Modeling of Seepage through Segregating Waste Rock: Part I

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ABSTRACT: Stratified layering occurs as a result of the manner in which waste rock is deposited over the face of the pile. The layer thickness and the saturated-unsaturated modeling parameters determine the underlying flow regime. This paper presents a summary of several models that were developed to investigate the processes that affect the flow within the Goat Hill waste rock pile. Reasonable flow parameters were developed based on four different modeling scenarios. The relative influence of each parameter on the overall regime was studied.

1 INTRODUCTION

Considerable segregation can take place in materials that are 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 consists of multiple layers of fine and coarse materials. This paper presents several multi-layer numerical models which were created to study the flow of water through the waste rock material.

2 OBJECTIVE

The objective of this numerical study is to investigate the possibility of preferential flow of water in the coarse materials and the fine materials. Specific objectives include the following:

- Determination of the soil parameters that produce preferential flow in coarse and fine layers.
- Determination of the relative flows through coarse and fine layers.
- Estimation of saturation and volumetric water contents in the fine and coarse layers.
- To describe the change in the flow regime between a homogenous system and a multi-layered system.
- Determine the reasonable layer thickness which may be used in the further numerical modeling.

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

- Step #1: Perform primary seepage modeling using different model scales with previously used soil parameters.

- Step #2: Perform a sensitivity study using different soil parameters.

3 PRIMARY SEEPAGE MODELING

Primary seepage modeling is performed to determine effects of various seepage model parameters on the flow of water through a multi-layer model. Due to the scale of the actual slope and the complexity of the geometry, three levels of model geometries were implemented in this study: i) a small sub-domain model, ii) a large sub-domain model, and iii) a full scale model (Figure 1). In the primary study, soil parameters are the same as the soil parameters used in a previous phase of seepage modeling. The following four sets of seepage models were implemented in this primary study:

- Set P1: Includes twelve computer runs on small sub-domain models with different soil parameters and applied surface fluxes. The series of computer runs were performed to determine the effect of the soil parameters and surface fluxes on flow in the gravel and sand layers.
- Set P2: Includes 5 computer runs on small sub-domain models with different layer thickness to study the effect of the layer thickness on flow through the multi-layer model.
- Set P3: A large sub-domain model is performed. The model results are used to compare with that of small sub-domain model to study the sensitivity of the size of the model.
- Set P4: A full-scaled model was performed. Similar to set P3, the model results are used to study the sensitivity to the size of the model

3.1 *Study effects of soil parameters and surface flux (P1)*

A series of small-scale steady-state models were run to study the effect of net surface flux and soil parameters on the flow of water in the waste rock slope. Details of the model geometry, soil parameters, boundary conditions, and model results are described in the following sections.

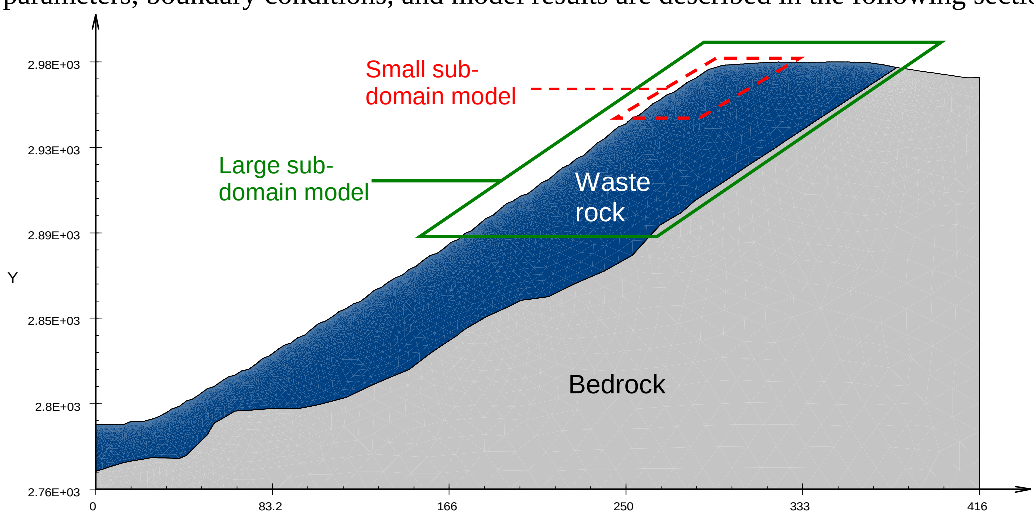

Figure 1 Schematic illustration of the full and 2 sub-domain models

3.1.1 *Model Geometry*

The small sub-domain model has 10 sandwich layers of sand and gravel (Figure 2). The thickness of each layer is 0.5 m. The surface layer of the model is assumed to be gravel. In order to avoid the concentration of water flow on the bottom layer (i.e., as described in the large-scaled transient model), a triangular soil region was added to the right side of the model. The triangular (i.e., blue) region can be either sand or gravel and the effect of soil type variation is examined in this model.

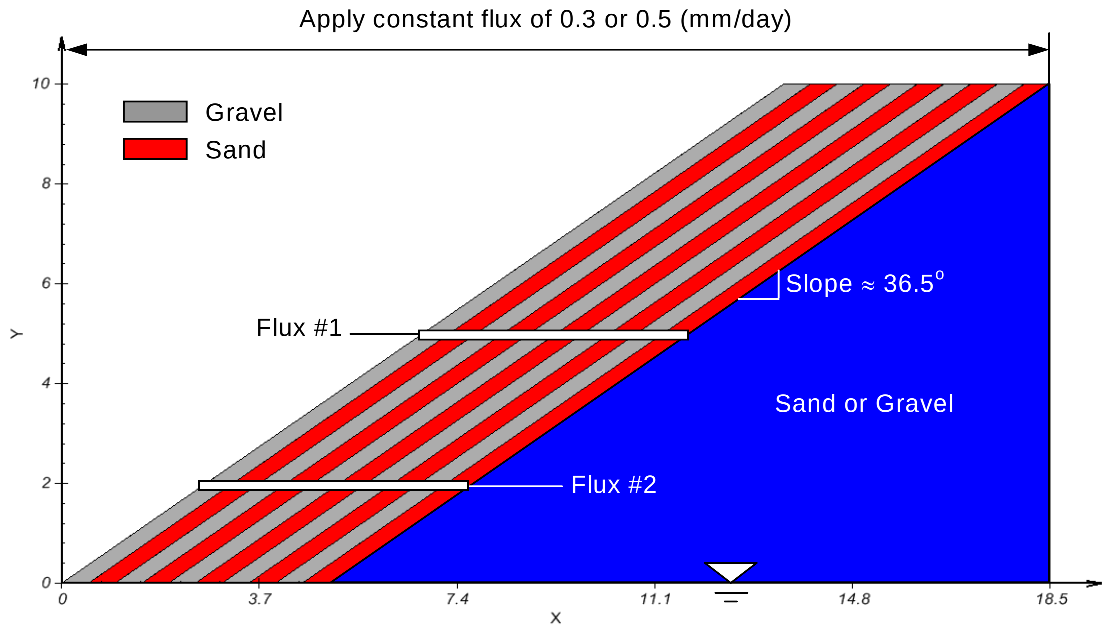

Figure 2 Geometry of the small sub-domain multi-layer model with layer thickness of 0.5 m.

3.1.2 *Soil Parameters*

There are three sets of soil parameters used in this modeling study:

i. Base case soil parameters: The base cases for sand and gravel used in the original study were used.

ii. One standard deviation difference: In this case, an attempt was made to produce as much differential flow as possible. Soil parameters in the gravel and sand were changed so that gravel tended towards a coarser material and sand tended towards a finer material. The following four soil parameters were changed by one standard deviation for both sand and gravel: a) Saturated volumetric water content; b) Air-Entry Value; c) Saturated hydraulic conductivity; and d) Slope of the unsaturated hydraulic conductivity curve. The other two soil parameters were kept the same (i.e., residual water content and residual soil suction) and it was assumed that the residual parameters would not significantly affect the flow of water in the soil.

iii. One standard deviation difference for the slope of unsaturated hydraulic conductivity: In the last set of soil parameters, the slope of the unsaturated soil parameters was studied since this soil property has the most effect on the flow of water in the soil. The slope of the unsaturated hydraulic conductivity for the gravel was chosen as the mean value plus one standard deviation, while the mean value minus one standard deviation was chosen for the sand.

Soil parameters for the sand and gravel for the three sets of model soil parameters are presented in Table 1. Plots of the soil-water characteristic curves, SWCCs, and the unsaturated hydraulic conductivity curves for the three sets of soil parameters are shown in **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**, respectively.

Table 1 Summary of 3 sets of soil parameters for the gravel and sand

Soil parameters	Base case: mean soil parameters values for sand and gravel		One SD difference: Gravel towards coarse, sand towards fine		Only slope k_{unsat}: Gravel k_{unsat} slope+SD, Sand kK_{unsat} slope-SD	
	Sand	Gravel	Sand	Gravel	Sand	Gravel
θ_s	0.302	0.302	0.253	0.351	0.302	0.302

ψ_{ae}, AEV (kPa)	1.64	0.408	2.913	0.199	0.4087	1.64
θ_r	0.133	0.104	0.133	0.104	0.104	0.133
ψ_r (kPa)	31.33	2.2	31.33	2.2	2.2	31.33
k_{sat} (m/day)	1.469	7.1	0.369	143.84	7.1	1.469
Slope of k_{unsat}	2.83	2.83	1.863	3.797	2.83	2.83

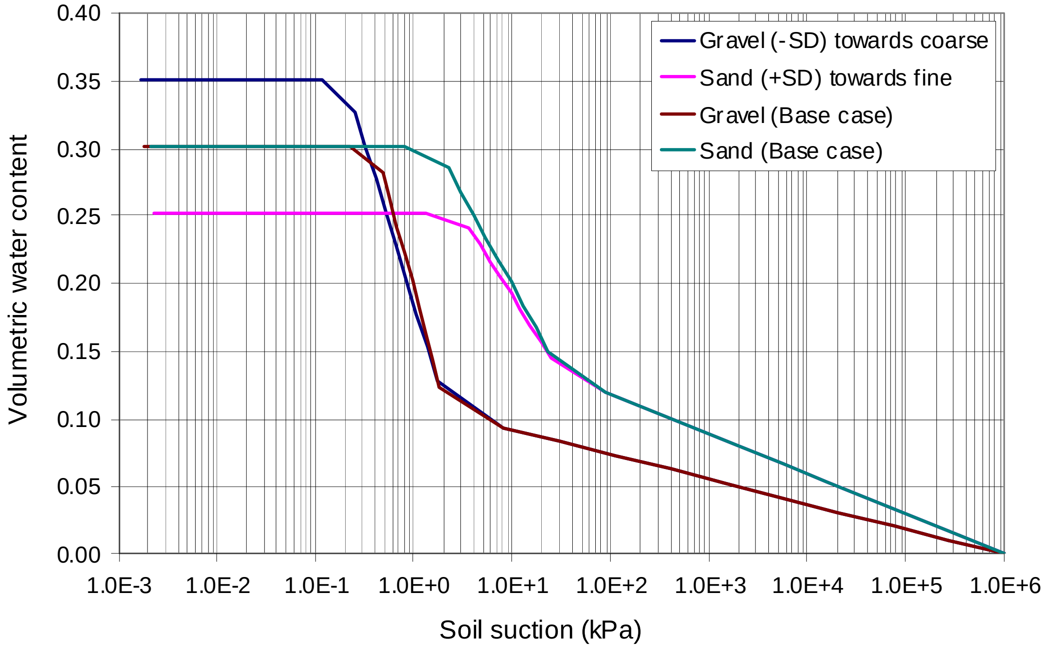

Figure 3 Soil-water characteristic curves for sand and gravel used in the numerical modeling of the multi-layer systems

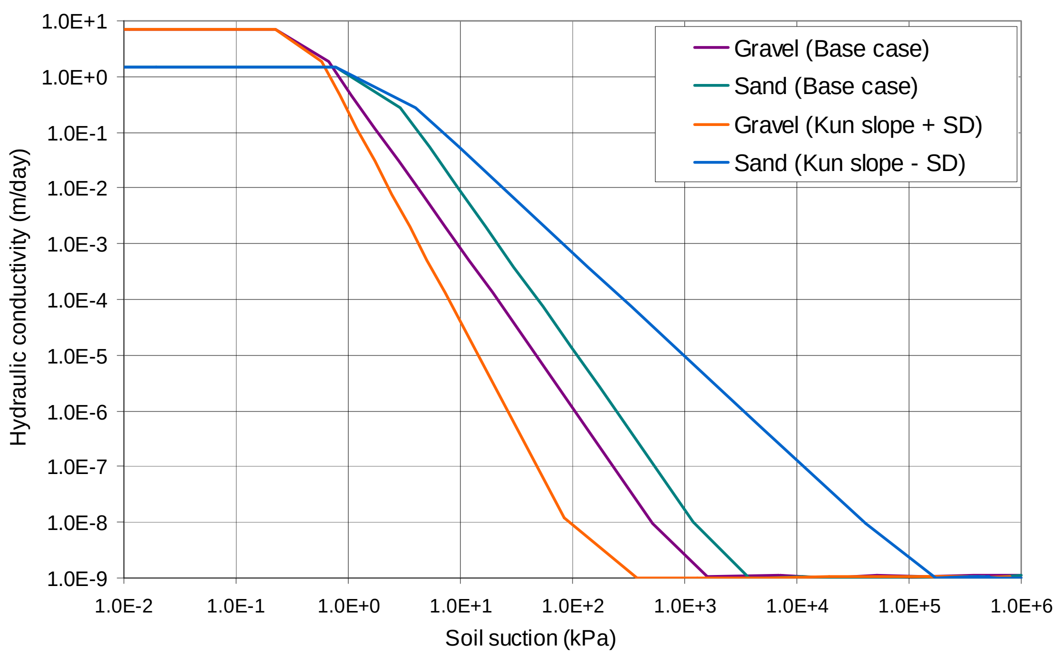

Figure 4 unsaturated hydraulic conductivity functions for the Sand and Gravel for the base case and one standard deviation for all soil parameters

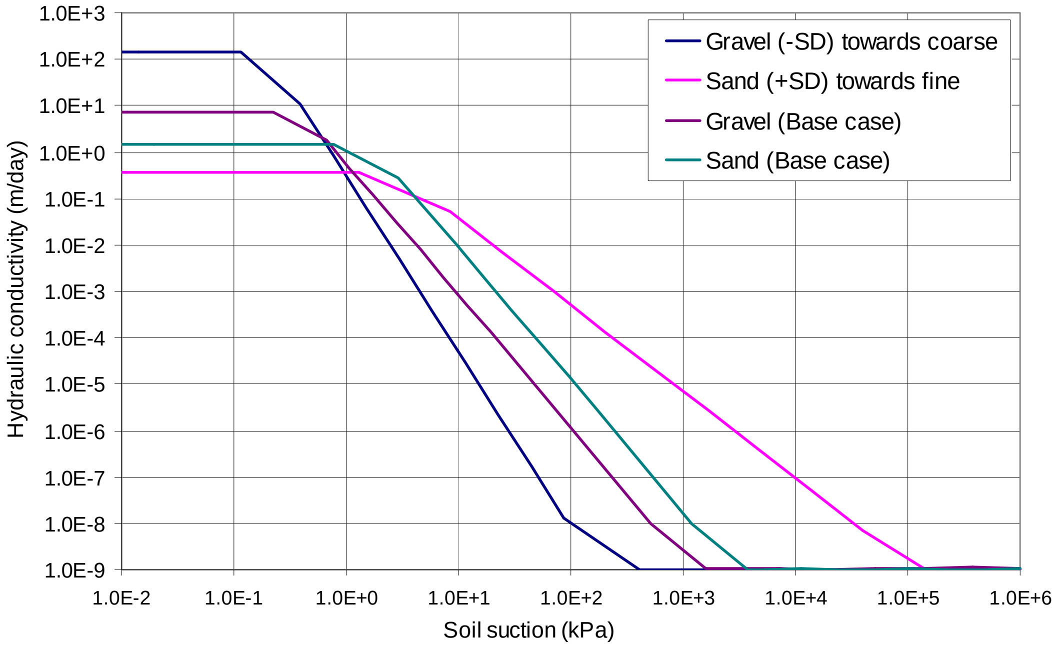

Figure 5 unsaturated hydraulic conductivity functions for the Sand and Gravel for base case and one standard deviation for k_{unsat} slope.

There are a combination of three sets of soil parameters for gravel and sand: two cases for soil parameters of the triangular region and two cases for the surface flux (i.e., 0.3 mm and 0.5 mm) result in 12 computer runs for the small sub-domain multi-layer model.

3.1.3 *Initial boundary conditions*

A soil suction of 90 kPa was set for the entire soil model as the initial condition. A constant flux of either 0.3 mm or 0.5 mm of water was applied at the ground surface. The right edge of the model was set as a "no flow" boundary condition. The water table (i.e., pressure head = 0.0 m) was assumed to be at the bottom edge of the model.

3.1.4 *Results and discussion*

Two flux sections were added to the models to monitor the amount of water flowing through the sand and gravel layers (Figure 2). Flux sections #1 were used to measure the amount of water flowing through the sand and gravel layer at the middle of the model (i.e., elevation of 5.0 m). Flux section #2 was used to measure the amount of water flowing through the sand and gravel at an elevation of 2.5 m above the bottom of the model.

Plots of the pore-water pressures and degrees of saturation for various computer runs are shown in Figure 6 to Figure 15. In these computer runs, soil suctions in the model were in the range from 5 kPa to 90 kPa.

A summary of two flux sections for the twelve computer runs is presented in Table 2 and Table 3. The percentages of water flow through the five layers of sand and through the five layers of gravel at two flux sections were calculated for each run. The results showed that there is no preferential flow at the base case of soil parameters.

The comparison of the case of changing four soil parameters and the case of changing only the slope of the unsaturated hydraulic conductivity function showed that the slope of the unsaturated hydraulic conductivity function plays an important role in the distribution of the water flow in sand and gravel. When the slope of the unsaturated hydraulic conductivity curve in the gravel was decreased by one standard deviation and the slope of the unsaturated hydraulic conductivity curve of the sand was increased by one standard deviation, the amount of water flow in the sand was more than 94% of the total flow in the ten layers of gravel and sand.

The results also show that there is no significant difference in the preferential flow when the triangular shape beneath the layers has soil parameters of either sand or soil parameters of gravel.

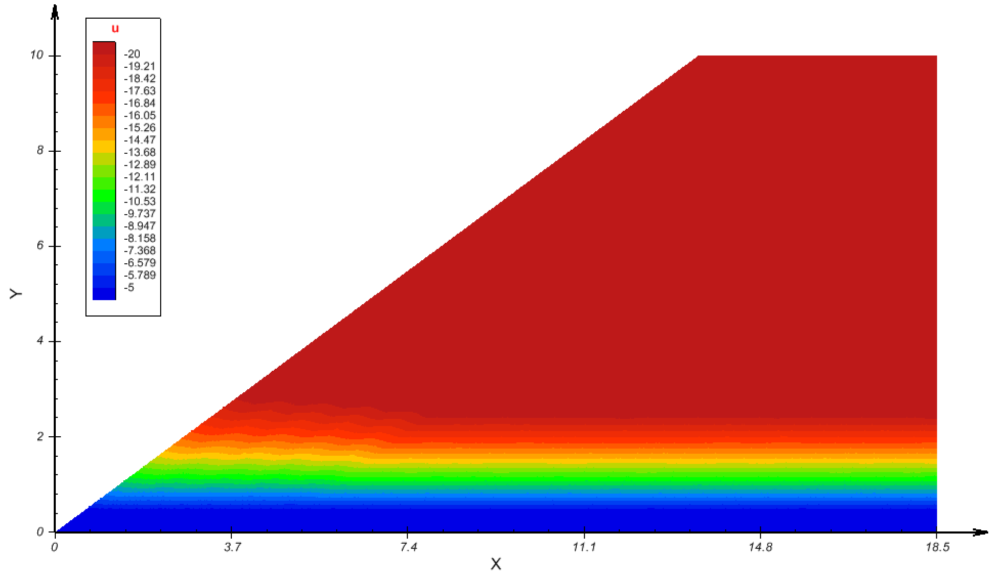

Figure 6 Pore-water distribution in a small sub-domain multi-layer model for the base case of soil parameters, 0.3 mm surface flux and Sand parameters for the triangular soil region.

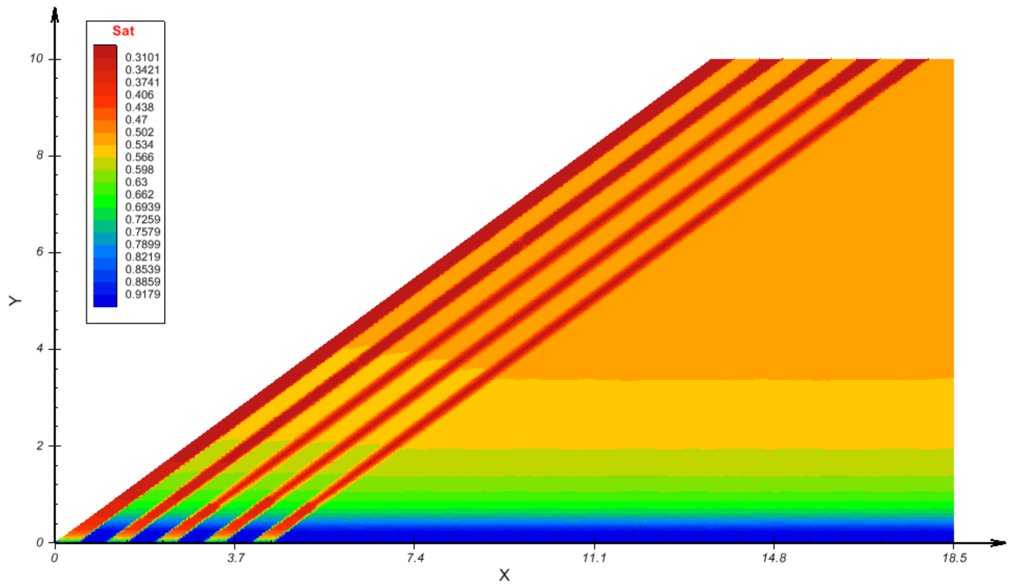

Figure 7 Degree of saturation distribution in a small sub-domain multi-layer model for the base case of soil parameters, 0.3 mm surface flux and Sand parameters for the triangular soil region.

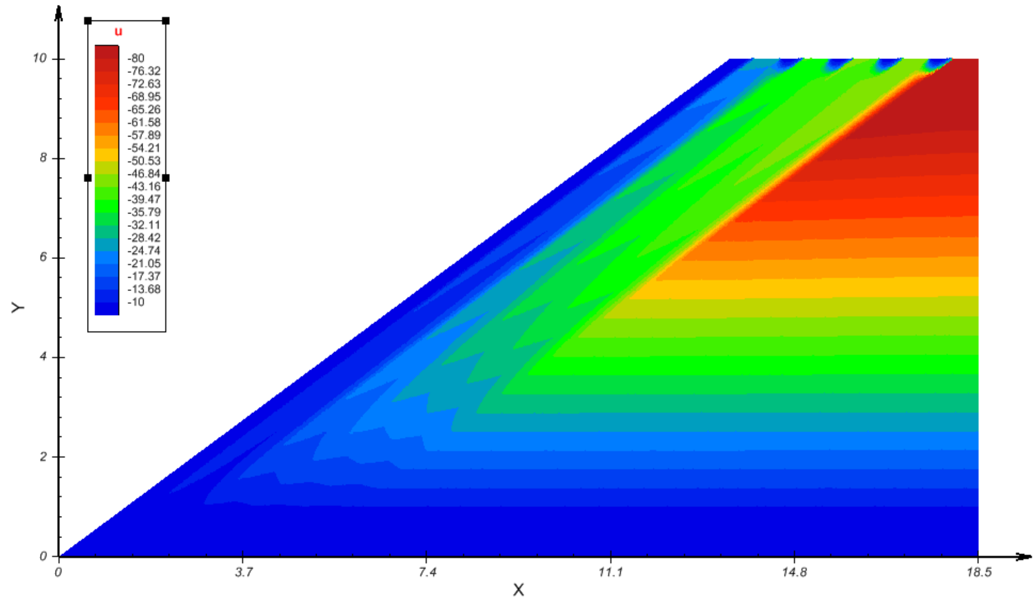

Figure 8 Pore-water distribution in a small sub-domain multi-layer model for the case where the gravel tends towards a coarser material (one standard deviation) and the sand tends towards a finer material (one standard deviation), 0.3 mm surface flux and Sand parameters for the triangular soil region.

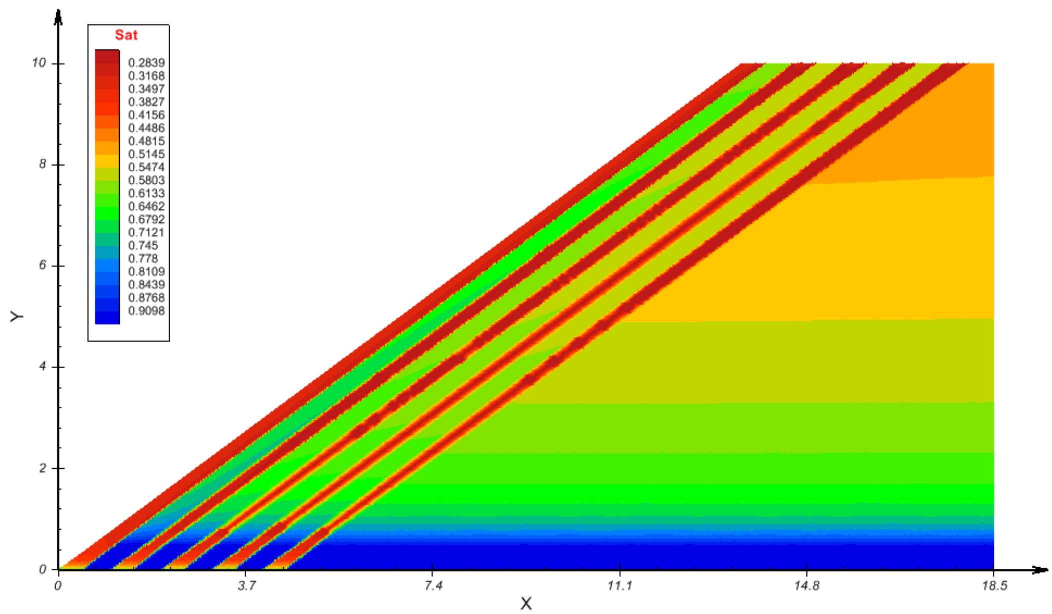

Figure 9 Degree of saturation distribution in a small sub-domain multi-layer model for the case where the gravel tends towards a coarser material (one standard deviation) and the sand tends towards a finer material (one standard deviation), 0.3 mm surface flux and Sand parameters for the triangular soil region.

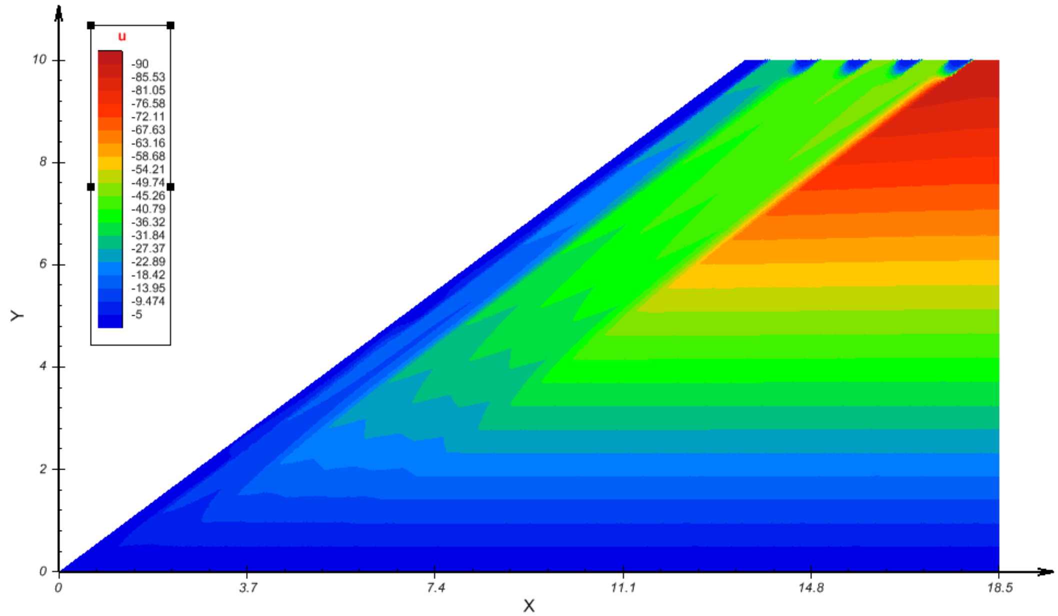

Figure 10 Pore-water distribution in a small sub-domain multi-layer model for the case when using a slope of k_{unsat} of Gravel plus SD (one standard deviation) and a slope of k_{unsat} of Sand minus SD, 0.3 mm surface flux and Sand parameters for the triangular soil region.

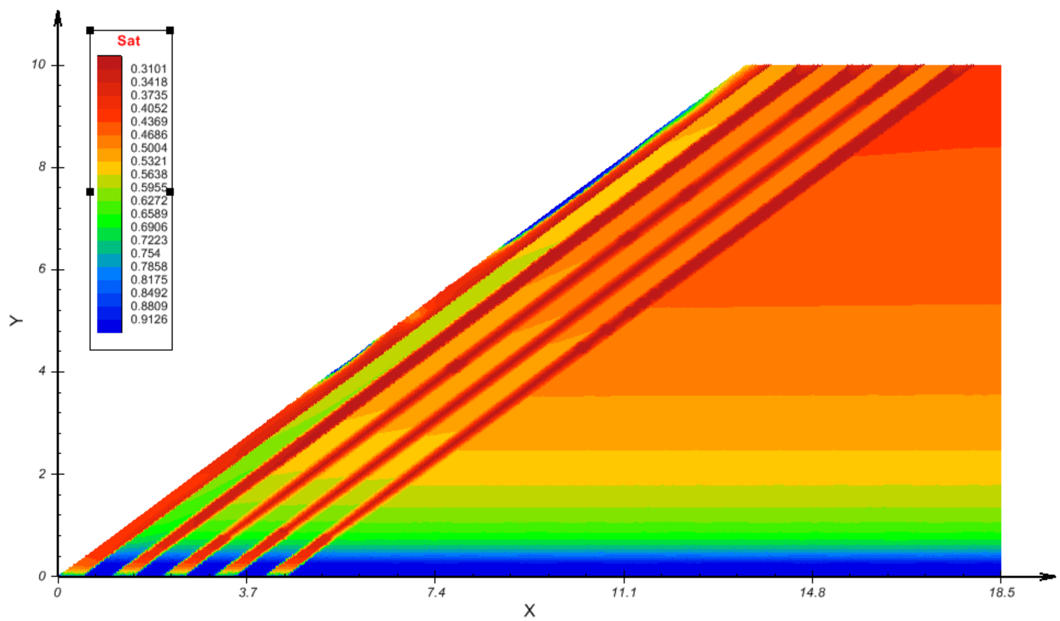

Figure 11 Degree of saturation distribution in a small sub-domain multi-layer model for the case when using the slope of k_{unsat} of Gravel plus SD (one standard deviation) and the slope of k_{unsat} of Sand minus SD, 0.3 mm surface flux and Sand parameters for the triangular soil region.

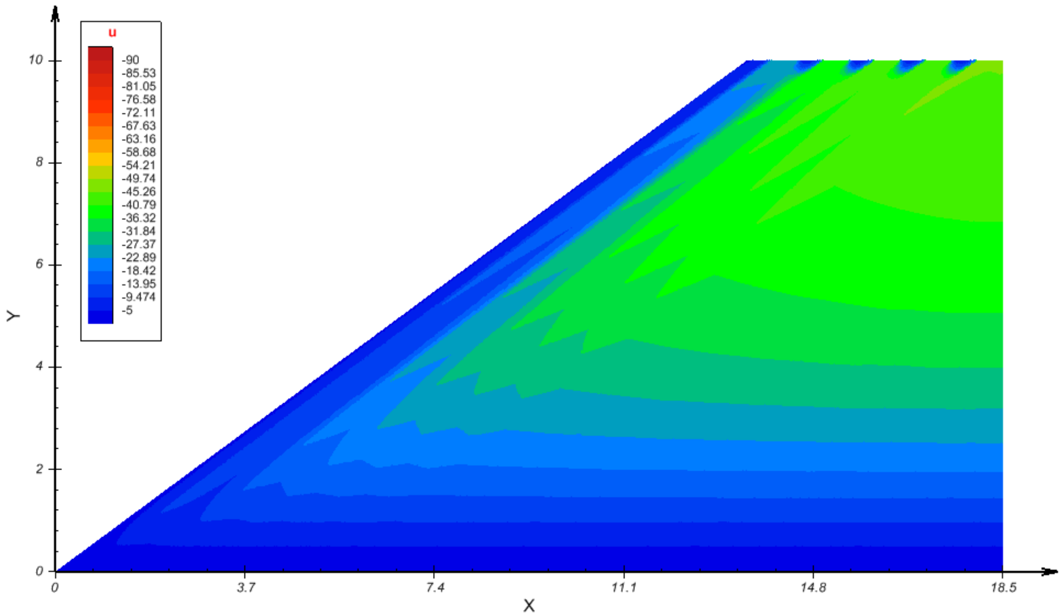

Figure 12 Pore-water distributions in a small sub-domain multi-layer model for the case when the gravel tends towards a coarser material (one standard deviation) and the sand tends towards a finer material (one standard deviation), 0.3 mm surface flux and Gravel parameters for the triangular soil region.

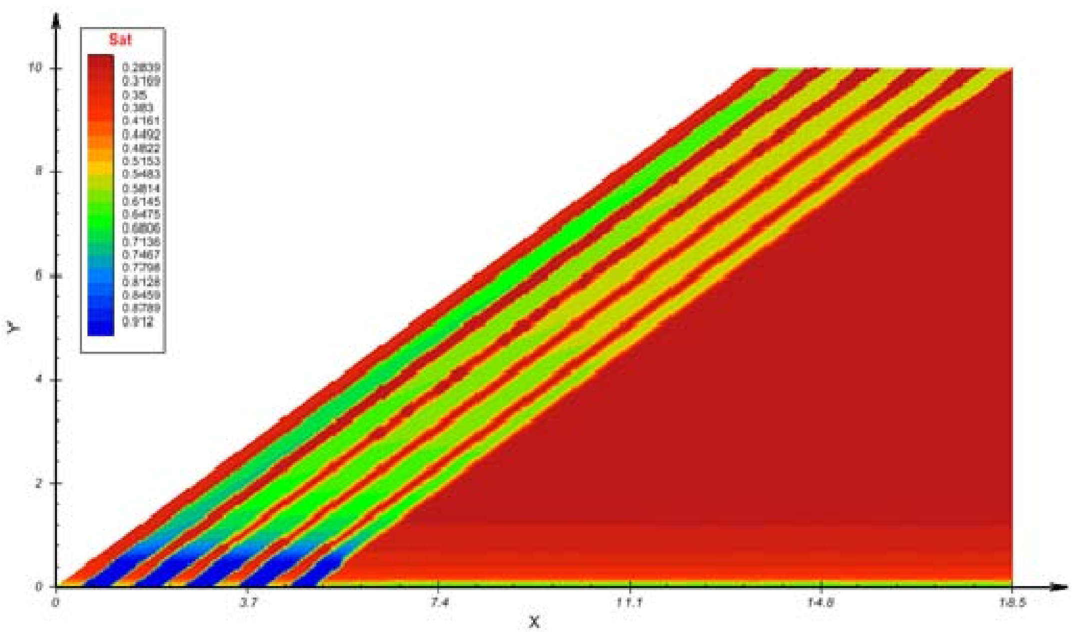

Figure 13 Degree of saturation distribution in a small sub-domain multi-layer model for the case where gravel tends towards a coarser material (one standard deviation) and the sand tends towards a finer material (one standard deviation), 0.3 mm surface flux and Gravel parameters for the triangular soil region.

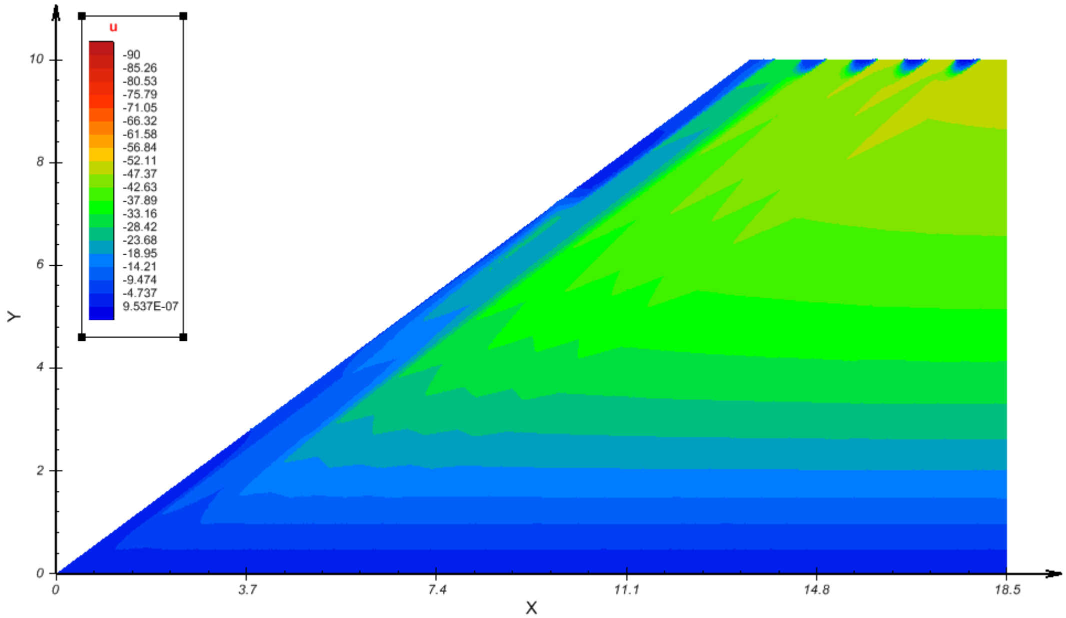

Figure 14 Pore-water distribution in a small sub-domain multi-layer model for the case when using a slope of k_{unsat} of Gravel plus SD (one standard deviation) and a slope of k_{unsat} of Sand minus SD, 0.3 mm surface flux and Gravel parameters for the triangular soil region.

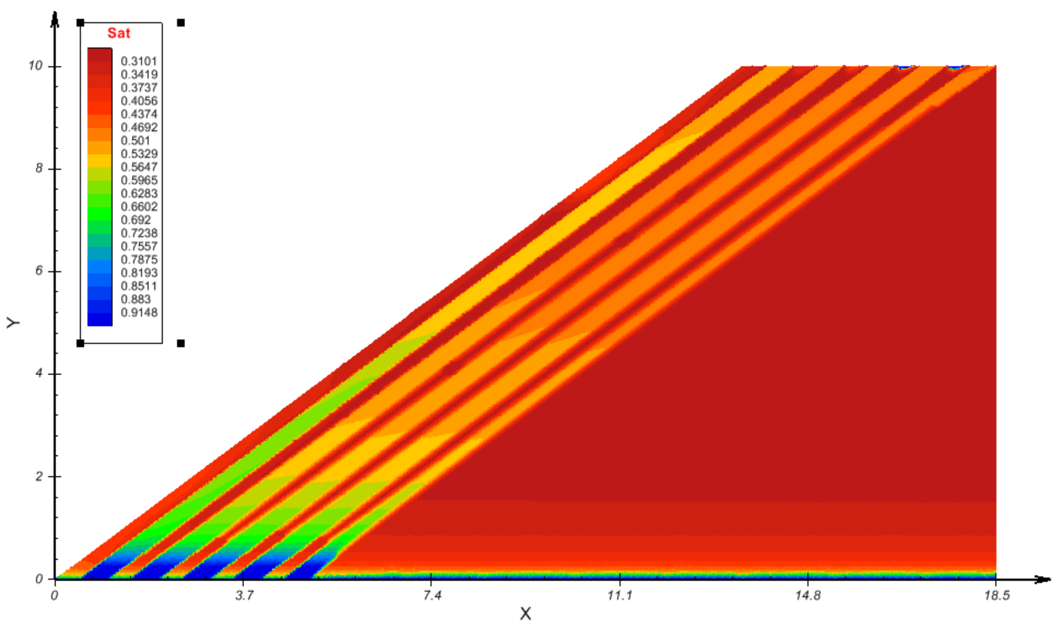

Figure 15 Degree of saturation distribution in a small sub-domain multi-layer model for the case when using a slope of k_{unsat} of Gravel plus SD (one standard deviation) and a slope of k_{unsat} of Sand minus SD, 0.3 mm surface flux and Gravel parameters for the triangular soil region.

Table 2 Summary of modeling results for the 6 computer runs with Sand parameters set for the triangular soil region

Flux	Soil	Percentage of Flow in sand and gravel					
		Base case: mean soil parameters values for sand and gravel		One SD difference: Gravel towards coarse, sand towards fine		Only slope k_{unsat}: Gravel k_{unsat} slope+SD, Sand k_{unsat} slope-SD	
		0.3 mm	0.5 mm	0.3 mm	0.5 mm	0.3 mm	0.5 mm
#1	Gravel	47.94%	46.31%	4.57%	4.65%	6.53%	3.64%
	Sand	52.06%	53.69%	95.43%	95.35%	94.47%	96.36%
#2	Gravel	46.03%	45.04%	3.66%	3.76%	5.48%	6.00%

	Sand	53.97%	54.96%	96.34%	96.24%	94.52%	94.00%

Table 3 Summary of modeling results for the 6 computer runs with Gravel parameters set for the triangular soil region

Flux	Soil	Percentage of Flow in sand and gravel					
		Base case: mean soil parameters values for sand and gravel		One SD difference: Gravel towards coarse, sand towards fine		Only slope K_{unsat}: Gravel k_{unsat} slope+SD, Sand k_{unsat} slope-SD	
		0.3 mm	0.5 mm	0.3 mm	0.5 mm	0.3 mm	0.5 mm
#1	Gravel	46.94%	44.32%	4.03%	4.18%	2.60%	4.36%
	Sand	53.06%	55.68%	95.97%	95.82%	97.40%	95.64%
#2	Gravel	44.58%	42.82%	3.37%	3.43%	1.48%	2.86%
	Sand	55.42%	57.18%	96.63%	96.57%	98.52%	97.14%

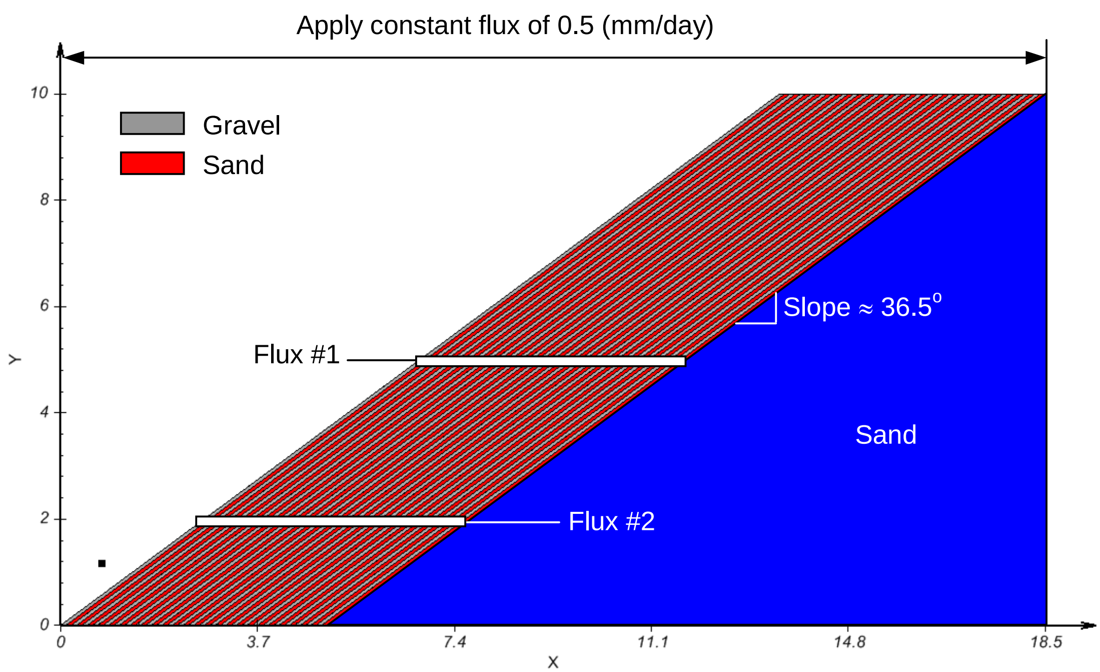

Figure 16 Geometry of the small sub-domain multi-layer model with a layer thickness of 0.1 m.

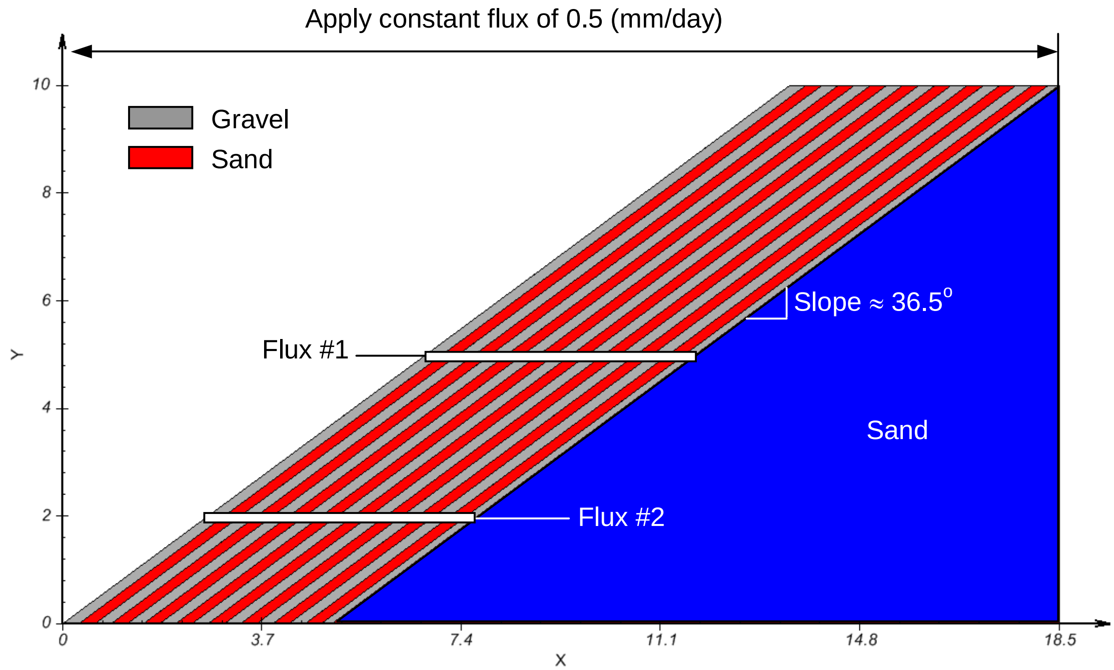

Figure 17 Geometry of the small sub-domain multi-layer model with a layer thickness of 0.3 m.

3.2 *Study effects of layer thickness (P2)*

The purpose of this section is to study the effect of the thickness of each soil layer on preferential flow in the gravel and sand layers. The model geometry, soil parameters, boundary condition, and simulation results are presented in the following sections.

3.2.1 *Geometry*

The geometry of the model is similar to that of the small sub-domain model. Five layer thicknesses were selected for this study: 0.1 m, 0.3 m, 0.5 m, 0.7 m and 1.0 m. The model geometry for the 0.5 m thicknesses is the same as presented in Figure 2 (i.e., previous set of modeling). Model geometries for 0.1 m, 0.3 m, 0.7 m and 1.0 m thick layers are shown in Figure 16 to Figure 19.

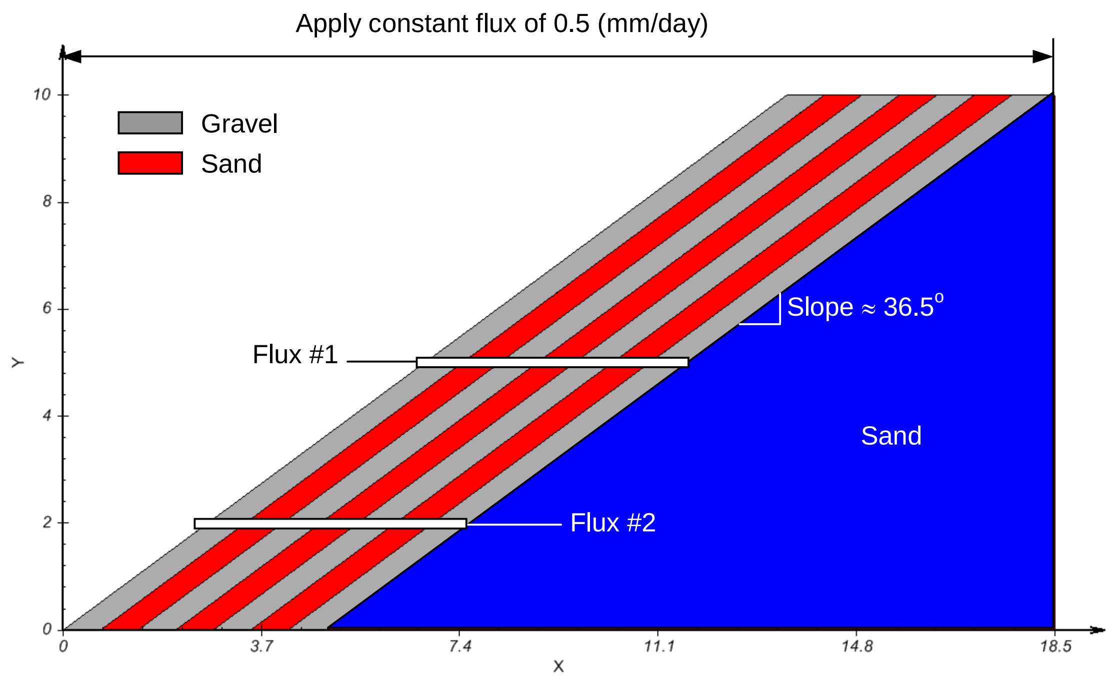

Figure 18 Geometry of the small sub-domain multi-layer model with a layer thickness of 0.7 m.

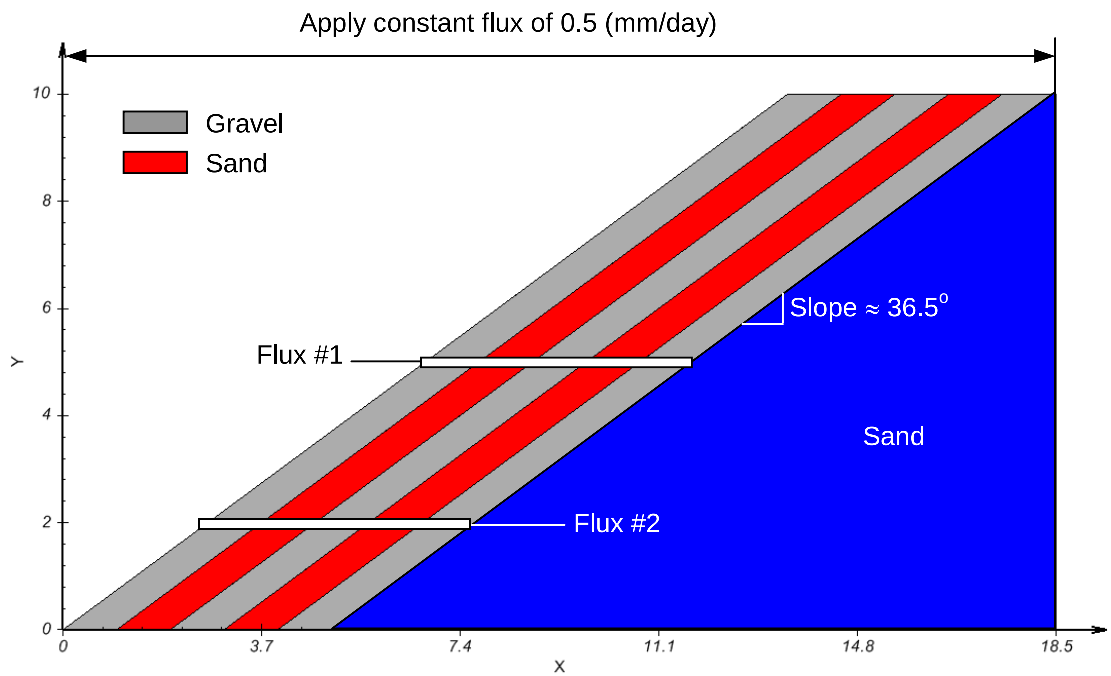

Figure 19 Geometry of the small sub-domain multi-layer model with a layer thickness of 1.0 m.

3.2.2 *Soil Parameters*

Soil parameters used in these model studies are the same as those used in the previous model study where the parameters of the gravel are one standard deviation towards a coarser material and the parameters of the sand are one standard deviation towards a finer material. Soil parameters for the gravel and sand are presented in Table 4.

Table 4 Soil parameters for the gravel and sand in the set of modeling P2

Soil parameters	One SD difference: Gravel towards coarse, sand towards fine	
	Sand	Gravel
θ_s	0.253	0.351
$\psi_{ae,}$ AEV (kPa)	2.913	0.199
θ_r	0.133	0.104
ψ_r (kPa)	31.33	2.2
K_{sat} (m/day)	0.369	143.84
Slope of K_{unsat}	1.863	3.797

3.2.3 *Initial and boundary conditions*

Similar to the above model, a soil suction of 90 kPa was set for entire soil model as the initial condition. A constant flux of 0.5 mm of water was applied on the ground surface. The right edge of the model was set as a "no flow" boundary condition. The water table (i.e., pressure head = 0.0 m) was assumed to be at the bottom edge of the model.

3.2.4 *Results and discussion*

Similar to the previous set of seepage modeling (P1), two flux sections were added to the models to monitor the amount of water flowing through the sand and gravel layers (Figure 2). Flux section #1 was used to measure the amount of water flowing through the sand and gravel layers at the middle of the model (i.e., elevation of 5.0 m). Flux section #2 was used to measure the amount of water flowing in sand and gravel layers at an elevation of 2.5 m from the bottom of the model.

Simulation results are summarized in Table 5. The results show that there is a significant difference in the flow in the sand and gravel. The amount of water flowing in the gravel is significantly increased with the thicknesses of the soil layer, especially when the layer thickness is equal to 0.7 and 1.0 m. Preferential flow can be significantly affected by the layer thickness.

In the next set the multi-layer seepage models, a large sub-domain model will be implemented with layer thicknesses of 2.0 m. The results are of value in order to be able to verify the above conclusion.

Table 5 Modeling results for the sub-domain model set P2

ID	Layer thickness (m)	Percentage of flow through sand and gravel			
		Flux #1		Flux #2	
		Gravel (%)	Sand (%)	Gravel (%)	Sand (%)
1	0.1	1.97	98.03	1.67	98.33
2	0.3	3.29	96.71	2.70	97.30
3	0.5	4.65	95.35	3.76	96.24
4	0.7	11.64	88.36	5.49	94.51
5	1	15.23	84.77	5.86	94.14

3.3 *Large Sub-domain Model (P3)*

The effect of the size of the model on the preferential flow in the gravel and sand is studied in this set of models. Model geometry, soil parameters, boundary condition, and simulation results are presented in the following sections.

3.3.1 *Geometry*

The large sub-domain model has a width of 90 m, a height of 100 m, and a slope of approximately 36.50. A total of 45 layers of soil with a thickness of 2 m/layer were used for the model. The surface waste rock layer was assumed to be a coarse material (gravel).

3.3.2 *Soil Parameters*

The soil parameters of the two soils used in this numerical analysis are the same as the "one standard deviation difference" values used in the Set P2. Details of the soil parameters for the sand and gravel are presented in Table 4.

3.3.3 *Initial and boundary conditions*

A soil suction of 90 kPa was set for entire model as the initial condition. As presented in the previous seepage report, the amount of water flow from waste rock into the bedrock was estimated to be insignificant (i.e., close to the crest); therefore, a "no flow" boundary condition was applied on the right edge of the model. A pressure head boundary condition of 0 kPa was applied on the bottom edge of the model.

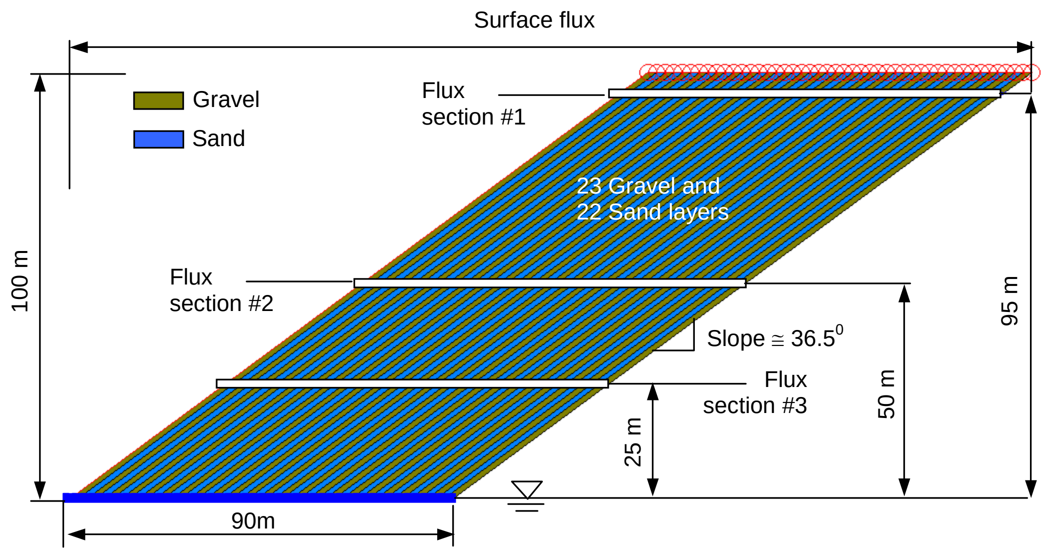

Figure 20 Geometry of the large sub-domain model

3.3.4 *Results and discussion*

Three flux sections were added to the model; namely fluxes #1, #2 and #3 (Figure 20). Flux sections #1, #2 and #3 have elevations of 95 m, 50 m and 25 m (i.e., referenced to the bottom of the model).

A summary of the simulation results is shown in Table 6. The results show that flow of water through the sand is significantly higher than flow through the gravel.

Table 6 Modeling results for the large sub-domain model (P3)

Flux	Percentage of flow through gravel and sand	
	Gravel (%)	Sand (%)
#1	2.41	97.58
#2	3.37	96.62
#3	3.83	96.17

3.4 *Summary and conclusions from primary study*

The primary study shows that the preferential flow in a multi-layer model is highly dependent on the soil parameters, particularly the slope of the unsaturated hydraulic conductivity curve. The thickness of each soil layer may not significantly affect the preferential flow in the soil.

A combination of the results from the small sub-domain model, large sub-domain model, and full-scaled model shows that the soil layer thicknesses and the scale of the model do not significantly affect the preferential flow through the materials involved.

The results also show that with an extreme set of soil parameters (i.e., soil parameters of the gravel being one standard deviation towards a coarser material and soil parameters of the sand being one standard deviation towards a finer material) there is almost no flow through the gravel.

4 SENSITIVITY STUDY (P4)

A sensitivity study was implemented in order to statistically present the effect of various model parameters on the preferential flow in a multi-layer model. A sensitivity study using twelve gravel and sand unsaturated soil parameters and the applied surface flux on the preferential flow in a multi-layer model are presented in this section.

The results of the primary study show that the thickness of the soil layers and the scale of the model do not significantly affect preferential flow in the soil. Therefore, a small sub-domain model can be used in the sensitivity study.

4.1 *Geometry*

The geometry of the multi-layer model used for the sensitivity study was selected as the sub-domain model with a uniform layer thickness of 0.1 m with 50 layers of sand and gravel (Figure 21). The right size of the model (i.e., triangular shape) has the sand parameters.

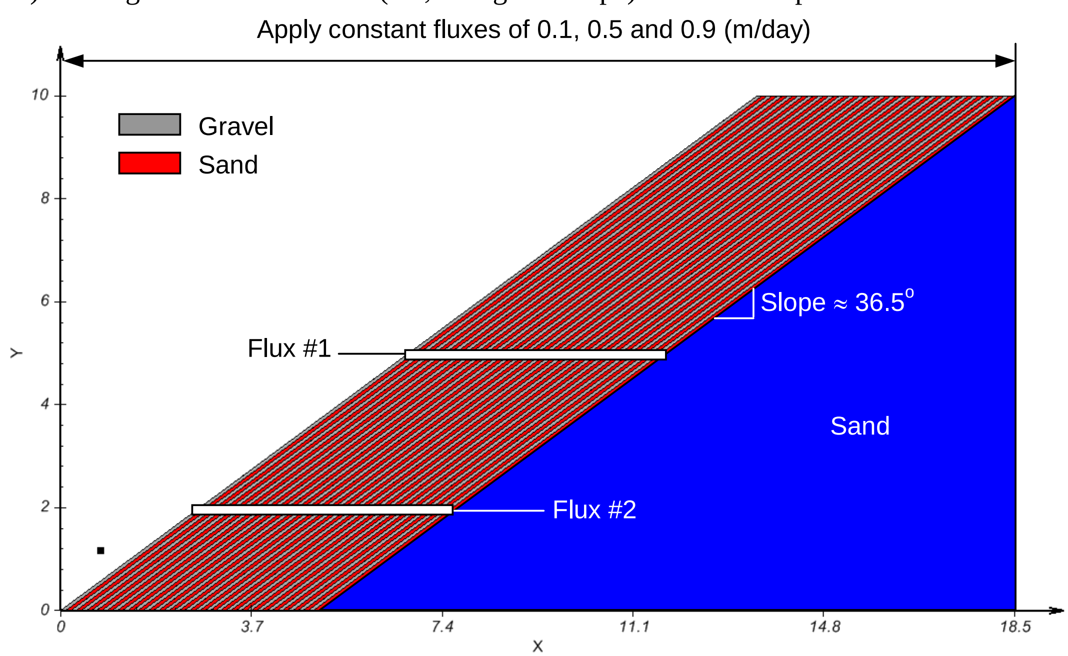

Figure 21 Geometry of the small sub-domain multi-layer model used for the sensitivity study.

4.2 *Sensitivity parameters*

For the sensitivity study, the soil parameters were varied in the range from minus one standard deviation to plus one standard deviation around the mean values. In order to perform a sensitivity study on a multi-layer model, the variation of the variables must guarantee that there is reasonableness to the soil parameters of the sand and gravel. In other words, the gravel parameters must always be greater than the sand parameters (Table 7).

Table 7 Comparison between unsaturated soil parameters of gravel and sand

Soil parameters	Gravel	Sand
Saturated *vwc*, θ_s	≥	≤
Air-Entry Value, *AEV* (kPa)	≤	≥
k_{sat} (m/day)	≥	≤
Slope of k_{unsat} (log-log scale)	≥	≤

The statistical soil parameters for the sand and gravel obtained from the experimental measurement are presented in Table 8 (i.e., presented in Phase I study). It can be seen from Table 8 that the saturated volumetric water content and the slope for unsaturated soil function (i.e., on log-log scale) for the sand and gravel, are the same. The saturated hydraulic conductivity for the gravel for the case of minus standard deviation is lower than that of the base case of the sand. Therefore, in order to perform a sensitivity study, an adjustment of the unsaturated soil parameters of the gravel and sand need to be made. There are three soil parameters that needed to be adjusted; namely, i) the saturated volumetric water content; ii) the saturated hydraulic conductivity; and iii) the slope of the unsaturated hydraulic conductivity function.

Table 8 Statistical soil parameters for the sand and gravel used in the Phase I of the study

	Gravel			Sand		
Soil parameters	M-SD	Mean	M+SD	M-SD	Mean	M+SD
Saturated *vwc*, θ_s	0.25	0.3	0.35	0.25	0.3	0.35
Air-Entry Value, *AEV* (kPa)	0.92	1.64	2.91	0.2	0.41	0.84
Residual *vwc*, θ_r	0.078	0.104	0.13	0.111	1.33	0.156
Residual suction, ψ_r (kPa)	1.09	2.2	4.47	6.33	31.33	155.13
k_{sat} (m/day)	0.35	7.10	143.84	0.074	1.469	5.84
Slope of k_{unsat} (log-log scale)	1.9	2.8	3.8	1.9	2.8	3.8

4.2.1 *Adjustment of the saturated volumetric water content*

A summary of the saturated volumetric water contents used by different study groups involved with this site was compiled in Table 9. It was found that the saturated volumetric water content ranges from 18.7% (Norwest) to 49.2% (University of British Columbia). The saturated volumetric water content used in the Phase I of the study is in the range from 26.8% to 36.2% with a mean value of 30%.

It is reasonable to assume that 30% and 35% are suitable two mean values for the saturated volumetric water contents of the sand and gravel, respectively. It is assumes that the standard deviation for the saturated volumetric water content for both soils is 2.5% (Table 10).

4.2.2 *Adjustment of the saturated hydraulic conductivity*

The saturated hydraulic conductivity for the sand used in the Phase I of the study was obtained by statistically analyzing the field measurement data for hydraulic conductivity for the sand in WR1. The data appears to be reasonable and agrees well with that used by Norwest and Golder Associates. Therefore, it is suggested that the saturated hydraulic conductivity for the sand should remain the same in the multi-layer model.

The saturated hydraulic conductivity for the gravel used in Phase I of the study was obtained by statistically analyzing the field measurement data for hydraulic conductivity for the gravel in WR2, WR3, Rubble and Colluvium's zones. This hydraulic conductivity represents the saturated hydraulic conductivity of a mixture sand and gravel and may be much lower than that of the gravel in a multi-layer model. Norwest suggested a typical value for the gravel of 86.4 m/day (i.e., 0.1 cm/s). This value is reasonable and may be suitable for the saturated hydraulic conductivity of the gravel in the sensitivity study of the multi-layer model. A standard deviation of a 0.6 log cycle (i.e., the same as that of the sand) was also selected for the saturated volumetric water content of the gravel (Table 10).

4.2.3 *Adjustment of the slope of the unsaturated hydraulic conductivity function*

The slope of the unsaturated hydraulic conductivity for the sand and gravel used in the Phase I of the study was in the range from 1.9 to 3.8. It was found that a slope of 3.8 was quite steep and only reasonable for a gravel soil. A slope of 1.9 is reasonable for silty sand. It was assumed that the slopes of the unsaturated hydraulic conductivity for the sand and gravel should be in the range from 1.9 to 2.8, and 2.8 to 3.8, respectively (Table 10).

Table 10 Statistical soil parameters for the sand and gravel sensitivity study

	Gravel			Sand		
Soil parameters	M-SD	Mean	M+SD	M-SD	Mean	M+SD
Saturated *vwc*, θ_s	0.325	0.35	0.375	0.275	0.3	0.325
Air-Entry Value, *AEV* (kPa)	0.199	0.409	0.841	0.922	1.64	2.913
Residual *vwc*, θ_r	0.078	0.104	0.13	0.111	0.133	0.156
Residual suction, ψ_r (kPa)	1.09	2.2	4.47	6.33	31.33	155.13
k_{sat} (m/day)	21.7	86.4	343.96	0.369	1.469	5.84
Slope of k_{unsat} (log-log scale)	2.8	3.3	3.8	1.9	2.35	2.8

4.2.4 *Summary of sensitivity parameters*

There were thirteen parameters studied in this sensitivity analysis including twelve unsaturated soil parameters for the two soils and the surface flux on the ground surface (Table 10). Plots of the soil-water characteristic curves and unsaturated hydraulic conductivity for the three cases of all soil parameters (i.e., Mean, Mean-SD and Mean + SD) are shown in Figure 22 and Figure 23. There were 27 computer runs as part of this sensitivity study. Log-normal distributions were used to represent the air-entry value, the residual suction, and the saturated hydraulic conductivities.

4.3 *Initial and boundary conditions*

Similar to the above models, a soil suction of 90 kPa was set for entire soil model as the initial condition. In twenty-five (i.e., of a total twenty-seven) computer runs, a constant water flux of 0.5 (mm/day) was applied on the ground surface. There were only two computer runs where surface water flux was 0.1 and 0.9 (mm/day). The right edges of the model were set as a “no flow” boundary condition. A water table boundary condition (i.e., pressure head = 0.0 m) was assumed at the bottom edge of the model.

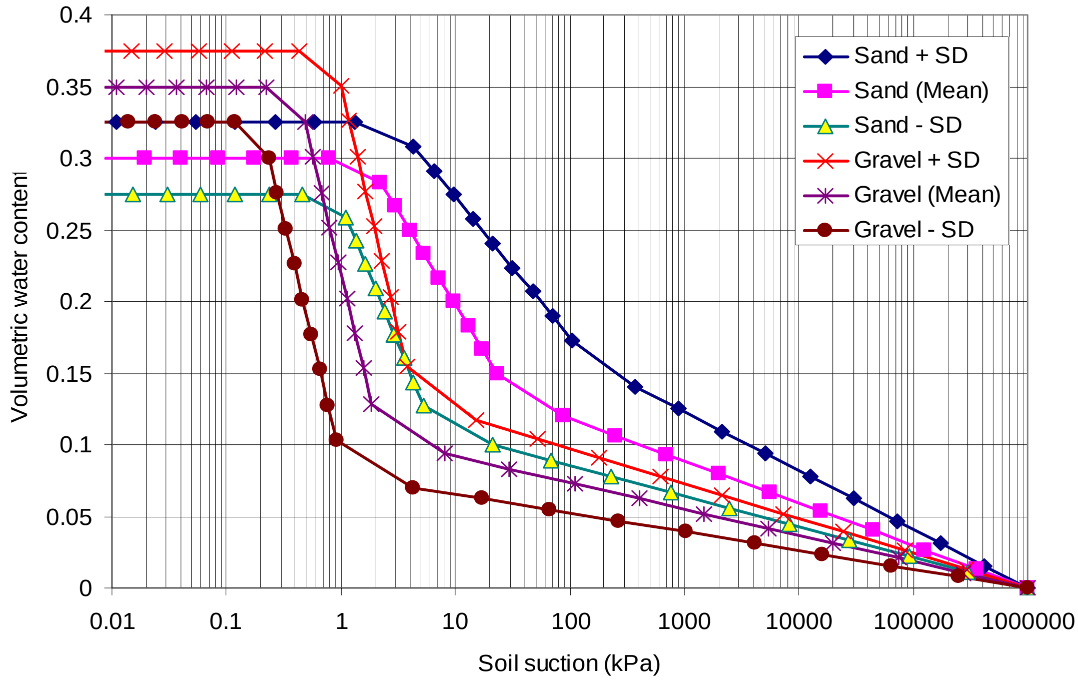

Figure 22 Soil-water characteristic curves for the sand and gravel using “mean”, “mean + SD”, and “mean –SD” unsaturated soil parameters.

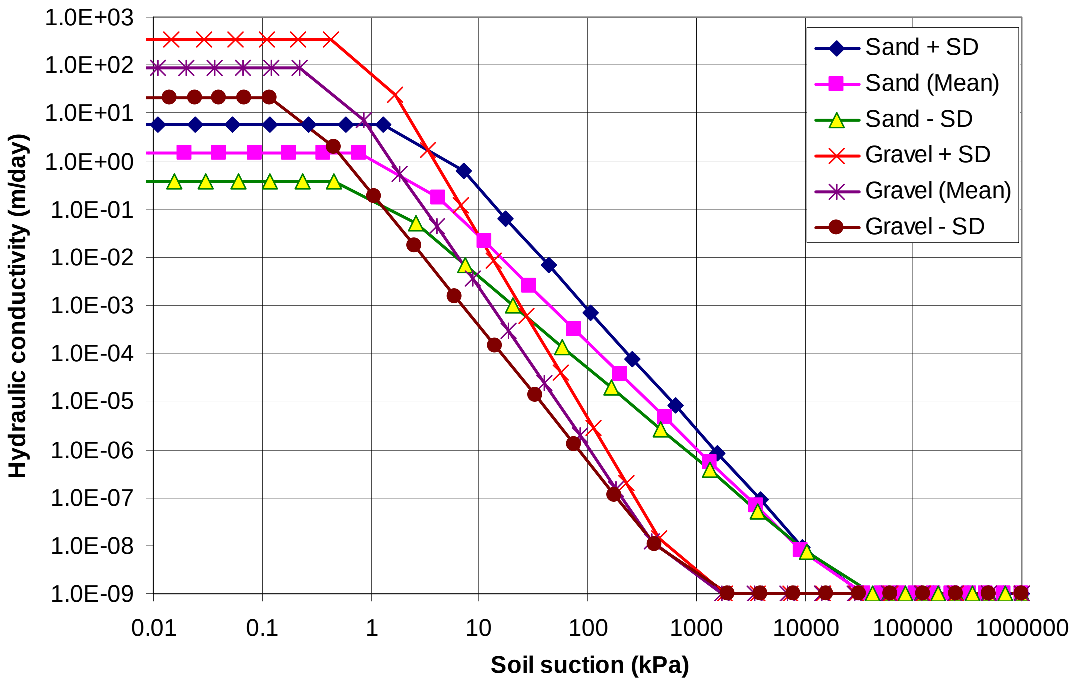

Figure 23 Soil-water characteristic curves for the sand and gravel using mean, mean + SD and mean –SD unsaturated soil parameters.

4.4 *Results and discussion*

The models were successfully run with an application of average flow of 0.5 mm/day. Some of the results were complicated from the fact that the rainfall was applied to both the top and the side-slope of the model. Therefore there was a portion of flow which strictly flowed down the layers and a portion which infiltrated through the layers from the surface.

The detailed results of the specific model flows are summarized in Table 11.

The results of Flux section #1 should be considered more representative as they are not influenced by ponding at the bottom of the model.

The results may be presented in the form of a tornado diagram to also show the relative importance of the different parameters. It also may be seen from the parameters which primarily control the division of flow between the sand and the gravel. From the following figures it may be seen that the division of flow through the sand and the gravel is primarily controlled by the saturated hydraulic conductivity and the air-entry vales of the two materials. Also noted should be the influence of the slope of the unsaturated hydraulic conductivity curve.

It should be noted that in this type of analysis the soil parameters can overlap due to the statistical variation.

Figure 24 illustrates the material parameters which affect the flow through the gravel layers. Of easy observation are the indications that as the air-entry value, saturated hydraulic conductivity, or the slope of the unsaturated hydraulic conductivity increase for the gravel there is an increase in the flow through the gravel. It is also worthy of note that as the saturated hydraulic conductivity of the sand increases there is an increase in the flow through the gravel. The reason for this may be found in a close examination of the relative portions of the unsaturated hydraulic conductivity between the sand and the gravel.

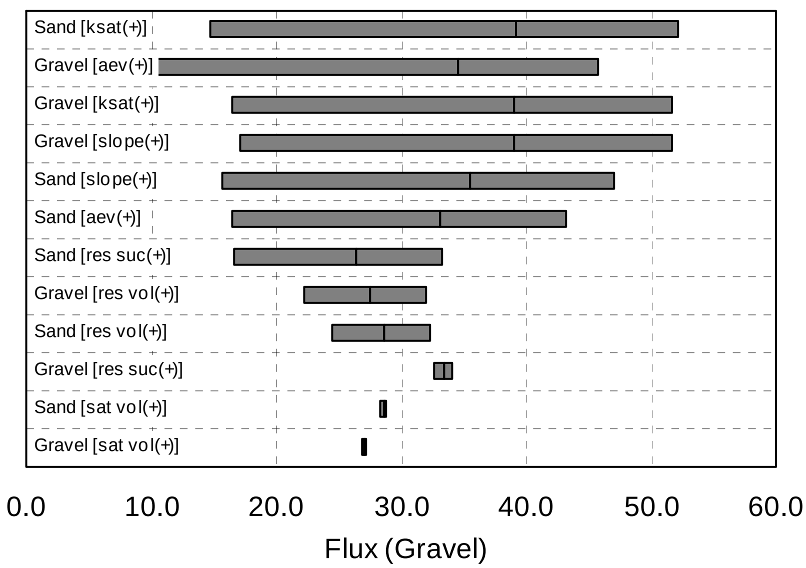

Figure 24 Deterministic tornado diagram of the influence of various flow parameters on the flow through gravel layers

The variance in the flow through the sand layer may be seen in Figure 25. This figure shows the variables that have a primary influence on the amount of flow through the sand layer. The primary variables are the air-entry value of the gravel, the saturated hydraulic conductivity of the sand and gravel and the slopes of the unsaturated hydraulic conductivity for both the sand and gravel materials.

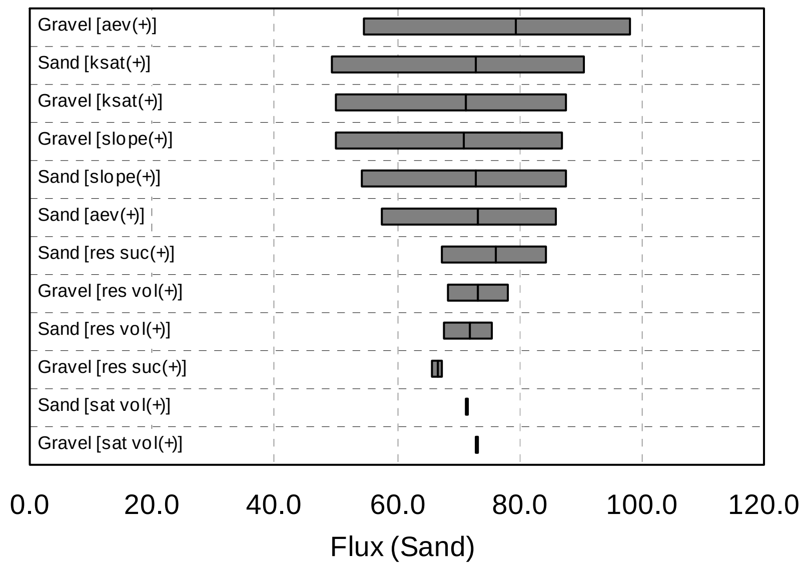

Figure 25 Deterministic tornado diagram of the influence of various flow parameters on the flow through sand layers

5 CONCLUSIONS

The present study is useful in determining the reasonable variation of material parameters given the extensive field program executed in the present study. Conclusions for this report may be divided in to four categories associated with the specific purposes of the modeling performed.

Modeling Set #1

The purpose of this modeling study was to determine reasonable soil parameters which will provide differentiation in flow between fine and coarse layers. A wide variety of grain-size distributions was measured in the field program. No distinctive categorization of a specific layer of coarse or fine material was identified in the field program. However, specific coarse layers were noted visually at the Goat Hill North site. Therefore professional judgement is used to identify reasonable soil parameters in the present study which will produce preferential flow.

The results of modeling set #1 is that it is shown that current base case Sand and Gravel soil parameters must be modified one standard deviation further apart from each other in order to produce reasonable preferential flow. It should be noted that the primary variable to which the results are sensitive is the slope of the unsaturated hydraulic conductivity curve. If this statistical separation was performed then flow values of approximately 95% for the sand and approximately 5% for the coarse were achieved. This differentiation also allows significant air volume in the coarse layer.

Modeling Set #2

Modeling of extremely fine layers in a full-scale model is computationally challenging. The amount of thickness increase of the fine and coarse layers which could be reasonably be assumed in the full scale numerical model without significant influence on the overall flow was studied. Actual coarse layers in the Goat Hill North rock pile were as thin as 10cm. From the numerical modeling it was found that increasing coarse layers to a thickness of 1m only increased the total flow in the coarse layers approximately 10%. Given that the reasonable error limit of the numerical model itself is 8% it is reasonable to conclude that this difference is acceptable in the current modeling program. It may be acceptable to consider this difference in the final modeling program.

Modeling Set #3

In the third modeling scenarios the upscaling of the small-scale models to a full-scale model was examined. From this model it can be seen that a 2m size layering could be used while preserving the concept of primary flow through the fine material. This was proven using reasonable averaged flow applications.

Modeling Set #4

In the sensitivity analysis the relative influences of the various material parameters was determined. The primary variables were i) air-entry value for the gravel, ii) hydraulic conductivity for the sand, iii) hydraulic conductivity for the gravel. Parameters which are also important are the slope of the unsaturated hydraulic conductivity curves for both the gravel and the sand.

Table 11 Results of the sensitivity analysis of the soil parameters

ID	Surface Flux (mm/day)	Soil Parameters		Percentage of flow in sand and gravel (%)			
				Flux 1		Flux 2	
		Gravel	Sand	Gravel	Sand	Gravel	Sand
1	0.5	Mean	Mean	29.54	70.46	33.94	66.06
2	0.5	Mean	AEV-SD	39.87	60.13	40.17	59.83
3	0.5	Mean	AEV+SD	17.53	82.47	21.22	78.78
4	0.5	Mean	Res Vol – SD	31.36	68.64	35.60	64.40
5	0.5	Mean	Res Vol + SD	25.21	74.79	29.54	70.46
6	0.5	Mean	Res Suc – SD	31.07	68.93	33.94	66.06
7	0.5	Mean	Res Suc + SD	17.66	82.34	22.64	77.36
8	0.5	Mean	Ksat – SD	47.68	52.32	43.00	57.00
9	0.5	Mean	Ksat + SD	14.78	85.22	18.11	81.89
10	0.5	Mean	Slope - SD	16.49	83.51	19.21	80.79
11	0.5	Mean	Slope + SD	43.12	56.88	40.37	59.63
12	0.5	Mean	Sat Vol - SD	28.78	71.22	33.20	66.80
13	0.5	Mean	Sat Vol + SD	28.44	71.56	32.95	67.05
14	0.5	AEV-SD	Mean	7.45	92.55	8.74	91.26
15	0.5	AEV+SD	Mean	42.32	57.68	43.43	56.57
16	0.5	Res Vol - SD	Mean	23.06	76.94	25.99	74.01
17	0.5	Res Vol + SD	Mean	30.80	69.20	33.02	66.98
18	0.5	Res Suc - SD	Mean	32.85	67.15	35.79	64.21
19	0.5	Res Suc + SD	Mean	33.96	66.04	35.52	64.48
20	0.5	*ksat* - SD	Mean	17.14	82.86	19.97	80.03
21	0.5	*ksat* + SD	Mean	47.34	52.66	48.25	51.75
22	0.5	Slope - SD	Mean	47.37	52.63	48.97	51.03
23	0.5	Slope + SD	Mean	17.88	82.12	20.26	79.74
24	0.5	Sat Vol - SD	Mean	26.91	73.09	29.52	70.48
25	0.5	Sat Vol + SD	Mean	27.20	72.80	30.00	70.00
26	0.1	Base	Mean	31.39	68.61	27.09	72.91
27	0.9	Base	Base	36.49	63.51	34.84	65.16

6 REFERENCES

SoilVision Systems Ltd., 2006, Seepage Numerical Modeling Report, Molycorp Weathering Study, Phase I, November.