Consideration of Snow Melt and Physical Aspect in Simulating Cover Performance

Amy L. Hudson, REM[1], Marybeth Dowell[2], and Pete Kowalewski, P.E.[3]
[1]Tetra Tech, Littleton, Massachusetts, USA, amy.hudson@tetratech.com
[2]Tierra Group International, Ltd., Elko, Nevada, USA, marybeth.dowell@tierragroupinternational.com
[3]Tierra Group International, Ltd., Salt Lake City, Utah, USA, pete.kowalewski@tierragroupinternational.com

Abstract

It has become common practice to consider soil covers when developing closure strategies for the prevention of acid rock drainage, with the optimized design of closure covers often developed through predictive modeling. However, using monitored field conditions of a closure cover constructed based on a modeled design, there is evidence that not all areas of the facility realize the same level of protection and may require increased evaluation. For the facility that is the basis of this case study, the north facing slope of the closed heap leach does not receive as much radiation from the sun and is moderately protected from the wind, allowing significant snow accumulation during the winter. In order to evaluate the influence of the accumulated snow, a simple numerical modeling exercise was completed to consider the average climatic conditions, and a simulated snow storm and thaw period to represent the worst case infiltration along the north facing slope. The modeling suggests that during the excess snow accumulation and subsequent thawing event, infiltration increases significantly beneath the northern slope compared to the average conditions and other areas of the heap. The results of this study suggest that soil cover modeling requires separate consideration of areas potentially subject to increased infiltration, such as a north facing slope.

Key Words: modeling, unsaturated flow, soil covers.

Introduction

This paper presents a case study of modeling and field observations (heap draindown rates, snowpack measurements, and site weather station data) of a reclaimed heap leach facility, but are broadly applicable to other surface facilities at mining sites. The heap leach facility that is the focus of this case study was operated for approximately 12 years and is located in the western United States in an arid climate. After cessation of operations the heap was regraded, covered, vegetated, and instrumented with four Time Domain Reflectrometry (TDR) stations with four sensors at each location. The initial cover design was developed through predictive modeling using HYDRUS 2D (Simunek et al, 1999). The cover has a 25 centimeters (cm) (ten inch) nominal thickness, with a minimum thickness of 15 cm (six inches), which was confirmed through field measurements. Data was collected from the TDR stations, and compared with laboratory data to evaluate the moisture content within the heap after the cover was placed.

The heap leach facility is lined with a geosynthetic liner (high density polyethylene liner, HDPE) with underdrains (placed above the liner) to collect process solutions and meteoric water percolating through the heap leach material. Flow from the underdrains reports to a lined collection sump which allows for accurate measurement of draindown flow rates using a flowmeter. Draindown flow rates observed were on the order of 65 cubic meters per day (m^3/day) (12 gallons per minute [gpm]), or approximately 20% of annual average precipitation. The observed draindown rate is much higher than would be expected from a heap that has been closed and covered for approximately ten years, suggesting that the cover is not performing as designed. So, a modeling study was performed to evaluate the current infiltration rate and to consider possible mitigation measures that could be implemented to minimize infiltration and the resulting draindown seepage.

The initial design was intended to limit infiltration of precipitation to a rate that is equal to 7% of mean annual precipitation. This is the regulatory guidance for the site that is the basis for this study. In addition, the targeted long-term performance of the cover (net infiltration of less than 7% of average annual precipitation) is intended to accommodate the post-closure water management facilities (evaporative cells). The results of the modeling study suggest that the cover thickness may not be sufficient to maintain the net infiltration rate below 7% of the annual precipitation (target infiltration rate) when considering slope aspect effects and potential drifting snow. The results indicated improved performance may be achieved by constructing a thicker soil cover, particularly on the slopes with an aspect (generally north-facing) that leads to decreased direct exposure to sunlight and increased accumulation of snow (drifting). In addition, it was determined that the north facing slopes of the heap are potentially subjected to additional infiltration during the winter and spring due to snow cover build-up and snow melt. Other studies of soil covers reviewed during the initial design phase of this project suggested that the cover could be operated within the target infiltration rate and that most studies have not considered different areas of the facility separately.

Seepage Model Construction – Baseline Conditions

The modeling of the subject heap was completed using VADOSE/W (GEO-SLOPE, 2007), a two dimensional finite-element model. The modeling was completed using both steady state and transient model scenarios. Previous modeling evaluations were completed using HYDRUS 2D (Simunek et al, 1999). During the previous modeling study, the maximum possible bare-soil evaporation was calculated using the Modified Penman Equation. The maximum possible bare-soil evaporation for this particular site was calculated to be 149.5 cm /yr (58.9 in/yr), which is distributed over the entire year. The bare-soil evaporation was then used to establish the potential evaporation from the soil in the HYDRUS 2D model. Using the maximum possible bare-soil evaporation calculated for the site, the HYDRUS 2D modeling suggested that 3.0 m (ten feet) of the upper profile of the facility is subjected to bare soil evaporation. Field measurements of actual root depth suggest that the root uptake zone is primarily limited to only the upper 30 cm (12 in), which also supports the use of a column limited to 3.0 m in height. Therefore, modeling has been limited to this portion of the facility. Table 1 presents the measured root distribution observed for vegetation established in the heap's soil cover. Figure 1 presents the model domain and mesh that was used in this modeling effort.

Table 1. Root Distribution

Depth Interval (cm)	Percent of Total Root Biomass (%)	Root Intensity (% per cm)
0 - 3	0.0	0.0
3 - 15	56.6	4.72
15 - 30	32.2	2.15
30 - 45	7.8	0.52
45 - 60	3.2	0.21
60 - 75	0.2	0.017

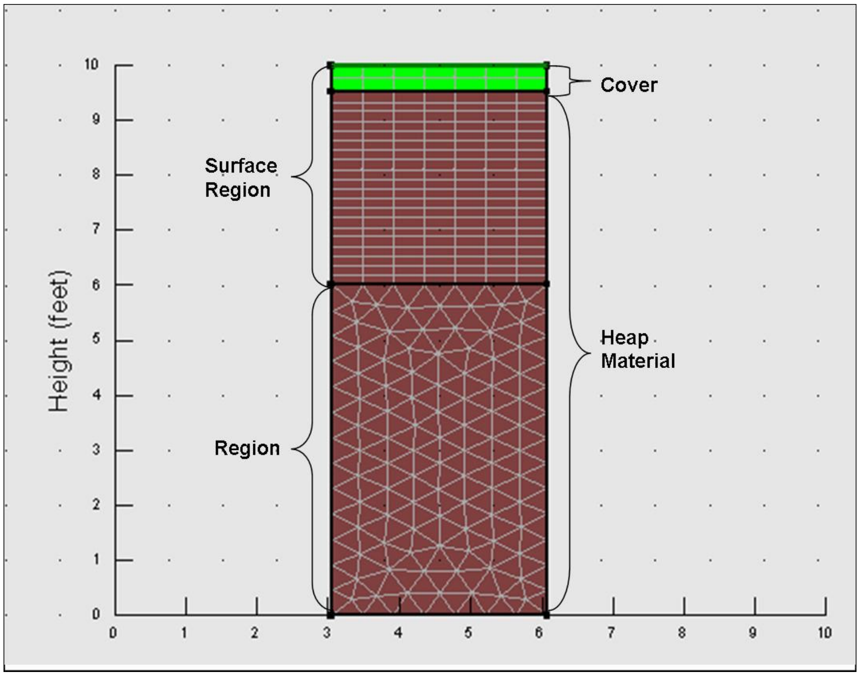

Figure 1. Model domain and meshing.

As shown in Figure 1, this modeling used a simplified column to represent the heap and cover material. The model has two distinct material property zones to represent the heap material (brown) and the cover material (green). Additionally, there are two zones of the model, the surface region (upper 1.2 m [four feet]) and a regular finite element meshed region (lower 1.8 m [six feet]). The use of a surface region allows for consideration of climatic conditions in the modeled simulations. The base of the model used a negative unit gradient boundary condition to ensure a free draining system, as is observed in the measured drainage conditions of the heap.

VADOSE/W (GEO-SLOPE, 2007) rigorously simulates the dynamics of the facility surface or cover by considering climate and soil condition interactions. VADOSE/W (GEO-SLOPE, 2007) simulates the entered climate conditions by breaking the model up into time increments with a maximum size of two hours. The daily precipitation data is distributed over a one day period according to a sinusoidal function that peaks at noon. The average annual precipitation for the site is 25 cm (10 in) and the average annual evaporation is 107 cm (42 in) resulting in a net negative annual water balance. In an environment with a net negative annual water balance (evaporation is greater than precipitation), such as the arid southwestern United States, evaporation is one of the most important and controlling components of the system. Evaporation and transpiration are calculated from the following climate, soil, and vegetation factors:

- Air temperature;
- Soil temperature;
- Relative humidity;
- Solar intensity (from latitude);
- Soil temperature;
- Soil moisture content;
- Leaf area index;
- Plant root depth;
- Plant wilting point;

- Wind speed; and
- Measured pan evaporation.

The combination of all the factors listed above provides a rigorous estimate of actual water evaporation and transpiration from the system. Infiltration is based on the unsaturated hydraulic conductivity [K(θ)] of the material at a given time. Excess precipitation that has not evaporated, transpired, or infiltrated is tabulated as runoff.

Previous work, which included field sampling and laboratory testing of the cover material and the heap leach ore, provided material properties (including moisture retention curve and saturated hydraulic conductivity) for the heap leach ore and the soil cover. Evaluation of the previously used material properties and observation of the soils during a site visit suggest that the soils used in the construction of the cover are consistent (have a similar texture) with the types of soil tested during the previous investigation. Therefore, the previously developed material properties were used to construct the initial model scenarios of this evaluation. Table 2 presents a summary of the hydraulic material properties used in this modeling study and Table 3 presents the grain size distribution of the cover and heap material for the laboratory testing.

The cover material data were taken from the HYDRUS-2D (Simunek et al, 1999) model database with a 24% reduction in residual and saturated water content to account for the fraction of rock in the material composition. The heap material data are from a laboratory moisture retention curve and the HYDRUS-2D (Simunek et al, 1999) database with a 9.5 % reduction in the residual and saturated water contents. The functions used in the VADOSE/W (GEO-SLOPE, 2007) modeling were estimated/ generated from the parameters listed in Table 2 using the van Genutchen method. Figure 2 presents the VADOSE/W (GEO-SLOPE, 2007) hydraulic conductivity functions associated with the heap and cover materials. Figure 3 presents the VADOSE/W (GEO-SLOPE, 2007) volumetric water content functions.

Table 2. Hydraulic material properties

Material Type	**Soil Type**	**Residual Water Content**	**Saturated Water Content**	**van Genuchten parameter n**	**van Genuchten parameter α (cm^{-1})**	**Saturated Hydraulic Conductivity (cm/s) [ft/hr])**
Cover Material	Loamy sand	0.0372	0.298	1.48	0.0120	2.00e-4 [2.36e-2]
Heap Material	Crushed ore	0.0469	0.291	1.34	0.0296	5.44e-4 [6.43e-2]

cm/s = centimeters per second
ft/hr = feet per hour (model units)

Table 3. Measured grain size distribution

Size Designation	**Grain-Size Range (mm)**	**Cover Material**	**Heap Material**
Rock	> 9.5	24.3%	9.5%
Sand	0.0075 - 9.5	28.1%	75.9%
Silt	0.0084 - 0.075	28.1%	9.6%
Clay	< 0.0084	19.5%	5%

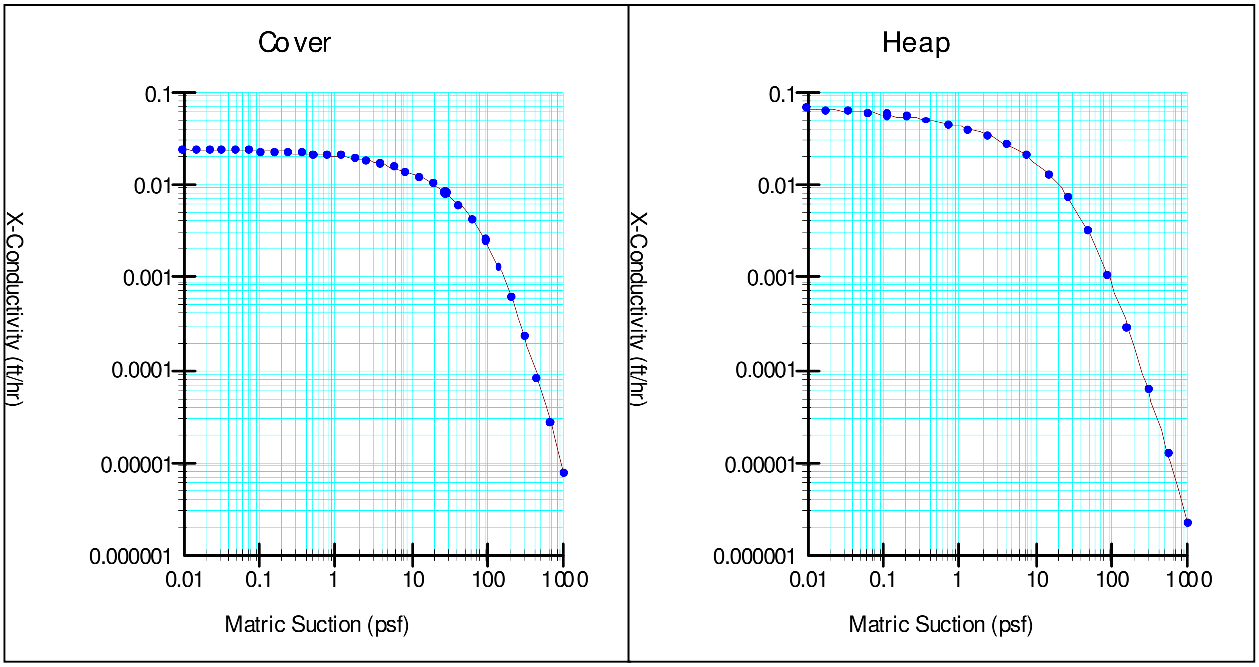

Figure 2. Model hydraulic conductivity functions.

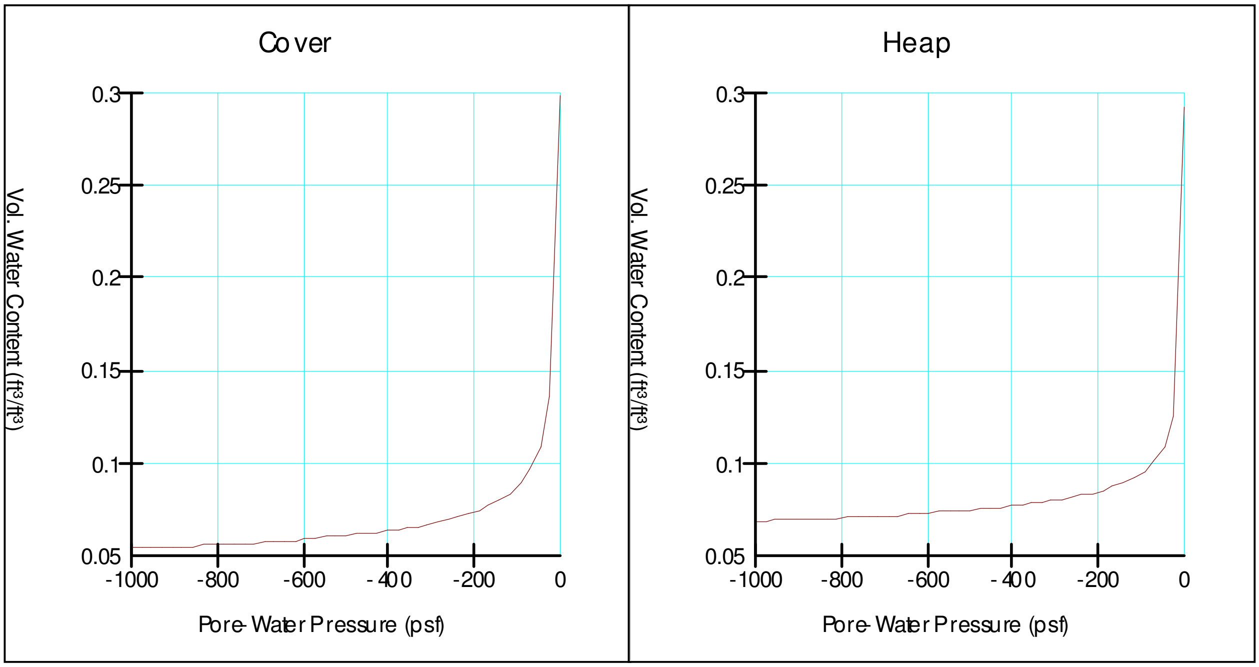

Figure 3. Model volumetric water content functions.

Three meteorological stations (met station) are in the vicinity of the subject heap. The first is located at the mine offices at the site, the second is located on the top of the heap and was installed as part of the TDR monitoring system, and the third is a Western Region Climate Center (WRCC) station. There is not good correlation between the two on-site datasets, so they were not used directly in the modeling, but provided a reference point for the regional meteorological station that was used. The WRCC meteorological station has the longest period of record and has been confirmed as reasonable compared to the onsite data collected, so it is the preferred source of climate information for this modeling study. Some adjustments to the data were necessary to correlate the potential evaporation rates calculated using the data from the WRCC meteorological stations with the altitude of the mine site. The Shevenell method (1996) was used to adjust the potential evaporation data from the WRCC station to correspond with the elevation of the mine site. Table 4 presents the adjusted evaporation values used in this modeling and the adjustment parameters used in the calculations.

Table 4. Adjusted site potential evaporation (after Shevenell, 1996).

Region: 4
Site Elevation: 1974 meters (6,475 feet)
ET_O (mm/month) = A(Elev,m)+b

	A	b	ET_O (mm)
January	---	---	0
February	-0.0204	37.366	0
March	-0.0510	112.225	11.6
April	-0.0656	188.083	58.6
May	-0.0827	295.112	131.9
June	-0.0800	356.229	198.4
July	-0.0758	416.297	266.7
August	-0.0507	314.878	214.8
September	-0.0537	241.125	135.1
October	-0.0316	117.220	54.9
November	-0.0197	41.245	2.4
December	---	---	0
Annual		mm in	1074.4 42.3

ET_O = Potential/Reference Evapotranspiration = (Pan Coefficient)(Pan Evaporation)

Previous modeling used a computer generated dataset. The dataset was generated using CLIGEN (Nicks et al., 1995) and included 20 years of information, including a total of 92 storm events with more than 13 mm (0.5 inches) of precipitation. The WRCC meteorological station used to develop the climate data for the modeling has over 70 years of daily data measurements. Because the years of operational data for the heap drainage have been approximately average, the current modeling effort focused on average climate conditions and utilized actual daily measurements of years within the 70 year record that are representative of near average annual precipitation (approximately 25 cm [10 in]). In order to get a complete data set, the WRCC meteorological station data was supplemented with multiple sources to develop a complete file of daily data.

Steady State Model

Steady state modeling is always challenging because mining facilities do not reach true steady state conditions until many years into the mine closure/post closure period. Therefore, the results of the steady state modeling are not designed to replicate true conditions, just to offer non-zero starting values for the subsequent transient modeling. A zero starting point for the transient modeling would require that the system be wetted before flow conditions would be representative of the actual heap. The goal of the steady state model step for this case study was to have a free draining column with a volumetric moisture content that is approximately seven to ten percent (7-10%), which represents the approximate drained moisture content of the heap leach ore based on field measurements of operational data from the heap leach facility (operational water balance) and from the TDR monitoring data. This produces a starting condition for the transient modeling than is representative of observed site conditions. Figure 4 presents the volumetric water content distribution resulting from the steady state model simulation. This was used as the starting conditions for the transient modeling using the daily climate data described above.

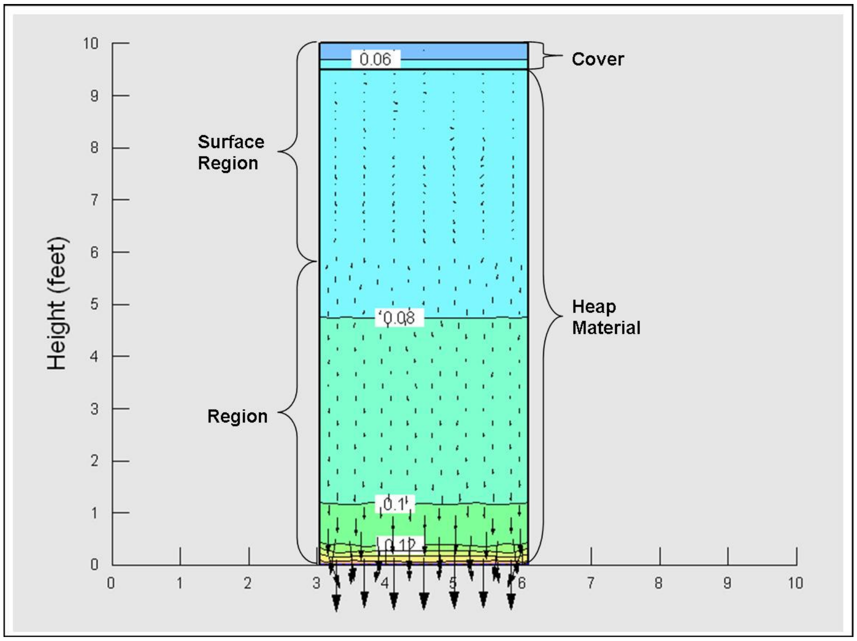

Figure 4. Model volumetric water content.

Transient Model

Transient modeling is used to simulate flow conditions within the facility over time. The surface region is the part of the model where climate and soil come in contact; it is also the layer that drives the water balance. Next, the water moves according to the rules of unsaturated flow physics through the heap material, and finally, water reaches the bottom of the model which is a free draining discharge point (unit gradient boundary condition). The transient flow dynamics within the heap were simulated over time and space. The model accounts for sudden transitions between material types and produces the following data sets:

- Water flux within the model domain;
- Moisture content;
- Water flow velocity; and
- Discharge (out of the model domain).

The scenarios considered for the baseline modeling effort focused on increased thicknesses of the cover to determine if this would improve the performance of the cover. Each of the varied cover thickness models considered a vegetated and a non-vegetated cover, because it can take more than three growing seasons to establish vegetation on the soil cover due to the arid climate. The soil cover thicknesses considered were:

- 15 cm (0.5 feet) (equivalent to the thinnest areas of the existing soil cover - based on field measurements);
- 46 cm (1.5 feet); and
- 91 cm (3.0 feet).

Each transient model was run for up to 20 years, using daily climate conditions representative of average annual precipitation quantities (approximately 25 cm [10 in] of precipitation). The long run period is intended to minimize the "noise" of the transition between infiltration and evaporation. Model "noise" results in large variations in the model results such as the water balance and drainage rates. Models run over short periods of time can be over influenced by close boundary conditions and may not represent actual distributions of moisture within the facilities, leading to "noise" in the model results. Running the model for multiple years in a row will minimize the influence of the boundary conditions and allow the moisture content to be more naturally distributed throughout the facility and thus smoothing the results.

Baseline Model Results

The results of the baseline modeling suggest that there is a significant amount of interaction between the climate and the heap materials below the cover. The results of the baseline model (15 cm [0.5 foot] cover) confirmed the observed field conditions that approximately 20% of annual precipitation is infiltrating into the heap. A flux section was placed in the model at a depth of approximately 1.8 m (six feet) to monitor the vertical flow of water across that point. The results from the flux section showed significant infiltration of precipitation and evaporation of water from the heap material. Increasing the cover thickness improved the performance of the cover and allowed less water to be infiltrated into the heap material. Increasing the cover to a thickness of 46 cm (1.5 feet) decreased the infiltration (as a percentage of precipitation) by 6.2% and 9.1% over the 15 cm (0.5 foot) cover for the non-vegetated and vegetated scenarios (13.8% and 10.9% of mean annual precipitation), respectively. The 91 cm (3.0 foot) cover decreased the infiltration by 16% and 16.5% over the non-vegetated and vegetated 15 cm (0.5 foot) covers (4.0% and 3.5% of mean annual precipitation), respectively.

The baseline model provides a good indication that the simple mitigation measure of increasing the cover thickness will be successful in decreasing the infiltration into the heap. This is likely due to the store and release characteristics of the soil cover material. Though the heap and the soil cover materials are similar in their saturated hydraulic conductivities, their grain size distribution (Table 3) results in a different behavior, which can be seen on the hydraulic conductivity functions (Figure 2). The conductivity of the soil cover remains relatively stable with increasing matric suction, while the heap material has a steadily decreasing conductivity with increasing matrix suction. Increasing the thickness of the cover material will move their behavior even further apart, which results in a hydraulic break forming between the cover and the heap material which helps to minimize the amount of precipitation that can infiltrate into the heap material. However, based on information obtained during a site visit, this heap may be experiencing other complicating factors beyond just soil properties. It was observed that the northern portion of the facility was accumulating large areas of snow and could be contributing more infiltration than the flat top of the facility which is well exposed to both solar radiation and wind. The baseline scenarios do not consider this area, so an evaluation phase of the modeling was completed.

Seepage Model Construction – Evaluation Scenarios

As with the baseline model scenarios, the evaluation modeling scenarios were completed using the program VADOSE/W (GEO-SLOPE, 2007). The material properties used during the baseline modeling were determined to be appropriate and were also used for the evaluation scenarios modeled. The one main flaw in the baseline modeling is that it only considers infiltration into the flat top surface of the heap. Although this area is likely a source of infiltration, the north facing slope of the facility could also be a significant source of infiltration.

The sides of the subject heap have a slope of 2H:1V with some areas being slightly flatter. The flat top of the facility is actually at approximate 0.5% grade to allow for runoff and to prevent ponding on the facility surface. The north facing area of the facility has the same overall slope as the other sides of the facility, but it does not receive as much radiation from the sun and is moderately protected from the wind. This allows for significant snow accumulation during the winter, which appears to increase infiltration during the spring when the snow slowly melts. To consider this particular area of the facility, a series of evaluation models were constructed that focus on a protected slope of a general heap configuration. Figure 5 presents the model domain and meshing for this series of evaluation models.

As with the baseline models, the evaluation models were limited to the top 3.0 m (ten feet) of the heap. The models have two distinct material property zones to represent the heap material (brown) and the cover material (green). Additionally, there are two zones of the model, the surface region (upper 1.2 m [four feet]) and a regular finite element meshed region (lower 1.8 m [six feet]). The use of a surface region allows for consideration of climatic conditions in the modeled simulations.

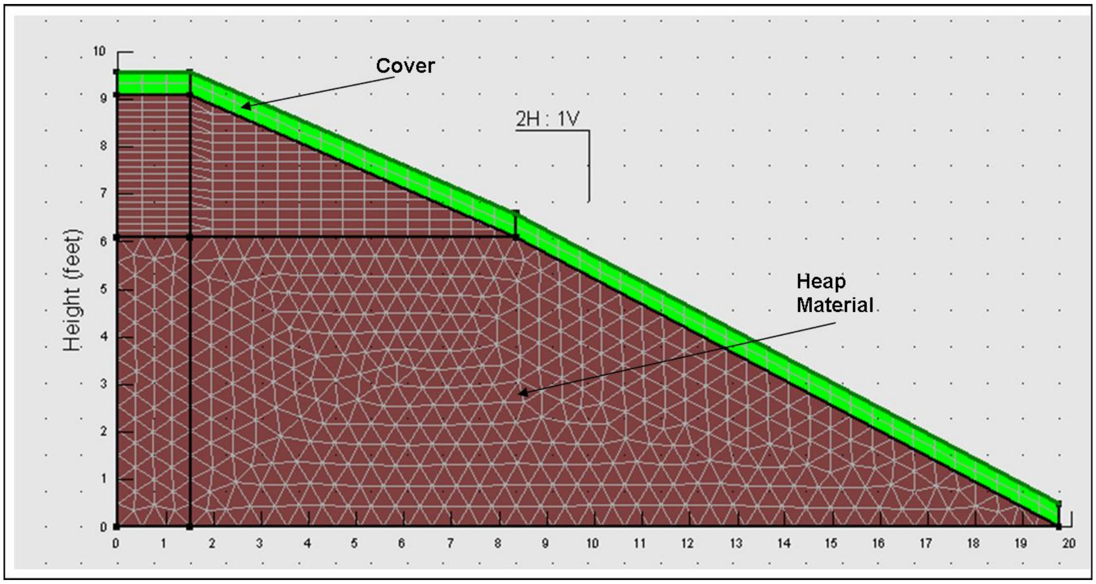

Figure 6. Model domain and meshing.

Evaluation Model Results

As with the baseline models, under average climate conditions and laboratory based material properties, the evaluation models suggest that the current cover may not performing in a manner that will meet the target infiltration rate of 7% of mean annual precipitation. The sloped area of the facility does perform better than the flat top surface of the facility that was considered for the baseline models under the average climatic conditions. As with the baseline models, increasing the cover thickness to 46 cm (1.5 feet) decreases the infiltration into the heap, but not enough to meet the target rate. A cover with a thickness of 91 cm (three feet) decreases the infiltration under average conditions to less than seven percent both with and without vegetation, which was also the case for the baseline models. Table 5 presents the results of the six baseline and evaluation models as infiltration rates as a percent of the mean annual precipitation.

Table 5. Infiltration as a percent of mean annual precipitation.

Model Scenario	Infiltration on Flat Top Surface	Infiltration on Sloped Surface
15 cm (0.5 ft) cover, no vegetation	20.0%	16.2%
46 cm (1.5 ft) cover, no vegetation	13.8%	7.4%
91 cm (3.0 ft) cover, no vegetation	4.0%	4.9%
15 cm (0.5 ft) cover, with vegetation	20.0%	9.6%
46 cm (1.5 ft) cover, with vegetation	10.9%	7.0%
91 cm (3.0 ft) cover, with vegetation	3.5%	5.3%

Seepage Model – Worst Case Scenario

As illustrated by the evaluation models, the sloped face of the heap can alter the infiltration rate compared to the flat top surface or sunny south facing slope. In general, we would expect that the sloped surfaces of the facility would have a greater percentage of runoff than the flat top surface, however, if a significant portion of the sloped surface is blocked from solar radiation and wind, then the accumulation of precipitation on the protected surface could alter the performance of the cover. For this site, the field observations suggested that this may be the situation controlling the drainage being observed from the closed heap, so a worst case scenario was considered to evaluate the influence the protected north slope could have on the overall performance of the system.

For this study the worst case infiltration scenario is an above average snow fall on the protected north facing slope, followed by a period of increased temperatures allowing the snow to melt and infiltrate into the facility. The climate file for these scenarios was developed to have three phases: snow storm, average conditions, and thaw. The snow storm and the average conditions were applied for a period of seven days each and the thaw period was applied for 14 days. The thaw period is longer to ensure that there is sufficient time during the model simulation for the water to reach the flux sections placed within the heap material.

The snow storm models were run after approximately three years of average conditions to ensure that any "noise" in the model would have minimized, and at a time in the model that corresponds to an appropriate time of year when such conditions could exist. These models were run using covers with and without vegetation, however, because this storm event is in the middle of winter when vegetation has the least impact, only the non-vegetated cover results were considered in the data evaluation. The results of these models are shown on Figure 6. Table 6 provides the water balance of these models at the end of each of the three climate phases being modeled.

Table 6. Snow storm model water balance results after snow storm, average conditions, and thaw as a percentage of the simulated precipitation.

	Day	Cumulative Boundary Fluxes	Cumulative Runoff Mesh	Cumulative Storage	Cumulative Water Balance	Cumulative Precip Mesh	Cumulative Surface Evaporation	Cumulative Plant Transpiration
15 cm (0.5 ft) cover	7	-0.02%	0.87%	37%	-0.02%	38%	0.0%	0.0%
	14	-32%	2.6%	38%	0.22%	73%	0.0%	0.0%
	31	-94%	2.6%	3.6%	0.22%	100%	0.0%	0.0%
46 cm (1.5 ft) cover	7	0.04%	0.00%	32%	0.00%	32%	0.0%	0.0%
	14	0.03%	0.04%	73%	0.08%	73%	0.0%	0.0%
	31	-53%	2.4%	44%	0.31%	100%	0.0%	0.0%
91 cm (3.0 ft) cover	7	0.05%	0.0%	30%	0.00%	30%	0.0%	0.0%
	14	-0.02%	0.0%	73%	0.00%	73%	0.0%	0.0%
	31	-0.06%	0.0%	100%	-0.03%	100%	0.0%	0.0%

On Figure 6, the infiltration rate of the three models are plotted on the left axis as a rate in gpm and the precipitation is plotted on the right axis with units of inches. During the snow storm event, infiltration is minimal because the ground surface is frozen and the snow is allowed to accumulate on the soil cover surface. This is supported by the cumulative storage of 100% of snow storm precipitation for each of the models at day seven (end of the snow storm) and at day 14 (end of the average conditions period), which represents the accumulation of snow on the surface of the modeled facility. During the average conditions phase of the models, the ground surface warms slightly, but is still allowing additional precipitation to accumulate on the surface of the facility (continued 100% percent of precipitation is going to increased storage at day 14 of the models [Table 6]). The final stage, thawing, is the most active for each of the models. The 15 cm (0.5 foot) cover allows the most infiltration (94% of the storm precipitation), but also recovers to more average conditions the fastest. The 46 cm and 91 cm (1.5 and 3.0 foot) covers allow significantly less infiltration as a result of the snow melting (53% and 0.06%, respectively), with the 91 cm (3.0 foot) cover performing the best. However, when the results are compared using infiltration units of percent of the storm precipitation, none of these covers are sufficient to prevent infiltration to the target rate of 7% based on average climatic conditions and laboratory based material properties.

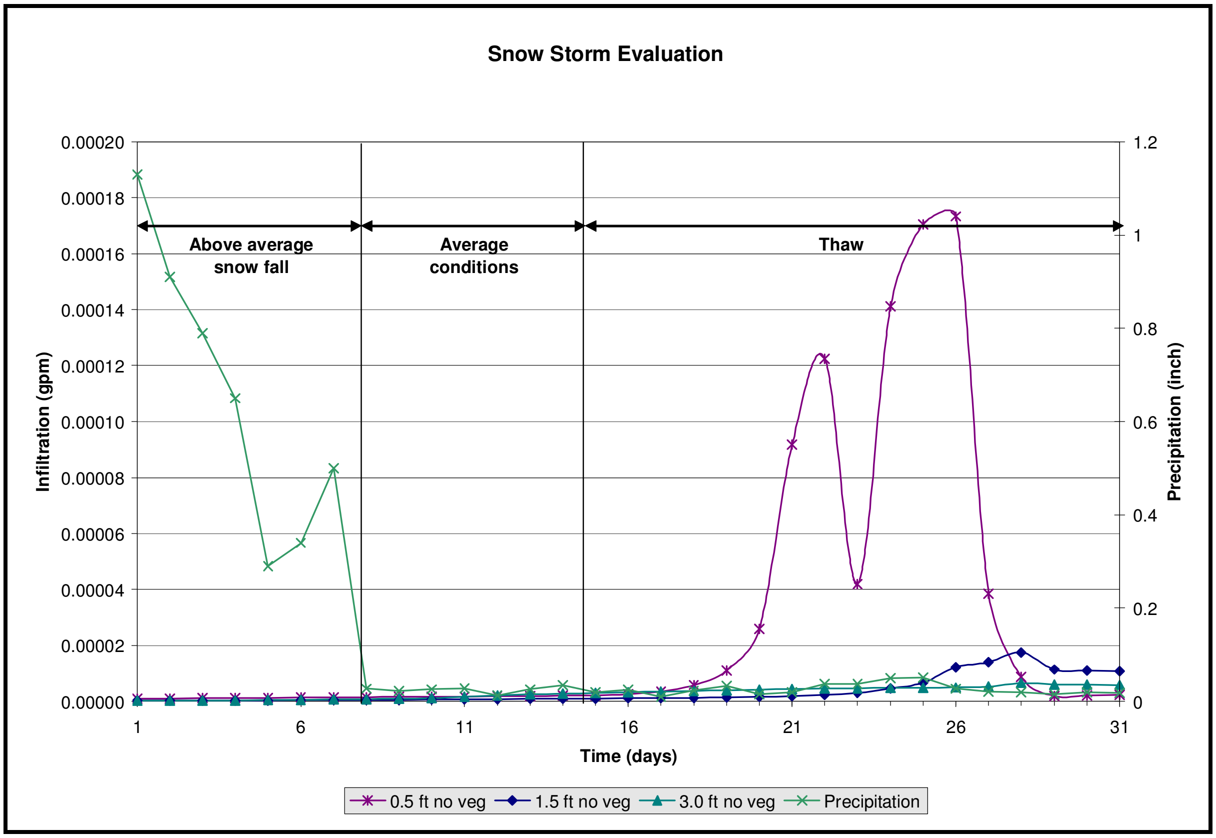

Figure 6. Snow storm scenario model results.

Conclusions

For the heap that is the subject of this case study, the current cover is allowing nearly 20% of mean annual precipitation to infiltrate into the heap material, which is resulting in continued drainage from the facility. The modeling completed in this study was intended to determine if mitigation measures such as increasing the cover thickness would improve the performance of the facility and lower the infiltration to below the target of 7% of mean annual precipitation. The results of the baseline and evaluation models showed that for a heap with the material properties and climatic conditions of this site, increasing the cover will decrease the infiltration to levels that meet the closure requirements. However, based on field observations, there may be other factors that require consideration, such as a protected area of the facility that has excess snow accumulation.

Based on modeling of a worst case snow and thaw cycle, infiltration increases beneath protected areas of the facility. As with the baseline and evaluation models, even under the worst case infiltration conditions, increasing the cover thickness does improve the performance of the facility. Though this mitigation measure has been proven at many sites to be effective in preventing infiltration into closed heap leach facilities, other options were also considered, such as using a liner over the top of the facility. While applying a liner over the entire facility is a highly effective method for preventing infiltration of precipitation into a heap, it is also expensive. If sufficient material is available to increase the cover to a minimum of 91 cm (three feet) thick, then this could be an effective mitigation measure for the heap that was the subject of this case study.

In order to field truth the conclusions made from the modeling completed as part of this study, it has been recommended that a series of on-site test cells be constructed and instrumented. In total, six test cells are recommended, three on the north facing aspect, and three on flat or south facing aspect. This will provide a better assessment of the impacts being observed due to snow accumulation and the increased infiltration associated with the snow melt suspected to be occurring on the north side of the heap leach facility, and could provide a means to validate this modeling study.

References

GEO-SLOPE International, Ltd. (GEO-SLOPE), 2007. Vadose Zone Modeling with VADOSE/W 2007: An Engineering Methodology. GEO-SLOPE International Ltd.: Calgary, Alberta, Canada.

Nicks, A. D., L. J. Lane, and G. A. Gander. 1995. Weather generator. Chapter 2 in USDA–Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation. D. C. Flanagan and M. A. Nearing, eds. SERL Report No. 10. West Lafayette, Ind.: USDA–ARS National Soil Erosion Research Laboratory.

Shevenell, L. 1996. Statewide Potential Evapotranspiration Maps for Nevada. Nevada Bureau of Mines and Geology Report 48. University of Nevada – Reno. Reno, Nevada.

Simunek, J., M. Senja and M.T. van Genuchten, 1999. The HYDRUS-2D Software Package for Simulating the Two Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. U.S. Salinity Laboratory, Agricultural Research Service, U.S.D.A, Riverside, California.