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Slope Stability Model of the Questa Rock Pile– Phase 2

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Abstract

A slope stability analysis was performed for the mine rock pile located at Molycorp's Questa Mine. The goal of this task is to provide a sensitivity analysis with respect to the influence of various input parameters on the slope stability model. The influence of a change in soil shear strength parameters as influenced by weathering factors was also investigated. A particular focus of the study is the examination of potential thin weak layers and their impact on the stability analysis. The weathering aspects of these weak layers and the resulting influence on stability will be determined through a sensitivity analysis. The 2D forward analysis for the Goat Hill North detailed conceptual model results in a peak shear strength factor of safety of approximately 1.4 and a large deformation shear strength factor of safety equal to 1.18. The probability of failure of a conceptual model similar to the Goat Hill North conceptual model displays a probability of failure greater than 4% only if the overall slope angle exceeds 37.5 degrees and the large deformation shear strength values are used in the model. For a weak layer to cause failure conditions the effective shear strength of the layer would have to drop to approximately 20-23 degrees.

Introduction

The mine rock piles at the Questa mine extend to a height of 488ft with slope angles of approximately 36°. Natural failures within alteration scars that produce debris flows have been observed in the vicinity of the mine rock piles. Furthermore, deep-seated movement has occurred in the Goat hill North, GHN, rock pile requiring excavation and earthworks to stabilize the slopes. The question to be addressed is whether similar or other types of failures will occur in the future within the mine rock piles as weathering of the mine rock progresses with time or under variable conditions associated with climatic events.

The purpose of the current work presented in this paper is to provide a sensitivity analysis with respect to the influence of various input parameters on the slope stability model.

Scope

The scope of the modeling project is divided into two separate sections. The seepage modeling study will focus on the influence of climate on the slope. The slope stability section will include analysis of the effects of weathering on slope stability. This paper will focus only on the slope stability analysis

There are many aspects of the numerical modeling program covered in the current study. Each aspect can be identified based on the process modelled. The interconnectivity between different processes and their influence on the stability of the slope can be seen in Figure 1.

Scope of Slope Stability Modeling

The scope of the slope stability study involves a slope stability analysis of a typical waste rock pile. The influence of a change in soil shear strength parameters as influenced by weathering factors will be determined. The study will involve the application of finite-element based stability analysis as well as the application of limit equilibrium methods. The SVSLOPE® and SLIDE slope stability software are used in the study.

The pore-water pressure distributions computed in the seepage study will be input into the slope stability analysis software to determine the influence of seepage scenarios on the stability model. Geometries used for the seepage model will also be used in the slope stability modeling scenarios.

A particular focus of the study is the examination of potential thin weak layers and their impact on the stability analysis. The weathering aspects of these weak layers and the resulting influence on stability will be determined through a sensitivity analysis of the slope stability model. Some soil layers may increase with strength in time and others may weaken with time. The influence of weathering on cohesion and the angle of internal friction will be examined in detail. Assumed variations of these parameters are then used in the determination of resulting influences on overall stability.

Modeling Approach

The gravitational stability of the theoretical Questa rock pile is analyzed using traditional limit equilibrium techniques. The SVSLOPE and SLIDE slope stability software packages will be used in order to analyze the slope. A combination of deterministic and probabilistic methods will be utilized in the analysis in order to convey the model results.

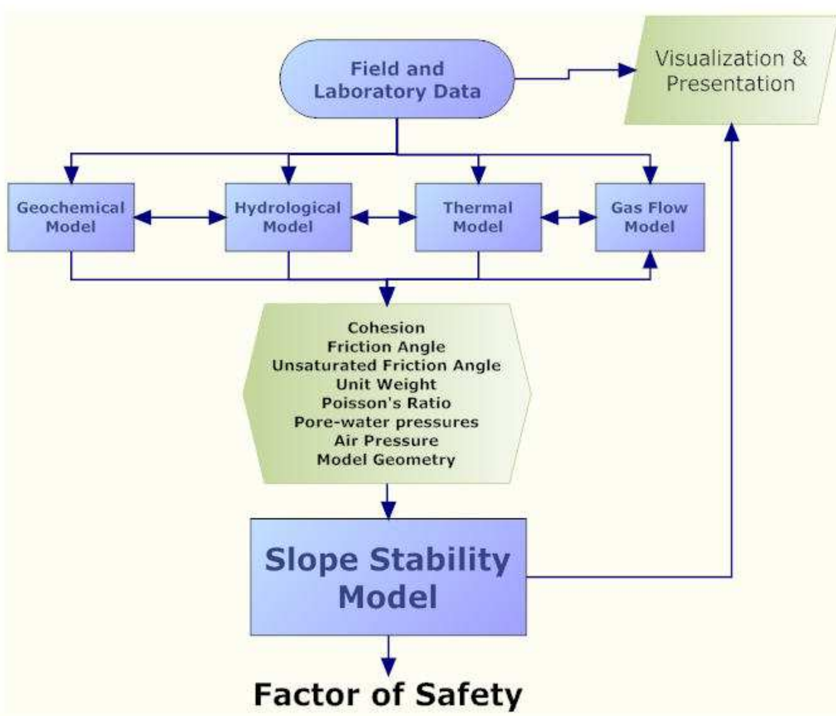

Figure 1: Overview of the numerical modeling processes relevant to the current site

This numerical modeling study is intended as a research study that will push the limits of applied numerical modeling. In particular, the following aspects of numerical modeling will be applied to the present rock pile:

- Alternate Point Estimate Method (APEM): this is an advanced statistical method which may be used in order to apply a probabilistic approach to a model with a large number of influencing parameters.
- Dynamic Programming: This new searching methodology will be applied to the current model. It has the benefit of a higher degree of accuracy in locating an irregular slip surface.

Given the current large number of model input parameters, it is of utmost importance to determine the relative influence of each of these input parameters on the factor of safety calculation. There is a complication that arises from a study in which so many input parameters are varying and it involves the determination of the relative influence of each parameter. It is also preferable to determine the relative influence of each model input parameter in a probabilistic manner. This study will attempt to provide a reasonable description of the influence of each input variable on the resulting factor of safety (FOS). The potential change in the FOS over time will also be described.

Failure Zones

In order to separate and identify different potential failure mechanisms the generalized slope stability model can be divided into three failure zones; namely, i) shallow, ii) intermediate, iii) and deep. These failure zones are illustrated in Figure 2.

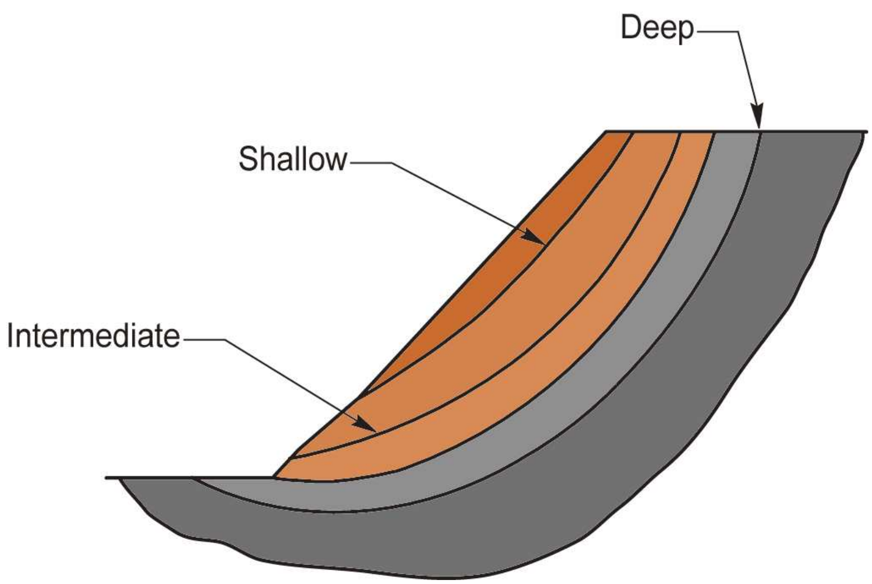

Figure 2: Identification of the three possible failure zones

The failure zones identified are not rigidly bounded but are loosely defined according to the following criteria.

Shallow Slip Surface

- Approximately < 10m max slip surface depth,
- Failures likely caused by slope angles exceeding the angle of internal friction or the influence of climate events, and
- Slides are generally of lesser consequence

Intermediate Slip Surface

- Comprised of upper (10-20m) and lower (20-45m) zones
- Still in the waste rock or rubble zone,

- Slip surface does not dip into weathered or unweathered bedrock,
- Likely not highly influenced by climatic events, and
- Chief failure mechanism likely due to a weaker layer in the zones above the bedrock.

Deep

- Failure slip surface would pass through the colluvium or weathered bedrock, and
- Deep springs or flow through fractured bedrock may influence the slip surface

The focus of the Phase II numerical modeling program is on the valuation of shallow or intermediate class slip surfaces. Deep failure surfaces may be considered at a later time.

Model Analysis

A number of different conceptual models have been developed in order to allow numerical modeling of one or more aspects of the waste rock site. It was discovered part-way through the numerical modeling that the conceptual model is approximately 2.6 degrees too steep. This error likely occurred through some conversion between various units on the site. The final conceptual model was therefore rotated 2.6 degrees clockwise and appears in Figure 3:

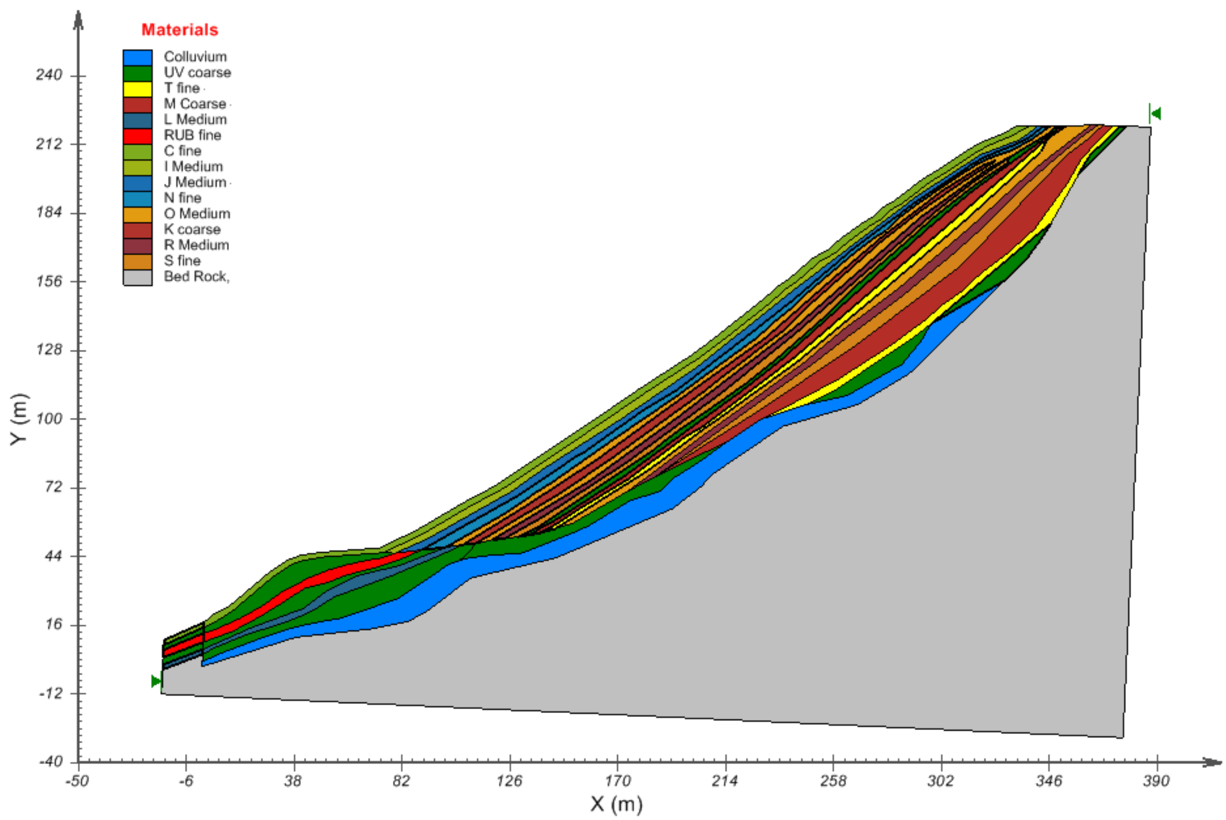

Figure 3: Final conceptual model used for slope stability analysis

Material Parameters

Material parameters used for the present slope stability analysis were arrived at through discussions with the Geotechnical Committee. Figure 4 and Table 2 on the following pages give the determined parameters representing residual and peak shear strength values, which were considered in model runs. Material parameters to use in the numerical modeling were provided by the Geotechnical Committee.

Calibration of Slope Stability Modeling

It was considered important in the present slope stability modeling study to provide continuity between new analysis methods and the traditional methods (e.g., the methods of slices). In particular, it was considered important to compare the dynamic programming method to more traditional methods. Two approaches were taken to provide this continuity:

- The dynamic programming methodology was compared to more classic limit equilibrium methods.
- The classic limit equilibrium methods were run on two separate software packages.

It was the intention that this approach would confirm the validity of the dynamic programming method and provide a reference to the more traditional methods.

Both the SVSLOPE (SoilVision Systems Ltd., 2008) and the SLIDE (Rocscience, 2008) software packages were used for this comparison. Over 100 benchmark models were set up in both software packages and run side-by-side. Almost all model comparisons resulted in differences in the calculated factors of safety that were less than a 1% between the software packages. Differences larger than 1% were investigated and were typically due to differences between the searching algorithms and not a reflection on the reliability of the calculations. Many of the models used in the final conceptual model analysis were run on the SLIDE software as well as the SVSLOPE software package. The differences between the two software packages were insignificant. It should also be noted that the probabilistic analyses for the present study were also compared between the two software packages and no significant differences were encountered.

Final comparisons between the limit equilibrium method and the dynamic programming method are ongoing.

2D Forward Deterministic Analysis

A classic limit equilibrium analysis of the 35.7 degree slope yields the reasonable factors of safety as presented in Figure 3. Input shear strengths both with and without cohesion were used in the numerical modeling. It should be noted that there is an influence on the slip surface depth. Only circular slip surfaces were considered for this analysis. Pore-water pressures were not considered in this analysis. It is useful to note that both soil suctions and 3D effects will potentially cause an increase in the calculated factor of safety.

The results of the analysis carried out for a peak strength and a residual strength analysis may be seen in Figure 3. The slip surface was forced deeper than would naturally occur with entered cohesion values.

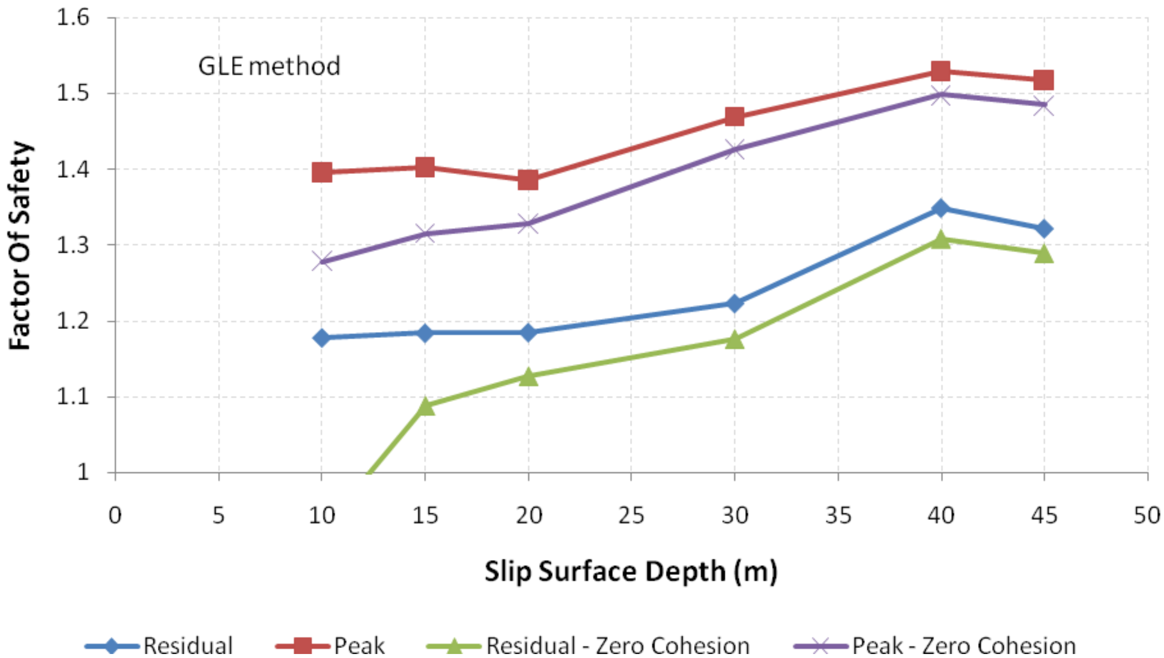

Figure 4: Factors of Safety as calculated by the GLE method

Table 1: Peak strength values

		Peak (2 in-dry)											
Layer	Hydrological Mapping	Phi (deg)					Cohesion (kPa)			Pore-water pressures (kPa)			Phi-b
		Average	Minimum	Maximum	COV	SD	Average	Minimum	Maximum	Average	SD	COV	Average
RUB	Fine	**43**	43	43	10%	4.3	0	0	0	12	6	50%	?
UV	Coarse	**41.8**	36.2	46.2	10%	4.18	0	0	0	12	6	50%	?
T	Fine	**37**	37	37	10%	3.7	10	3	17	12	6	50%	?
L	Medium	**40**	40	40	10%	4	5	5	5	12	6	50%	?
Colluvium	Fine	**40.8**	36.9	45.8	10%	4.08	0	0	0	12	6	50%	?
M	Coarse	**42.7**	42.7	42.7	10%	4.27	10	3	17	12	6	50%	?
S	Fine	**43.2**	43.2	43.2	10%	4.32	10	3	17	12	6	50%	?
I	Medium	**38.9**	35.2	41.6	10%	3.89	10	3	17	12	6	50%	?
N	Fine	**42.3**	41.7	43.4	10%	4.23	10	3	17	12	6	50%	?
J	Medium	**43.7**	41.7	44.9	10%	4.37	10	3	17	12	6	50%	?
R	Medium	**42.3**	39.2	45.4	10%	4.23	10	3	17	12	6	50%	?
K	Coarse	**42.3**	36.9	46.9	10%	4.23	10	3	17	12	6	50%	?
O	Medium	**42.3**	36.9	47.8	10%	4.23	10	3	17	12	6	50%	?
C	Fine	**45.7**	45.7	45.7	10%	4.57	10	3	17	12	6	50%	?
AVERAGE		**41.9**											

Table 2: Residual strength values

Layer	Hydrological Mapping	Ultimate (2 in - dry) Phi (deg)					Cohesion (kPa)			Pore-water pressures (kPa)		Phi-b
		Average	Minimum	Maximum	COV	SD	Average	Minimum	Maximum	Average	SD	Average
RUB	Fine	**40**	40	40	10%	4	0	0	0	12	6	?
UV	Coarse	**37**	32.5	41.6	10%	3.7	0	0	0	12	6	?
T	Fine	**33**	33	33	10%	3.3	10	3	17	12	6	?
L	Medium	**37**	37	37	10%	3.7	5	5	5	12	6	?
Colluvium	Fine	**40**	40	40	10%	4	0	0	0	12	6	?
M	Coarse	**40.7**	40.7	40.7	10%	4.07	10	3	17	12	6	?
S	Fine	**39.3**	39.3	39.3	10%	3.93	10	3	17	12	6	?
I	Medium	**34.9**	33.7	35.9	10%	3.49	10	3	17	12	6	?
N	Fine	**38.1**	35.8	39.7	10%	3.81	10	3	17	12	6	?
J	Medium	**36.8**	33.7	37.9	10%	3.68	10	3	17	12	6	?
R	Medium	**37.4**	36.5	38.2	10%	3.74	10	3	17	12	6	?
K	Coarse	**36.8**	35.7	37.5	10%	3.68	10	3	17	12	6	?
O	Medium	**37.2**	30.5	42.1	10%	3.72	10	3	17	12	6	?
C	Fine	**36.6**	36.6	36.6	10%	3.66	10	3	17	12	6	?
AVERAGE		**37.5**										

During the course of this analysis it was noted that the slope is sensitive to the angle of the upper slope. In order to quantify this sensitivity the geometry of the model was rotated through a set of angles and the above analysis repeated. The results may be seen in Figure 5.

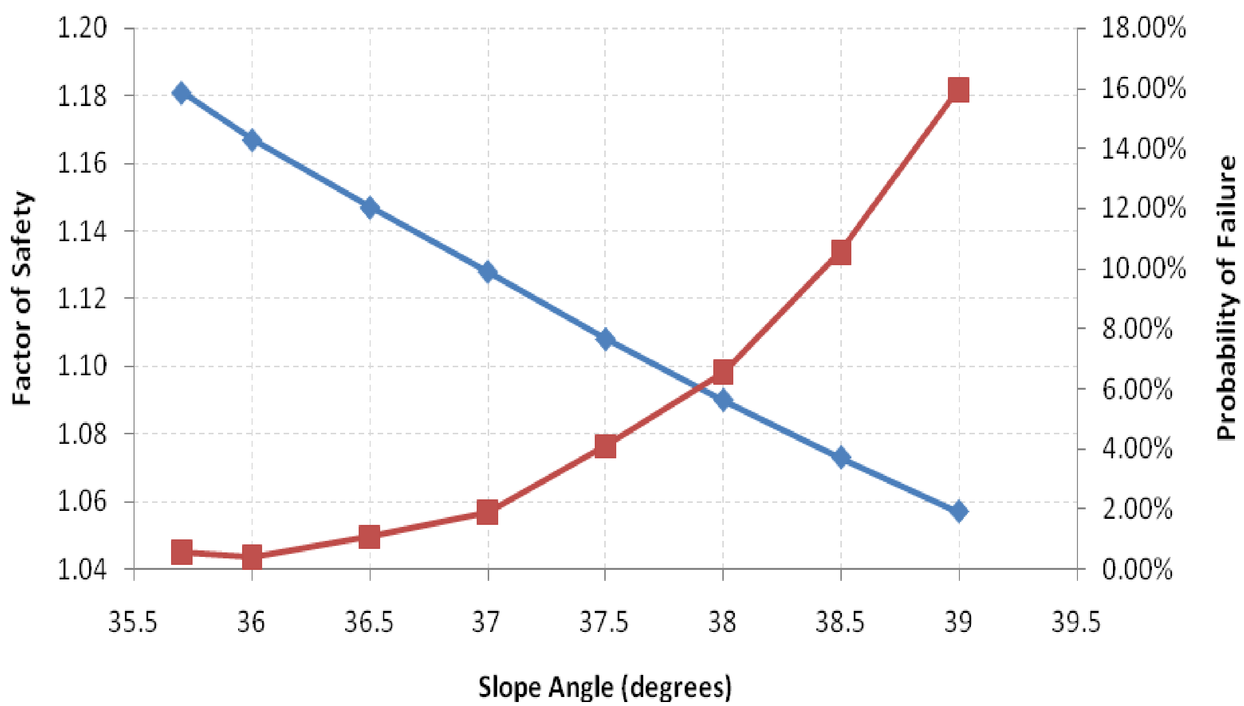

Figure 5: Sensitivity of the factor of safety to the slope angle

Weak Layer Analysis

A weak layer analysis was performed on the slope in order to determine the extent to which a weak layer with a decrease in shear strength might result in a potential slope failure. The most common failure mechanism was a failure in the upper intermediate zone. In order to identify potential weak layers an APEM statistical analysis was first run on the slope. This identified the weakest layers as layer O, K, N, and R.

Individual sensitivity analyses were subsequently performed on each of these layers. The cohesion for each layer was held constant at 10 kPa and the effective friction angle was then decreased until the factor of safety was approximately equal to 1.0. The friction angles needed in order to produce failure conditions can be seen in the Table 3.

Table 3: Effective friction angles needed to produce failure conditions in respective layers.

Description	Results	
Layer O	20	degrees
Layer K	23-24	degrees
Layer N	22	degrees
Layer R	21	degrees

The location of layers O, K, and N may be seen in Figure 6.

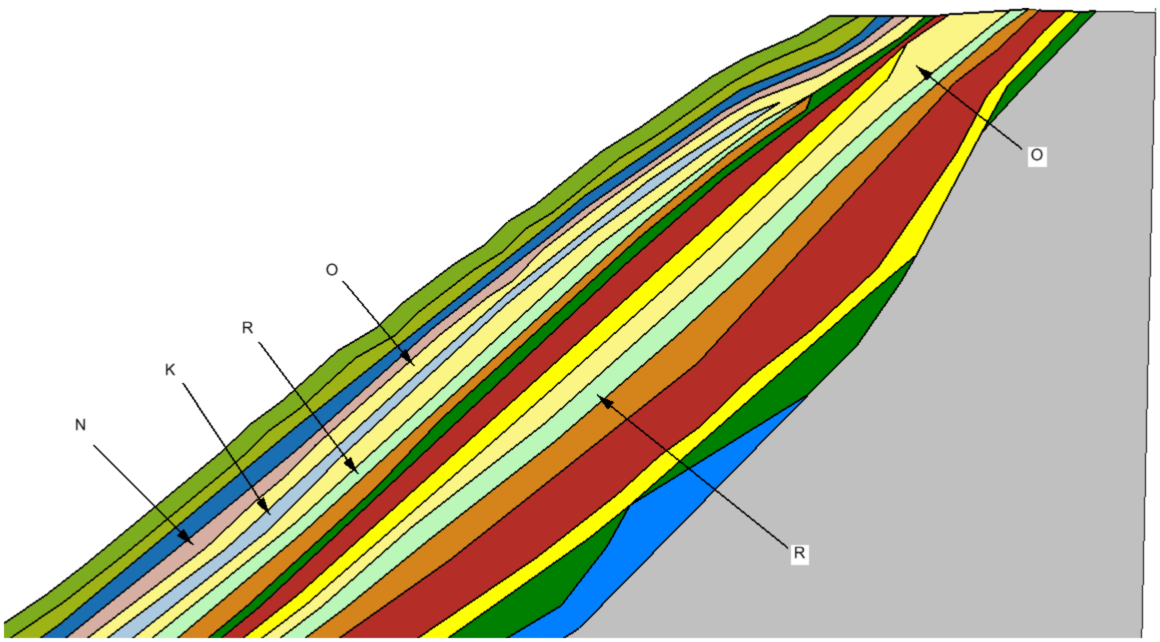

Figure 6: Location of weak layers O, K, and N (colored white)

Future 2D Analysis

The present modeling study results were compared to potential scenarios in the future in which the shear strength properties of the material were assumed to change. For the purposes of this analysis future reductions in the shear strength of 3 or 5 degrees were analyzed. Also included in the sensitivity analysis were the scenarios where the cohesion of the waste rock materials was increased. It should be noted that this modeling study does not imply any physical change in material parameters but is intended to be a "what if" scenario regarding the potential for change.

The results of the analysis can be seen in Table 5. It can be seen that while the factor of safety does not change significantly when the angle of internal friction is reduced, the probability of reaching failure conditions is increased. As a result the probability of failure increases for a 3-degree decrease in the angle of internal friction and dramatically increases for a 5 degree decrease (50%). It is interesting to also note that a reasonably small cohesion increase of 10kPa has a significant ability to decrease the probability of failure in these situations.

It should be further noted that the present analysis is conservative and real-world slope stability factors may actually be significantly higher for the following reasons:

- The analysis performed was 2-D. The factors of safety produced in a 3-D analysis would be higher, and
- This analysis does not include the effect of unsaturated soil suctions which will also have the effect of increasing the factor of safety.

The type of climatic event which could possibly lead to a potential failure of the slope has been given consideration in this study. One of the potential failure mechanisms is the possibility of a large rainfall or snowmelt event that might cause net percolation of an unnaturally large amount of water into the rock pile which could lead to a potential failure.

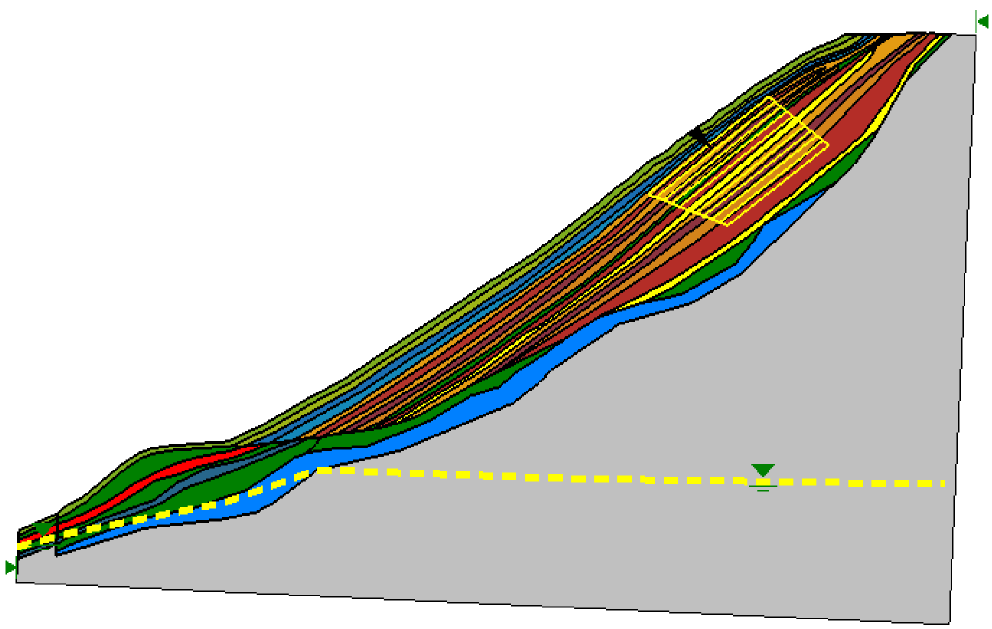

Figure 7: Level 1 water level

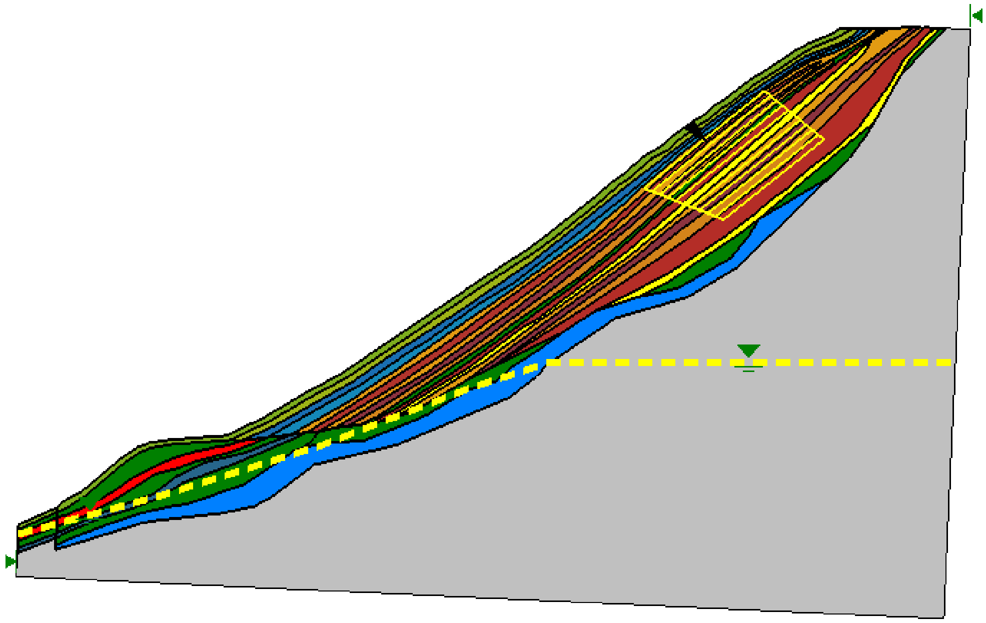

Figure 8: Level 2 water level

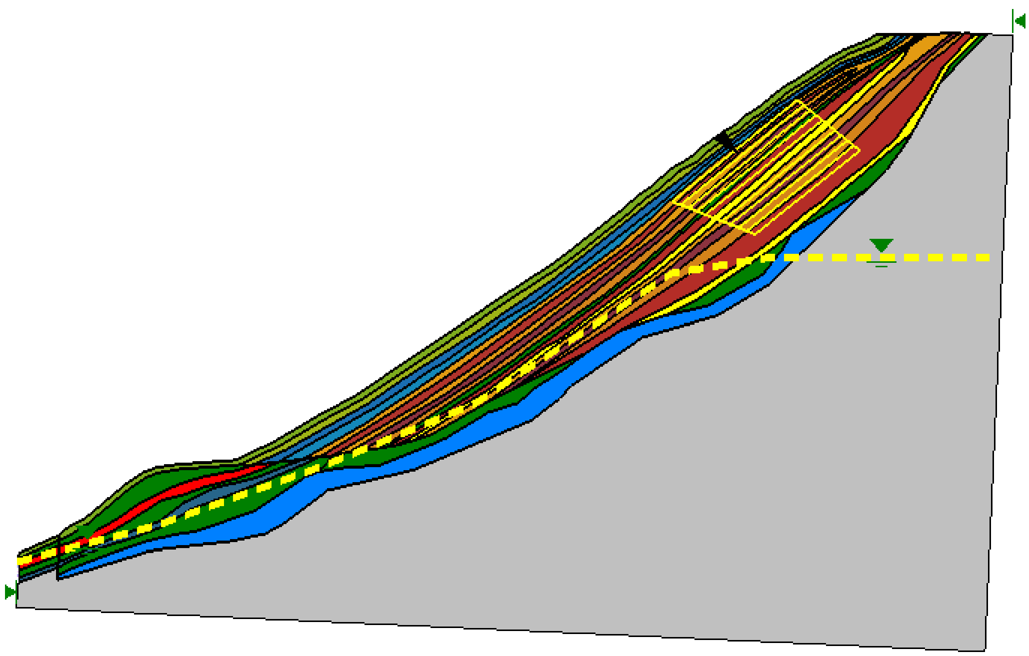

Figure 9: Level 3 water level

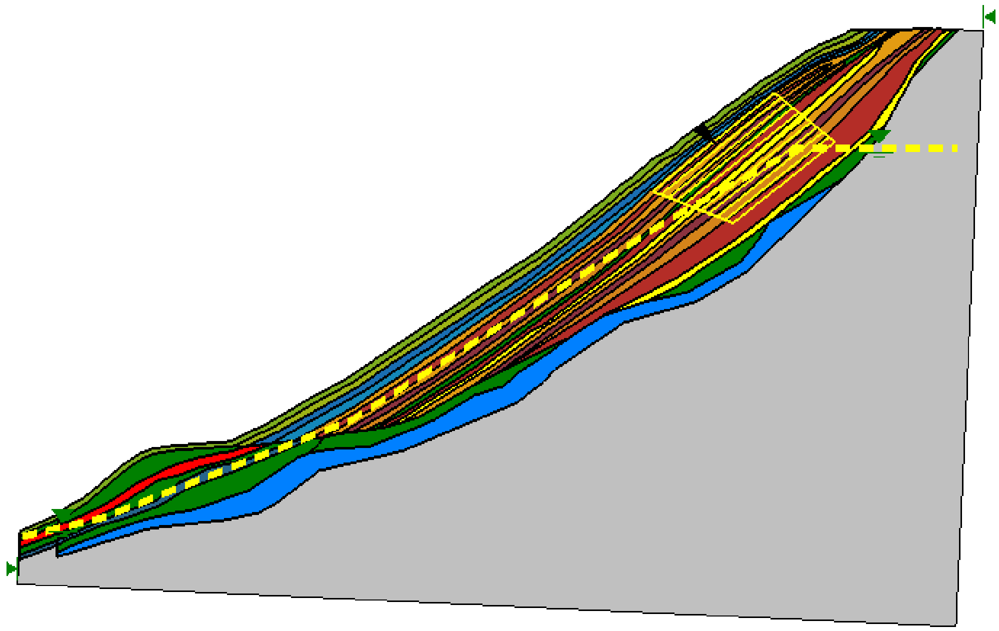

Figure 10: Level 4 water level: Failure conditions reached

Saturation Induced Failure

This scenario was analyzed in two ways in the current study. In the first scenario presented in this report, a water table is directly placed on the rock pile. This extremely high level of pore-water pressures will significantly change in the calculated factor of safety. In further analyses six different water level conditions were also analyzed. The resulting factors of safety are presented in Table 4.

Table 4: Summary of factors of safety associated with various water levels

Level 1	1.181
Level 2	1.181
Level 3	1.181
Level 4	1.019
Level 5	0.724
Level 6	0.479

A graphical description of the locations of these various water levels can be seen in Figures 7 to 10.

The yellow trapezoids represent the tangent search boxes used for the trial slip surfaces.

Conclusions

The analysis of the GoatHill conceptual model results in the following conclusions:

- The 2D forward analysis for the GoatHill North detailed conceptual model results in a peak shear strength factor of safety of approximately 1.4 and a large deformation shear strength factor of safety equal to 1.18.
- The probability of failure of a conceptual model similar to the GoatHill North conceptual model displays a probability of failure greater than 4% only if the overall slope angle exceeds 37.5 degrees and the large deformation shear strength values are used in the model.
- For a weak layer to cause failure conditions the effective friction angle of the layer would have to drop to between approximately 20-23 degrees (with a cohesion of 10 kPa in the weak layer).

- A water table would have to rise to extend approximately ¾ of the way up the slope in order to have a significant impact on the slope stability. This analysis does not determine the likelihood of this significant rise in the rock pile water table.
- A potential 3-degree reduction in the friction angle in all layers has the potential to reduce the factor of safety from 1.18 to 1.14 (3%) if a related increase in cohesion of 10 kPa accompanies the reduction in friction angle. This is for the large deformation friction angles.
- A potential 5-degree reduction in the friction angle in all layers has the potential to reduce the factor of safety from 1.18 to 1.06 (10%) if a related increase in cohesion of 10 kPa accompanies the reduction in friction angle. This is for the large deformation friction angles.

Table 5 Summary of peak and large displacement results for present and future conditions

	Peak Shear Strength		Large Displacement Strength	
Condition	FOS	$p_{f(\%)}$	FOS	$p_{f(\%)}$
Present Conditions				
Upper Intermediate	1.37	6.4E-07	1.18	0.8%
Lower Intermediate	1.39	1.3E-07	1.19	0.1%
Future Conditions - Upper Intermediate				
3 degree reduction	1.27	0.007	1.08	11.0%
3 degree reduction +10 kPA	1.37	2.75E-10	1.14	0.2%
5 degree reduction	1.19		1.00	50.0%
5 degree reduction +10 kPA	1.29	0	1.06	9.5%
Future Conditions - Lower Intermediate				
3 degree reduction	1.24	0.0035	1.09	4.5%
3 degree reduction +10 kPA	1.29	5.4E-05	1.13	0.3%
5 degree reduction	1.16	0.30	1.00	46.0%
5 degree reduction + 10 kPA	1.21	0.01	1.05	11.3%

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