The Use of Two-Dimensional Soil-Atmosphere Modelling in the Design of Dry Cover Systems for Mine Waste

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Abstract

Dry cover systems are a common prevention and control technique used for the management and decommissioning of waste rock piles and tailings impoundments. In general the effectiveness, or performance, of the cover system is dependent on a number of factors including soil properties, location of the water table, and the surface boundary condition defined by site-specific climate conditions. A one-dimensional soil-atmosphere model is commonly used in the design of dry cover systems. Dry cover systems overlying waste rock piles or tailings impoundments are two-dimensional systems. The surface of a significant number of cover systems are contoured to control surface runoff and erosion, or promote vegetation growth. The side slopes of waste rock piles are often a significant percentage of the total waste rock pile footprint area. Flow within these areas is not one-dimensional and cannot always be properly characterized with a one-dimensional model. The emergence of a two-dimensional modelling technique allows for the investigation of two-dimensional flow within a dry cover system. This paper discusses the influence of sloping cover systems on the percolation of meteoric water to the underlying waste. Results from one-dimensional and two-dimensional analyses are compared. Implications to cover system design include different cover materials and cover material thickness for sloping and non-sloping surfaces. The objective of this paper is to illustrate the need to progress dry cover system design from a one-dimensional approach to that which includes two-dimensional analysis.

Introduction

Dry cover systems are increasingly being implemented as part of the reclamation and closure strategies for mining operations. In general, the objectives of dry cover systems are to minimize the influx of water and provide an oxygen diffusion barrier to minimize the influx of oxygen. Apart from these functions, dry covers are expected to be resistant to erosion and provide support for vegetation.

Dry covers can be simple or complex, ranging from a single layer of earthen material to several layers of different material types, including native soils, non-reactive tailings and/or waste rock, geosynthetic materials, and oxygen consuming organic materials (MEND, 2001). Single layer "store and release" cover systems typically utilize the high evaporative demand prevalent at semi-arid and arid sites to store precipitation during wet periods for subsequent release back to the atmosphere during dry periods. Multi-layer cover systems utilize the capillary barrier concept to keep one (or more) of its layers near saturation under all climatic conditions, or utilize a "barrier" layer, which typically possesses good moisture retention properties. These layers create a "blanket" of water over the reactive waste material, which reduces the influx of atmospheric oxygen and subsequent production of acidic drainage.

The main objective of this paper is to demonstrate the importance of 2D analysis in the design of dry cover systems by comparing the results of an identical cover system placed on horizontal and sloping waste materials. In addition, the use of 2D analysis as a tool in optimizing cover system design is discussed. The 2D numerical modeling conducted in support of this paper was completed with the VADOSE/W model.

Background

Considerable fundamental and applied research has been devoted to investigate the performance of soil cover systems for mine waste rock and tailings (MEND, 2001). A review of published literature suggests the majority of soil cover designs deal with vertical, or one-dimensional (1D) flow of heat and moisture in horizontal layers, using numerical models as well as laboratory or field scale physical models. Field performance monitoring has also typically evaluated performance from a 1D perspective as most monitoring systems are implemented on the flat areas of waste rock piles and tailings impoundments. However, a large percentage of mine waste rock piles have sloping surfaces as a result of waste rock pile construction methods. The performance of a dry cover system placed on these slopes will differ from the performance of a horizontal, 1D cover system. The ability of the cover system to mitigate the net percolation of water to the underlying waste material and function as an oxygen ingress barrier will be influenced by sloping, two-dimensional (2D) effects.

Figure 1 is a schematic illustration of the hydraulic components of a dry cover system placed on a sloping surface. Runoff, as well as lateral percolation within the cover system materials, are the additional components present in a sloping 2D cover system, as compared to a horizontal 1D system. Runoff and lateral percolation transport water towards the toe of the slope, or to a lateral berm, often reducing the net percolation through the cover system at the crest of the slope as compared to the toe of the slope.

Numerical Models Typically Utilized for Cover System Design

The application of soil-atmosphere numerical models to assist with the design of dry cover systems for waste rock piles and tailings impoundments has developed in recent years. Among the first coupled heat and water transfer models were the 1D SoilCover, SWIM, and UNSAT-H models.

Bruch (1993) utilized the SWIM (Soil Water Infiltration and Movement) model to analyze the soil-atmosphere flux for a layered soil column in a laboratory setting. The SWIM model, developed within the CSIRO Division of Soils, Australia (Verburg *et al.*, 1999) produced reasonable agreement between the measured and calculated evaporative fluxes. UNSAT-H was developed to simulate water and heat flow in unsaturated media for assessing water dynamics at arid sites (Fayer, 2000). Fayer *et al.* (1992) utilized UNSAT-H to simulate the change in storage of lysimeters consisting of a silty loam over a coarse waste material. SoilCover is a 1D finite element package, developed by the Unsaturated Soils Group at the University of Saskatchewan, Canada, which models transient water and heat transport in a soil profile (MEND, 1996). Swanson (1995) calibrated the SoilCover model to field performance-monitoring data at the Equity Silver mine near Houston, BC. The calibrated model was then used to predict the long-term performance of the waste rock cover system.

The application of 2D soil-atmosphere models to the simulation of soil cover systems offers the distinct advantage of being able to account for lateral movement within and beneath the cover system (Swanson, 1995). In the absence of a coupled 2D soil-atmosphere model, one dimensional evaporative flux models were used to develop a surface boundary condition that was then applied within a 2D seepage model (Newman *et al.*, 2002). However, use of the 1D models precluded the effects of lateral percolation and runoff on the designated surface boundary condition input to the 2D seepage model.

Newman *et al.* (2002) describe the formulation of the rigorous 2D coupled soil-atmosphere numerical model, VADOSE/W, developed by Geo-Slope International. A simple cross-section was used to demonstrate the effects of a sloping cover system on runoff, evapotranspiration, and net percolation through the base of the cover system.

Discussion of Modeling Program

Description of Dry Cover System

The dry cover system utilized in the modeling demonstration was generalized, as opposed to a site-specific cover system design. A sloping waste rock surface measuring 24 m long at a four to one horizontal to vertical slope (25%) was used at the base of the cover system. The cover system consisted of a 0.5 m compacted clayey till barrier layer placed directly on the waste surface, with an overlying 1.0 m thick non-compacted, well-graded growth medium material. The cover system was placed over a relatively well-graded waste rock material. Figure 2 presents the soil water characteristic curve (SWCC) and hydraulic conductivity function used for the materials. Figure 3 shows the 1D and 2D models used in the modeling program. The phreatic surface was placed two metres below the base of the cover system at the toe of the slope for the 2D simulation and approximately 8 m below the base of the cover system for the 1D simulation, approximately the same height above the phreatic surface as the midpoint of the slope in the 2D simulation.

The climate year used in the modeling program was adapted from climate data collected at a site in the interior of northern British Columbia. A simulation period of 200 days was selected to represent the "frost-free" period of a typical Canadian mine site. The water equivalent of snowfall measured during the winter season was applied as a surface boundary flux condition for the first 30 days of the simulations. Three different climate years were simulated for both the 1D and 2D models. The surface boundary flux was altered to produce low, average, and high precipitation conditions while the remaining climate data, including temperature, relative humidity, and wind speed remained constant for each simulation.

Comparison of 1D and 2D Model Results

The net percolation across the 2D cover system was measured near the crest of the slope, the midpoint of the slope, and the toe of the slope. The highest net percolation occurred at the toe of the slope for each of the three 2D simulations. The results of the modeling program are summarized in Table 1. The data points presented in the table are situated at 2 m, 12 m, and 24 m for the crest, midpoint, and toe of the slope. The values in brackets represent the net percolation expressed as a percentage of the simulation precipitation.

The net percolation measured near the crest and midpoint of the slope for the average precipitation simulation is approximately 10 to 15 mm lower than the net percolation estimated at the toe of the slope. If the net percolation is expressed as a percentage of the annual precipitation, the results are 4.7%, 5.3%, and 7.2% for the crest, midpoint, and toe of the slope, respectively. The results indicate that runoff and lateral flow within the cover system have an effect on the net percolation. The 1D simulation predicted 30.9 mm (4.8%) of net percolation, which is between the values estimated at the midpoint and the crest of the slope in the 2D simulation.

The net percolation estimated in the high precipitation simulation is shown in Table 1. The net percolation represents 5.1%, 6.6%, and 10% of the annual precipitation for the crest, midpoint, and toe of the slope locations, respectively. In this simulation, the difference in the predicted net percolation for the crest and midpoint of the slope was more pronounced than shown in the average precipitation simulation. In addition, the discrepancy between the midpoint and toe of slope net percolation was much higher for the high precipitation simulation (10% to 6.7%) as compared to the average precipitation simulation (7.2% to 5.3%). The 1D simulation predicted a net percolation of 5.6%, which was slightly greater than the net percolation predicted near the crest of the slope.

The 2D effects of runoff and lateral percolation had little influence on the net percolation results of the low precipitation simulation. The predicted net percolation ranged from 16.8 mm at the crest of the slope to 18.4 mm at the base, or approximately 4% of the annual precipitation.

The 1D simulation predicted 17.8 mm of net percolation, which is between the values estimated at the midpoint and toe of the slope for the 2D simulation. The results indicate that the 2D effects of runoff and lateral percolation had little influence during the dry year simulation.

Figure 4 shows the net percolation, expressed as a percentage of the annual precipitation, estimated at each point along the slope. For each of the climate years simulated, the net percolation increases from the crest of the slope to the toe of the slope. The largest increases in net percolation occur between the midpoint of the slope and the toe of the slope. As discussed above, net percolation is approximately 4% across the modeled slope for the low precipitation simulation. Net percolation increases from approximately 5% at the crest of the slope in the high precipitation simulation to 10% at the toe of the slope.

The objective of the modeling program was to investigate whether a 1D model could be used to simulate the net percolation of meteoric waters through a sloping cover system. The results shown in Table 1 demonstrate that the net percolation estimated by the 1D model did not agree with the net percolation predicted using the 2D model for the crest, midpoint, and toe of the slope for all precipitation conditions modeled. The discrepancy was a function of the "type" of precipitation conditions modeled. Reasonable agreement was predicted for the dry precipitation year. However, during average and wet precipitation years the net percolation predicted by the 1D model did not agree with that predicted by the 2D model for the entire length of the slope. In these cases, the net percolation predicted by the 1D model underestimated net percolation in the lower regions of the slope by nearly 100%. This "underestimation" is significant given that over the long term the higher net percolation would lead to an increase in seepage (likely with elevated metal concentrations due to the sulphidic waste material) emanating from the waste storage facility. Note that the discrepancy between the 1D and 2D conditions, in the absolute sense as well as in terms of the location along the slope, will be a function of the precipitation conditions, the slope angle, and the slope length, given that the material properties remain constant.

2D Analysis in Cover System Design

In many mining areas the availability of borrow materials, particularly fine-textured materials, for cover system construction is limited. The fine-textured materials are often used as a compacted barrier layer within the cover system to limit water percolation and the ingress of oxygen. A 2D analysis can aid in optimizing the cover design and reducing the amount of fine-textured material required to meet the cover system design objectives.

The results in the previous section illustrated that net percolation at the crest of the slope can be less than net percolation towards the base of the slope. Additional numerical simulations were completed to investigate the change in net percolation if the 0.5 m compacted till layer was reduced to 30 cm in the upper half of the slope (from 0 – 12 m along slope, see Figure 3). The initial conditions used in the subsequent simulations were identical to the initial conditions for the average, low precipitation, and high precipitation simulations. Table 2 compares the results of the 30 cm barrier layer to the constant 50 cm thick barrier layer for the three monitoring points used in the simulations.

The reduction in the thickness of the compacted barrier layer in the upper slope led to increases in the net percolation measured at the crest and midpoint of the slope but not the toe of the slope. In the case of the average precipitation year, net percolation at the crest of the slope was 33.9 mm across the 30 cm thick barrier layer cover system as compared to 30.3 mm for the original cover system design. The difference between the net percolation values decreased to 1.3 mm (35.3 mm to 34.0 mm) at the midpoint of the slope and there was no difference predicted for the base of the slope. Figure 5 presents the net percolation estimated along the distance of the slope for both cover system designs during the average precipitation year. The barrier layer thickness remained at 50 cm below the midpoint of the slope for each of the model simulations.

Essentially no difference exists in the estimated net percolation between the midpoint of the slope and the toe of the slope.

The model simulations showed that a reduction in the barrier thickness layer in the upper half of the slope resulted in a marginal increase in the overall net percolation into the underlying waste material. The results must be viewed on a cost/benefit basis in order to determine if a change in the cover design for the upper portions of a sloping cover system is beneficial. The reduction of the barrier layer thickness from 50 cm to 30 cm decreases the required fine-textured material by 2 m^3 per unit width and increases net percolation by an average of 1.5 mm across the length of the cover system cross-section.

The numerical model presented in this paper is not specific to any mine site in Canada or the world. However, due to the nature of numerical models that require detailed material properties, slope geometry, and climate data, the results discussed above are applicable to this specific cover design. For example, the results showed limited 2D flow under low precipitation conditions and significant 2D effects at average and high precipitation conditions on the 4H:1V slope. Other sites with different material properties and climate conditions may find significant 2D flow, or no 2D effects at all when the cover system design is evaluated. The design of the dry cover system should entail proper characterization of the material properties and slope geometry. This will allow the implementation of a site-specific numerical model to characterize the 2D flow effects of the cover system design.

Summary

Advances in numerical modelling techniques have produced rigorous 2D coupled soil-atmosphere numerical models. These models can be used to investigate the performance of dry cover systems for mining waste on horizontal and sloping surfaces. The modelling program described in this paper investigated the change in net percolation with slope position and the result of decreasing the thickness of the compacted barrier layer within the cover system. Climate conditions typical of many mine sites situated in Canada were used for the modelling demonstration.

A simple 24 m long, 4H:1V slope was used in the modelling demonstration. Net percolation increased with distance along the slope, with net percolation being lowest at the crest of the slope and greatest at the toe of the slope. A decrease in the compacted barrier thickness for the upper half of the slope resulted in only a marginal increase in the predicted net percolation. The results of this analysis could be used as part of a cost/benefit analysis to determine if the change in the cover design and marginal decrease in performance provided measurable reduction to the total cost for constructing the cover system.

The model results presented in this paper clearly demonstrate a mine waste cover system design should be conducted utilizing a rigorous 2D coupled soil-atmosphere model. Utilizing a 1D model significantly increases the potential to incorrectly predict the performance of a mine waste cover system design.

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Table 1 Summary of 1D and 2D simulation results.

Simulation	**Precipitation (mm)**	**2D Net Percolation (mm)**			**1D Net Percolation (mm)**
		Crest of Slope	**Midpoint of Slope**	**Toe of Slope**	
Low Precipitation	436	16.8 (3.8%)	17.1 (3.9%)	18.4 (4.2%)	17.8 (4.1%)
Average Precipitation	645	30.3 (4.7%)	34.0 (5.3%)	46.3 (7.2%)	30.9 (4.8%)
High Precipitation	859	43.9 (5.1%)	57.8 (6.7%)	87.2 (10%)	48.3 (5.6%)

Table 2 Comparison of net percolation predicted for the 30 cm upper barrier layer cover design to the constant 50 cm barrier layer.

	Net Percolation (mm)					
Simulation	**Crest of Slope**		**Midpoint of Slope**		**Toe of Slope**	
	30 cm Barrier Layer	**50 cm Barrier Layer**	**30 cm Barrier Layer**	**50 cm Barrier Layer**	**30 cm Barrier Layer**	**50 cm Barrier Layer**
Low Precipitation	18.0	16.8	17.7	17.1	18.4	18.4
Average Precipitation	33.9	30.3	35.3	34.0	46.3	46.3
High Precipitation	54.2	43.9	60.5	57.8	87.2	87.2

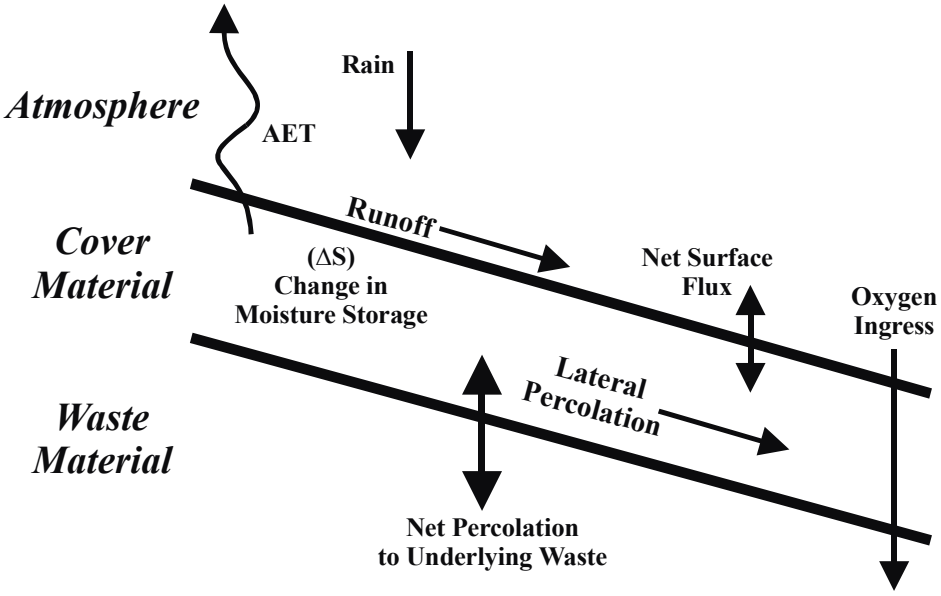

Figure 1 Schematic of the hydraulic components within a sloping cover system.

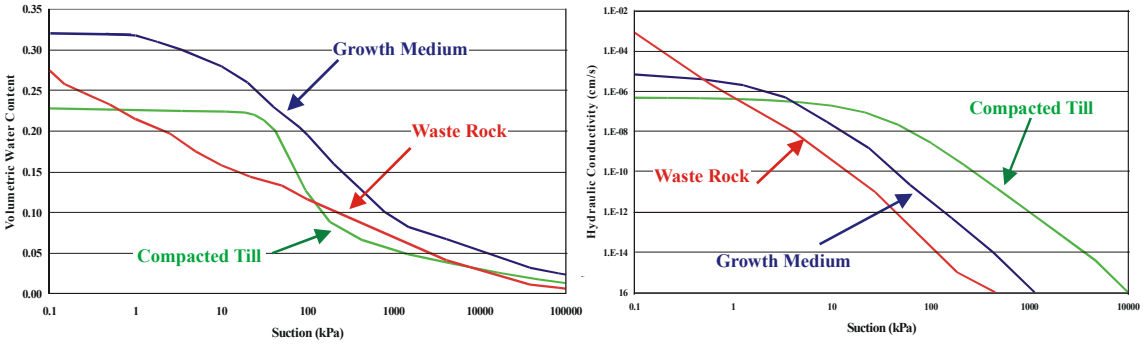

Figure 2 SWCC and hydraulic conductivity functions of the cover and waste rock materials.

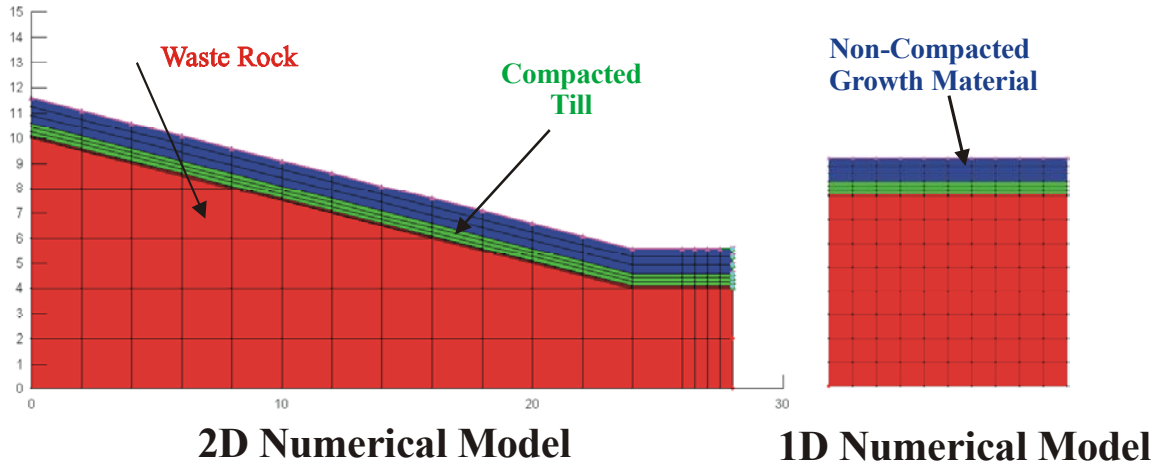

Figure 3 Schematic of the 1D and 2D numerical models.

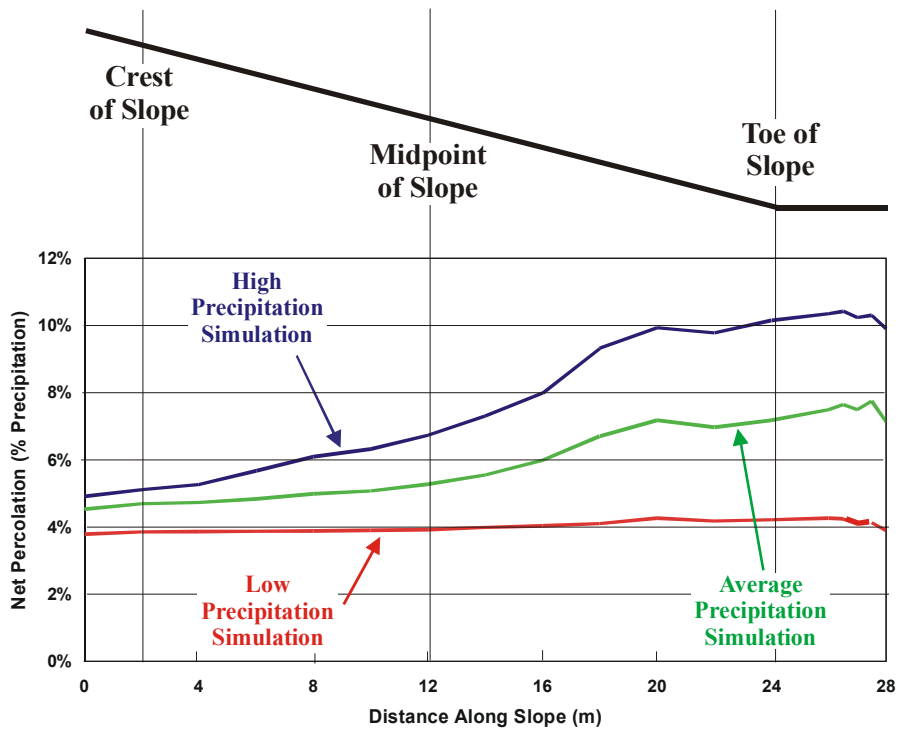

Figure 4 Net percolation as percentage of annual precipitation as a function of slope distance.

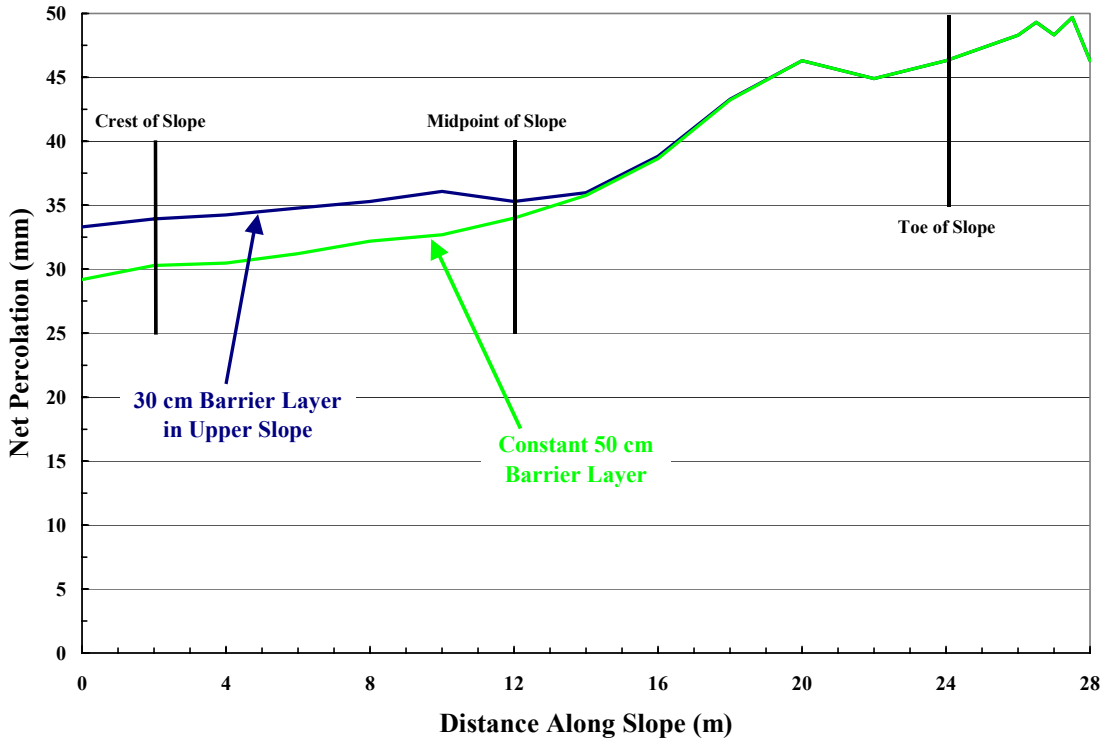

Figure 5 Comparison of the predicted net percolation for the 30 cm barrier layer cover system and the constant 50 cm barrier layer cover system.