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Modeling of seepage through segregating waste rock: part II

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ABSTRACT

This study examines seepage flow through coarse and fine layers formed through end-dumping of material onto a waste rock pile. Of particular importance is determining whether a saturated zone will form after significant storm events. The modeling is based on detailed analysis of a conceptual model which was presented in the Part 1 paper. The findings indicate that the net percolation for the average slope is 41-44% of precipitation and the expected actual evaporation rate is 56-59%. These estimates are highly determinate on the status of the crust material. It is expected that storm events will not cause the pore-water pressure to be significantly altered below a depth of 5m. It would take a sequence of many precipitation events to form a well-developed water table in the waste rock pile.

Key Words: unsaturated flow, seepage, actual evaporation, stability

1 INTRODUCTION

Considerable segregation can occur when material is end-dumped onto a waste-rock pile. The process of creating a slope by dumping waste rock materials from the crest of the slope creates a multi-layer structure within the waste rock dump. The random dumping process can result in layers of fine and coarse materials coming to rest at roughly the angle of repose. This is similar to the stratification found in soil layers laid down by wind or water. The waste rock at the Goat Hill North rock pile appears to have been formed by multiple layers of fine and coarse materials.

This paper examines the flow of rainfall through detailed layers of coarse and fine materials. The modeling is based on detailed analysis of a conceptual model which was presented in Part 1 (Fredlund, 2013).

Figure 1. Photo of Goat Hill North prior to destruction

2 OBJECTIVE

The objectives of the present study may be summarized in the following list:

- Refine the calculation of recharge and actual evaporation such that the treatment of the upper crust in the numerical model is improved.
- Determination of the flow regime of the detailed conceptual model with an understanding of the anticipated saturation and water content levels in the numerical model.
- Determination of the relative flows through coarse, medium and fine layers.
- Estimation of saturation and volumetric water contents in the fine, medium and coarse layers.
- Determine the reasonable seasonal changes in pore-water pressures in the upper 10m of the model.
- To determine the reasonable seasonal and annual changes in pore-water pressures in the layers deeper than 10m.
- To determine the reasonable times taken by a particle of water through the system.

In order to achieve the above objectives, the multi-layer seepage modeling was implemented in two steps:

- Step #1: Steady-state models used to determine a generalized flow regime
- Step #2: Transient models used to determine the establishment of longer-term results

3 CONCEPTUAL MODEL

The conceptual model used for the hydrological Phase II modeling may be seen in Figure 2.

Table 1. Material parameters used for phase II hydrological modeling

	Soil-water characteristic curve					Hydraulic conductivity	
Unit	Porosity, n	θ_s	$\psi_{ae,}$ AEV (kPa)	θ_r	ψ_r (kPa)	K_{sat} (m/day)	Slope of K_{unsat}
colluvium	0.3585	0.3585	1.15	0.054	3.439	8.71E-02	2.83
rubble	0.3623	0.3623	0.217	0.065	1.127	1.58E-02	2.83
Sand Base Case	0.302	0.302	1.64	0.133	31.33	1.469	**2.83**
Sand+1SD Finer H/C Slope	0.302	0.2528	2.913	0.133	31.33	1.469	1.863
Gravel+1SD Coarser H/C Slope	0.351	0.351	0.1985	0.104	2.2	7.1	3.797

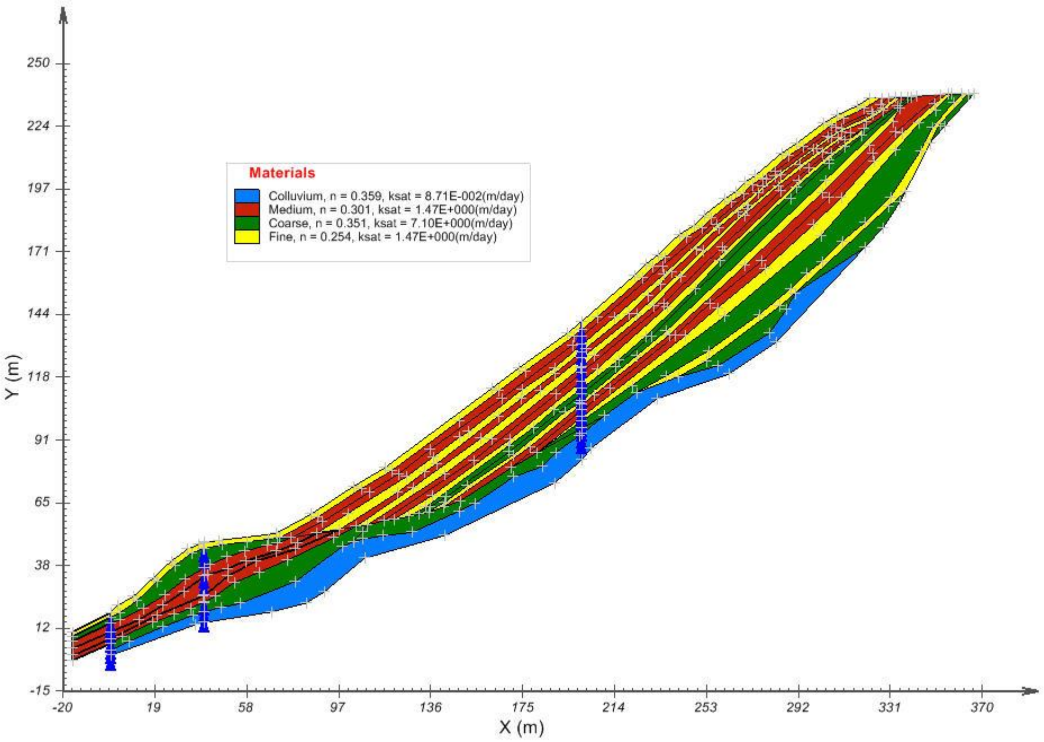

Figure 2. Conceptual model used for the phase II numerical modeling

4 MATERIAL PARAMETERS

In Phase I of the numerical modeling, averages for the sand portion and the gravel portion of the materials were established. Exploratory numerical modeling was performed in the first part of Phase II in order to determine if the selected averages matched observed field results. During this process it was noted that venting of steam was observed at the Goat Hill North (GHN) site. In order to represent this coarse/fine flow in the numerical model it was found that the following changes needed to be made to the average soil parameters in order to keep the coarse layer desaturated enough in order to have the majority of the flow travel through the fine layers:

The sand “average” property needed to have the air-entry value (AEV) and the slope of the unsaturated hydraulic conductivity curve moved to a position of a soil which was one standard deviation finer. This adjustment is reasonable and within the limits of the observed soil parameters for the site.

The gravel “average” property was adjusted one standard deviation coarser by changing the AEV and the slope of the unsaturated hydraulic conductivity. This adjustment is reasonable and within the limits of the observed soil parameters for the site.

The resulting soil parameters may be seen in the following diagrams. The soil water characteristic curves presented are illustrated using a two-slope technique. These curves were subsequently fit with the Fredlund and Xing (1991) equation in order to provide a smoother representation to the numerical model.

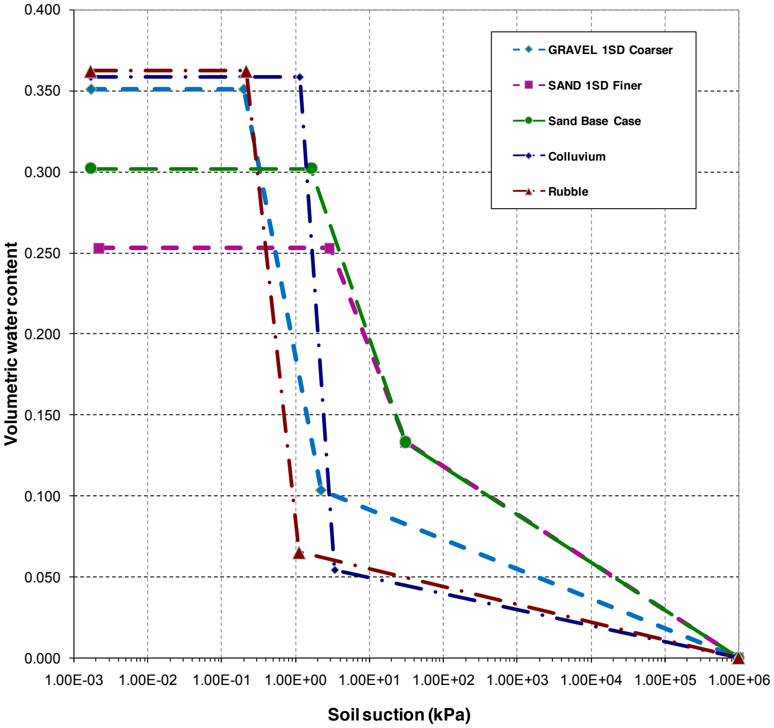

Figure 3. SWCC data used for the phase II hydrological modeling

The unsaturated hydraulic material parameters for the site are inherently based on the grain-size distributions measured at the site. The full methodology for moving from the grain-size distributions to reasonable hydraulic soil parameters may be seen in the Phase I report. The grain-size distributions which form the basis of the estimated hydraulic soil parameters may be seen in Figure 5.

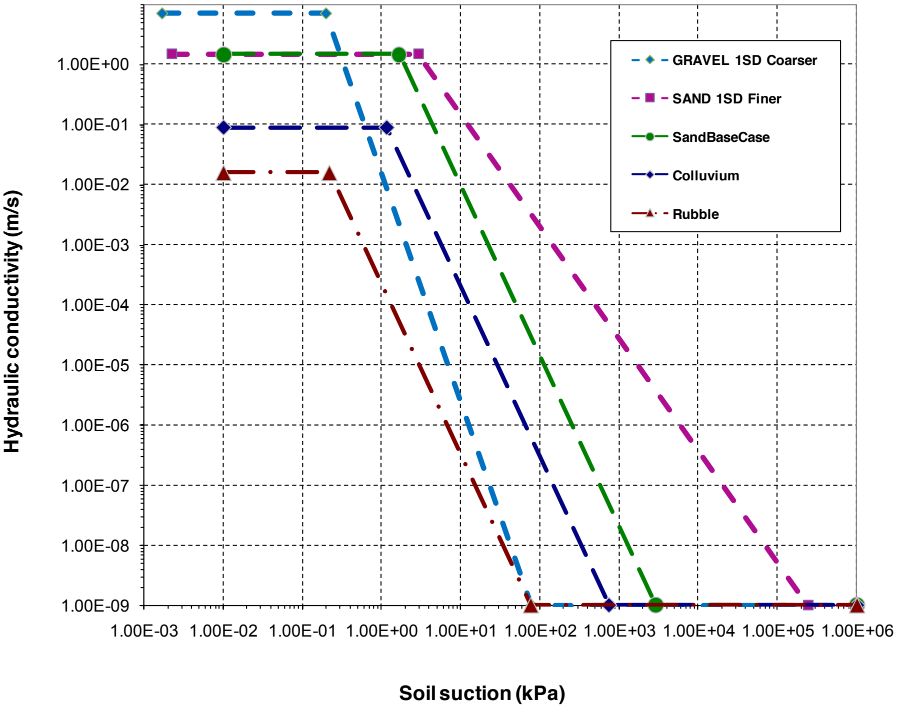

Figure 4. Hydraulic conductivity curves for all materials used in the phase II hydrological numerical modeling

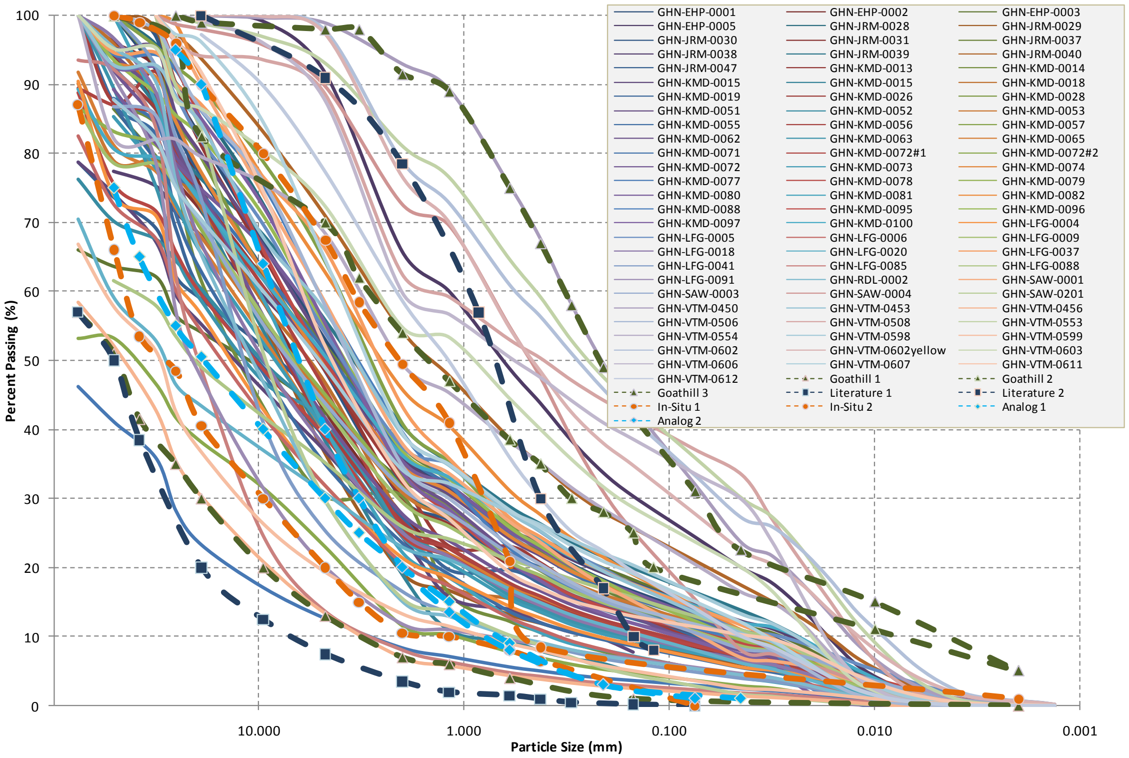

Figure 5. Grain-size distributions measured by NMT at the Goat Hill site

5 1 D NUMERICAL MODELING

The upper crust was identified in the Phase I numerical modeling as controlling the water balance for the system. Therefore a significant part of the Phase II numerical modeling involved the quantification of the flows at the top boundary. Most specifically, the crust was identified in the Phase I numerical modeling as significantly inhibiting evaporation. It was theorized in the Phase I numerical modeling that the crust was formed of a salt layer which inhibited flow due to osmotic pressures. Further testing was therefore performed on the crust material and it was determined that osmotic suctions were not influencing actual evaporation (AE) rates. However it was noted that the crust was i) obviously forming over approximately 80% of the waste rock surface and ii) was a very hard layer which was difficult to break with a boot. The crust thickness ranged from a few inches to approximately 1.5 ft. thick. A white powder was deposited in the pores between the gravel in the crust making the crust relatively impermeable. It was hypothesized that the crust was formed through minerals dissolved in the pore-water being transported to the surface of the waste rock and then deposited during the evaporation of the water phase.

The crust was physically observed to dissolve instantly in water and the gravel portion of the crust material then dominated flow.

The crust is formed through the precipitation of minerals near the surface during the evaporation process. The detailed numerical modeling of this process is a complex multi-phase process. A simplified approach was taken for the Phase II numerical modeling. The concept for the upper boundary is described in the following paragraph.

Figure 6. Example showing the crust material on the Sugar Shack rock pile

It is assumed, firstly, that rain-fall events wipe out the crust. In particular, rain-fall events of more than 5mm/day would cause the crust to “disappear” in the numerical model. The crust would begin forming immediately after a rain-fall event and would be fully formed 3 days after. At the three-day point all evaporation from the numerical model would be reduced to 20% of the full evaporation (assuming 80% coverage of the crust).

The physically observed crust material is located at Sugar Shack West rock pile at the Questa site. Due to the close proximity of Sugar Shack West to the Goat Hill North pile this crust is considered analogous to the crust formed at the Goat Hill North site. While there are possible locations of thin and thick crusts found at varying spatial locations on the rock pile, the crust of interest is characterized in the following sections. It should be noted that the following quantification of the crust is not intended to represent an exact quantification of the exact crust at all points on the rock pile. It is intended to represent an average condition of the GHN rock pile which is adequate for capturing the flow parameters required for performing the flow modeling for the hydrological aspect of the weathering program.

5.1 Climate and Boundary Conditions

Central to the calculation of flow within the pit is the issue of how much precipitation is entering the top of the rock pile. A significant amount of analysis has been performed to date and climate data from a number of weather stations near the Questa site has been compiled. The most relevant weather stations are TP4 and TP5. The data from each of these weather stations is available for approximately the past 20 years. Also available is data from the Red River weather station for the past 100 years. Previous studies on the climate have involved scaling the Red River data such that it is relevant to the Questa site.

Table 2. Wet, average, and dry climate years for station TP4

Model	**Year**	**Precipitation**			**Potential Evaporation**		**Temp**	**RH**
		Avg	**Avg**	**Avg**	**Avg**	**Avg**	**Avg**	**Avg**
		cm/year	**mm/day**	**in/year**	**cm/year**	**in/year**	**deg C**	
Wet	2000	46.19	1.27	18.18	97.38	38.34	5.0	53%
Average	2006	42.67	1.17	16.80	109.34	43.05	5.2	48%
Dry	1954	23.72	0.65	9.34	108.28	42.63	6.3	47%

The TP4, TP5, and Red River weather stations were all considered in this analysis. It was realized that certain data subsets would be needed for the analysis. It was also recognized that there is not necessarily a correlation between high precipitation and high infiltration. Wet, average, and dry years were selected from the 100-year and the TP5 data sets. Since infiltration is more influenced by a sequence of wet events, the 5-year wet, average, and dry data segments were extracted from the climate datasets. This data has provided the basis for the numerical modeling program. A summary of the wet, average, and dry years of data for the 1-year data for Questa may be seen in

Table 2. The location of the weather stations may be seen in Figure 8. Also relevant is the precipitation data for the past 7 years for weather station TP5 (Figure 7).

The following 5-year climate sequences were selected for use in the numerical modeling:

- The Wettest 5YR period is 1990-1994
- The Average 5YR period is 1934-1938
- The Driest 5YR period is 1950-1954

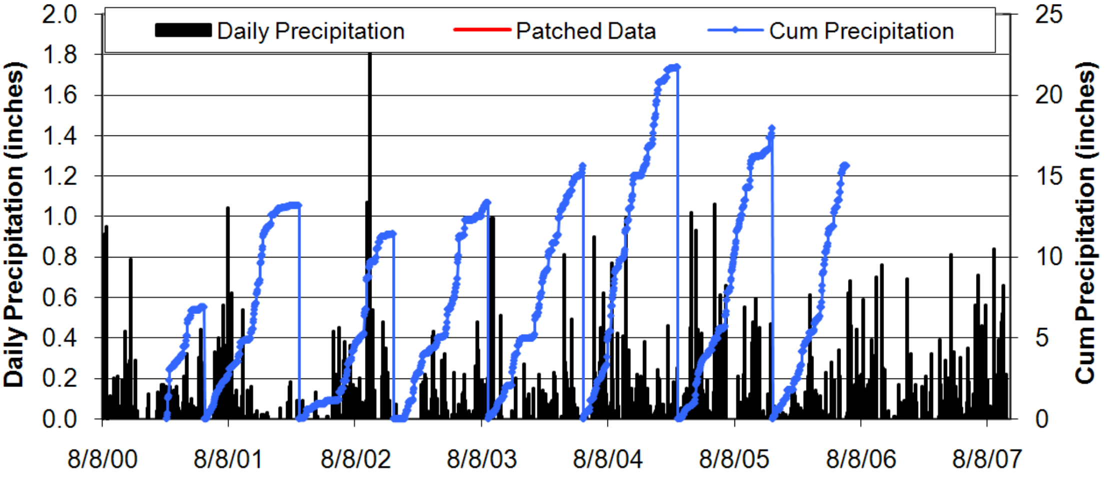

Figure 7. Summary of climate data for the past 7 years (Golder, 2005)

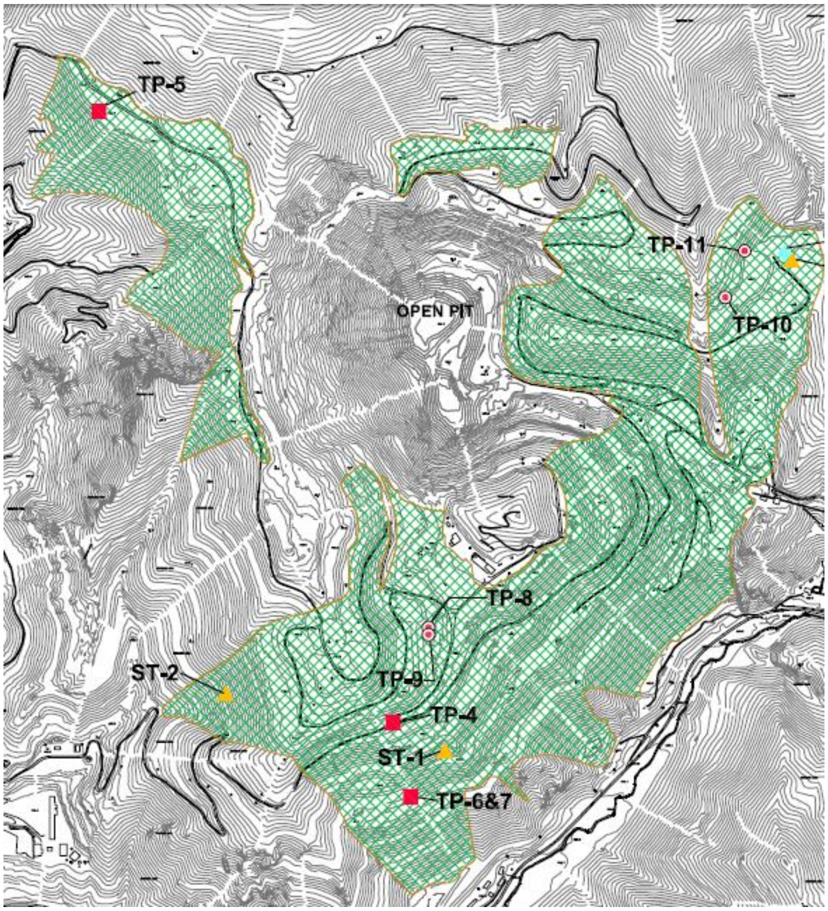

Figure 8. Weather station locations (Golder, 2005)

5.2 Transient 1-YearModel Runs

A series of 1-year numerical models were set up and run using a combination of the sand and gravel material parameters. The numerical models were homogeneous and had geometries of 10m. A ½ unit gradient boundary condition was applied to the bottom of each numerical model and climate data as determined by the Golder (2005) study was applied to the top of the numerical model. The models were run through a combination of wet, average, and dry years as determined from the precipitation measurements.

For all numerical models, a crust was fully formed after 3 days and an 80% coverage of the crust is assumed

5.2.1 Crust Effect on Actual Evaporation

Crusts are common when dealing with mining waste rocks. The existence of the salt crust can significantly reduce the evaporation of water from the material. The process can lead to the build-up of a crust which can be described as follows:

1. During the evaporation process, water is pulled out of the soil. This process delivers salt or other precipitates in the soil to the surface, and crust begins to form. After a certain period of drying, the crust formation is complete.
2. Once the crust is formed, there will be a reduction in future evaporation of water from the material. The ratio of evaporation reduction is referenced as crust coverage.
3. At the time of a rainfall event, and if the rainfall is over a certain amount, water will tend to dissolve some the precipitate on the surface of the material and water will flow into the material.

This type of crust can be modeled in the SVFlux software through a specification of the time for a crust to begin forming after a precipitation event, the time until a crust is complete, and the percentage coverage of the crust material.

Considering the crust effect on evaporation, the actual evaporation AE is modified as

$$AE_c = C_f AE \tag{1}$$

where:

AE_c = Actual evaporation after consideration of crust effect

C_f = A factor of crust effect on evaporation. C_f changes from 0 to 1

C_f is related to crust drying day C_{dd},

$$C_f = 1 \qquad \text{If } C_{dd} < F_s \tag{2}$$

$$C_f = 1 - C_V \qquad \text{If } C_{dd} > F_c \tag{3}$$

$$C_f = 1 + C_V \frac{(F_s - C_{dd})}{F_c - F_s} \qquad \text{If } F_s \le C_{dd} \le F_c \tag{4}$$

where :

C_{dd} = Crust drying day

F_s = Crust starting formulation

F_c = Crust formulation completion

C_V = Crust coverage in percentage. If $C_V = 100\%$ meaning no evaporation happens after the crust is formulated.

The crust drying days are calculated between precipitation events according to the following formula:

$$C_{dd} = 0 \qquad \text{If } P_T > P_h \tag{5}$$

$$C_{dd} = C_{dd} - 1 \qquad \text{If } P_T = 0 \tag{6}$$

$$C_{dd} = C_{dd}(1 - P_T / P_h) \qquad \text{Otherwise} \tag{7}$$

Where:

P_T = daily precipitation

P_h = A dissolved threshold of precipitation. If a daily precipitation is over this threshold, the crust effect will be dissolved.

Figure 9 illustrates how the crust factor is calculated with the changing daily climate. In this figure, the crust starting formulation = 1 day, crust formation completion = 4 days, crust coverage = 80%, and dissolved threshold of precipitation = 0.5 mm.

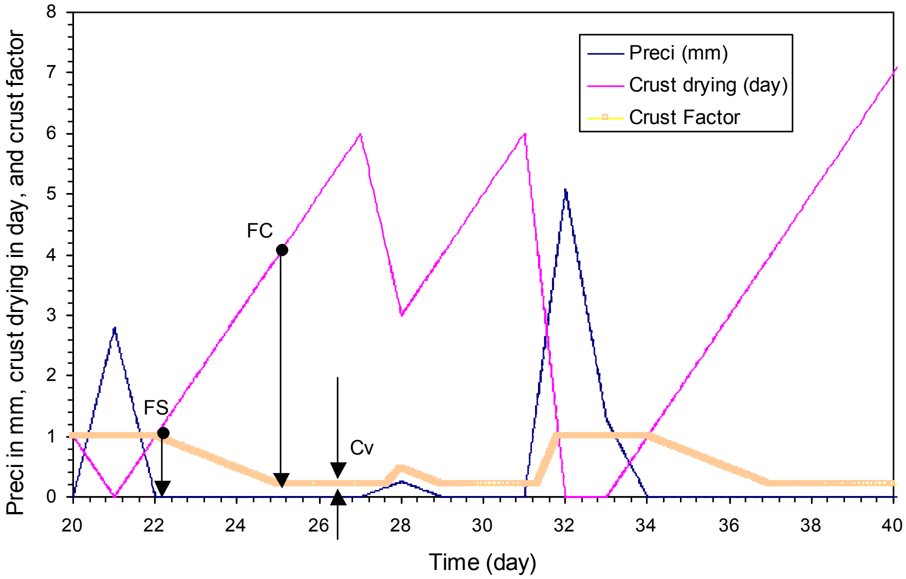

Figure 9. Illustration of crust factor changing with precipitation

5.2.2 *Transient 1-Year Model Results*

The new climate boundary condition was calibrated to the suction readings measured by New Mexico Tech (NMT). The data was collected between August 6th and October 5 of the year 2004. The data shows extremely low matric suctions (< 10 kPa) in the upper depths between 63-204 cm. The tensiometer readings were taken at the upper crest of the GHN rock pile prior to the destruction of the rock pile. A “quick-draw” tensiometer was used which has a maximum suction reading capacity of approximately 80-100 kPa.

Some of the model runs were not able to come to steady-state within the time period of a year. The current modeling study ran out of time in order to extend the runtimes of these models such that a true steady-state condition can be achieved with all of these one-year models. However, enough data could be obtained from the 5-year datasets such that reasonable conclusions could be drawn. The 1-year datasets did provide the benefit of seeing the breakdown of reasonable percolation rates for months where precipitations were reasonably high. An annual summary of the hydrological data may be seen in Table 3.

Table 3. Summary of annual flux rates for the 1-year numerical models

Model name	Time Period	Preci (m^3)	Prec Rank	AE (m^3)	AE Rank	NP Top (m^3)	NP Top Rank	NP (m^3)	NP Rank	PE (m^3)		Percent AE(%)	Percent NP Top(%)
SB_dry_1Y_FS0FC3	2009	0.2372	9	-0.17182	9	0.065468	6	-2.76E-06	5	-1.08096		-72.4	27.6
GB_Base_1Y_FS0FC3	2009	0.4282	4	-0.32072	3	0.107531	4	-2.99E-05	4	-1.09398		-74.9	25.1
SB_Base_1Y_FS0FC3	2009	0.4276	6	-0.31097	4	0.116642	3	-2.75E-06	6	-1.09409		-72.7	27.3
SB_Wet_1Y_FS0FC3	2009	0.4628	3	-0.28058	6	0.18247	1	-2.75E-06	6	-0.96861		-60.6	39.4
GB_Wet_1Y_FS0FC3	2009	0.4634	1	-0.29138	5	0.172427	2	-2.99E-05	4	-0.96782		-62.9	37.2
SF_base_1Y_FS0FC3	2009	0.4280	5	-0.37543	2	0.052363	8	-0.0061	2	-1.0933		-87.7	12.2
SF_wet_1Y_FS0FC3	2009	0.4634	2	-0.37993	1	0.08326	5	-0.00965	1	-0.96836		-82.0	18.0
GB_Dry_1Y_FS0FC3	2009	0.2375	8	-0.1782	8	0.059417	7	-2.99E-05	4	-1.08087		-75.0	25.0
SF_dry_1Y_FS0FC3	2009	0.2377	7	-0.2405	7	-0.00304	9	-0.0055	3	-1.08012		-101.2	-1.3
											Average	**-76.6**	**23.4**

These results indicate an average annual evaporation rate of 77% and a net percolation rate of 23%. Close examination of the data surrounding these numerical models yielded the following conclusions:

- Data from dry months tended to skew the net percolation data, and
- Much of the evaporation data was controlled by the current crust coverage (80%).
- The current crust coverage number is considered low and may in actuality be 90-95%.

Time was not available to perform further sensitivity results on these scenarios. Therefore it was deemed reasonable to throw out the 25% driest months in calculating the net percolation results. If this is done then the 1D average evaporation and net percolation values are:

- Actual Evaporation (AE): 56%
- Net Percolation (NP): 44%

Further clarification of the numerical modeling results can be viewed by plotting the minimum and maximum saturation and pore-water pressure values with depth. Profiles for a select group of the 1-year numerical models are shown in the following figures. The fine sand results in higher-than-average suctions in the upper profile. It should be noted that the results for the sand base-case are presented in the 5-year modeling section.

5.3 Transient 5-Year Model Runs

A series of 5-year numerical models were set up and run using a combination of the sand and gravel material parameters. The numerical models were homogeneous and had geometries of 10 m. A ½ unit gradient boundary condition was applied to the bottom of each numerical model and climate data as determined by the Golder (2004) study was applied to the top of the numerical model. The models were run through a combination of wet, average, and dry years as determined from the precipitation measurements. The summary of the cumulative flows by year may be seen in the following table.

Average annual net percolation at surface for the 5-year datasets was 18%. Close examination of the data surrounding these numerical models yielded the following conclusions:

- Data from dry months tended to skew the net percolation data, and much of the evaporation data was controlled by the crust coverage (80%).
- The current crust coverage number is considered low and may in actuality be 90-95%.

Time was not available to perform further sensitivity results on these scenarios. Because of these model influences it is considered reasonable to adjust the results of the numerical model to the following numbers:

- Actual Evaporation (AE): 66%
- Net Percolation (NP): 34%

Min/max plots were also utilized for the 5-year modeling study in order to quantify the reasonable variation in saturation and pore-water pressures during the modeling period. In Figure 10, the sand base-case modeling results for wet years are presented to give an idea of the reasonable variation in the profiles. It should be noted that even in the wet years the suction and saturation profiles are not significantly affected at depths below 8 m. It should also be noted that drying events reasonably only significantly affect the saturation profiles to a maximum depth of 2-3 m.

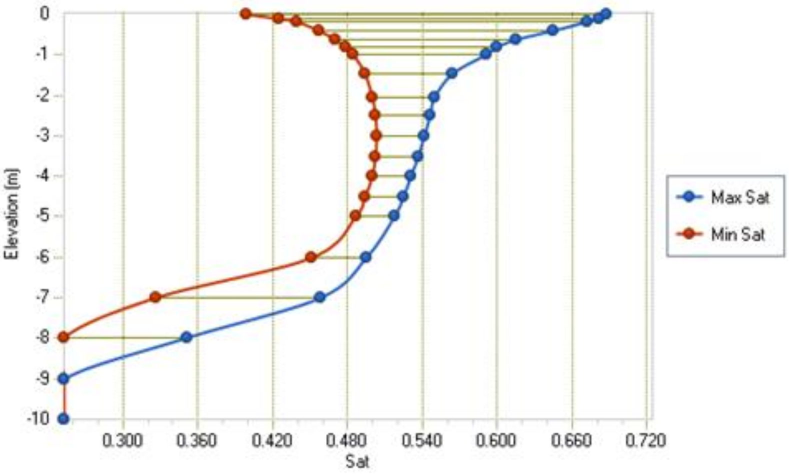

Figure 10. Saturation minimum / maximum for year 5 of the sand base-case wet years model

6 2D NUMERICAL MODELING

2D analysis were performed for the complex conceptual model in order to determine the reasonable distributions of pore-water pressure and saturation levels which can be reasonably expected in the rock pile.

6.1 Steady-State Analysis

Steady-state analyses are set up for this model in order to determine reasonable saturation levels and pore-water pressure variations throughout the domain of the numerical model. For this model, only average material parameters are implemented in the numerical model as presented in the preceding section. Average climate net flows of 0.5 mm/day, 0.75 mm/day, 1.0 mm/day, and 1.5mm/day are applied to the numerical model. From the previous Phase I analysis it was previously determined that the most appropriate approximation of net flow is 0.75 mm/day. The results of the analysis are presented in the following figures. Average saturation levels and pore-water pressures may be seen.

An average to high precipitation rate per year (including snowfall) is 20 inches. This type of precipitation results in an average daily value of approximately 1.0 mm/day. Steady-state application rates of 0.5 and 0.75 mm/day were chosen in this case because these would be approximate net infiltration rates if reasonable evaporation rates of 25% to 50% are considered.

Higher precipitation rates are presented in this report for the interest of providing an upper-bound on the numerical modeling. Precipitation rates of 10mm/day and 100mm/day are needed to produce a significant water table in the numerical model. It should be noted that these are steady-state numerical models so they assume a constant precipitation of the amount specified every day and forever into the future. Current precipitation rates average 1mm/day annually if all precipitation and snowmelt is averaged. It is highly unlikely that a constant precipitation rate of 10mm/day or higher could be applied in the real-world to this upper boundary condition for an extended period of time. The 10mm/day and 100mm/day steady-state model results therefore represent an extreme upper bound of which the probability of occurrence is approximately zero.

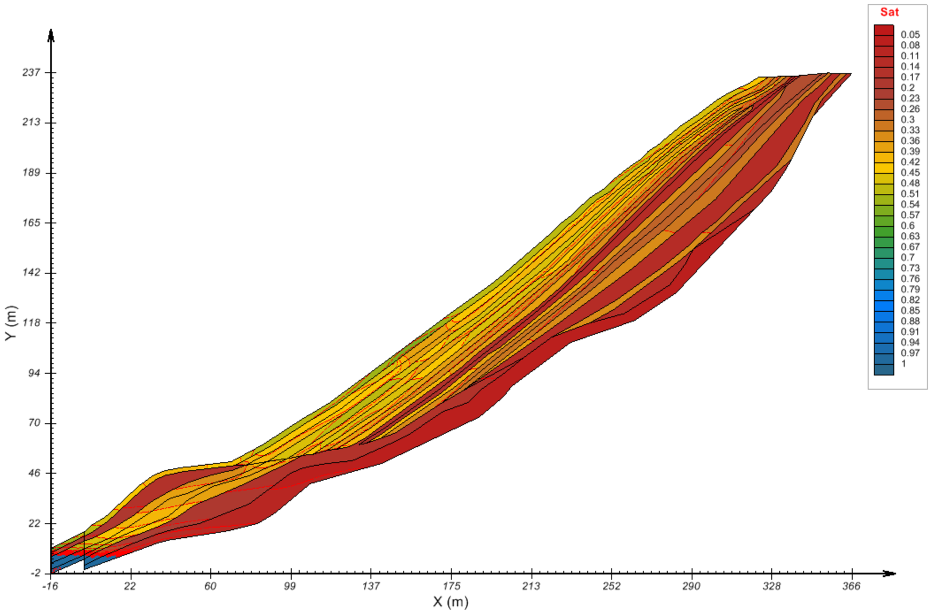

Figure 11. Saturation levels for a steady-state application of 0.5 mm/day

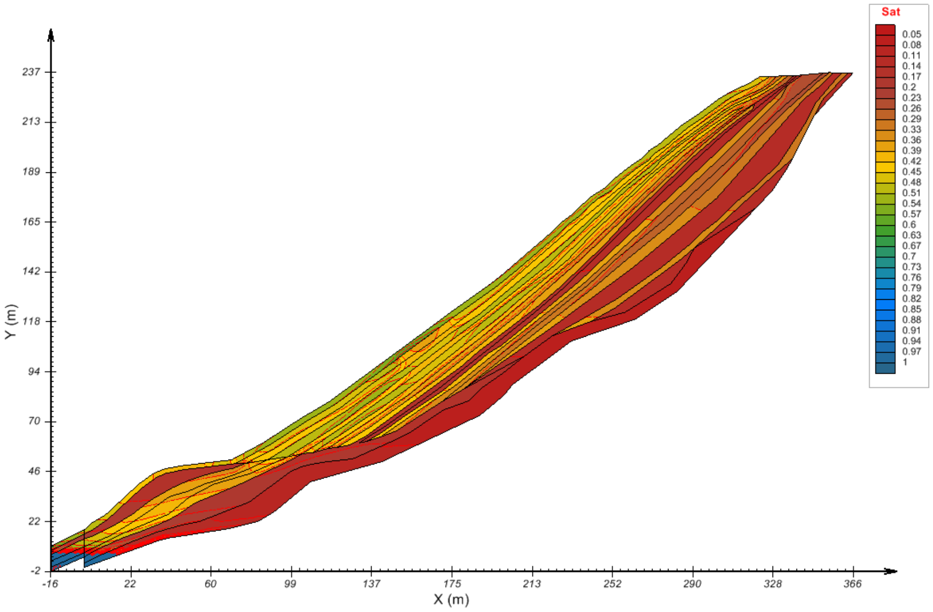

Figure 12. Saturation levels for a steady-state application of 0.75 mm/day

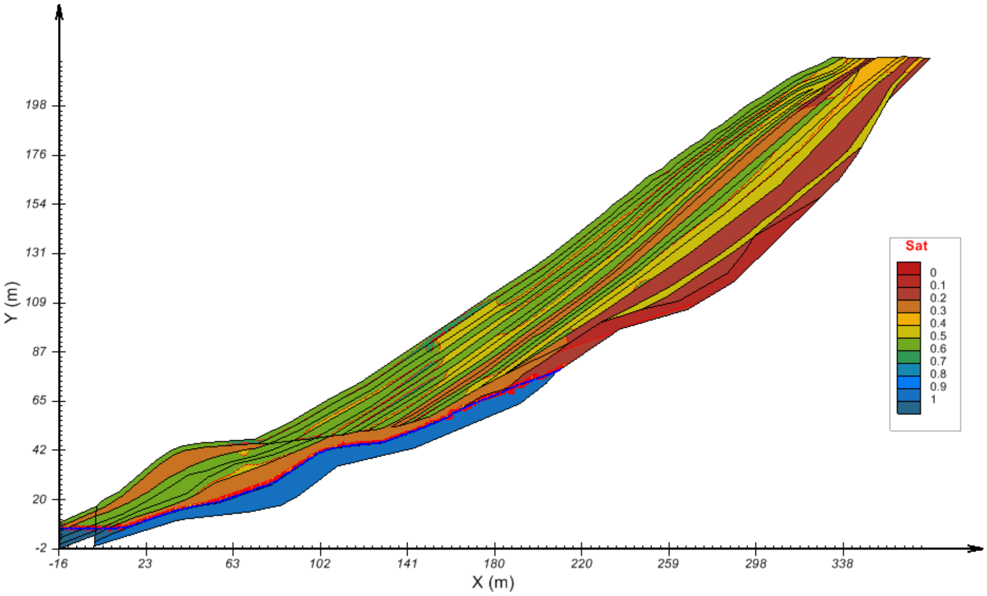

Figure 13. Saturation levels for a steady-state application of 2.5 mm/day

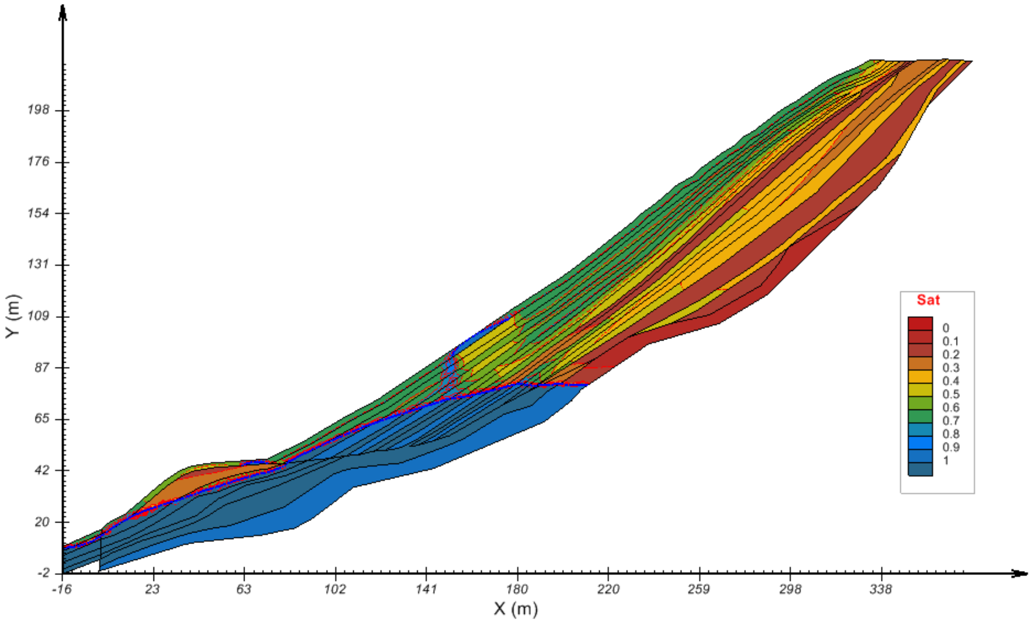

Figure 14. Saturation levels for a steady-state application of 100 mm/day

Based on the 1D numerical modeling of the Phase II program, the final conclusions for the hydrological concept remain largely similar to the conclusions in Phase I but for differing reasons. In the Phase I study it was assumed that the evaporation was being reduced due to osmotic suction. Part way through Phase II, it was found that osmotic suction does not play a significant role. A re-examination of the crust material led to a further theorization regarding the behavior of the upper crust. This new theory was implemented into the SVFLUX software and all 1D numerical models were re-run. The resulting net percolations were between 20-50% with the most likely value being estimated at 44% (Figure 24). This is largely similar to the findings of the Phase I study (Fredlund, 2013) and reinforces the previously held conceptual model.

7 CONCLUSIONS

From the current analysis the following conclusions can be drawn:

- The net percolation for the average slope is 41-44% of precipitation and an expected actual evaporation rate of 56-59%. These estimates are highly determinate on the status of the crust material.
- It is expected that storm events will not cause the pore-water pressure to be significantly altered below a depth of 5m.
- The expected variation in pore-water pressures for the upper 10m of the slope is between 10 kPa to approximately 200 kPa (this does not account for extreme drying of the powdered crust material).
- It would take a sequence of many precipitation events in order to realize a well-developed water table in the waste rock pile.

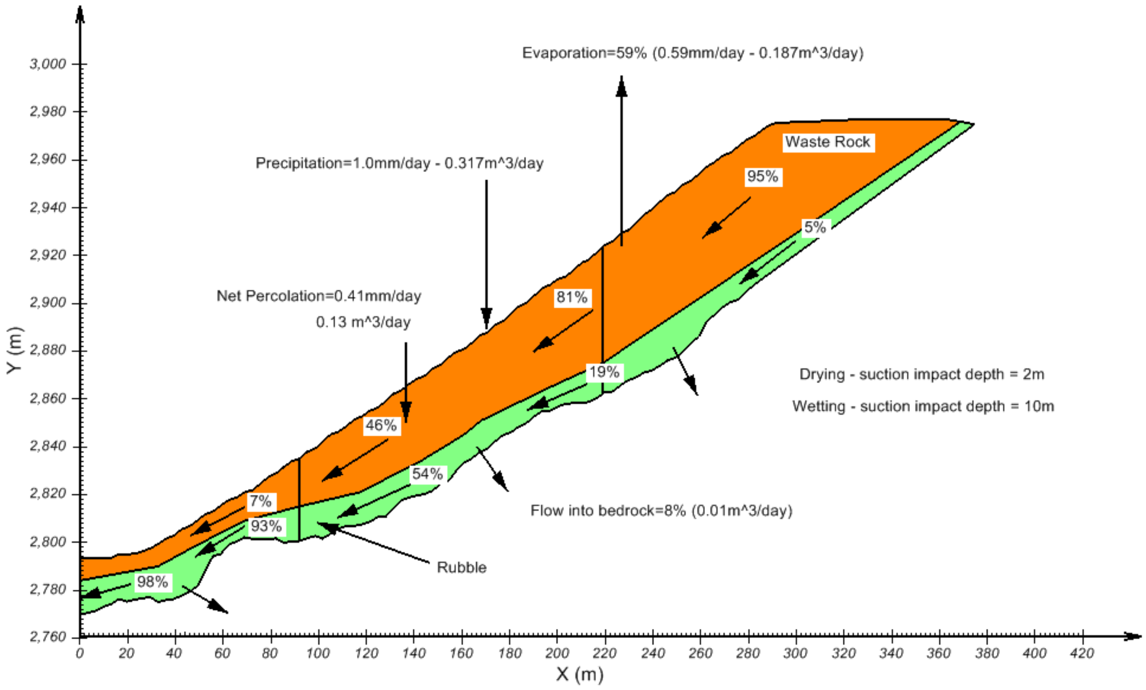

Figure 15. Final conceptual model for hydrological flow through the system

8 REFERENCES

Fredlund, M.D., Thode, R.C., 2013. Modeling of Seepage through Segregating Waste Rock: Part I, Tailings & Mine Waste Conference, Banff, AB, Canada, November 3 - 6, 2-13

Golder Associates, 2005. Fourth Monitoring and Modeling Report for Infiltration Test Plot Study, April, Denver, CO, USA.

Golder Associates, 2005. Mine Rock Water Balance Study, April, Denver, CO.

SVFLUX User's / Theory / Verification Manual, 2007, Fredlund, M. D., SoilVision Systems Ltd, Saskatoon, SK, Canada