) Thermal property analysis
4) Shrinkage limit tests
5) Saturated consolidation-hydraulic conductivity tests

The laboratory tests listed above will aid in interpreting the temperature, suction, and water content profiles, as well as the actual and potential evaporation rates predicted by SoilCover. However, modelling of a soil cover system with SoilCover requires an accurate measure of the relationship between the suction and water content of all soils in the cover/waste profile. Wilson (1990), Haug et al (1993), Wilson et al (1991), Yanful (1991) provide discussion on some of the laboratory procedures listed above.

Moisture Retention Characteristics

Measuring the moisture retention characteristics of a soil is a relatively simple laboratory procedure. The moisture retention characteristics are determined by laboratory pressure plate testing and vapour equilibrium testing. The moisture retention curve of a soil determines the relationship between suction and water content for the soil. Pressure plate testing provides a relationship between matric suction and water content for soil suctions between 0 and 500 kPa. Vapour equilibrium testing is used to determine a relationship between total suction and water content for soil suctions greater than 500 kPa. Total suction is defined as the sum of the matric suction and osmotic suction as follows:

$$\Psi = M + O \qquad (5)$$

where:

Ψ = Total suction or potential in the liquid water phase
M = Matric suction
= $(U_a - U_w)$
U_a = Pressure on the air side of the air water interface
U_w = Pressure on the water side of the air water interface
O = Osmotic suction

The matric suction is to a large extent a function of texture (grain size) and structure (Nicholson et al, 1989). Essentially, matric suction is the difference in pressure across the air water interface. Pressure plate cells have a saturated ceramic disk at the bottom of the cell. Air does not flow through the cell unless the air pressure exceeds the air entry value of the ceramic disk. Small amounts of air can diffuse through the water in the pores of the high air entry disk. However, the test is not affected as the air pressure in the cell is maintained by the inlet pressure. The high air entry disc at the base of the pressure plate cell must be saturated prior to the start of the test. A typical pressure plate cell is shown in Figure 1.

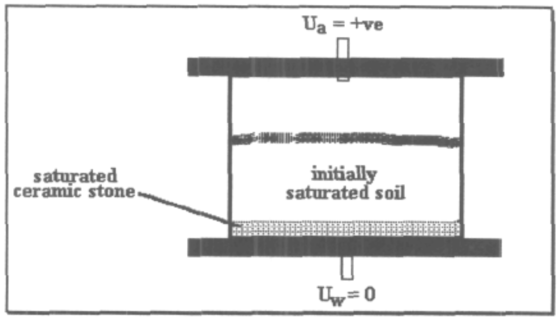

Figure 1 Pressure plate testing apparatus

Osmotic suction occurs because of the presence of dissolved matter in the water in the soil matrix voids. Conventional glass desiccators, such as a Labline Model 3553 Incubator (Wilson, 1990) can be used to determine the moisture retention characteristics of a soil for suctions greater than 500 kPa. The relative humidity and vapour pressure in the glass desiccators is controlled using saturated salt solutions. The total suction is calculated using the Edlefsen & Anderson (1943) formulation described in equation 2 after the water content of the soil sample has come to equilibrium in the desiccator. Temperature has a significant effect on the humidities of saturated salt solutions. Appropriate temperatures for the vapour equilibrium test should be chosen to represent the varying seasonal temperatures of the study area. Moisture retention characteristics for a typical silt and sand are illustrated in Figure 2.

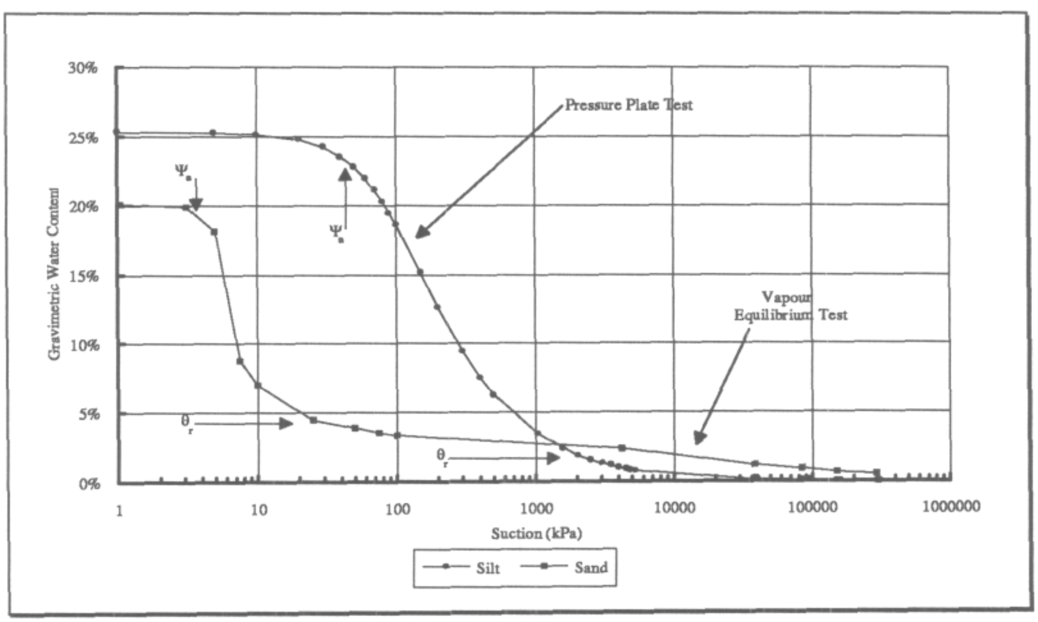

Figure 2 Moisture retention curves for the silt and sand

The hydraulic conductivity of an unsaturated soil is a function of water content and soil suction. Laboratory procedures are available for determining the relationship between hydraulic conductivity and matric suction. Various methods of calculating the hydraulic conductivity using the moisture retention curve are available. Such as, Laliberte et al (1968), and Van Genutchen (1980). The hydraulic conductivity functions for the silt and sand as determined using the relationships described by Laliberte et al (1968) are shown in Figure 3.

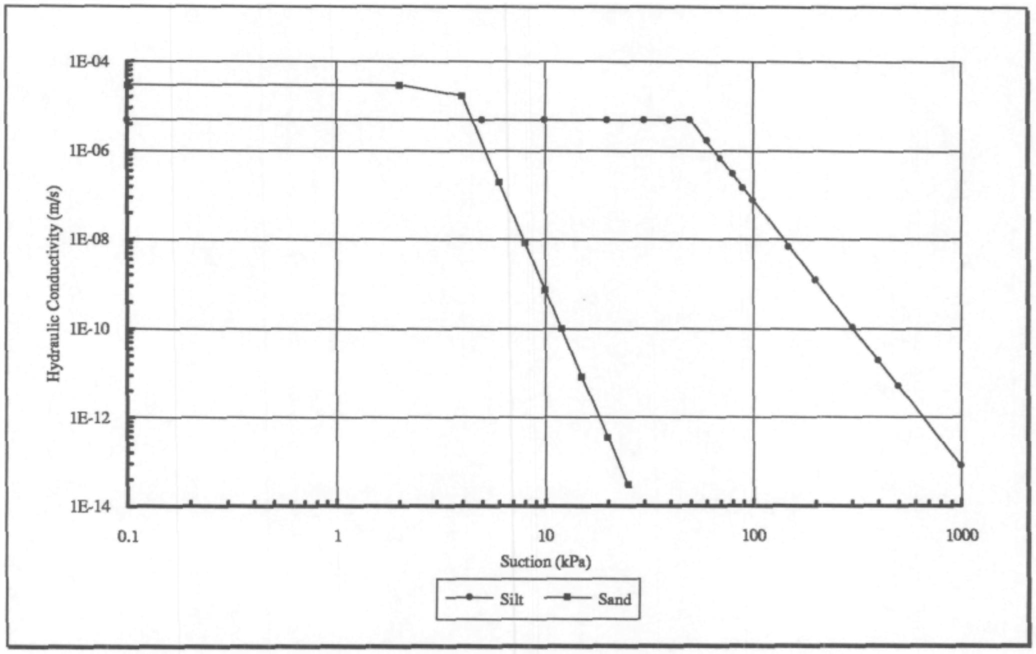

Figure 3 Hydraulic conductivity versus suction for the silt and sand

Climatic Parameters

The equations used for atmospheric coupling require climatic parameters. Regional climatic data is available from Environment Canada. If site specific data is desired, a weather station can be utilized. The weather station can be very complex or as simple as gauges to measure mean, maximum, and minimum temperature combined with a manually operated rain gauge. A complex weather station can include such devices as a rechargeable battery, solar panel, temperature probe, wind velocity monitor, ultrasonic depth/level sensor, relative humidity sensor, all season precipitation gauge, short wave radiation measurement device, net radiometer, and an evaporation pan. All of the instrumentation could be connected to a datalogger.

Vegetation Parameters

Vegetation plays a significant and dynamic role in the evapotranspiration process, particularly on well vegetated areas used for agricultural crops (Saxton, 1982). SoilCover accounts for crop effects in a manner that is dependent on the input specified by the user. A vegetative uptake source term method is combined with a shade, or cover factor term. The method used by SoilCover accounts for the effects of canopy cover, phenology, root depth and density, and water stress.

MODEL SIMULATIONS

A soil profile consisting of a coarse grained soil overlying a fine grained soil will form a capillary barrier at the interface of the soils. The concept of capillary barriers has been applied by Rasmuson & Erikson (1986), Nicholson et al (1989), Barbour (1990), and Yanful (1991) to reduce acid generation of mine tailings. SoilCover is used to predict the evaporative fluxes and water content profiles of a uniform soil profile and a layered soil profile.

Single Soil Layer

An initially saturated soil profile consisting of 400 cm of fine grained soil was modelled for a 60 day period. Climatic data was used to simulate an initial period of precipitation followed by a period of zero precipitation. The effects of vegetation were not modelled. The 400 cm soil profile consisted of the silt described earlier. Figure 4 illustrates the grain size distribution for the sand and the silt. The silt was assumed to represent a tailings material. This is a reasonable assumption based on the grain size distribution of the silt. The thermal conductivity and volumetric specific heat of the silt and sand were computed using the method described by de Vries (1963).

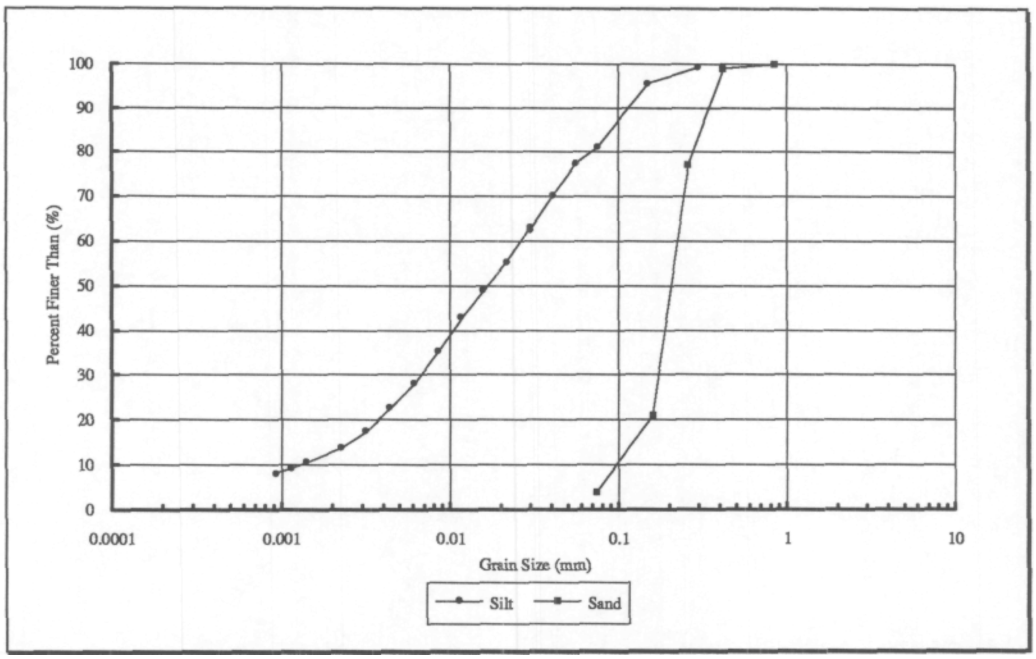

Figure 4 Grain size distribution for the silt and sand

Figure 5 shows the prediction of actual and potential evaporative flux from the soil surface of the 400 cm profile of tailings. The infiltrative fluxes due to precipitation are illustrated by the square symbols. The initially saturated profile, combined with precipitation events and the moisture retention characteristics of the tailings material cause the soil surface to have the same rate of evaporation as from a free water surface. However, during the simulation the water content of the tailings profile decreases due to the evaporative demand from the atmosphere. Figure 6 illustrates the change in the water content profile during the model simulation. The degree of saturation during the latter dry period of the simulation fell to 80%. Given an extended dry period of more than 30 days the degree of saturation in the tailings profile will continue to decrease below 80%.

Nicholson et al (1989) and Yanful (1991) have shown that oxygen diffusion through a soil is reduced as the degree of saturation of the soil profile increases. The minimum flux of oxygen, limited by the infiltration of oxygen saturated water (Nicholson et al, 1989), will occur when the soil is saturated. Zones of oxidation in a tailings profile occur 0.5 to 3.0 meters from the tailings surface (Nicholson et al, 1989). The water content profile predicted by SoilCover illustrates that the tailings profile will fall below the saturation level at these depths and allow oxygen to diffuse to potential zones of oxidation. If the tailings are susceptible to sulphide oxidation, acid generation will occur as oxygen diffuses though the gas filled pores.

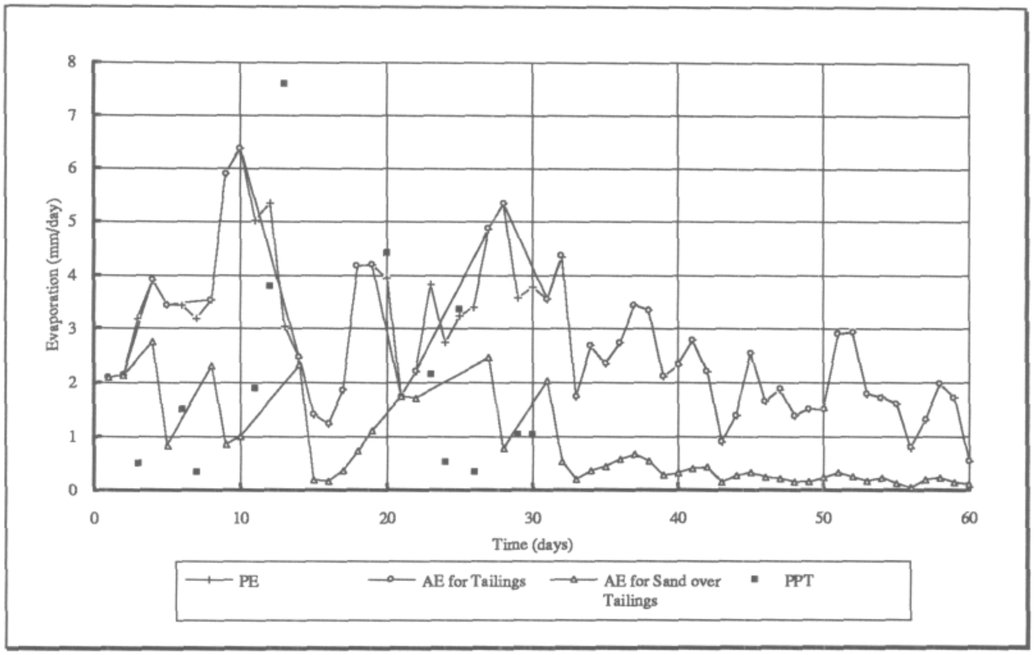

Figure 5 Potential and actual evaporation versus time for the tailings and sand over tailings profiles

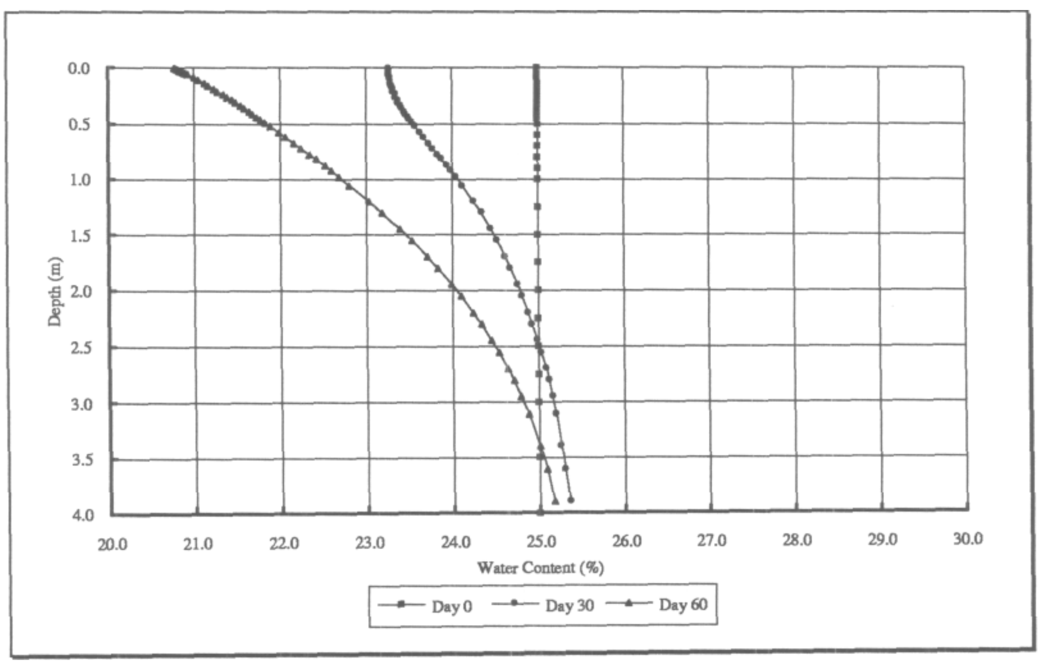

Figure 6 Water content versus depth for the tailings profile

<u>Layered Soil System</u>

Extensive laboratory and field research has shown that limiting the availability of oxygen to potentially acid generating tailings or waste rock will reduce acid drainage (BC AMD, 1989). A coarse grained soil overlying the fine grained tailings will enable the tailings to remain saturated. The coarse grained soil will dry out as water evaporates from the soil surface and soil suction increases. A capillary barrier will be established at the coarse and fine grained soil interface. A similar soil suction will be present at the interface in both the silt and the overlying sand. However, figure 2 illustrates that for a given value of matric suction the silt will have a higher water content than the sand.

Theoretically the tailings will remain saturated if the suction corresponding to the residual water content (9_r) of the sand is less than the air entry value (¥$_a$) of the tailings. The air entry value is the highest suction for which the largest pores in the soil will retain water. If the soil suction increases above the air entry value the largest pores will drain. As the soil suction increases the progressively smaller pores drain. The residual water content is defined as the water content of a soil such that a significant increase in soil suction does not correspond to a decrease in water content. Figure 3 shows that the hydraulic conductivity of the sand at the residual water content is less than $10^{'20}$ m/s. At this extremely low value, water in the underlying tailings is unable to flow upward through the sand and the underlying tailings will remain saturated.

The water content profile predicted by SoilCover for the layered system is shown in figure 7 and demonstrates the effects of a capillary barrier. Above the sand/tailings interface the water content in the sand layer increases and decreases as precipitation and evaporation occurs. However, the water content of the underlying tailings remains high even during the prolonged dry period. In general, an engineered cover consisting of a layer of oxidized tailings between the overlying sand cover and underlying unoxidized tailings should significantly reduce the potential acid generation.

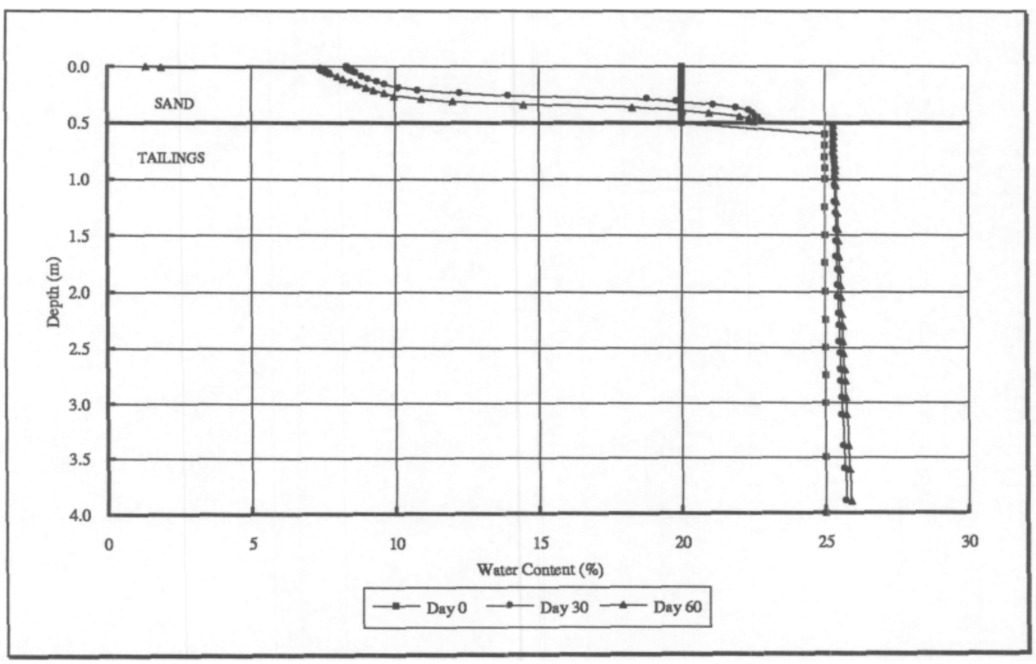

Figure 7 **Water content versus depth for the sand over tailings profile**

The actual evaporation from the layered soil profile is shown in figure 5. The evaporative flux to the atmosphere will continue to decrease the water content in the overlying sand. SoilCover predicted the soil suction in the 4 mm of sand below the surface to be greater than 1 x 10^5 kPa. At this value of soil suction, the hydraulic conductivity of the sand is less than 10^{-18} m/s. Hence, the flow of water to the surface is reduced and consequently the evaporation rate falls below the potential.

During prolonged dry periods the water content of the sand will continue to decrease slowly. The hydraulic conductivity in the sand will approach zero. The evaporative flux from the surface of the sand will occur only through water vapour diffusion which is very slow. The underlying tailings will remain saturated as the sand above the interface will not allow the water in the tailings to flow to the surface. The diffusive flux of oxygen to potential zones of oxidation in the tailings will be minimized as the tailings remain saturated.

Nicholson et al (1989), and Barbour (1990) discuss the use of a fine soil layer overlying a coarse soil layer to reduce acid generation in mine tailings. An example of this occurs when materials with a large contrast in texture, such as a clay till cover material placed over a porous waste rock dump, are used. The capillary barrier created at the interface will allow the retention of water in the fine overlying layer and reduce the diffusive flux of oxygen into the potentially acid generating waste rock. However, the clay till cover material may also be desiccated by evaporation in the same manner as the tailings surface previously demonstrated.

SUMMARY AND CONCLUSIONS

The results of the two model simulations demonstrate that SoilCover can be an effective aid in the design of soil cover systems as oxygen barriers for the long term closure of sulphitic tailings and waste rock dumps. The water content profile predicted by SoilCover demonstrates the transient distribution of water due to evaporation and infiltration. The flux from the surface predicted by SoilCover can be used as a flux boundary condition for two dimensional modelling of an engineered soil cover system. Although not presented here, SoilCover will also predict the transient soil temperature profile as heat flows through the cover material.

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