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THE MODELLING OF MOISTURE MOVEMENT IN ENGINEERED SOIL COVERS FOR MINE WASTE ROCK DUMPS

PHASE II OF A COVER MODELLING RESEARCH PROGRAM

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ABSTRACT

A two-phased cover instrumentation and modelling research program has been initiated at a waste rock dump site. The first phase of the research program involves field instrumentation and monitoring of the in-place cover. The second phase involves modelling infiltration and evaporation in the cover system using a soil/atmosphere flux model that has been developed at the University of Saskatchewan. The soil/atmosphere model used is a one dimensional, transient, finite element, water and heat transport model that uses a physically based method to predict the exchange of water between the atmosphere and a saturated or an unsaturated soil surface. This paper describes the application of the soil/atmosphere model in predicting the field responses of the in-place cover system at the waste rock dump site.

INTRODUCTION

Mine waste rock and tailings that contain sulphides can generate leachate which is low in pH and high in heavy metals. Exposure of the sulphidic materials to oxygen provides the mechanism for the acid generating process and infiltrating waters provide the means of transport for the acidic pore-water. This process is referred to as acid mine drainage (AMD). Soil covers are being used as the closure option for many sites where AMD is of concern.

The objective of the engineered soil cover for AMD problems is two-fold. The first objective is to reduce the infiltration of rain water into the waste rock that transports the leachate. The second objective of the cover system is to limit the acid generating process by limiting oxygen diffusion into the waste rock. In humid or "wet" regions this is accomplished by maintaining a high degree of water saturation in the cover soil. In order to achieve these objectives an accurate quantification of the exchange of moisture at the surface of the engineered soil cover is required for both design and analysis. Accuracy in design and analysis is required as minining companies need to come up with effective and economical decommissioning strategies. Furthermore, regulatory agencies must be able to assess the decommissioning strategies to determine their effectiveness and acceptability.

A physically based computer model has been developed at the University of Saskatchewan to predict the exchange of moisture between the atmosphere and a soil surface. A two-phased research program has been initiated to evaluate the ability of the soil/atmosphere model to predict the field response of in-place cover systems. The first phase of the research program involves the installation of field monitoring equipment to measure climate conditions and to measure field response such as soil water content, matric suction, and temperature within the cover. The second phase of the research program involves applying the soil/atmosphere model to the instrumented site to evaluate the ability of the model to simulate the responses as seen in the field and to develop a generalized methodology for application of the model to the analysis and design of engineered soil covers. This paper describes preliminary results of computed and measured field responses of an in-place cover system for a waste rock dump.

THEORETICAL BACKGROUND

Water movement through soils can be generalized as a three component system made up of a soil / atmosphere interface, the unsaturated zone, and the saturated zone (Figure 1). In the past, modelling has been restricted to the saturated zone only. Advances in unsaturated soil technology in the past decade have led to the present day modelling of saturated / unsaturated soil systems. The third component as described by the soil-atmosphere interface governs the net surface inflow in a natural system. The soil-atmosphere interface is a dynamic zone consisting of both liquid and vapor flow. This component is crucial to many modelling situations but has only been approximated in the past because an accepted physically based method to quantify moisture movement in this zone was not available.

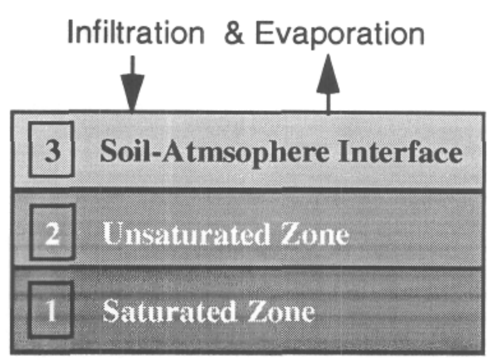

Figure 1 Generalized flow components in a natural soil system

The soil/atmosphere system is a coupled system in two ways. Firstly, moisture movement in the soil is influenced by both hydraulic (i.e., total head) gradients and temperature gradients which form a a coupled system involving both water and heat transfer. Secondly, the movement of moisture within the soil profile is linked to the supply and demand established by atmospheric conditions (i.e., rainfall and evaporation). Moisture supply is relatively straightforward but the evaporative demand is somewhat more complex as it is a function of climatic and soil conditions.

Penman (1948) developed a relationship to estimate the potential evaporation rate from a saturated surface. The rate of evaporation from a soil surface will decrease from the potential rate as a soil begins to dry out. For unsaturated soils the original Penman equation will overestimate evaporation resulting in drier profiles and underestimated infiltration rates (Machibroda et al, 1993; Morton 1975). Wilson (1990) developed a theoretical heat and water transport model which is coupled to the atmosphere through a modified Penman formulation that allows for the calculation of evaporation from a saturated or an unsaturated soil surface. SoilCover Version 0.9 and 1.0 (MEND, 1993) is based on the model developed by Wilson (1990) and is the focus of this paper.

THEORETICAL DEVELOPMENT

The SoilCover model uses a one-dimensional finite element formulation. The theory is based on the well known principles of Darcy's and Pick's laws to describe the movement of liquid water and water vapor respectively in the soil profile. The evaporation from the soil surface is calculated on the basis of atmospheric and soil conditions using a modified Penman formulation.

Water and Heat Transfer Coupling Equations (1) and (2) present the coupled water and heat transfer relationships (Wilson, 1990; Wilson et al, 1991; Fredlund and Rahardjo, 1993) The equations are coupled through the vapour pressure term (Pv) which is determined using a relationship by Eldefson and Anderson (1943) shown in Equation (3).

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

$$C_h \frac{\delta T}{\delta t} = \frac{\delta}{\delta y}\left(\lambda \frac{\delta T}{\delta y}\right) - L_v \left(\frac{P + P_v}{P}\right) \frac{\delta}{\delta y}\left(D_v \frac{\delta P_v}{\delta y}\right) \quad (2)$$

$$P_v = P_{sv} h_r \quad (3)$$

Atmospheric Coupling

The influence of the atmosphere on the system (i.e., atmospheric coupling) is accomplished through the calculation of water flux and temperature boundary conditions. The evaporative flux at the soil surface is a function of the vapor pressure gradient between the soil surface and the atmosphere and is described by a modification to the Penman (1948) equation proposed by Wilson (1990) (Equation 4). The temperature at the soil surface is estimated using a relationship proposai by Wilson (1990) given in Equation (5). Equation (5) utilizes the same wind speed function and psychometric constant as seen in the modified Penman equation.

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

$$T_s = T_a + \frac{1}{\nu f(u)}(Q - E) \qquad (5)$$

Daily Variations in Climate Parameters

Daily climatic data is required as input to the SoilCover model. Detailed climate parameters such as minimum and maximum air temperature, minimum and maximum relative humidity, daily net radiation, and average wind speed are used. The net radiation, air temperature, and relative humidity values are varied during the day using a sinusoidal relationship to represent the diurnal variation that occurs throughout the day. Machibroda (1993) incorporated the modified Penman formulation and diurnal variations into the SoilCover model and evaluated its application in field situations. Joshi (1993) developed the finite element formulation for the original model developed by Wilson (1990).

PRESENTATION OF RESULTS

Model Input: Cover Cross-section, Material Properties, and Climatic Data

The cover system that is studied in this paper is shown in Figure 2. The cross-section consists of approximately 50 cm of compacted glacial till overlain with approximately 50 cm of loose glacial till. A vegetative cover has not yet been fully established at the location being studied and therefore the cross-section is analyzed as a bare soil.

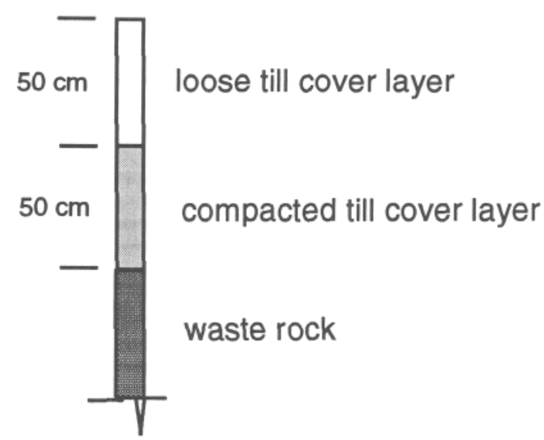

Figure 2 Cover cross-section

The hydraulic properties for the cover are shown in Figure (3a) and (3b). The laboratory moisture retention properties of the compacted cover (Figure 3a) were determined for the full range of suctions from 0 to 100000 kPa using the pressure plate and vapor equilibrium methods during Phase I work by (O'Kane 1993). A field moisture retention curve for the loose and compacted till cover layers was estimated using results of neutron probe water content and matric suction sensor readings. As seen in Figure 3a the compacted till field moisture retention is slightly different than the laboratory curve. This is attributed to the larger macro-structure present in the field that is difficult to represent in a small-scale laboratory testing (Ho, 1988). The saturated hydraulic conductivity for the compacted and the loose till materials were determined through lab testing by O'Kane (1993) and others. Laboratory values of 2.0 e-8 cm/s and 6.0 e-7 cm/s were typical for the compacted and loose materials respectively. Field values may be higher than the reported laboratory values due to the larger macro-structure likely present in the field. The unsaturated hydraulic conductivity functions for the compacted and the loose materials were estimated using the computer program KCAL (Geo-Slope, 1993). The thermal properties are not presented in this paper but were estimated using the computer program "TheHyProS" (Tarnawski and Wagner, 1993). The thermal conductivity versus gravimetric water content and specific heat versus gravimetric water content functions were estimated using percent clay, silt, sand, and gravel and the bulk density as input into the "TheHyProS" model.

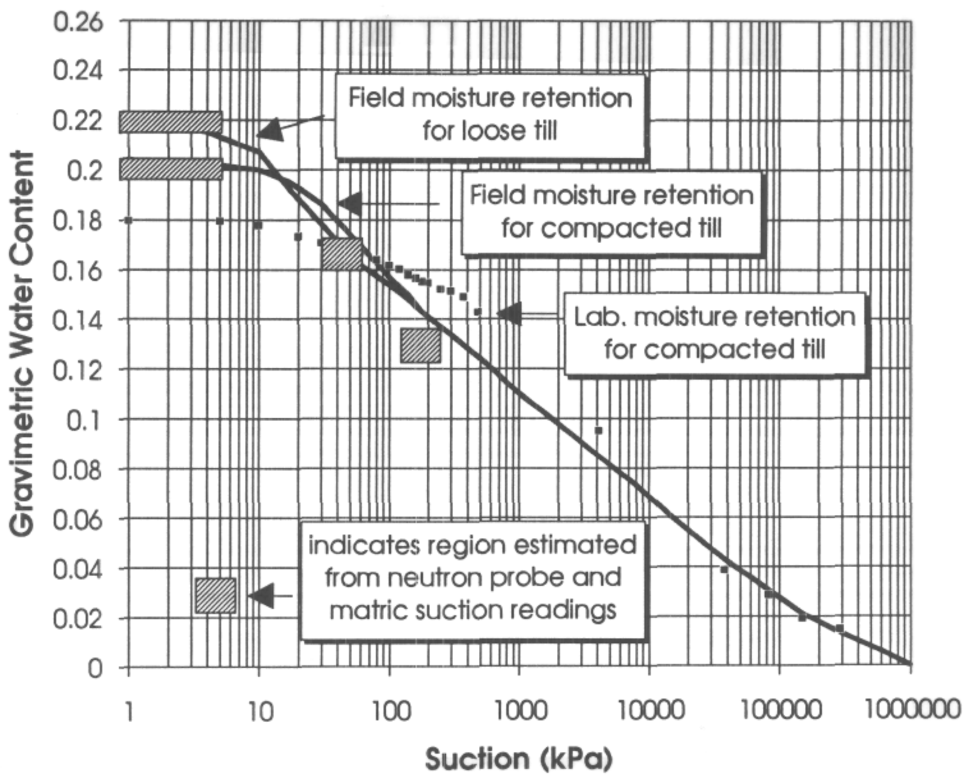

Figure 3a Laboratory and field moisture retention functions for the compacted and loose till cover materials

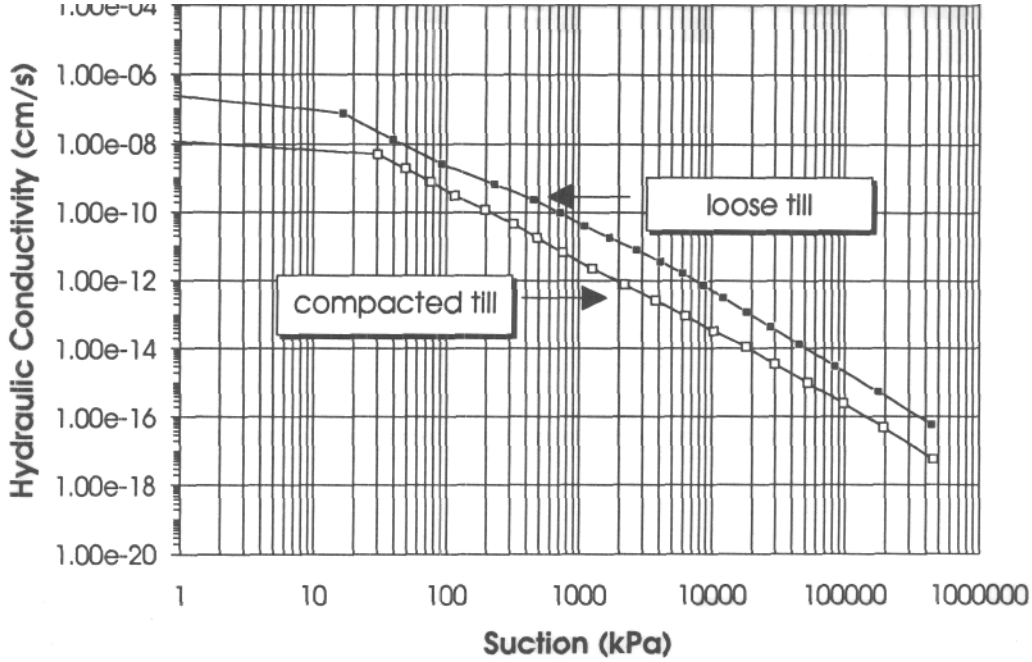

Figure 3b Unsaturated hydraulic conductivity functions for the compacted and loose till cover materials

The waste rock material is represented in the model as a granular material. A preliminary sensitivity analyses on the cover system revealed that accurate quantification of the hydraulic properties of the waste rock were not required for this particular situation due to the high air entry value and the low hydraulic conductivity of the compacted till cover.

Detailed daily climate data was measured with an on-site weather station that was installed during Phase I by O'Kane (1993). Values of minimum and maximum air temperature and relative humidity were therefore available along with average wind speed and net radiation for each day during the simulation period May 1 to August 31. Daily precipitation values were also used.

Modelling Results: A comparison of Measured and Computed Field Responses

The measured and computed field responses were compared over a summer period from May 1 to August 31. Water content readings were available from a nearby neutron probe access tube. Soil matric suction and temperature readings were available at various depths within the cover profile. The measured values of water content, matric suction, and temperature form the measured field responses that are used to compare to computed field responses determined by SoilCover.

Figure 4 presents a comparison between measured and computed suction values at a depth of 13 cm. The first 30 days were used as a calibration phase by adjusting the saturated hydraulic conductivity of the loose and compacted materials to achieve similar responses. This phase was necessary as the material properties determined in the laboratory do not represent field conditions to the degree of accuracy required for this evaluation. The net surface flux calculated by SoilCover is shown at the top of Figure 4 as a reference for the soil suction responses seen at a depth of 13 cm. Comparison of the measured and computed matric suction response in the soil reveals similar trends.

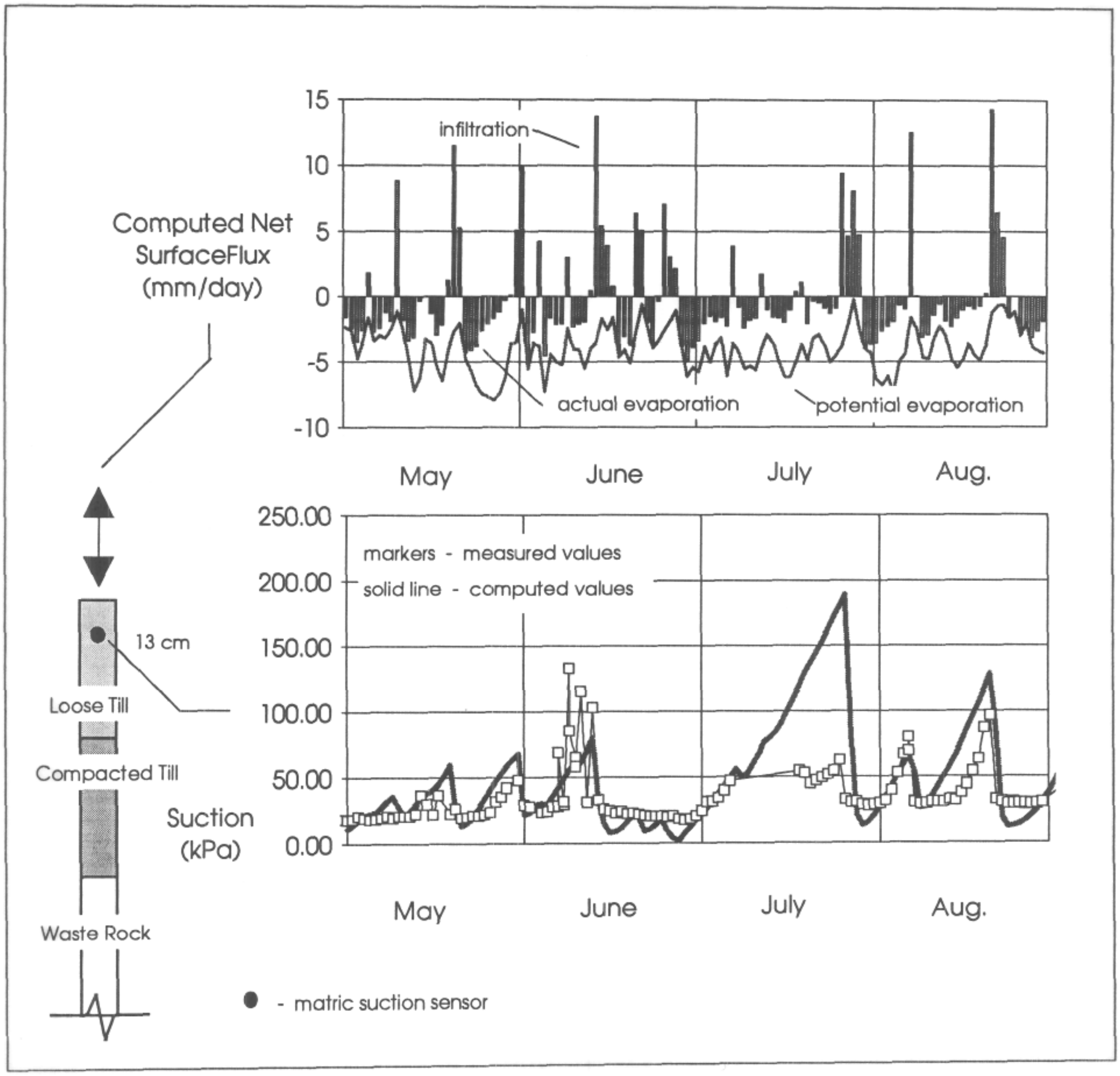

Figure 4 Net surface flux and computed and measured matric suctions at a depth of 13 cm for the cover system during the four month simulation period.

Figure 5 presents a profile view of gravimetric water content within the cover and waste rock. The cover was initially assumed to be close to 100 % saturation after snowmelt. The June 4 reading was used for the calibration phase; that is, the saturated hydraulic conductivity for the loose and compacted layers was adjusted within an expected range until the computed response was similar to the measured response. This calibration phase was an iterative procedure based on the measured June 4 water content profile and the matric suction values measured during the first 30 days at a depth of 13 cm. Comparison of measured and computed water content readings reveals similar trends throughout the four month simulation for both the compacted and loose cover layers.

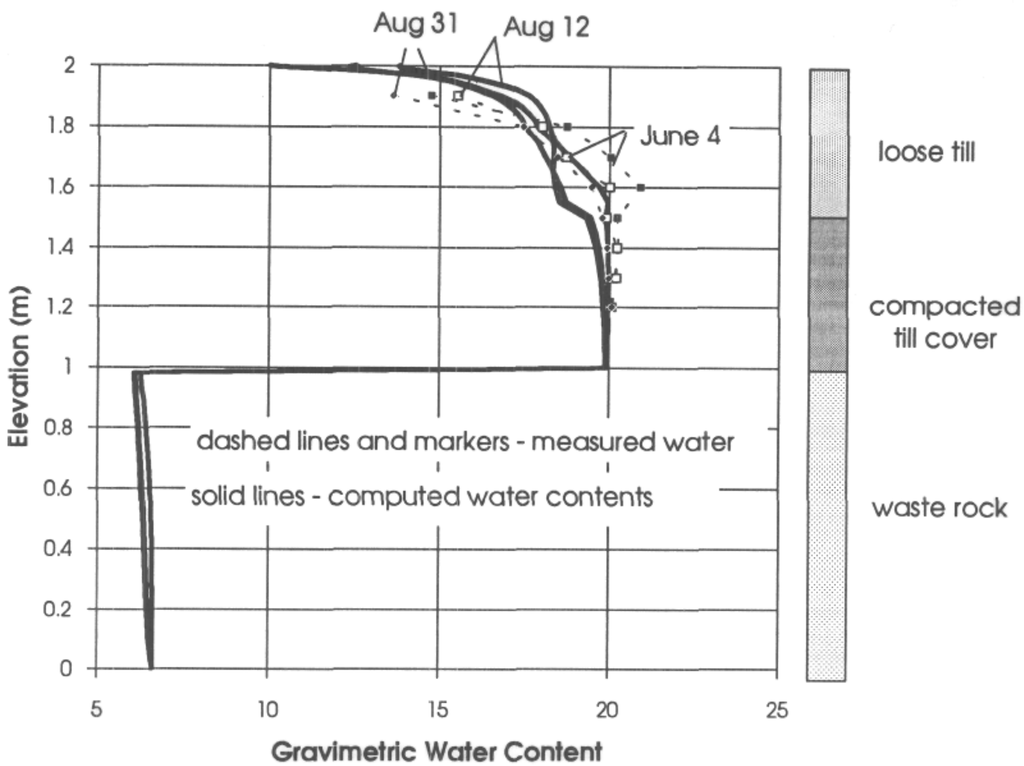

Figure 5 Computed and measured gravimetric water content profiles for the cover system during the four month simulation period

Figure 6 presents a comparison between measured and computed soil temperatures. The model did not require calibration with respect to heat flow. The temperature values shown in Figure 6 correspond to the end of each day. Comparison of the measured and computed temperatures shows very good agreement.

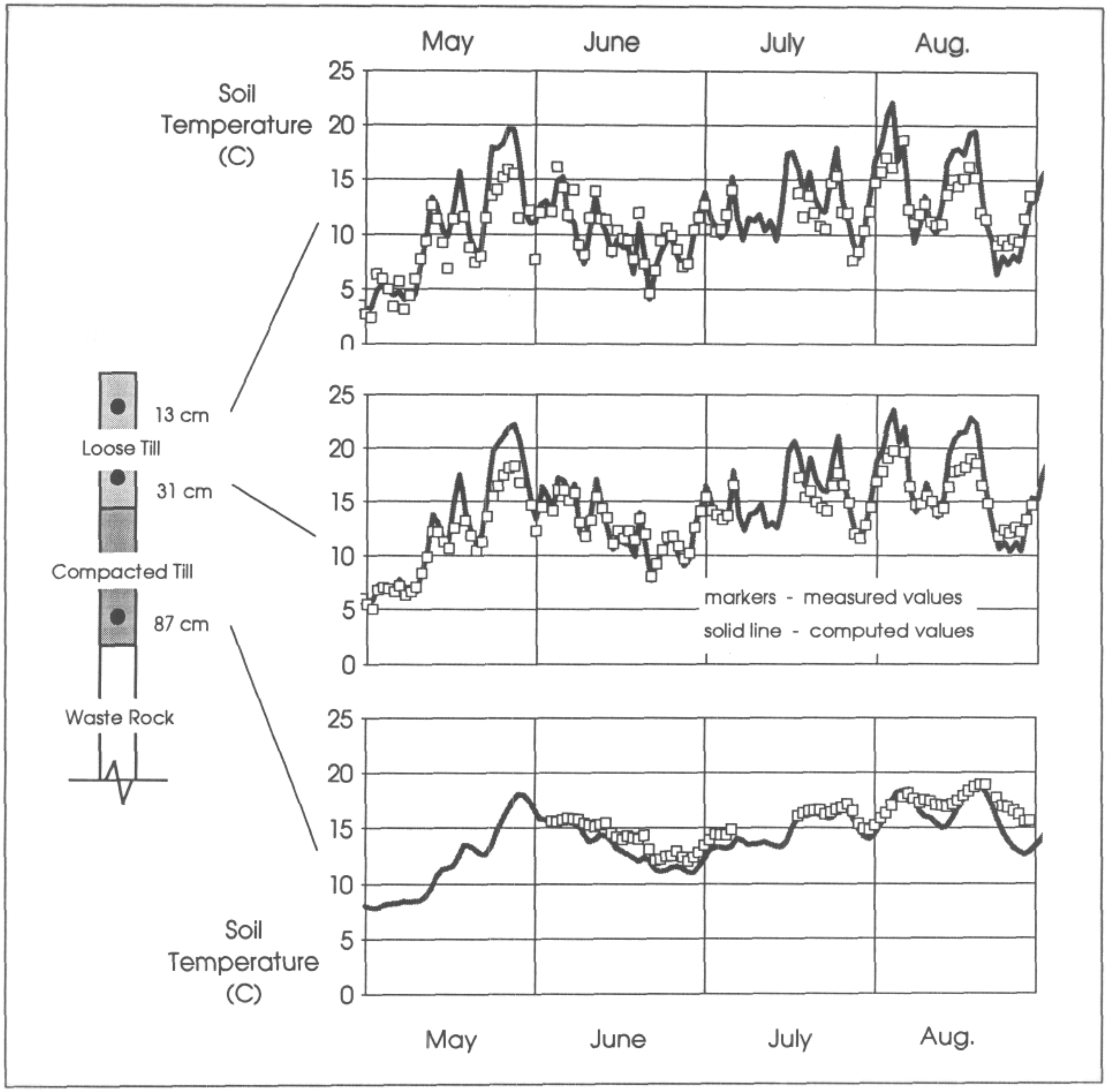

Figure 6 Computed and measured soil temperatures for various depths within the cover system during the four month simulation period

ANALYSES AND DISCUSSION

The computed and measured field responses for matric suction, water content, and temperature show similar trends throughout the 123 day period studied. The matric suction response at a depth of 13 cm was quite important to the study as it provides an indirect evaluation of the atmospheric coupling in the SoilCover model. Viewing the net surface flux graph together with the suction at 13 cm graph in Figure 4 reveals that the suction in the top 13 cm drops rapidly after a heavy rainfall. This trend was noticed in both the computed and measured results. The measured suctions in the dry periods following heavy rainfall reveal an increase which is also quite rapid. The response of the computed suction is somewhat faster but nonetheless follows similar trends indicating that the model is calculating evaporative conditions similar to actual field conditions for this situation.

The measured water contents for the cover revealed that the loose till cover was a dynamic zone with little change in water content noticed in the compacted layer for the four month period. Like the field response the computed values revealed that moisture storage in the loose material supplied the majority of the evaporative demand during the four month period.

The measured temperature readings showed that the soil temperature fluctuates near the surface and remains quite steady for the deeper cover zones. This trend was revealed also with the computed values which compared very closely to the measured values. The surface temperature equation for atmospheric coupling (i.e., Equation 5) is the driving force behind heat flow for the profile. Good agreement between measured and computed values indicates that the surface temperature equation may be a good representation of the field situation.

Predictive Modelling

The focus of this paper is on reporting the results of field response modelling. It is worth noting the reason for modelling is to provide a predictive tool for analysis and design. For example, extreme climate conditions may be investigated once the modeller has confidence that the model is adequately describing field conditions. Important questions may be addressed such as, will a compacted layer desaturate enough during an extreme dry summer to increase oxygen diffusion rates significantly. The objective is to predict cover performance (i.e., degree of saturation or net moisture movement through the cover) for periods of extreme climate conditions where measured field data cannot be used.

In general, the objective of the present research program described here is to examine field monitoring techniques for engineered soil cover systems and to evaluate the SoilCover model and develop a generalized methodology for its application as a predictive tool in the analysis and design of engineered soil covers.

SUMMARY AND CONCLUSIONS

A computer model has been developed for the purpose of quantifying the exchange of water between the atmosphere and a soil surface. A research program has been initiated to study the moisture movement within a cover system constructed at a waste rock dump site. Good agreement between measured field and computed responses (i.e., soil suction, temperature and water content) for the in-place cover was achieved for a four month summer period. The preliminary results indicate that the soil/atmosphere model is providing a good characterization of the field situation.

Research in the application of this model to cover system analysis is ongoing at a number of sites. The ultimate objective of the research described is to provide verification of the computer model in field situations so that it can be utilized by mine owners and regulatory agencies as a design and analysis tool for cover systems to reduce acid generation rates.

GLOSSARY OF EQUATION VARIABLES

h_w = Total head (m)
t = Time (s)
C_w^1 = Coefficient of consolidation with respect to the liquid water phase = $\frac{1}{\rho_w g}$
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 = $\frac{(P + P_v)}{P \rho_w^2 g m_2^w}$
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) = $0.229 \times 10^{-4} (1 + \frac{T}{273.15})^{1.75}$ where T=Temp. in degree (K)
  W_v = Molecular weight of water (0.18 kg/kmole)
  R = Universal gas constant (8.314 J/mole/K)
T = Temperature (^{0}C)
C_h = Volumetric specific heat of the soil as a function of water content (J/m^3/^{0}C) = $C_v \rho_s$
  C_v = Specific heat of the soil (J/kg/^{0}C)
  ρ_s = Mass density of the soil (kg/m^3)
λ = Thermal conductivity of the soil (W/m/^{0}C)
L_v = Latent heat of vapourization of water (J/kg)
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)
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)
v = Psychrometric 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 = $\frac{1}{h_r}$
T_s = Temperature at the soil surface (^{0}C)
T_a = Temperature of the air above the soil surface in (^{0}C)

REFERENCES

Edlefsen, N.B. & Anderson, A.B.C., 1943. Thermodynamics of soil moisture. Hilgardia 15: 2: pp. 31-298.

Fredlund, D. G. and Rahardjo, H. , 1993 Soil Mechanics for Unsaturated Soils. John Wiley and Son's, Inc., NewYork.

Geo-Slope International Ltd., 1991. KCAL: a program to determine hydraulic conductivity of unsaturated soils. SEEPAV User's Manual. Calgary, Alberta, Canada.

Ho, D., 1988 The relationship between the volumetric deformation moduli of unsaturated soils. PhD Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Joshi, B., 1993. A finite element model for the coupled flow of moisture and heat in soils under atmospheric forcing. M. Sc. Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Machibroda, R. M., 1993. Soil evaporative flux modelling of layered cover systems. Unpublished M. Sc. Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

MEND, (1993). SoilCover User's Manual, Version 1.0, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

Morton, F. I., 1975. Estimating evaporation and transpiration from climatological observations. Journal of Applied Meteorology, 14 (4): 488 - 497.

O'Kane, M., 1993. Unpublished M. Sc. Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Penman, H.L., 1948. Natural evapotranspiration from open water, bare soil and grass. Proc. R. Soc. London Ser. A. 193:120-145.

Tarnawski, V. R., and Wagner, B., 1992. A new Computerized Approach to Estimating the Thermal Properties of Unfrozen Soils. Canadian Geotechnical Journal, 29, 714 - 720.

Wilson, G.W., 1990. Soil evaporative fluxes for geotechnical engineering problems. PhD Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Wilson, G.W., Fredlund, D.G., & Barbour, S.L. 1991. The evaluation of evaporative fluxes from soil surfaces for problems in geotechnical engineering. In, 44th Canadian Geotechnical Conference, Volume 2. September, 29 - October, 2,1991. Paper No. 68.