COMPARISON OF FIELD PERFORMANCE OF A SILT COVER WITH NUMERICAL MODEL SIMULATIONS

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ABSTRACT
The field performance of a test cover on a 20% sloping acid generating waste rock platform is predicted using the commercial, two-dimensional soil-atmosphere model Vadose/W. The barrier layer in the cover is a 0.60 m thick silt layer containing approximately 5% clay. Input data for the model included soil, climate and vegetation data obtained in the field and laboratory. The model results were compared to field data. The model reasonably simulated field response patterns of volumetric water content and soil suction. Divergence between field data and model predictions were significantly influenced by soil temperature, evaporation and flow through preferential pathways. This work is part of a study to evaluate the effectiveness of three soil cover systems, (0.46 m thick 92% sand-8% bentonite mixture, 0.60 m thick silt layer containing approximately 5% clay and 0.008m thick geosynthetic clay liner (GCL), in reducing acid rock drainage with the view to selecting a final cover for full scale decommissioning of the waste rock. The calibrated model will be used to assist in the design of the final cover.

RÉSUMÉ
La performance d'une couverture d'essai, sur le terrain des roches produisant des déchets acides, incliné en 20%, est prédite l'utilisation la modèle bidimensionel Vadose/W. Le barrière dans la couverture est compose limon contenir approximativement 5% argile de 0.60 m épaisseur. Les données d'entrée pour le modèle ont inclus du sol, les données de climat et végétation ont obtenu dans le terrain ou le laboratoire. Les résultats modèles ont été comparés pour les résultats obtenu du terrain. Les modèle a simulé raisonablement les résultats du terrain pour le contenu d'eau volumétrique et la succion. Les divergences entre les données d'exécution du terrain et les prédictions modèles ont été significativement influencées par les températures de sol, l'évaporation et le flux par les chemins préférentiels. Le travail fait partie d'une étude pour évaluer l'efficacité de trois systèmes de couverture de sol, (92% sable-8 % le mélange de bentonite 0.46 m épaisseur, limon contenir approximativement 5% argile 0.60 m épaisseur et membrane argile-géosynthétique (MAG) 0.008 m épaisseur, dans réduire de drainage des roches produisant des déchets acides. L'objectif est de choisir le meilleur couverture pour le finale fermé du site de "Whistle mine. Le modèle calibré sera utilisé pour aider dans la conception de la couverture finale.

1 INTRODUCTION

The oxidation of sulphides in mine waste rock results in acid rock drainage (ARD), which causes pollution to the environment by releasing acid and heavy metals to the groundwater system and subsequently to other water bodies that are recharged from groundwater. Soil covers prevent or minimize ARD by reducing the ingress of oxygen and meteoric waters (precipitation) to the waste rock. Usually, evaporation from the barrier is minimized by using an evaporation barrier, typically a loose uncompacted soil layer that is also able to sustain vegetation growth and prevent erosion. Water is prevented from draining out from the base of the cover under gravity by the underlying coarse waste rock (Yanful et al, 1993).

The water balance of the cover with respect to evaporation and drainage is crucial to its performance and long-term sustainability. This is because evaporation and internal drainage in the soil under gravity or due to suction gradients significantly contribute to soil moisture loss and redistribution (Wilson, 1990; Yanful et al., 2003) and may compromise the integrity of the barriers. It is therefore important that the long-term water balance of a soil cover be effectively predicted and understood. Regulatory agencies require that mining companies demonstrate the long-term (100 years or more) suitability of any remediation (for example the use of a soil cover) measure in minimising pollution. However there is not enough data from long-term field monitoring of soil covers, to aid in designing and predicting soil cover performance. Usually, to derive a better understanding of how a soil cover will perform at a specific site, test cover plots are constructed, instrumented and their performance is monitored (Yanful et al., 1993; Khire and Benson, 1994; Ayres et al., 2003). However, due to the impracticality of monitoring the test covers over several years, before construction of the final cover, the long-term evaluation of cover performance is done using computer model simulations. Given the right information computer models can be used to reasonably predict the long-term behaviour of covers as required by regulatory agencies.

In order to make reasonably accurate predictions, it is important that the soil properties and physical processes are accurately estimated and are representative of field conditions. Limitations of laboratory tests such as human errors and failure to obtain representative samples make laboratory estimated values often inaccurate. Soil properties representative of field conditions, may be derived by comparing model simulations to experimental field data, and modifying the soil properties and physical conditions until the model reasonably simulates the field data. This process, referred to as model calibration, allows for more accurate determination (predictions) of the temporal and spatial variation of water balance and soil properties of a cover. Model calibration also helps to understand the processes that control moisture movement in unsaturated media hence improving current design methodologies for design of soil cover systems. The objective of this paper is to present the calibration of a model of two-dimensional finite element program Vadose/W.

2 BACKGROUND

Three test covers plots, comprising a 0.008 m thick, geosynthetic clay liner (GCL), a 0.46 m thick silt with 5% clay (STC) and a 0.46 m thick 92% sand-8% bentonite mixture (SB) over a 20%-sloping mine waste rock platform were constructed at Whistle mine near Capreol Ontario. The test plots were constructed to provide short-term evaluation of the effectiveness of the soil covers to reduce ARD, with the view to choosing the best option for final decommissioning of waste rock from the mine. The evaluation criterion is the effectiveness of each cover system in maintaining saturation thereby limiting oxygen ingress and maintaining a low hydraulic conductivity, which limits percolation of meteoric waters to the underlying waste rock. The barriers were designed as two-layer capillary barrier systems consisting of 0.90-m non-compacted pit run gravelly sand overlying a barrier layer. A fourth plot without a cover was also constructed as a control for comparison to the covered plots. Field instrumentation on site include a weather station to measure air temperature, relative humidity, solar radiation, wind speed, precipitation including snow, time domain reflectometry (TDR) probes for volumetric moisture content measurements, suction sensors, and soil temperature sensors. Percolation, runoff and interflow were also measured. Detailed description of the test plots and instrumentation are given in O'Kane Consultants Inc., (2001) and Adu-Wusu et al. (2002). Monitoring and evaluation of the performance of the plots have been ongoing for the past 3 years (October 2000 to September 2003) and are reported in (Adu-Wusu and Yanful, 2004). Model results presented in this paper are only that for the silt test plot.

3 METHODOLOGY

Simulation of field response was conducted using the finite element model, Vadose/W, a 2-D version of the 1-D soil-atmosphere model, Soil Cover (Geo-Slope Ltd (2002). Vadose/W accounts for the physical processes of evaporation and infiltration in unsaturated soils, using the Penman-Wilson model (1990, 1994) and the modified form of the Richard's equation (Richard, 1931). The model predicts the water balance of saturated and unsaturated soils using as input, atmospheric conditions, soil properties and vegetation characteristics. Two-dimensional modeling of the cover accounts for both lateral and vertical flow, both of which would influence the movement and distribution of water in the cover because of the 20% slope. It was not necessary to model in 3-D as the length of the covers compared to its width made it essentially a 2-D plane strain problem.

3.1 Input Data

Input data for Vadose/W can be grouped into soil data, climate data and vegetation data. The user has to specify the initial and boundary conditions for the specific problem.

3.1.1 Soil Data

Soil properties used as input in Vadose/W include soil porosity, coefficient of compressibility (M_v), saturated hydraulic conductivity, unsaturated hydraulic conductivity function, soil water characteristic curves (SWCC) and the curve fitting parameters for the soil water characteristic curve functions. The saturated hydraulic conductivity (K_{sat}), soil water characteristic curve and porosity were measured in the laboratory. The coefficient of compressibility and unsaturated hydraulic conductivity functions (Figure 1) were generated from the program using fitting parameters from Fredlund and Xing (1984). This method was also used to fit the laboratory SWCC data.

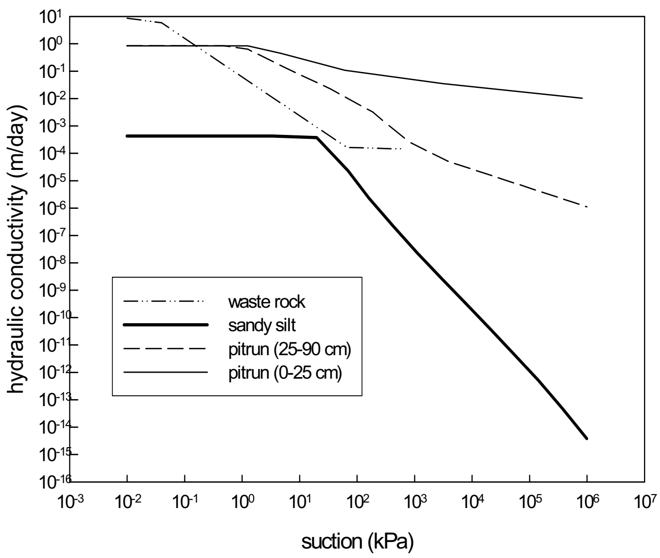

Figure 1 Unsaturated hydraulic conductivity function (waste rock and cover materials)

3.1.1.1 Soil Water Characteristic Curve (SWCC)

The SWCC for the silt was derived from laboratory tests. The percent fraction of the pit run material less than 4.75

mm was used for the SWCC test. It was assumed the SWCC for the pit run material was bi-modal with different air entry values, because of the presence of cobble size material (15 mm) and fine sand (0.15 mm). The SWCC of the waste rock was estimated from its grain size distribution and then fitted using the Fredlund and Xing equation. Generally, fitting the SWCC of the waste rock was based on ensuring it drained quickly, an assumption consistent with its large particle size. Figure 2 shows the SWCC used as input for the cover and waste rock materials.

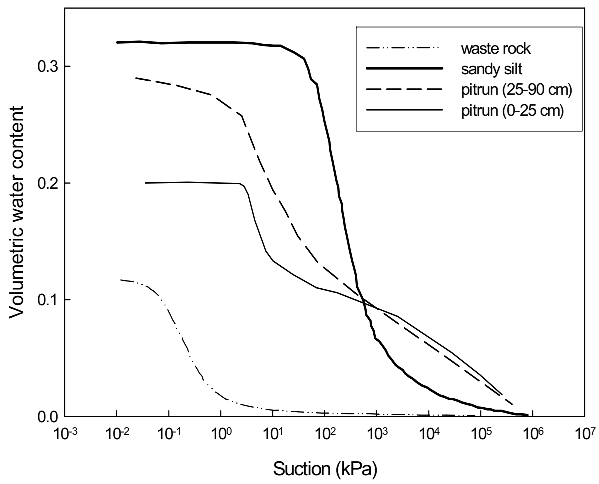

Figure 2 Soil Water characteristic curves of waste rock and cover materials

3.1.1.2 Thermal Properties

Generally thermal effects in saturated soils are small, however thermally driven flows in unsaturated soils can be very important. In unsaturated soils, temperature and moisture content gradients influence both vapour and liquid flow. For soil covers, thermally driven flows becomes crucial for expansive soils such as bentonite and also for heat transfer issues such as freezing and drying. Heat transfer properties of the soil including evaporation are characterized by its volumetric heat capacity and thermal conductivity. Soil temperature and evaporation are influenced by its thermal properties. Typical values of volumetric specific heat capacity and thermal conductivity were assumed for the soils in this study and were derived from the Vadose/W User's guide (Geo-Slope Ltd., 2002**)** based on soil mineralogy.

3.1.2 Climate Data

Climatic data input into Vadose/W included the daily minimum and maximum temperature, daily minimum and maximum relative humidity, daily wind speed and daily precipitation data measured on site for the period October 2001 to September 2002. Net radiation and potential evaporation were output by the program based on user specified climate data and the location of the site, specified by its latitude. It is also possible to input measured net radiation and evaporation data if available. The minimum temperature for rainfall was specified to be –0.1ºC and the maximum temperature for snowfall was 0.5ºC. Climate parameters were applied in a sinusoidal pattern between the sunrise and sunset times (Geo-Slope Ltd, 2002) by choosing the sinusoidal distribution pattern. Precipitation was distributed in a sinusoidal pattern between 8 and 1600 hours.

3.1.3 Vegetation Data

Vegetation data needed as input for the program include, leaf area index (LAI), plant moisture liming point, root depth and the length of the growing season. The vegetation used on the test plots was a seed mix made up of *(30%) creeping red fescue, (20%) canada bluegrass, (20%) annual rye grass, (20%kentucky bluegrass), (5%) chewings fescue, (3%) red top bentgrass and (2%) aliske clover*. The vegetation was specified as poor grass and the growing season was specified as starting in May and ending in October. Root depth was measured from samples of vegetation collected on site (40 cm). It was assumed that the root depth distribution was triangular, which implied that moisture loss from the roots was greater towards the surface, and decreased with depth. A plant moisture limiting point function derived from the program had a value of about -100 kPa and a wilting point of about -1500 kPa.

3.2 Modeling Progression

A typical cross section of the finite element mesh used for the field response model is shown in Figure 3. The mesh consists of 2 m of waste rock, 60 cm thick barrier and a 90 cm thick pit run layer. The top 25 (10) cm of the pit run material was modelled as with different soil properties, being more porous than deeper layers, to account for desiccation and cracking due to atmospheric fluxes and soil disturbance. Its conductivity function was selected such that its unsaturated hydraulic conductivity will remain constant at 1×10^{-2} m/day even at high suctions.

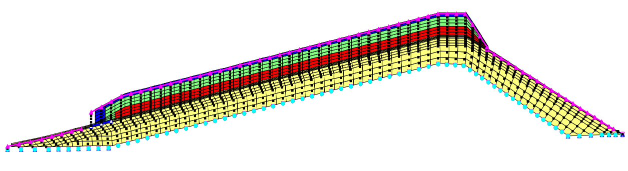

Figure 3 Typical mesh used for modeling

Initially the set of data needed that described the different soil materials (SWCC, K_{sat}, porosity, thermal properties etc), the physical environment (climate, initial conditions, boundary conditions), was defined and used as input. Then based on the comparison of field and model results, this set of data was modified until the model reasonably simulated the field measurements. A sensitivity analysis was then conducted to determine major factors that affect model behaviour. The calibrated model will be used in a predictive model.

3.2.1 Boundary Conditions

Based on the results of several model simulations, the thickness of the waste rock used for the simulation was reduced to 2 m instead of 6 m. Because of the coarse nature of the waste rock, any pressure heads would be quickly dissipated and not affect barrier performance. A drained condition was simulated in the waste rock by specifying a suction boundary condition of 2 kPa, which is the residual suction based on its SWCC. This boundary condition is consistent with the field measured suction in the waste rock for the test cover plots, which indicated that the waste rock maintained a constant suction of (kPa) throughout the year. A thermal boundary condition was specified at the base of the waste rock using average temperatures measured in the waste rock. This helped to simulate soil temperatures that were reasonably close to measured data. A no flux boundary condition was specified at the base of the waste rock pile to simulate an impermeable geomembrane at the bottom of the waste rock platform. A climate boundary condition with vegetation functions was specified for all test covers. A climate boundary condition with no vegetation functions (pseudo climate) was specified for the parts of the plots without cover (back of plots).

3.2.2 Initial Conditions

Initial head conditions were determined by running a steady state analysis using an initial flux value of 0.00086 m/day, and used as the initial condition file for the transient model. Also to simulate temperature gradients between layers in the field, different temperatures were specified in each of the 3 cover layers.

4 COMPARISON OF MODEL AND FIELD RESULTS

The model was run to simulate the period October 2001 to September 2002 and the results were compared to field data. Parameters compared were, temperature, suction, volumetric water content (expressed as soil water storage), percolation and runoff.

4.1 Soil Moisture Storage

Figure 4 shows the predicted soil water storage for the pit run and barrier layers compared to measured data. Measured trends showed an increase in moisture storage during the fall and spring and a decrease during the summer and winter periods. Trends predicted by the model were similar to field data, though the model underestimated change in storage in both layers. Measured storage for the barrier indicated an increase during the winter months, however, the model predicted near steady values with only a slight decrease. In the pit run material the model correctly predicted the decrease in moisture during the winter. According to the model results, the barrier layer experiences very little change in storage. Under-estimation of storage in the pit run and barrier layers was a result of overestimation of evaporation by the model (Figure 5). Also soil temperatures predicted by the model were higher than the field measured values, especially during the summer months, leading to greater evaporation than existed in the field. It is also possible that the hydraulic conductivities used in the model were greater than existed in the field. Frequent fluctuations in air temperature and hence water available for replenishing the different soil layers, present a challenge in numerical modeling, as the model might not be able to pick such details. For example warm air temperatures in the middle of winter may lead to infiltration events that may not be captured by computer models.

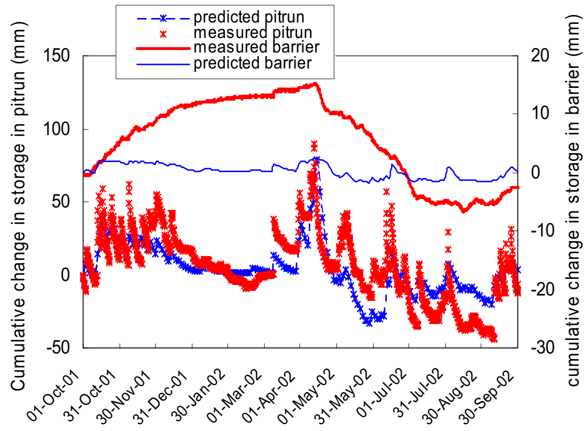

Figure 4 Comparison of predicted and measured soil water storage

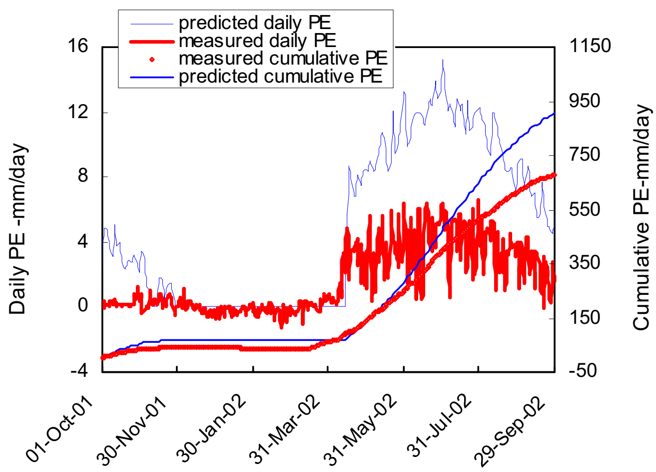

Figure 5 Estimated measured and predicted potential evaporation

4.2 Evaporation

Potential evaporation (PE) at the site was estimated from the Penman (1948) formulation, using as input the net radiation, wind speed, air temperature and relative humidity. Vadose/W estimated cumulative PE as 905 mm, about 33% more than the field cumulative PE (678 mm) which was estimated from measured net radiation. However, using measured net radiation as input gave a better match of model predicted PE to that of field estimated PE. The model also reasonably predicted trends in potential evaporation and accurately predicted no evaporation during winter. Winter predictions differed from that of (Khire, 1992) who reported over prediction of evaporation with UNSAT-H even under sub zero temperatures when snow was on the ground.

4.3 Temperature

Generally predicted trends in soil temperature were reasonably close to measured soil temperatures, with lower layers being warmer in winter and cooler in the summer relative to higher layers. Minimum temperature at the top of the barrier was –4°C compared to field minimum temperature of 2°C and the maximum temperature was 38°C compared to field values of 25°C. Generally there was better agreement between measured and predicted soil temperatures in the fall and summer than for the winter. Lower temperatures in winter could be because the model does not account for protection against temperature loss provided by a thick snow cover (40- 50 cm).

4.4 Pressure

Suction trends predicted by the model in the barrier were reasonably consistent with the field data, clearly responding to climatic trends and infiltration events, though the model over estimated suction in the pit run and barrier layers and indicated drying out consistent with low water contents. Also the model predicts a decrease in suction at the start of the spring freshet, contrary to measured data.

Complexities involved with using adequate soil properties and comparison parameters is shown by the fact that though the model was able to reasonably predict volumetric water content on the 17 April, corresponding suction values did not match field data. Other than the inadequacy of the SWCC, suction values are not a good criterion for determining suitability of this model. It may be more desirable to compare soil water storage than suction. This is because the method of suction measurement by suction sensors in the field is prone to errors. Usually the sensor measures water content and then relate it to suction, at low water contents in the soil, any small error in measured water content can generate big errors in measured suction, especially if the slope of the SWCC is steep. For example a change in suction between 10,000 kPa and 500,000 kPa, for some soils near their dry state may be significant in the model but depending on the shape of the SWCC this may not result in significant changes in water content. However, in reality both the model and the field indicate a dry soil. Another challenge in field response modeling is the fact that field data might not necessarily be accurate and may be dependent on a host of other factors, which the model may not be able to account for. For instance temporary malfunction of a sensor may produce measured responses that may not represent what really prevails in the field.

4.5 Net Percolation

Measured and predicted net percolation for the silt barrier is shown in Figure 6, the model predicted total percolation of about 300 mm, compared to 514 mm measured onsite. The onset of percolation predicted by the model agrees reasonably well with that measured between October and December, with model values 20% less than measured. The model reasonably predicted the magnitude of increase (about 90 mm) in net percolation during the spring freshet though about a month earlier than existed in the field. The possible reason why model predictions of percolation after the winter were earlier than the measured could be because the model significantly overestimated precipitation in April compared to measured precipitation data used as input. The model also predicted warmer soil temperatures allowing for infiltration, though measured soil temperatures indicated frozen top layers.

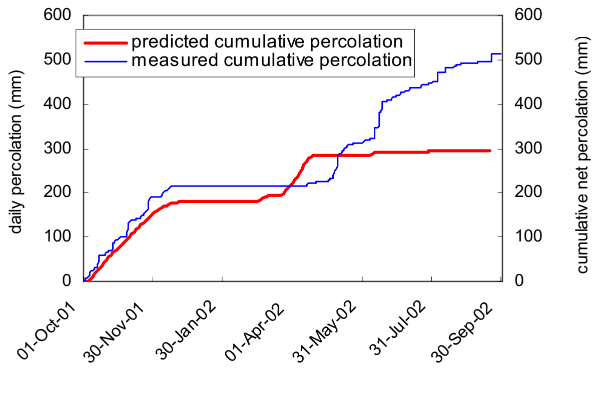

Figure 6 Measured and predicted net percolation

The model essentially predicted a shut down of the soil pores after the spring. This could be because the model over predicted evaporation during the summer resulting in lower water contents and lower unsaturated hydraulic conductivities during the summer and fall months. Another reason for lower net percolation than measured could be because the model only accounts for flow through micro pores and not through preferential pathways, which probably exist in the field. The presence of preferential pathways is confirmed by the sharp increases in net percolation in the measured data compared to that generated by the model.

4.6 Runoff

The model predicted zero runoff, though runoff measured for this plot was 6% of total precipitation for the same period. The reason for Vadose under predicting runoff may be because the saturated hydraulic conductivity assumed for the pit run material may be too high, allowing for more percolation. Another reason could be the model overestimating evaporation than pertains in the field.

5 SUMMARY AND CONCLUSIONS

Results of the field response modeling of a silt soil cover over acid generating waste rock using the 2-D flow model Vadose/W were presented. The results showed that the model reasonably predicted trends in soil moisture storage, soil temperature and suction. However some of these values were either over predicted or under predicted. The results also indicated that suction might not be a good criterion for comparing model results to measured. Results show that over prediction of potential evaporation significantly affected the water balance leading to under prediction of net percolation, runoff and soil water storage. Sensitivity studies conducted indicated that more accurate estimation of potential evaporation could be made using measured net radiation data as input.

The main challenge with the calibration exercise was being able to reasonably predict soil properties especially the SWCC and the unsaturated hydraulic conductivity. Varying the saturated hydraulic conductivity, unsaturated conductivity function, and SWCC significantly affected the results. For example, increasing the saturated hydraulic conductivity from 1×10^{-4} cm/s to 5×10^{-4} cm/s, had the effect of increasing water storage in the springtime and decreasing it in the summer.

Generally soils exhibit differences in properties both spatially and with depth as a result of segregation, compaction quality, and desiccation and freeze thaw effects and settlement. For example, field results of suction and volumetric water content for the pit run material seem to indicate its SWCC may vary with depth, it may therefore be possible to obtain a better match to field data by dividing the pit run material into smaller layers and specifying different SWCCs for these layers. Another challenge is accurately accounting for the hysteretic behaviour of the SWCC of any soil. However it must be noted that numerical models have limitations and are not always able to simulate the complex nature of the processes that take place in nature. For instance the assumption of a homogeneous soil and also uniform initial soil wetness are unrealistic and not representative of field conditions.

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