

Slope Stability Model of the Questa Rock Pile – Phase 1

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Abstract

The Goat Hill mine rock piles at the Questa Mine in New Mexico have experienced natural debris flow and deep seated movement requiring mitigation measures be designed and implemented. This paper describes the slope stability modeling completed using the SVSlope finite element slope stability software, as well as the method with which material parameters were determined. The relative impact of parameters such as slip surface depth, friction angle, cohesion and Poisson's ratio were also examined. It was found that shallow failures will most likely be caused by changes in the matric suction due to rainfall events. Deeper slip surfaces required a corresponding increase in cohesion. The angle of internal friction of the layers is deemed to be the determining factor in any slope stability analysis.

Introduction

The mine rock piles at the Questa mine extend to a height of 488 meters 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 Goathill North (GHN) rock pile requiring excavation and earthworks to stabilize the slopes. This paper summarizes the numerical modeling related to the stability of the Goathill North rock pile. The question to be addressed is whether further 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.

Slope Stability Modeling

The scope of the slope stability study involves a sensitivity analysis for the Goathill North (GHN) 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 slope stability software is used in order to study the influence of weak layers on the stability of the slope.

The pore-water pressure distributions were computed in a separate seepage study. These are used as input into the slope stability analysis software to determine the influence of seepage scenarios on the stability model.

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 combination of seepage and slope stability models will be first used to quantify model inputs. The effects of each model input on the resulting factor of safety are then examined.

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. The Alternate Point Estimate Method (APEM) was utilized to quantify variability in this study.

The purpose of the numerical modeling of Phase I of this project was to identify parameters sensitive to the slope stability numerical modeling as well as the seepage numerical modeling study. Subsequent phases of the project will address the variation of model parameters in a more comprehensive manner. The focus of the Phase I numerical modeling program is on the valuation of shallow or intermediate class slip surfaces. Deep failure surfaces may be considered at a later time.

Soil Parameters

A considerable amount of field and laboratory information has been collected. It was proposed that the best approach to the numerical modeling study was to take a “snap shot” of the data at a particular time and use this as a starting point for the numerical modeling program. Subsequent field and laboratory results can allow further numerical model refinement in the future.

Data was obtained from the University British Columbia Team, UBC, or extracted from the New Mexico Tech, NMT, database on November 24, 2005.

Samples collected by NMT were obtained from the locations in the trenches created during destruction of the waste rock pile.

Slope Stability Results

Phase I of the numerical modeling slope stability study started with the use of a selected generic geometry. Subsequent to the generic slope study, a series of scenarios were examined based on a particular two-dimensional slice taken through the Goat Hill North geometry.

The study involves an analysis of potential intermediate and shallow failure surface mechanisms. An infinite slope analysis provided an analysis of shallow slides. The effect of Poisson's ratio on the depth of the slip surface generated using SVSlope was also examined.

A specific slice through the GHN pre-destruction geometry was selected for further analysis. Analyses performed include the evaluation of a homogeneous slope, the evaluation of a layered slope, and the analysis of a more rigorous version of the two-dimensional slice through the rubble and colluvium layers.

Layered Analysis with Varying Poisson's Ratios

The influence of Poisson's Ratio on the location of the slip surface and the value of the factor of safety prompted further study regarding possible limits of variation. A model was therefore selected which had layered stratigraphy in a reoccurring weak and strong sequence. The strong layers were then left unchanged and the soil parameters of the weak layers were changed.

Three scenarios were considered in which the angle of internal friction (ϕ) was varied between 20-40 degrees. The Poisson's Ratio values for the three scenarios are 0.32, 0.42 and 0.48. The angle of internal friction (ϕ) was changed for three Poisson's Ratio values. The results are presented in Figure 1. The effect of varying the angle of internal friction can be seen to be essentially linear in each scenario. A constant slope angle of 38 degrees was considered for all layered analysis scenarios.

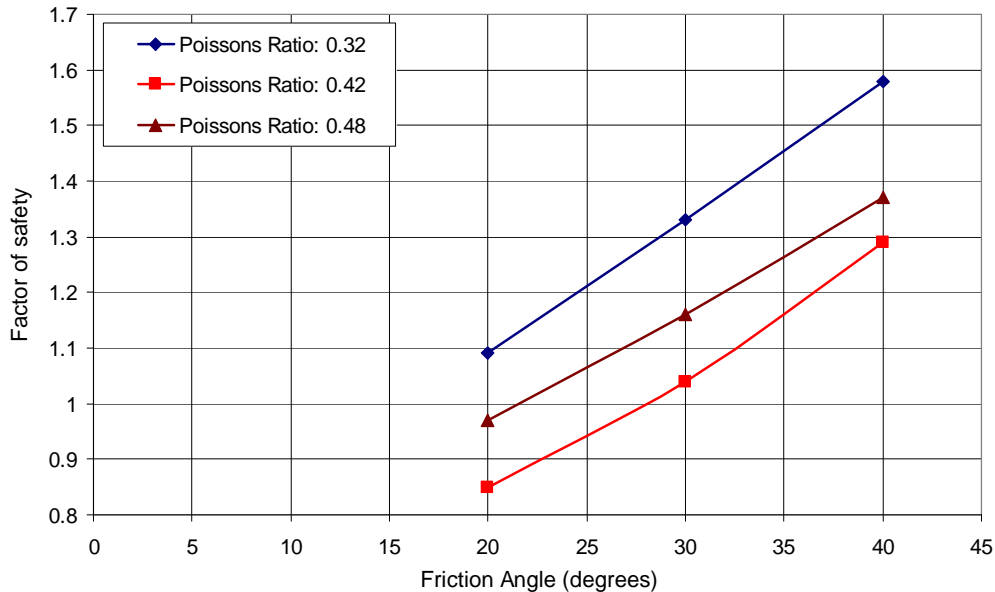


Figure 1: Effect of Changing the Angle of internal friction at three Poisson's Ratios

The location of the slip surface does not seem to change significantly when varying the angle of internal friction. The results presented in Figure 2 illustrate this point. It can also be seen in Figure 3 that the location of the critical slip surface does not vary significantly. The only difference between Figure 2 and Figure 3 is that the Poisson's Ratio is changed from 0.32 to 0.42. It should also be noted that when the angle of internal friction of the weak layer is reduced to a value less than the angle of internal friction of the contiguous layer the slip surface tends to follow the weak layer. Slip surface points above the ground are a numerical artifact of the numerical method and can be ignored.

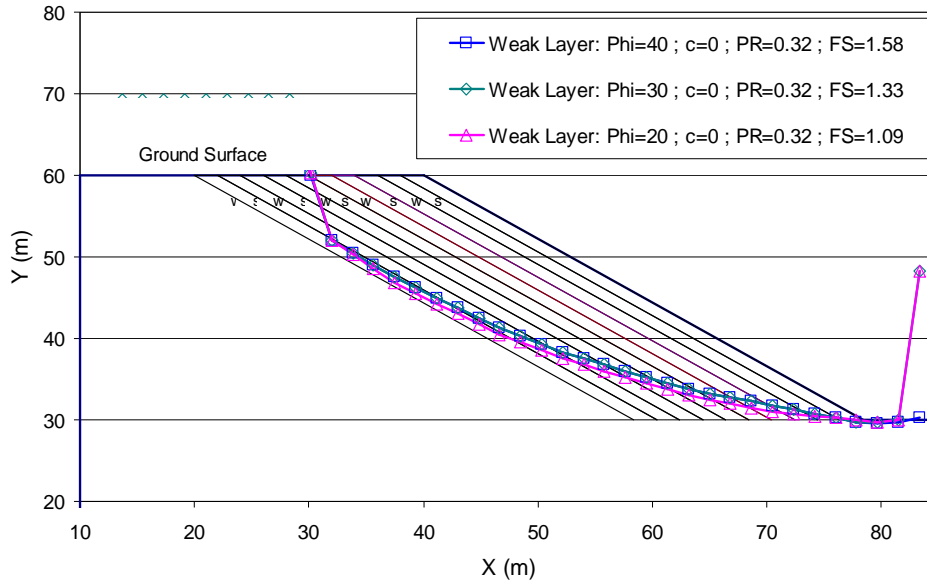


Figure 2: Effect of varying the angle of internal friction when Poisson's Ratio is equal to 0.32. Slope angle is 38 degrees.

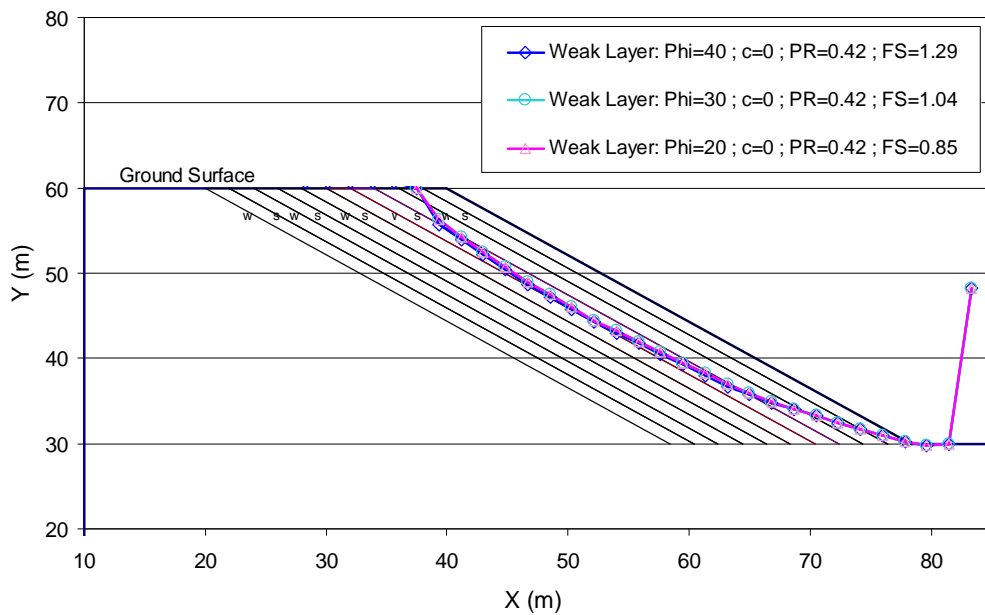


Figure 3: Effect of varying the angle of internal friction when Poisson's Ratio is equal to 0.42. Slope angle is 38 degrees.

Figure 4 presents the results of varying the angle of internal friction with a constant Poisson's Ratio of 0.48 and a cohesion of 10 kPa. The variation in the location of the slip surface can be seen to be minimal but the value of the factor of safety varies between 0.97 and 1.32.

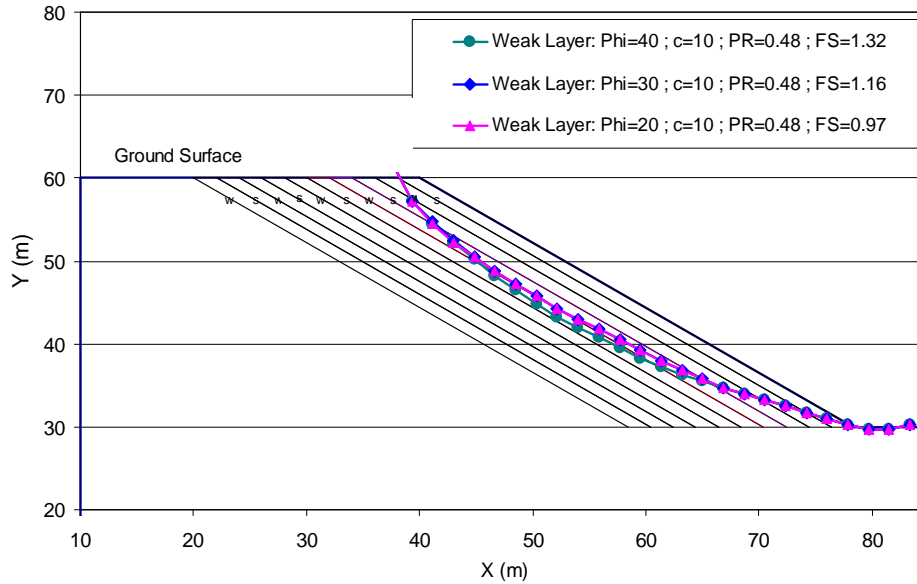


Figure 4: Effect of varying the angle of internal friction when Poisson's Ratio is equal to 0.48 and cohesion is equal to 10 kPa. Slope angle is 38 degrees.

The preceding figures have illustrated the changes in factor of safety that can be associated with varying the angle of internal friction. Figure 5 presents the results of varying the cohesion in weak layers. The angle of internal friction of the weak layers was made to be 20° for the material with a Poisson's Ratio of 0.42 and 40° for the material with a Poisson's Ratio of 0.48. The figure shows that there is a muting effect on the cohesion of a soil as the Poisson's Ratio is lowered. The relative influence of increases in cohesion can be seen by the slopes of each line. The break in the slope represents the condition where the final slip surface moves from one weak layer to the adjacent weak layer.

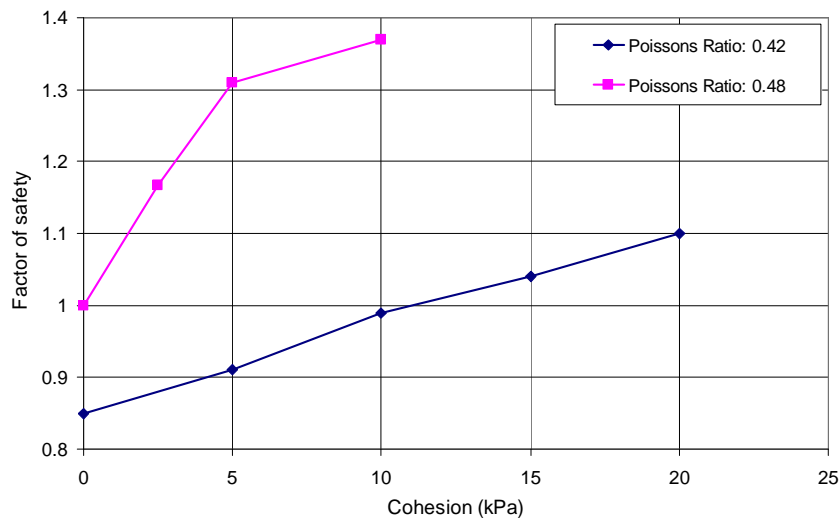


Figure 5: Variation in factor of safety for weak layer cohesion

One of the observations that can be made is that a Poisson's Ratio less than or equal to 0.44 will mean that cohesion will have minimal effect on the computed factor of safety for the slope. As Poisson's

Ratio decreases the effect of the cohesion on the computed factor of safety is minimized (i.e., when using SVSlope).

In Figure 6 and Figure 7 the location of the critical slip surface can be observed as cohesion is varied. It can be seen that the location of the slip surface generally moves from one weak layer to another.

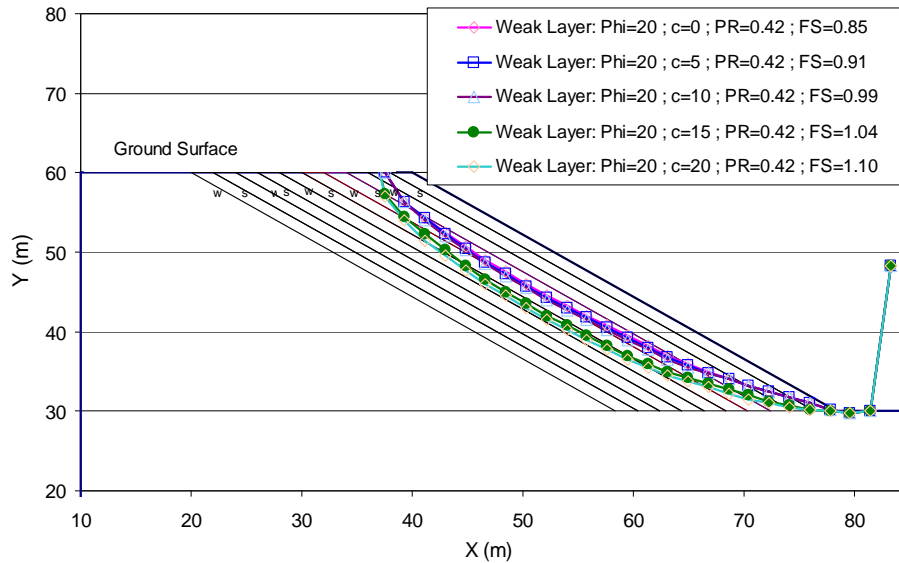


Figure 6: Variation in factor of safety and the location of the critical slip surface for weak layers with varying cohesion and an angle of internal friction = 20 degrees. Slope angle is 38 degrees.

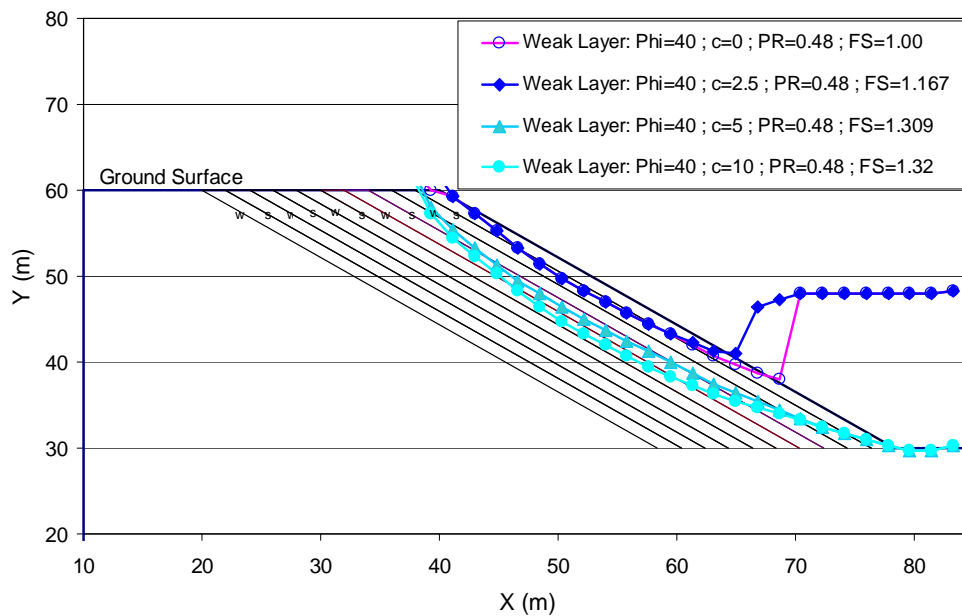


Figure 7: Variation in the computed factor of safety and the location of the critical slip surface for weak layers with varying cohesion and an angle of internal friction = 40 degrees. Slope angle is 38 degrees.

GHN 2D Cross-Section

A homogeneous 2-D cross-section has been selected through the stable portion of the GoatHill North site. The proximity of the stable and unstable portions of the GoatHill North site may be seen in Figure 8.



Figure 8: Goathill North rock pile before re-grading and looking east. Solid line indicates approximate location of trenches completed in summer-fall 2004; dashed line indicates the boundary between the stable and unstable portions of the rock pile (after McLemore et al., 2006)

The location of the cross-section was selected because of its proximity to the data obtained in the field trenching program. The cross-section went approximately through the middle of the field trenches as shown in Figure 6. The cross-section proceeds down to the toe of the GoatHill North site. The data collected in the field program will be applied to this cross-section.

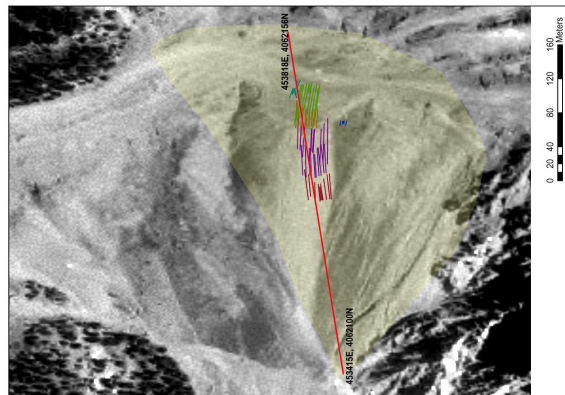


Figure 9: Location of the selected 2-D cross section on the GoatHill North site

The 2-D cross-section was determined by personnel from New Mexico Tech by interpolating intersection points on topology maps. The upper surface was determined using a 2003 topology map extracted from an AutoCAD file provided by Molycorp. The lower surface was interpreted from a 1962 AutoCAD topology file. It is assumed that the 1962 file represents the topology of the site prior to any dumping of waste rock.

For the homogeneous slope it is assumed that the bottom surface represents the interface with the impermeable bedrock material. It is also assumed for the homogeneous model that the slip surface

cannot be lower than the bottom surface. The dimensions of the selected 2-D cross-section can be seen in Figure 10. The slope angle of the surface of the waste rock at the site is approximately 38°.

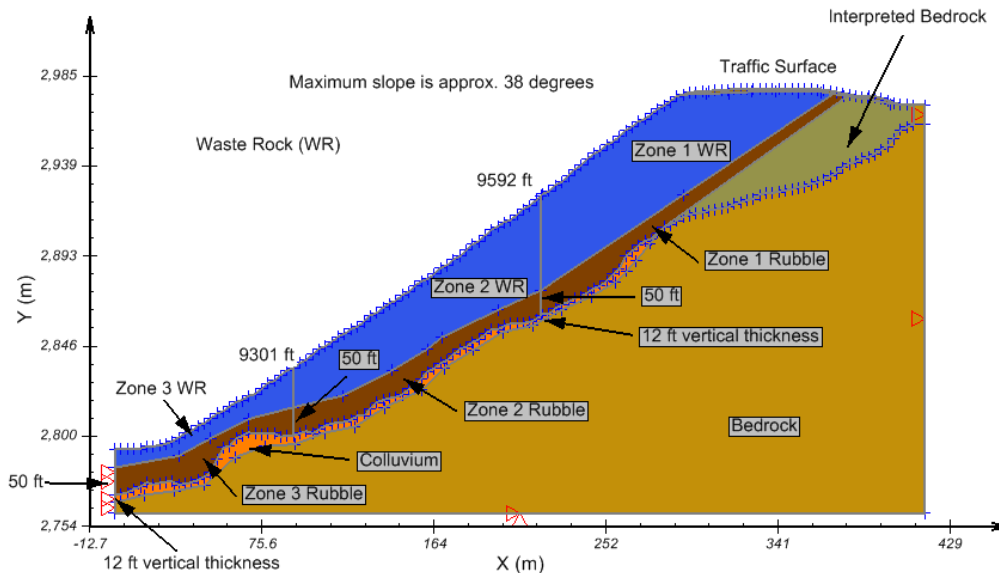


Figure 10: Cross-section extracted from the GoatHill North site representing pre-destruction condition.

GHN Intermediate SVSlope Statistical Analysis

A two layer numerical model was generated in order to study the effects of a potential weak layer through the rubble or colluvium zones. The traffic zone was also ignored. A statistical analysis was performed for the factor of safety based on data in Table 1.

The results of the slope stability analyses are shown in Figure 11 and summarized in Table 1 and the following observations can be made:

- The angle of internal friction of the rubble zone has by far the most significant influence followed closely by the angle of internal friction of the waste rock zone.
- The influence of pore-water pressures and cohesion could not be properly quantified as the variational distribution for this data was not available.

Given the measured distribution of phi angles of the colluvium zone by Norwest it appears statistically reasonable that a failure could be triggered by an assumed weakness in the lower zones.

Table 1: Soil parameters for intermediate SVSlope analysis. Rubble zone friction angles are taken from the presented Norwest weak colluvium layer.

Zone	Parameter	Mean	Standard Deviation	Source
WR1	Phi	40.03	2.69	Norwest
WR1	Cohesion	4.00	2.00	Assumed
WR1	PWP (kPa)	-2.05	2.76	NMT tensiometer data
WR1	Unit Weight (kN/m ³)	17.68	1.74	NMT data
Rubble	Phi	23.00	3.93	Norwest
Rubble	Cohesion	4.00	2.00	Assumed
Rubble	PWP (kPa)	-10.00	5.00	Assumed
Rubble	Unit Weight (kN/m ³)	16.66	0.43	NMT data

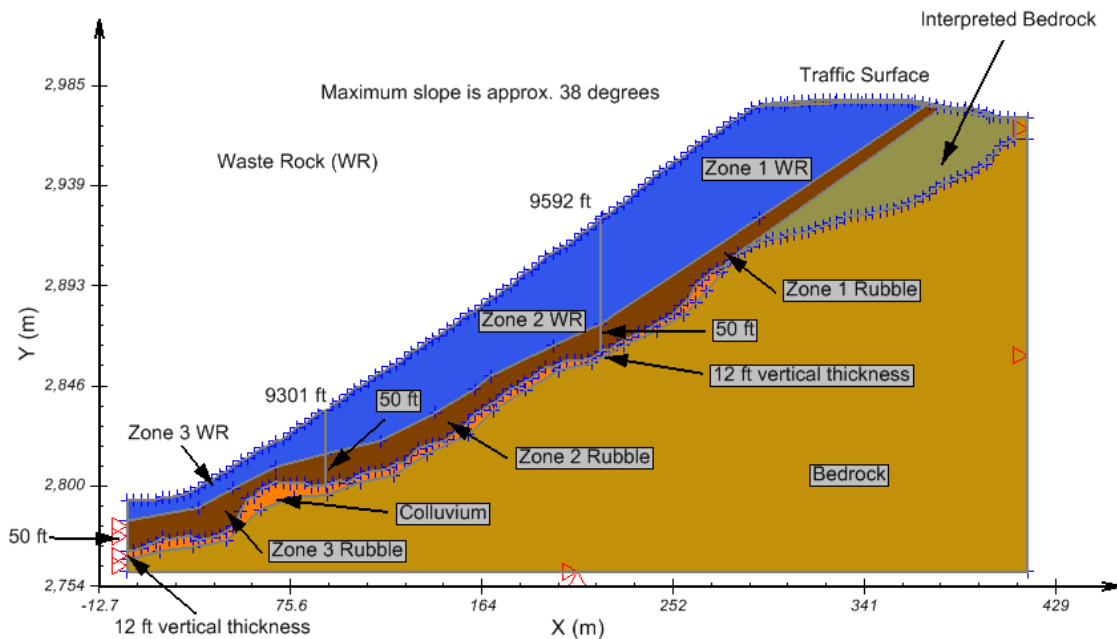


Figure 11: Cross-section extracted from the GoatHill North site representing pre-destruction

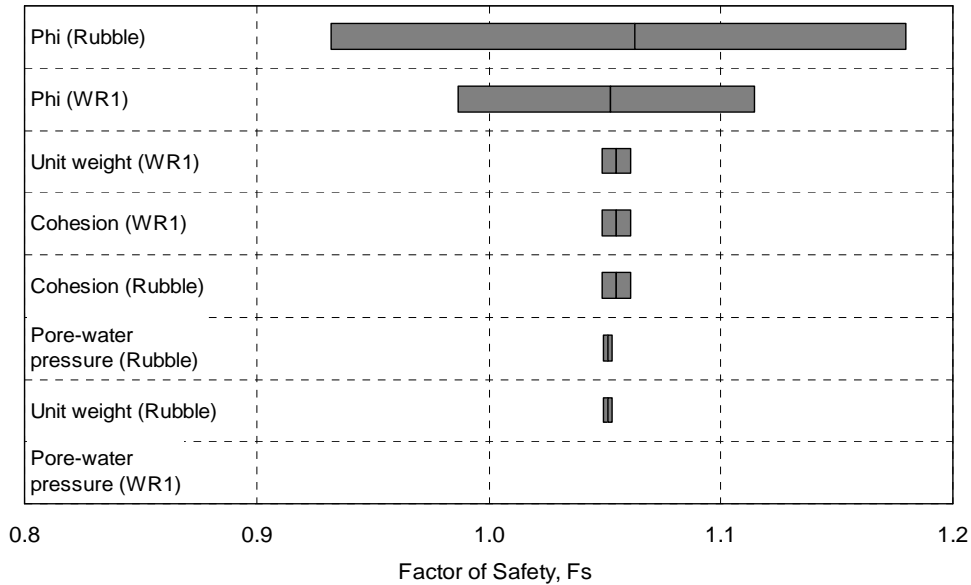


Figure 12: Tornado diagram for the factor of safety for the slope with two different layers for waste rock (90th percentile value)

Conclusions

The following conclusions can be made based on the analyses performed in the weathering study. The conclusions will be presented categorized according to the material removed.

Generic Slope

The conclusions drawn from the analysis of a generic slope are presented under the shallow and intermediate sections.

Intermediate

- Cohesion is needed to cause a slip surface to go deep in a homogeneous slope.
- From this analysis it can be estimated that $\phi = 30^\circ$ and a cohesion of approximately less than 4 kPa would be required to produce failure in a homogeneous slope.
- The location of the assumed slip surface influences the resulting factor of safety in a significant way.
- For a homogeneous slope with a cohesion of 10 kPa and an angle of internal friction of 34 degrees, it is impossible to find a slip surface with a factor of safety below 1.0.
- The depth of the slip surface and the resulting factor of safety are influenced by Poisson's Ratio. A Poisson's Ratio of 0.48 is most consistent with a traditional limit equilibrium analysis.
- In a weak/strong layered analysis varying the Poisson's Ratio between 0.42 and 0.48 requires an angle of internal friction between 20 to 30° in the weak layer in order to achieve failure conditions.
- In a weak/strong layered analysis varying the angle of internal friction of the weak layer will not affect slip surface location. Varying the cohesion of the weak layer will affect the slip surface location and cause the slip surface to "skip" between adjacent weak layers.

Goat Hill North

The following conclusions may be derived from the analysis of the Goat Hill North geometry scenarios.

Shallow

- In a limit equilibrium analysis of a homogeneous slope the factor of safety will drop below 1.0 with a $\phi = 36^\circ$ and a cohesion less than 1 kPa. Addition of 5 kPa of cohesion will result in a lowering of $\phi = 33^\circ$ required to achieve stability.
- Based on the statistical analysis of a shallow failure mode the following conclusions can be drawn:
 - The angle of internal friction has the most significant influence on the factor of safety.
 - The influence of unit weight on the computed factor of safety appears negligible.
 - The influence of cohesion on the factor of safety is of importance and needs to be further studied.
 - Realistic variance of suctions due to climatic events needs to be determined.
 - Given the present field-measured soil property statistical distributions it appears unlikely that shallow failure conditions can be achieved if the material is assumed to be homogeneous.

Intermediate

- Based on the current analysis it has been shown that a weak layer with an angle of internal friction less than 30° and a cohesion of zero may cause failure conditions.
- The statistical analysis provides further insight into the potential behaviour of the system as noted by the following conclusions:
 - The angle of internal friction of the rubble zone has by far the most significant influence followed closely by the angle of internal friction of the waste rock zone.
 - The influence of pore-water pressures and cohesion could not be properly quantified as the variational distribution for this data was not available.
 - Given the measured distribution of phi angles of the rubble zone by Norwest it appears statistically reasonable that a failure could be triggered by weakness in the rubble zone.

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