ROSEMONT MINE LANDFORMING

Evaluation of Mine Waste Slope Geometry

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EXECUTIVE SUMMARY

SWCA Environmental Consultants (SWCA) commissioned Golder Associates, Inc. (Golder) as part of the Environmental Impact Statement (EIS) under preparation by SWCA to determine the feasibility of using mine waste rock material at the proposed Rosemont Copper Project to implement landforming approaches.

Golder theoretically evaluated the erosion stability limits of three basic landform geometries (consisting of a planar concave slope, a flow expanding concave slope and a flow concentrating concave slope – Figure 4) when subject to runoff from the 100 yr 1 hr storm event. This was done to determine if it was feasible to engineer stable, natural-looking landforms from mine waste materials at the Rosemont site. The principal focus was on preventing excessive erosion. Geotechnical slope stability has not been addressed in this phase of the study.

*Stable*, for the purposes of this analysis, refers to the prevention of significant erosion (e.g., rill/gully formation leading to significant head-cutting) that could potentially expose materials beneath the waste rock cover such as the stacked tailings. It is likely inevitable that some erosion will occur on stable landform elements, but the intent is for it to occur over longer time scales, more akin to natural erosion rates of the surrounding landscape.

Based on the results of the stable slope analysis provided in Figure 6, Figure 7, Figure 8, and Appendix C, it was found that feasible landforming will require using multiple tiers of alternative landform elements at differing elevations and providing erosion resistant drainage where flow concentrates at the landform element interfaces. Successful implementation of the latter design element, i.e. protection against concentrated flow erosion, will require a robust engineering approach. The use of a single landform element over the maximum anticipated elevation difference for the waste rock pile of 500 ft will likely not work.

As such, Golder recommends investigating alternative solutions to convey concentrated flows from the bottom of each tier off the hill slope, beyond the use of hardened channels. Additional recommendations can be found in Section 6.0 of this report.
1.0 INTRODUCTION
SWCA Environmental Consultants (SWCA) commissioned Golder Associates, Inc. (Golder) as part of the Environmental Impact Statement (EIS) under preparation by SWCA to determine the feasibility of using mine waste rock material at the proposed Rosemont Copper Project to implement landforming approaches. Landforming refers to the engineering of natural-looking hill slopes that maintain functionality (i.e., ability to pass runoff from rain events) and stability (i.e., resistance to significant erosion and geotechnical slope failures).

During this assessment Golder’s focus has been to define the limits of landform geometries (i.e., slope profiles) constructed of waste rock materials that are capable of resisting erosion when subject to anticipated hydraulic conditions. Geotechnical slope stability has not been considered at this point in time as its assessment is more effectively executed once conceptual landform designs has been developed. The results presented provide guidance as follows:

- To aid in decision making to determine if the landforming approach is feasible at the Rosemont site, and
- To serve as a guideline for developing landforming geometries at waste rock piles if it is determined that landforming is potentially feasible.

As implied, the current report does not contain an actual landformed design for the waste rock hill slopes, but only guidance to feasible dimensions of landforming elements.

The general project location is shown in Figure 1.
Figure 1: Rosemont Copper Project location.
2.0 DESIGN CRITERIA

The objective of this analysis is to determine if it is feasible to engineer stable, natural-looking hill slopes from mine waste materials at the Rosemont site. Stable, for the purposes of this analysis, refers to the prevention of significant erosion (e.g., rill/gully formation leading to significant head-cutting) that could potentially expose materials beneath the waste rock cover such as the stacked tailings. It is likely inevitable that some erosion will occur on stable landform elements, but the intent is for it to occur over longer time scales, more akin to natural erosion rates of the surrounding landscape. The objective is that such erosion would not pose a significant threat to the materials underlying the waste rock.

Design criteria for defining landform geometries can be broken down into three categories:

- Materials
- Precipitation
- Geometry

Each of these is discussed further below.

2.1 Materials

Material comprising the landformed hill slopes will be waste rock derived from mining operations. This material can provide resistance to erosion, within limits. For granular materials, such as the waste rock, erosion resistance is a function of earth material particle sizes and friction between particles. Current gradations for waste rock material have been provided by Call & Nicholas and are shown in Figure 2. Note that the median particle diameter ($d_{50}$) of the waste rock material ranges between 0.6 ft (7 in) from the Willow Canyon / Alluvium source, and up to 1.5 ft to 1.9 ft (18 in to 23in) from Paleozoic and igneous rock sources.

Such gradations were calculated based on rock mass data collected from boreholes drilled in the project area. Based on experience, the actual gradation of the waste rock may be significantly finer. Subsequently, Golder has developed landforming element criteria assuming waste rock gradations with a $d_{50}$ varying between 1 in and 7 in.

Later on, materials may also include vegetation. At this time, however, the stability of the waste rock pile slopes has been evaluated solely based on the presence of waste rock material.
2.2 Precipitation

The 100 yr 1 hr event design storm was selected to estimate runoff. Based on experience in the area, using a shorter duration event (e.g., the 1 hr storm), is preferable to using a longer duration event (e.g., the 24 hr storm). Higher rainfall intensity associated with a shorter duration event results in higher peak runoff when compared to a longer duration event, even though the total amount of rainfall is less. Using a higher peak discharge is preferable for analyzing stability of materials under hydraulic loads.

The rainfall depth for the 100 yr 1 hr storm event is 3.56 in, which corresponds to the upper bound of the 90% confidence interval from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (NOAA, 2008). Using the 1 hr rainfall distribution provided in the Tetra Tech design storm memorandum (2009) a maximum rainfall intensity of 9.87 in/hr was determined to occur over the duration of the event.

2.3 Geometry

At this stage in the landforming assessment, it is not necessary to have an exact layout and geometry of the waste rock pile as this, in part, will be derived from the current analysis. Conceptual drawings of waste rock pile location and size were provided to Golder from SWCA (2009). Based on these drawings and communication with SWCA, the maximum length of the pile is on the order of 3 miles to 4 miles long, with a maximum height of approximately 500 ft. Subsequently, these parameters were kept in mind for evaluating the feasibility of the landforming approach.
3.0 METHODOLOGY
The methodology followed by Golder was done to define the extents of natural-looking landform geometries (i.e., slope profiles) protected by waste rock materials that are capable of resisting erosion when subject to the design hydraulic conditions. The analysis consisted of:

- Assessment of the natural landform geometries
- Determination of stable slope profiles
- Evaluation of armoring capability

3.1 Natural Landscape
Photos from the vicinity of the Rosemont site were analyzed to determine what types of natural landforms were present so that these geometries could be considered in the development of the engineered landforms. Below are some of the key elements observed:

- Irregular ridgelines
- Basins (of varying sizes)
- Flow expanding / flow concentrating areas
- “Sinusoidal” pattern across contours
- Concave slope profiles
- Presence of vegetation on the landforms

Figure 3: Natural landscape near Rosemont site showing flow expanding / concentrating areas.
From a hydrologic standpoint, ridgelines divide flow between different basins. Their irregularity is key to providing an aesthetic natural look in comparison to the typical linear landforms most commonly associated with waste rock piles.

Basins contribute to the volume of runoff and are often comprised of many other basins of differing sizes. In the most simplistic form, basin geometry can be represented by flow expanding and flow concentrating areas. These areas, as shown in Figure 3, either spread flow out (i.e., decrease erosive capacity) or bring flow together (i.e., increase erosive capacity) as it is traveling down the hill slope. Alternating flow expanding and flow concentrating areas produce a “sinusoidal” pattern across contours on the hill slope. This variation in the slope face is also important in providing natural aesthetics.

Concave slopes are steeper near the top and gradually flatten out with increased slope length. Runoff from the slope continually accumulates as the slope length increases due to rainfall uniformly falling over the entire slope. When the discharge is increased, flow erosive capacity is increased. To counteract the change in erosive capacity, the slope flattens to reduce flow velocity.

Finally, the presence of vegetation is important for both the aesthetics of the hill slope and its stability. As mentioned above, the effects of vegetation on hill slope stability have been neglected from this analysis.

### 3.2 Stable Slope Profiles

Determination of stable slope profiles for a hill slope is a function of three key parameters:

- Hill slope geometry
- Runoff
- Erosive capacity / material resistance

#### 3.2.1 Hill Slope Geometry

To begin to understand and quantify stable hill slope configurations comprised of waste rock material, three basic types of landforms were analyzed. The types of geometries were 1) a planar concave slope, 2) a flow expanding concave slope, and 3) a flow concentrating concave slope (Figure 4).

All geometries incorporate a concave slope profile, similar to those witnessed in the natural surroundings of the project location. The planar concave slope is a simplistic scenario, while the flow expanding and flow concentrating slopes are more attuned to what is observed in the project area. These geometries were selected as they are the most basic elements of an individual drainage basin. Once their dimensions are defined within the context of runoff and materials, they become essentially the “building blocks” for constructing more complex landforms.
The configuration of each of these basic basin elements is such that runoff flows uniformly over the slope face (i.e., no channels are necessary to convey water down the slope). Some allowance has been made to account for localized flow concentrations which will be discussed more in detail later on.

**Figure 4: Basic hill slope landforms.**

### 3.2.2 Runoff

To evaluate stable slope profiles, it was necessary to determine the amount of runoff as a function of the slope length. The following equation for shallow flow conditions could be applied (Henderson, 1966):

\[
q = (i - i_f) \cdot L \cdot CF \cdot W_L = \alpha \cdot D^m
\]

Where:

- \( q \) = runoff discharge per slope width (i.e., unit discharge) (m³/s/m)
- \( i \) = rainfall intensity (m/s)
if = infiltration rate (m/s). It has been assumed there is no infiltration, relating to full saturated ground conditions.

L = slope length (m)

D = flow depth (m)

\[ m = \frac{5}{3} \]

\[ \alpha = \frac{1}{s^2} \]

\[ k = \frac{1}{k_6^{1.6}} \]

s = bed slope (dimensionless)

k = absolute roughness of bed material (m) assumed equal to the d_{50}.

CF = concentration safety factor to account for localized flow concentrations assumed equal to 2.

\[ W_L = \text{factor dependent on the degree of flow expansion / concentration for the expanding concave and concentrating concave slopes (for the planar concave slope } W_L = 1). \]  This factor relates the width at the top of the slope (a function of the initial radius, r_{o}) to the slope width at any given slope length (a function of the radius, r_{L}) as shown in Figure 4.  This can be expressed as:

\[ W_L = \frac{(r_o + r_L)}{2r_L} \]

As indicated, the unit discharge increases linearly with increasing slope length (i.e., no attenuation).  This is likely a reasonable assumption given the corresponding basin size would be relatively small and that the bed slope is relatively steep, thus making basin time of concentration very short.

### 3.2.3 Flow Erosive Capacity – Material Resistance

After runoff has been determined as a function of slope length, it is possible to determine the flow erosive capacity applied to the materials as a function of slope length.  Flow erosive capacity can be quantified in terms of shear stress:

\[ \tau = \rho \cdot g \cdot D \cdot s \]

Where:
\( \tau = \text{bed shear stress (Pa)} \)

\( \rho = \text{density of water equal to 1000 kg/m}^3 \)

\( g = \text{acceleration due to gravity equal to 9.81 m/s}^2 \)

\( s = \text{bed slope (dimensionless)} \)

\( D = \text{runoff flow depth (m). By re-arranging the runoff discharge equation from above, the flow depth can be expressed as a function of slope length:} \)

\[
D = \left( \frac{(i - i_f) \cdot L \cdot CF \cdot W_L}{\alpha} \right)^{1/m}
\]

The resistance to erosion supplied by the waste rock material can be quantified using the Shields parameter (Shields, 1936). Using the Shields parameter, the threshold (critical) shear resistance of the material can be expressed as:

\[
\tau_c = \theta_c \cdot (\rho_s - \rho) \cdot g \cdot d \frac{1}{FS}
\]

Where:

\( \tau_c = \text{critical shear stress for particle of size “d” (Pa)} \)

\( \theta_c = \text{critical Shields parameter (dimensionless). This is function of the particle Reynolds number (Re - Figure 5), but for rough turbulent flow conditions, such as those to be encountered on the landforms, the value is constant at 0.047.} \)

\( \rho_s = \text{density of waste rock material assumed equal to 2620 kg/m}^3 \)

\( d = \text{representative diameter of waste rock material equal to the d}_{50} \text{ particle size} \)

\( FS = \text{safety factor equal to 2. For selection of an appropriate safety factor, guidance was sought from the National Resource Conservation Service (NRCS) (1989). As indicated, a value of 2 corresponds to significant uncertainty in the design, which is reasonable for this analysis.} \)
TABLE 1
SAFETY FACTOR SELECTION CRITERIA FROM NRCS

<table>
<thead>
<tr>
<th>Condition</th>
<th>Stability Factor Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform flow: straight or mildly curving reach; little or no uncertainty in design</td>
<td>1.0 – 1.2</td>
</tr>
<tr>
<td>Gradually varying flow: moderate bend curvature; limited or minor impact from floating debris or ice</td>
<td>1.2 – 1.4</td>
</tr>
<tr>
<td>Sharp bend: Significant impact potential from floating debris or ice; significant wave &amp;/or boat generated waves, (1.0-2.0 ft); high flow turbulence</td>
<td>1.4 – 1.6</td>
</tr>
<tr>
<td>Rapidly varying flow (particularly due to rapid drawdown at flow constrictions); Significant uncertainty in design</td>
<td>1.6 – 2.0</td>
</tr>
</tbody>
</table>

When the erosive capacity of the flow exceeds the critical resisting capacity of the waste rock material, the material will erode (and is subsequently considered unstable). Therefore, for each incremental increase in slope length, the bed slope is adjusted until the erosive capacity is just below the threshold resistance of material. The resulting profile is thus considered to be the stable slope profile for the given conditions. Stable slope profiles were generated for each of the three landform slope types (planar concave, expanding concave, and concentrating concave) assuming median waste rock sizes varying between 1 in and 7 in.

Stable slope calculation sheets for the planar concave, expanding concave and concentrating concave slopes can be seen in Appendix A.

3.3 Gessler Armor Layer Evaluation

The Gessler method provides a means of evaluating changes in entire grain size distributions due to the effects of flowing water (Gessler, 1965). For the stable slope calculation above, stability is assessed in terms of the representative particle size for a gradation (i.e., the $d_{50}$). This is common practice for sizing riprap, for example. Obviously, some grain sizes in a gradation are smaller than the $d_{50}$ and, subsequently, are susceptible to movement when subject to hydraulic loads. Under such conditions, the finer sizes wash away leaving the coarser particles behind. This phenomenon is referred to as “armoring” and is commonly witnessed in stream channels.

As such, the Gessler method can be used to provide additional insight on the stability of the entire waste rock gradation beyond the stable slope evaluation performed above that is based on a single representative grain size.

This method assumes a normal probability distribution can be applied to the threshold curve of the Shields diagram (Figure 5), where the probability of movement increases or decreases as the Shields parameter, $\theta$, for a given grain size diverges from the critical Shields parameter, $\theta_c$. For each particle size...
in the waste rock gradation, the critical resisting shear stress, $\tau_c$, is determined and compared to the bed shear stress, $\tau$, induced by the runoff. Depending on the ratio of $\tau_c / \tau$, the probability that a particle will not be transported, $p$, can be determined (based on experimental data by analyzed Gessler (1965)). By doing this for each particle size in the waste rock material gradation, the percentage of material from each size class that is not transported is determined, and can be used to construct the future armor layer gradation for given flow conditions.

**Figure 5: Shields diagram with Gessler probability assumption (from Oehy, 1999)**

When the mean value of the probabilities for all particle sizes in the armoring gradation is above 0.5, the armor gradation is considered to be stable (Gessler, 1970)

The depth of degradation from the initial waste rock gradation to the armored waste rock gradation can be calculated from Julien (2002):

$$\Delta z = 2 \cdot d_c \cdot \left( \frac{1}{\% P} - 1 \right)$$

Where:

$\Delta z =$ depth of degradation before armoring (in)

$d_c =$ critical particle size equal to the $d_{50}$ for this analysis (in)

$\% P =$ probability
%P = percentage of material coarser than \( d_c \) in the initial gradation (i.e., before armoring). As \( d_c = d_{50} \) for this analysis, %P = 0.5, and \( \Delta z \) simplifies to 2*\( d_{50} \).

Note the above equation assumes the armor layer thickness is twice that of the critical particle size.

Calculations for Gessler armor layer gradation and stability can be found in Appendix B.
4.0 RESULTS

4.1 Stable Slope Profiles

Stable slope profiles were determined for each of the three landform slope types (planar concave, expanding concave, and concentrating concave – Figure 4) assuming the median waste rock diameter varied incrementally between 1 in and 7 in. For each landform type, the following was calculated:

- Stable slope, $s$, vs. slope length, $L$
- Stable slope, $s$, vs. horizontal slope length, $x$
- Vertical slope length, $y$, vs. horizontal slope length, $x$

It should be noted that for the expanding concave slope and the concentrating concave slope scenarios it was necessary to specify the initial radius, $r_o$ (Figure 4), at the top of the slope. The value of the initial radius has an effect on the degree of flow expansion / concentration and, therefore, multiple values for $r_o$ were analyzed.

Additionally, it should be noted that the value of $\beta$, representing the angle of expansion / concentration for the basin (Figure 4), is negligible when considering the slope profile as long as it is constant with increased slope length. Subsequently, this means that for the flow conditions and a given material size, $\beta$ could be 10 deg or 180 deg and the slope profile provided would be same throughout the basin.

Finally, a slope of 2H:1V was used as a practical upper limit for slope steepness. Geotechnical analysis on reworked fill material suggested a stable slope of 1.5H:1V (Tetra Tech, 2007). Therefore, when considering hydraulic conditions, a maximum slope of 2H:1V was deemed reasonable at this level of analysis.

Results from the three landform types are discussed in detail below:

4.1.1 Planar Concave Landform

Figure 6 shows the results for planar concave slope profiles for the various waste rock $d_{50}$ sizes. For the graph on the upper left the stable slope is plotted versus the horizontal distance. Initially for all rock sizes at a horizontal slope length of 0 ft, the bed slope is steepest at 2H:1V ($y/x = 0.5$). As the horizontal distance increases, the slope must begin to flatten to accommodate the additional discharge and increased erosive capacity.

For example, for a $d_{50}$ rock size of 3 in (orange line), a horizontal slope length of approximately 200 ft is the maximum length that can be at 2H:1V. If the slope is longer than 200 ft at a slope of 2H:1V, then it is likely significant erosion will begin to occur. Subsequently, beyond 200 ft the slope must flatten out in order to accommodate increased erosive capacities due to accumulating discharge. The graph on the
lower left is identical except that the stable slope is plotted versus the length along the slope (not the horizontal length).

**Basin Geometry - Planar Concave Slope**

**Figure 6: Stable slope profiles for planar concave slope.**

The graph on the upper right shows the actual stable slope profile which is essentially a cross-section cut along the slope (not to scale). From this graph it is easy to see the vertical drop achievable for each rock size, keeping in mind that the maximum vertical drop anticipated for the Rosemont waste rock pile is approximately 500 ft. From this, it would appear for a planar concave slope profile, waste rock would need to have a d50 of approximately 5 in (light green line) to 7 in (blue line).
It should be noted that in all of the graphs, a constructed slope may be milder than those outlined for a given slope length, but it cannot be steeper.

### 4.1.2 Expanding Concave Landform

Figure 7 shows the results for expanding concave slope profiles with an initial radius, \( r_o = 50 \) ft, and varying waste rock \( d_{50} \) sizes. The graphs provide are similar to those provide for the planar concave landform geometry.

Due to expanding nature of the hill slope, the runoff unit discharge does not accumulate as fast and thus steeper slopes can be sustained for longer slope lengths. For the case of waste rock material with a \( d_{50} = 3 \) in, a 2H:1V slope can be maintained for horizontal slope length of approximately 350 ft (upper left - Figure 7) before having to flatten out. This can be compared to the planar concave example from above where waste rock with a \( d_{50} = 3 \) in could sustain a 2H:1V slope for approximately 200 ft (upper left - Figure 6).

Similarly, looking at the stable slope profile (upper right - Figure 7), waste rock gradations with a \( d_{50} \) greater than approximately 3 in can achieve a vertical drop of nearly 500 ft within a reasonable horizontal slope length (whereas with a planar concave landform, a rock \( d_{50} \) greater than 5 in was required).

As before, it should be noted that in all of the graphs a constructed slope may be shallower than those outlined for a given slope length, but it cannot be steeper.

Results for other initial radius, \( r_o \), values of 10 ft, 100 ft, 150 ft, 200 ft, 250 ft, 300 ft, 350 ft and 400 ft can be found in Appendix C. As indicated by the results, as \( r_o \) becomes very large the slope profiles approach those determined for a planar concave landform. Additional results for values of \( r_o \) that are not provided can be made available upon request.
4.1.3 Concentrating Concave Landform

Figure 7: Stable slope profiles for an expanding concave slope with an initial radius, $r_o = 50$ ft.

Figure 8 shows the results for concentrating concave slope profiles with an initial radius, $r_o = 300$ ft, and varying waste rock $d_{50}$ sizes. The graphs provided are similar to those provide for the planar concave and expanding concave landform geometries.
Figure 8: Stable slope profiles for a concentrating concave slope with an initial radius, $r_0 = 300$ ft.

Due to concentrating nature of the hill slope, the runoff unit discharge accumulates faster and thus steeper slopes can only be sustained for relatively short slope lengths. For the case of waste rock material with a $d_{50} = 3$ in, a 2H:1V slope can only be maintained for horizontal slope length of approximately 120 ft (upper left - Figure 8) before having to flatten out. This can be compared to the planar concave and expanding concave examples from above where waste rock with a $d_{50} = 3$ in could sustain a 2H:1V slope for approximately 200 ft (upper left - Figure 6), and 350 ft (upper left - Figure 7), respectively.
Similarly, looking at the stable slope profile (upper right - Figure 8), none of the waste rock gradations analyzed would be capable of achieving a vertical elevation difference of nearly 500 ft. Based on the results, the maximum vertical drop attainable with an initial radius, $r_0 = 300$ ft, is approximately 130 ft given a waste rock gradation with $d_{50} = 7$ in (Appendix C).

As before, it should be noted that in all of the graphs a constructed slope may be milder than those outlined for a given slope length, but it cannot be steeper.

Results for other initial radius, $r_0$, values of 100 ft, 200 ft, 400 ft, 500 ft, 600 ft, 700 ft, and 800 ft can be found in Appendix C. As indicated by the results, as $r_0$ becomes very large the slope profiles approach those determined for a planar concave landform. Additional results for values of $r_0$ that are not provided can be made available upon request.

### 4.2 Gessler Armor Layer Evaluation

The stability of the waste rock material as a whole was evaluated using the Gessler armor layer methodology described above. The gradation used was that for the Willow Canyon / Alluvium source provided in Figure 2 ($d_{50} \sim 7$ in). At this time, it was only possible to evaluate this gradation as no other size data is available for the smaller assumed values of the waste rock $d_{50}$.

For the analysis, three locations were selected on the planar concave landform geometry at slope lengths of 500 ft, 1000 ft, and 1500 ft. Flow conditions at these locations were determined and used as input for the Gessler calculation (Table 2). The planar concave landform was used for simplicity and likely provides an adequate representation of the armoring capability of the waste rock material at this level of study.

Figure 9 shows the initial waste rock gradation along with the “armored” waste rock gradations for the three slope lengths analyzed. As indicated, some of the finer material will likely wash out over time. The armoring gradation at the various slope lengths did not vary significantly.

The mean value of the probabilities for all particle sizes in the armoring gradation in all three scenarios is above 0.5, which according to Gessler (1970) indicates the gradation is likely stable. These values are provided in Table 2.

The amount of degradation that can be expected for the initial waste rock gradation to armor is approximately 14 in (Table 2).
Figure 9: Gessler armor layer evaluation of waste rock material.

TABLE 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Length (ft)</td>
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</tr>
<tr>
<td></td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>Landform Geometry</td>
<td>Planar Concave</td>
</tr>
<tr>
<td></td>
<td>Planar Concave</td>
</tr>
<tr>
<td></td>
<td>Planar Concave</td>
</tr>
<tr>
<td>Gradation</td>
<td>Willow Canyon / Alluv.</td>
</tr>
<tr>
<td></td>
<td>Willow Canyon / Alluv.</td>
</tr>
<tr>
<td></td>
<td>Willow Canyon / Alluv.</td>
</tr>
<tr>
<td>Flow Depth, D (in)</td>
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<tr>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>1.38</td>
</tr>
<tr>
<td>Slope, s</td>
<td>0.500</td>
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<tr>
<td></td>
<td>0.347</td>
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<tr>
<td></td>
<td>0.245</td>
</tr>
<tr>
<td>Gessler Stability Value*</td>
<td>0.923</td>
</tr>
<tr>
<td></td>
<td>0.904</td>
</tr>
<tr>
<td></td>
<td>0.906</td>
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<td>Degradation, Δz (in)</td>
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<td>14.4</td>
</tr>
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<td></td>
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</tbody>
</table>

Notes:
* Gradation is considered stable if Gessler Stability Value is above 0.5 (Gessler, 1970)
5.0 CONCLUSIONS

Golder theoretically evaluated the erosion stability limits of three basic landform geometries (consisting of a planar concave slope, a flow expanding concave slope and a flow concentrating concave slope – Figure 4) when subject to runoff from the 100 yr 1 hr storm event. This was done to determine if it was feasible to engineer stable, natural-looking landforms from mine waste materials at the Rosemont site. The principal focus was on preventing excessive erosion. Geotechnical slope stability has not been addressed in this phase of the study.

5.1 Stable Slope Profiles

Based on the results of the stable slope analysis provided in Figure 6, Figure 7, Figure 8, and Appendix C, it was found that feasible landforming will require using multiple tiers of alternative landform elements at differing elevations and providing erosion resistant drainage where flow concentrates at the landform element interfaces. Successful implementation of the latter design element, i.e. protection against concentrated flow erosion, will require a robust engineering approach. The use of a single landform element over the entire elevation difference of 500 ft will likely not work.

Assuming the actual waste rock median particle diameter ($d_{50}$) will likely be on the order of 3 in, it is found that the maximum elevation difference that can be retained in a stable condition within reasonable horizontal extents for the three alternative landform elements are approximately 300 ft for a planar concave landform (upper right - Figure 6), 420 ft for an expanding concave landform (upper right - Figure 7), and only 100 ft for a concentrating concave landform (upper right - Figure 8). Note that Appendix C provides similar information for varying initial radii, $r_o$. However, the values presented in Figure 7 and Figure 8 are considered representative of overall trends.

Logically, the concentrating concave landforms are the limiting factor as increased erosive capacities due to flow concentration result in milder slopes. Even for larger rock sizes, the maximum stable vertical drop attainable is approximately 300 ft (Appendix C). Subsequently, to achieve a stable vertical drop approaching 500 ft, multiple “tiers” of landforms will be required (Figure 10).

A multiple tier landform slope may pose difficulties as flow exiting at the bottom of each tier is highly concentrated and will need to be drained from the hill slope (Figure 10). Channels with heavy armor can be used, but are subject to capacity loss due to sediment shedding from the hill slope, increasing overtopping potential. Failure of a channel carrying highly concentrated flow would likely be detrimental to the stability of the waste rock pile. Finally, a channel cutting horizontally across the landform does not give a natural appearance.
Figure 10: Conceptual model of multiple tier landform hill slope.

5.2 Armoring Capability

Results from the Gessler analysis suggest that waste rock material from the Willow Canyon / Alluvium source will armor and be stable with a relatively small amount of degradation occurring prior to armoring (Table 2 and Figure 9).
6.0 RECOMMENDATIONS

The following recommendations are made regarding the landforming analysis performed by Golder:

- Results provided in this report defining basic landform shapes are recommended for use as an initial guideline for examining more complex natural-looking hill slope geometries. It should be noted, however, that significant further analysis beyond the scope of this report is required prior to achieving any final design.

- As indicated by the results, a multiple “tier” landformed slope would likely be required in order to achieve the anticipated maximum vertical drop in elevation of 500 ft. Therefore it is recommended to investigate alternative solutions to convey concentrated flows from the bottom of each tier off the hill slope, beyond the use of hardened channels.

  - One option may be the use of small retention ponds at the bottom of each tier with a pipe draining to the bottom of the hill slope (Figure 11).

![Conceptual Slope Profile](image)

Figure 11: Potential option to deliver water from landform tiers.
In order to validate the theoretical results presented herein, execution of large-scale field tests using actual waste rock material and simulated rainfall, similar to that shown in Figure 12 is recommended.

![Figure 12: Example of large-scale rainfall simulation field test.](image)

- Any landform geometries developed from the results in this analysis should be subjected to geotechnical slope stability analysis. The focus of the current effort was to evaluate hydraulic stability without considering geotechnical stability.
- Any subsequent landform geometries developed from the results in this analysis are also recommended to be re-examined from a hydrology and hydraulic standpoint in order to get the “big picture” interactions between different areas of the hill slope. The results presented herein are essentially small “building blocks” to constructing a larger complex landform. As such, interactions between different components were not considered in detail.
- Prior to any final design it is recommended to more accurately characterize the waste rock gradation to be used on the hill slope. As indicated from the results, the particle size is significant to determining stable slope profiles. Additionally, it is recommended to re-evaluate the armoring capability of the actual waste rock gradation to ensure stability.
- As the hill slope design progresses, it will be necessary to examine erodibility of vegetative cover and to establish how such a cover may influence flow patterns and the stability of the waste rock material.
7.0 CLOSURE

Golder Associates is pleased to present this report to SWCA and is thankful for this opportunity to be of service. If there are any questions or comments please feel free to contact us.

GOLDER ASSOCIATES INC.

Michael F George, PE
Project Geological Engineer

George W. Annandale, D. Ing., PE
Senior Program Leader
8.0 REFERENCES

Call & Nicholas, Inc. Unknown date. Report Section 8.0: Fragmentation. Excerpt from unknown report, provided by Tetra Tech at Rosemont Copper’s direction.


APPENDIX A

STABLE SLOPE PROFILE CALCULATIONS
Calculation of Slope Length Prior to Rill Formation

*Planar Concave Slope*

Project: Rosemont Landforming 093-81962  
By: MFG  
Date: February 15, 2010  
Checked By: GWA

The following calculation is loosely based on the paper:


***User Input***

### Constants

\[\rho_w := 1000 \, \text{kg} \, \text{m}^3\]  
Unit weight of water

\[\rho_s := 2620 \, \text{kg} \, \text{m}^3\]  
Particle density of hillslope material

\[g = 9.807 \, \text{m} \, \text{s}^{-2}\]  
Acceleration due to gravity

\[\nu := 1.01 \times 10^{-6} \, \text{m}^2 \, \text{s}^{-1}\]  
Kinematic viscosity of water

### Safety Factors

**FS := 2**  
Select an appropriate stability factor (from NRCS table below). This factor is applied to the resisting power of the material.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Stability Factor Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform flow: straight or mildly curving reach; little or no uncertainty in design</td>
<td>1.0 – 1.2</td>
</tr>
<tr>
<td>Gradually varying flow: moderate bend curvature; limited or minor impact from floating debris or ice</td>
<td>1.2 – 1.4</td>
</tr>
<tr>
<td>Sharp bend: Significant impact potential from floating debris or ice; significant wave &amp;/or boat generated waves. (1.0-2.0 ft); high flow turbulence</td>
<td>1.4 – 1.6</td>
</tr>
<tr>
<td>Rapidly varying flow (particularly due to rapid drawdown at flow constrictions); Significant uncertainty in design</td>
<td>1.6 – 2.0</td>
</tr>
</tbody>
</table>
Factor to account for flow concentration. This to account for local flow concentrations that may occur b/w particles. Applied to the unit discharge.

Design Storm Data

Total rainfall depth for design storm (100yr 1hr)

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Fraction of Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>5 0.231</td>
</tr>
<tr>
<td>2</td>
<td>10 0.448</td>
</tr>
<tr>
<td>3</td>
<td>15 0.65</td>
</tr>
<tr>
<td>4</td>
<td>20 0.816</td>
</tr>
<tr>
<td>5</td>
<td>25 0.901</td>
</tr>
<tr>
<td>6</td>
<td>30 0.936</td>
</tr>
<tr>
<td>7</td>
<td>35 0.965</td>
</tr>
<tr>
<td>8</td>
<td>40 0.986</td>
</tr>
<tr>
<td>9</td>
<td>45 0.997</td>
</tr>
<tr>
<td>10</td>
<td>50 0.999</td>
</tr>
<tr>
<td>11</td>
<td>55 1</td>
</tr>
<tr>
<td>12</td>
<td>60 1</td>
</tr>
</tbody>
</table>

\[ T_r := \text{Storm} \cdot \text{min} \quad \text{Rainfall time} \]

\[ D_r := \text{Storm} \cdot D_{r\text{total}} \quad \text{Cumulative rainfall distribution over time} \]
For loop to determine the maximum rainfall intensity over the design storm event.

\[
I := \begin{cases} 
   i & \leftarrow 1 \\
   & \text{for } i \in (1, 2, \ldots, 12) \\
   \leftarrow \frac{D_{r_i} - D_{r_{i-1}}}{T_{r_i} - T_{r_{i-1}}} \\
   i & \leftarrow i + 1 \\
   \text{max}(I)
\end{cases}
\]

\[ I = 9.868 \text{ in} \frac{\text{in}}{\text{hr}} \] Rainfall intensity
Function to determine the stable slope based on the slope length. The discharge represented by the flow depth, D, increases with slope length due to rainfall on the slope. This function compares the erosive capacity, E, at slope length, L, versus the resisting power of the hillslope material, P_c. The slope, s, is increased until the erosive capacity exceeds the erosion resistance of the hillslope material. The x and y profile of the resulting slope is calculated.

\[ d_{\text{max}} := 7 \text{in} \]

Enter the maximum D50 of the material to analyze in INCHES. MUST be a WHOLE NUMBER. The program will calculate stable profiles assuming a D50 = 1in, 2in,...d_{max}
\[
(s' x' y' D' \Sigma) := \begin{align*}
&i \leftarrow 1 \\
&j \leftarrow 1 \\
&d_{\text{max}} \leftarrow \frac{d_{\text{max}}}{\text{in}} \\
&\theta_s \leftarrow 0.047 \\
&\Delta s \leftarrow 0.0002 \\
&\lambda \leftarrow 457 \\
\text{for } j \in 1..d_{\text{max}} \\
&y_{0,j} \leftarrow 0\text{m} \\
&x_{0,j} \leftarrow 0\text{m} \\
&d_{j} \leftarrow j\cdot\text{in} \\
&k_{j} \leftarrow d_{j} \\
&\tau_{c,j} \leftarrow \theta_s \left( \rho_s - \rho_w \right) g \cdot d_{j} \\
&PC_{c,j} \leftarrow \frac{3}{2} \frac{7.853 \cdot \rho_w \left( \frac{\tau_{c,j}}{2} \right)^2}{\rho_w} \\
\text{for } i \in 1,2..\lambda \\
&L_{i,j} \leftarrow i\cdot\text{m} \\
&\Delta \leftarrow -1 \frac{\text{W}}{\text{m}^2} \\
&s_{i,j} \leftarrow 0.001 \\
\text{while } \Delta < 0 \frac{\text{W}}{\text{m}^2} \\
&\left[ \begin{array}{c}
\frac{k_j}{\text{SIUnitsOf}(k_j)} \\
\frac{1}{6}
\end{array} \right]^{\frac{1}{26}} \\
&\frac{1}{\text{SIUnitsOf}(L_{i,j})} \\
&\frac{\text{SIUnitsOf}(L_{i,j})}{\text{SIUnitsOf}(L_{i,j})} \\
&\frac{1}{\text{SIUnitsOf}(L_{i,j})} \\
&\frac{1}{\text{SIUnitsOf}(L_{i,j})} \\
&\left[ \begin{array}{c}
\left( \frac{s_{i,j}}{2} \right)^2 \\
\text{CF} \\
\cdot \text{m}
\end{array} \right]^{\frac{3}{5}} \\
&\tau. \leftarrow \rho_w \cdot g \cdot s. \cdot D. \\
\end{align*}
\]
Assign units to the model output:

\[ \begin{align*} 
  x &= x^\text{m} \\
  y &= y^\text{m} \\
  D &= D^\text{m} 
\end{align*} \]

\[ \begin{array}{c|c}
  \Sigma & \text{458} \\
  \hline
  0 & 0 \\
  1 & 458 \\
  2 & 458 \\
  3 & 458 \\
  4 & 458 \\
  5 & 458 \\
  6 & 458 \\
  7 & 458 \\
\end{array} \]

Sigma is the number of iterations, "i", for each of the "j" particle diameters. Sigma is also the slope length when multiplied by meters.
For plotting purposes (sets the range of data plotted for each particle diameter)

\[ i_1 := 1, 2 \ldots \Sigma_1 \]
\[ i_2 := 1, 2 \ldots \Sigma_2 \]
\[ i_3 := 1, 2 \ldots \Sigma_3 \]
\[ i_4 := 1, 2 \ldots \Sigma_4 \]
\[ i_5 := 1, 2 \ldots \Sigma_5 \]
\[ i_6 := 1, 2 \ldots \Sigma_6 \]
\[ i_7 := 1, 2 \ldots \Sigma_7 \]

Basin Geometry - Planar Concave Slope

Stable Slope vs. Horizontal Dist.

Horizontal Distance, x (ft)

Slope (y/x)

D50 = 1in
D50 = 2in
D50 = 3in
D50 = 4in
D50 = 5in
D50 = 6in
D50 = 7in
Program Commentary

i,j - initialize counters ("j" corresponds to change in particle diameter, and "i" corresponds to slope length)

dmax - maximum particle size (based on user input)

θ\_s - Shields parameter for rough turbulent flow conditions

Δs = incremental increase in slope

λ = number of iterations (equal to maximum slope length in meters)

- for loop to increase particle size
  \( x_{0,j} = \) initial x value (assumed)
  \( y_{0,j} = \) initial y value (assumed)

\( d_j = \) particle size in inches (increased by increments of "j")

\( k_j = \) absolute roughness assumed equal to \( d_j \)

\( \tau_{cj} = \) critical shear stress of material (based on Shields parameter).

\( P_{cj} = \) critical resisting stream power of the material (based on relationships from Annandale, 2006).

- for loop to determine stable slope for each incremental increase in slope length up to max. length of \( \lambda \).

\( L_{i,j} = \) slope length (increased by increments of "i")

\( \Delta = \) initial value for threshold comparison (see below)

\( s_{i,j} = \) initial guess value for stable slope

- while loop to iterate values of \( s_{i,j} \) until \( \Delta \) meets criteria.

\( D_{i,j} = \) flow depth (assuming shallow flow conditions) from Henderson (1966)

\( \tau_{i,j} = \) flow shear stress

\( E_{i,j} = \) erosive capacity expressed in units of stream power

\( \Delta = \) erosive capacity "E" - material resistance "\( P_c \)"
\( s_{ij} = \text{revised value of slope based on previous } s_{ij} \text{ value} + \Delta s \)

\text{break = program will exit if the stable slope is steeper than } 2H:1V \text{ (this is a practical upper limit)}

\( x_{ij} = \text{horizontal profile as a function of slope length} \)
\( y_{ij} = \text{vertical profile as a function of slope length} \)

- "i" counter increased by one to start next loop (increase slope length)

\( \Sigma_j = \text{Number of "i" iterations through the loop for each "j" particle diameter.} \)

- "j" counter increased by one to start next loop (next grain size)

- the stable slope, horz profile, vert. profile, flow depth, and no. of iterations are output from the program
Calculation of Slope Length Prior to Rill Formation

Expanding Concave Slope

Project: Rosemont Landforming 093-81962
By: MFG                                 Date: February 15, 2010
Checked By: GWA

The following calculation is loosely based on the paper:


User Input

Constants

\[\rho_w := 1000 \text{ kg/m}^3\]
Unit weight of water

\[\rho_s := 2620 \text{ kg/m}^3\]
Particle density of hillside material

\[g = 9.807 \text{ m/s}^2\]
Acceleration due to gravity

\[\nu := 1.01 \cdot 10^{-6} \text{ m}^2/\text{s}\]
Kinematic viscosity of water

Safety Factors

FS := 2
Select an appropriate stability factor (from NRCS table below). This factor is applied to the resisting power of the material.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Stability Factor Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform flow: straight or mildly curving reach; little or no uncertainty in design</td>
<td>1.0 – 1.2</td>
</tr>
<tr>
<td>Gradually varying flow: moderate bend curvature; limited or minor impact from floating debris or ice</td>
<td>1.2 – 1.4</td>
</tr>
<tr>
<td>Sharp bend: Significant impact potential from floating debris or ice; significant wave &amp;/or boat generated waves, (1.0-2.0 ft); high flow turbulence</td>
<td>1.4 – 1.6</td>
</tr>
<tr>
<td>Rapidly varying flow (particularly due to rapid drawdown at flow constrictions); Significant uncertainty in design</td>
<td>1.6 – 2.0</td>
</tr>
</tbody>
</table>
Factor to account for flow concentration. This to account for local flow concentrations that may occur b/w particles. Applied to the unit discharge.

**Design Storm Data**

\( D_{r\text{ total}} := 3.56 \text{in} \) Total rainfall depth for design storm (100yr 1hr)

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Fraction of Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>5.00</td>
</tr>
<tr>
<td>2</td>
<td>10.00</td>
</tr>
<tr>
<td>3</td>
<td>15.00</td>
</tr>
<tr>
<td>4</td>
<td>20.00</td>
</tr>
<tr>
<td>5</td>
<td>25.00</td>
</tr>
<tr>
<td>6</td>
<td>30.00</td>
</tr>
<tr>
<td>7</td>
<td>35.00</td>
</tr>
<tr>
<td>8</td>
<td>40.00</td>
</tr>
<tr>
<td>9</td>
<td>45.00</td>
</tr>
<tr>
<td>10</td>
<td>50.00</td>
</tr>
<tr>
<td>11</td>
<td>55.00</td>
</tr>
<tr>
<td>12</td>
<td>60.00</td>
</tr>
</tbody>
</table>

\( T_r := \text{Storm} \langle 0 \rangle \cdot \text{min} \) Rainfall time

\( D_r := \text{Storm} \langle 1 \rangle \cdot D_{r\text{ total}} \) Cumulative rainfall distribution over time
For loop to determine the maximum rainfall intensity over the design storm event.

\[
\begin{align*}
  I := & \quad i \leftarrow 1 \\
  \text{for } & \quad i \in (1, 2 \ldots 12) \\
  \quad & \quad I_i \leftarrow \frac{D_{r_i} - D_{r_{i-1}}}{T_{r_i} - T_{r_{i-1}}} \\
  & \quad i \leftarrow i + 1 \\
  \text{max}(I) \\
  I &= 9.868 \text{ in/hr} \\
\end{align*}
\]

Rainfall intensity
Function to determine the stable slope based on the slope length. The discharge represented by the flow depth, D, increases with slope length due to rainfall on the slope. This function compares the erosive capacity, E, at slope length, L, versus the resisting power of the hillslope material, $P_c$. The slope, s, is increased until the erosive capacity exceeds the erosion resistance of the hillslope material. The x and y profile of the resulting slope is calculated.

\[ \text{Enter the maximum D50 of the material to analyze in INCHES. MUST be a WHOLE NUMBER. The program will calculate stable profiles assuming a D50 = 1in, 2in,...d_{\text{max}}.} \]

\[ r_0 := 50 \text{ft} \]

Initial radius at top of hillslope.
\[(s', y', D', \Sigma) := \]
\[
i \leftarrow 1 \]
\[
j \leftarrow 1 \]
\[
d_{\text{max}} \leftarrow \frac{d_{\text{max}}}{\text{in}} \]
\[
\theta_s \leftarrow 0.047 \]
\[
r_0 \leftarrow r_0 \]
\[
\Delta s \leftarrow 0.0002 \]
\[
\lambda \leftarrow 457 \]

for \(j \in 1..d_{\text{max}}\)
\[
y_{0,j} \leftarrow 0\text{m} \]
\[
x_{0,j} \leftarrow 0\text{m} \]
\[
d_j \leftarrow j \cdot \text{in} \]
\[
k_j \leftarrow d_j \]
\[
\tau_{c,j} \leftarrow \theta_s \left(\rho_s - \rho_w\right)g \cdot d_j \]

\[
7.853 \cdot \rho_w \left(\frac{\tau_{c,j}}{\rho_w}\right)^{\frac{3}{2}} \]
\[
P_{c,j} \leftarrow \frac{3}{2} \cdot \frac{\tau_{c,j}}{\rho_w} \cdot \Delta_{1-W} \]

for \(i \in 1, 2..\lambda\)
\[
L_{i,j} \leftarrow i \cdot \text{m} \]

\[
\Delta \leftarrow -\frac{W}{m^2} \]
\[
s_{i,j} \leftarrow 0.001 \]

while \(\Delta < 0 \frac{W}{m^2}\)
\[
q_{i,j} \leftarrow \frac{L_{i,j} \cdot \text{CF}}{2} \left[\frac{r_0 + \left[r_0 + \left(x_{i-1,j} + \cos(\tan(s_{i,j}) \text{m})\right]\right]}{2} \right]^{\frac{3}{5}} \]

\[
\frac{k_j}{\text{SIUnitsOf}(k_j)}^{\frac{1}{6}} \]
\[
\frac{q_{i,j}}{\text{SIUnitsOf}(q_{i,j})}^{\frac{3}{5}} \]

---

Rosemont Mine Landforming

5 February 2010
\[ D_{i,j} \leftarrow \left( \begin{array}{c} 1 \\ \left( s_{i,j} \right)^2 \end{array} \right) \cdot m \]

\[ \tau_{i,j} \leftarrow \rho_w \cdot g \cdot s_{i,j} \cdot D_{i,j} \]

\[ E_{i,j} \leftarrow 7.853 \cdot \rho_w \left( \frac{\tau_{i,j}}{\rho_w} \right)^{\frac{3}{2}} \]

\[ \Delta \leftarrow E_{i,j} - P_{c_j} \]

\[ s_{i,j} \leftarrow s_{i,j} + \Delta s \]

\( \text{(break) if } s_{i,j} \geq \frac{1}{2} \)

\[ x_{i,j} \leftarrow x_{i-1,j} + \cos(\frac{\pi}{2}) \cdot m \]

\[ y_{i,j} \leftarrow y_{i-1,j} - \sin(\frac{\pi}{2}) \cdot m \]

\[ i \leftarrow i + 1 \]

\[ \Sigma_j \leftarrow i \]

\[ j \leftarrow j + 1 \]

\( \begin{bmatrix} s \\ \frac{x}{m} \\ y \\ \frac{D}{m} \\ \Sigma \end{bmatrix} \)

Assign units to the model output:

\[ x := x^i \cdot m \]

\[ y := y^i \cdot m \]

\[ D := D^i \cdot m \]

\[
\begin{array}{|c|c|}
\hline
\sigma & 0 \\
0 & 0 \\
1 & 458 \\
2 & 458 \\
3 & 458 \\
4 & 458 \\
5 & 458 \\
6 & 458 \\
7 & 458 \\
\hline
\end{array}
\]

Sigma is the number of iterations, "i", for each of the "j" particle diameters. Sigma is also the slope length when multiplied by meters.
For plotting purposes (sets the range of data plotted for each particle diameter)

\[ i_1 := 1, 2 \ldots \Sigma_1 \]
\[ i_2 := 1, 2 \ldots \Sigma_2 \]
\[ i_3 := 1, 2 \ldots \Sigma_3 \]
\[ i_4 := 1, 2 \ldots \Sigma_4 \]
\[ i_5 := 1, 2 \ldots \Sigma_5 \]
\[ i_6 := 1, 2 \ldots \Sigma_6 \]
\[ i_7 := 1, 2 \ldots \Sigma_7 \]

**Basin Geometry - Expanding Concave Slope, \( r_0 = 50 \text{-ft} \)**

**Stable Slope vs. Horizontal Dist.**

<table>
<thead>
<tr>
<th>Slope (y/x)</th>
<th>Horizontal Distance, x (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D50 = 1in</td>
<td></td>
</tr>
<tr>
<td>D50 = 2in</td>
<td></td>
</tr>
<tr>
<td>D50 = 3in</td>
<td></td>
</tr>
<tr>
<td>D50 = 4in</td>
<td></td>
</tr>
<tr>
<td>D50 = 5in</td>
<td></td>
</tr>
<tr>
<td>D50 = 6in</td>
<td></td>
</tr>
<tr>
<td>D50 = 7in</td>
<td></td>
</tr>
</tbody>
</table>
Program Commentary

i,j = initialize counters ("j" corresponds to change in particle diameter, and "i" corresponds to slope length)

dmax = maximum particle size (based on user input)

θs = Shields parameter for rough turbulent flow conditions

r0 = initial radius of at top of slope (see diagram) (based on user input)

Δs = incremental increase in slope

λ = number of iterations (equal to maximum slope length in meters)

- for loop to increase particle size
  x0,j = initial x value (assumed)
  y0,j = initial y value (assumed)

dj = particle size in inches (increased by increments of "j")

kj = absolute roughness assumed equal to dj

τcj = critical shear stress of material (based on Shields parameter).

Pcj = critical resisting stream power of the material (based on relationships from Annandale, 2006).

- for loop to determine stable slope for each incremental increase in slope length up to max. length of λ.

Lij = slope length (increased by increments of "i")

Δ = initial value for threshold comparison (see below)

sij = initial guess value for stable slope

- while loop to iterate values of sij until Δ meets criteria.

qij = unit discharge. CF is added as a safety factor. The bracketed portion of the equations determines the degree of flow expansion based on the starting radius at the top of the slope

Dij = flow depth (assuming shallow flow conditions) from Henderson (1966)

τij = flow shear stress
$E_{ij} =$ erosive capacity expressed in units of stream power

$\Delta = $ erosive capacity $"E" - $ material resistance $"P_c"$

$s_{ij} =$ revised value of slope based on previous $s_{ij}$ value + $\Delta s$

break = program will exit if the stable slope is steeper than $2H:1V$ (this is a practical upper limit)

$x_{ij} =$ horizontal profile as a function of slope length

$y_{ij} =$ vertical profile as a function of slope length

- "$i"$ counter increased by one to start next loop (increase slope length)

$\Sigma_{j} =$ Number of "$i"$ iterations through the loop for each "$j"$ particle diameter.

- "$j"$ counter increased by one to start next loop (next grain size)

- the stable slope, horz profile, vert. profile, flow depth, and no. of iterations are output from the program
Calculation of Slope Length Prior to Rill Formation

Concentrating Concave Slope

Project: Rosemont Landforming 093-81962
By: MFG                                Date: February 15, 2010
Checked By: GWA

The following calculation is loosely based on the paper:


User Input

Constants

\[ \rho_w := \frac{1000 \text{ kg}}{\text{m}^3} \]  Unit weight of water

\[ \rho_s := \frac{2620 \text{ kg}}{\text{m}^3} \]  Particle density of hillslope material

\[ g = 9.807 \frac{\text{m}}{\text{s}^2} \]  Acceleration due to gravity

\[ \nu := 1.01 \cdot 10^{-6} \frac{\text{m}^2}{\text{s}} \]  Kinematic viscosity of water

Safety Factors

FS := 2  Select an appropriate stability factor (from NRCS table below). This factor is applied to the resisting power of the material.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Stability Factor Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform flow: straight or mildly curving reach; little or no uncertainty in design</td>
<td>1.0 – 1.2</td>
</tr>
<tr>
<td>Gradually varying flow: moderate bend curvature; limited or minor impact from floating debris or ice</td>
<td>1.2 – 1.4</td>
</tr>
<tr>
<td>Sharp bend: Significant impact potential from floating debris or ice; significant wave &amp;/or boat generated waves, (1.0-2.0 ft); high flow turbulence</td>
<td>1.4 – 1.6</td>
</tr>
<tr>
<td>Rapidly varying flow (particularly due to rapid drawdown at flow constrictions); Significant uncertainty in design</td>
<td>1.6 – 2.0</td>
</tr>
</tbody>
</table>
Factor to account for flow concentration. This to account for local flow concentrations that may occur b/w particles. Applied to the unit discharge.

**Design Storm Data**

Total rainfall depth for design storm (100yr 1hr)

<table>
<thead>
<tr>
<th>Storm :</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>60</td>
</tr>
</tbody>
</table>

\[ T_r := \text{Storm}^{(0)} \cdot \text{min} \quad \text{Rainfall time} \]

\[ D_r := \text{Storm}^{(1)} \cdot D_{r\text{total}} \quad \text{Cumulative rainfall distribution over time} \]
For loop to determine the maximum rainfall intensity over the design storm event.

\[
I := \begin{align*}
&i \leftarrow 1 \\
&\text{for } i \in (1, 2 \ldots 12) \\
&i_i \leftarrow \frac{D_{r_i} - D_{r_{i-1}}}{T_{r_i} - T_{r_{i-1}}} \\
&i \leftarrow i + 1 \\
&\text{max}(i)
\end{align*}
\]

\[
I = 9.868 \frac{\text{in}}{\text{hr}}
\]

Rainfall intensity
Function to determine the stable slope based on the slope length. The discharge represented by the flow depth, \( D \), increases with slope length due to rainfall on the slope. This function compares the erosive capacity, \( E \), at slope length, \( L \), versus the resisting power of the hillslope material, \( P_c \). The slope, \( s \), is increased until the erosive capacity exceeds the erosion resistance of the hillslope material. The x and y profile of the resulting slope is calculated.

\[ d_{\text{max}} := 7\text{in} \]

Enter the maximum D50 of the material to analyze in INCHES. MUST be a WHOLE NUMBER. The program will calculate stable profiles assuming a D50 = 1in, 2in,...,\( d_{\text{max}} \)

\[ r_0 := 300\text{ft} \]

Initial radius at top of hillslope.
\[(s \ x' \ y' \ D' \ \Sigma \ := \ \begin{align*}
i & \leftarrow 1 \\
j & \leftarrow 1 \\
d_{\text{max}} & \leftarrow \frac{d_{\text{max}}}{\text{in}} \\
\theta_s & \leftarrow 0.047 \\
r_0 & \leftarrow r_0 \\
\Delta s & \leftarrow 0.0002 \\
\lambda & \leftarrow 500 \\
\text{for } j \in 1..d_{\text{max}} \\
y_{0,j} & \leftarrow 0 \text{m} \\
x_{0,j} & \leftarrow 0 \text{m} \\
d_j & \leftarrow j \cdot \text{in} \\
k_j & \leftarrow d_j \\
\tau_{c_j} & \leftarrow \theta_s (\rho_s - \rho_w) g d_j \\
p_{c_j} & \leftarrow \frac{\frac{3}{2} \left( \frac{\tau_{c_j}}{\rho_w} \right)^{\frac{2}{3}}}{F_S} \\
\text{for } i \in 1,2..\lambda \\
L_{i,j} & \leftarrow i \cdot m \\
\Delta & \leftarrow -1 \frac{W}{m^2} \\
s_{i,j} & \leftarrow 0.001 \\
\text{while } \Delta < 0 \frac{W}{m^2} \\
q_{i,j} & \leftarrow \frac{1-L_{i,j} \cdot CF}{2} \left[ \frac{r_0 + \left[ r_0 - \left( x_{i-1,j} + \cos(\tan(s_{i,j})) m \right) \right]}{r_0 - \left( x_{i-1,j} + \cos(\tan(s_{i,j})) m \right)} \right]^{\frac{3}{5}} \left[ \frac{k_j}{\text{SIUnitsOf}(k_j)} \right]^{\frac{1}{6}} \frac{q_{i,j} \cdot \text{SIUnitsOf}(q_{..})}{26} \right] \end{align*}\]
\[ D_{i,j} \leftarrow \frac{1}{\left( s_{i,j} \right)^2} \]

\[ \tau_{i,j} \leftarrow \rho_w \cdot g \cdot s_{i,j} \cdot D_{i,j} \]

\[ E_{i,j} \leftarrow 7.853 \cdot \rho_w \left( \frac{\tau_{i,j}}{\rho_w} \right) \]

\[ \Delta \leftarrow E_{i,j} - P_{c_j} \]

\[ s_{i,j} \leftarrow s_{i,j} + \Delta s \]

(break) if \( s_{i,j} > \frac{1}{2} \)

\[ x_{i,j} \leftarrow x_{i-1,j} + \cos(\arctan(s_{i,j})) \cdot m \]

\[ y_{i,j} \leftarrow y_{i-1,j} - \sin(\arctan(s_{i,j})) \cdot m \]

(break) if \( (x_{i,j} + 1m) > (r_0 - 1m) \)

\[ i \leftarrow i + 1 \]

\[ \Sigma_j \leftarrow i \]

\[ j \leftarrow j + 1 \]

\[ \begin{bmatrix} x \\ y \\ D \end{bmatrix} = \begin{bmatrix} m \\ m \end{bmatrix} \]

Assign units to the model output:

\[ x \coloneqq x^\prime \cdot m \]

\[ y \coloneqq y^\prime \cdot m \]

\[ D \coloneqq D^\prime \cdot m \]

\[ \Sigma = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ \end{bmatrix} \]

Sigma is the number of iterations, "i", for each of the "j" particle diameters. Sigma is also the slope length when multiplied by meters.
For plotting purposes (sets the range of data plotted for each particle diameter)

\[ \begin{align*}
    i_1 & := 1, 2, \Sigma_1 \\
    i_2 & := 1, 2, \Sigma_2 \\
    i_3 & := 1, 2, \Sigma_3 \\
    i_4 & := 1, 2, \Sigma_4 \\
    i_5 & := 1, 2, \Sigma_5 \\
    i_6 & := 1, 2, \Sigma_6 \\
    i_7 & := 1, 2, \Sigma_7 
\end{align*} \]

**Basin Geometry - Concentrating Concave Slope, \( r_0 = 300\text{-ft} \)

Stable Slope vs. Horizontal Dist.

![Graph showing the relationship between horizontal distance and slope for different particle diameters.](image)

\( r_0 = 300\text{-ft} \)

Horizontal Distance, \( x \) (ft)
Program Commentary

i, j = initialize counters ("j" corresponds to change in particle diameter, and "i" corresponds to slope length)

d_{max} = maximum particle size (based on user input)

\( \theta_s \) = Shields parameter for rough turbulent flow conditions

r_o = initial radius of at top of slope (see diagram) (based on user input)

\( \Delta s \) = incremental increase in slope

\( \lambda \) = number of iterations (equal to maximum slope length)

- for loop to increase particle size

x_{0,j} = initial x value (assumed)
y_{0,j} = initial y value (assumed)

d_j = particle size in inches (increased by increments of "j")

k_j = absolute roughness assumed equal to d_j

\( \tau_{cj} \) = critical shear stress of material (based on Shields parameter).

P_{cj} = critical resisting stream power of the material (based on relationships from Annandale, 2006).

- for loop to determine stable slope for each incremental increase in slope length up to max. length of \( \lambda \).

L_{ij} = slope length (increased by increments of "i")

\( \Delta \) = initial value for threshold comparison (see below)

s_{ij} = initial guess value for stable slope

- while loop to interate values of s_{ij} until \( \Delta \) meets criteria.

q_{ij} = unit discharge. CF is added as a safety factor. The bracketed portion of the equations determines the degree of flow expansion based on the starting radius at the top of the slope

D_{ij} = flow depth (assuming shallow flow conditions) from Henderson (1966)

\( \tau_{ij} \) = flow shear stress
\[ E_{i,j} = \text{erosive capacity expressed in units of stream power} \]

\[ \Delta = \text{erosive capacity } "E" - \text{material resistance } "P_c" \]

\[ s_{i,j} = \text{revised value of slope based on previous } s_{i,j} \text{ value} + \Delta s \]

break = program will exit if the stable slope is steeper than 2H:1V (this is a practical upper limit)

\[ x_{i,j} = \text{horizontal profile as a function of slope length} \]
\[ y_{i,j} = \text{vertical profile as a function of slope length} \]

break = program will exit loop if the horizontal slope length, x, approaches the initial specified radius, \( r_0 \). (As x approaches \( r_0 \), q approaches infinity).

- "i" counter increased by one to start next loop (increase slope length)

\[ \Sigma_j = \text{Number of } "i" \text{ iterations through the loop for each } "j" \text{ particle diameter.} \]

- "j" counter increased by one to start next loop (next grain size)

- the stable slope, horz profile, vert. profile, flow depth, and the number of iterations are output from the program
APPENDIX B
GESSLER ARMOR LAYER EVALUATION
Gessler Armor Layer Calculation

*Planar Concave Slope*

Project: Rosemont Landforming 093-81962
By: MFG                                 Date: February 15, 2010
Checked By:

The following calculation is based on the papers:


**User Input**

**Particle Size Distribution**

The input particle size distribution is that provided from Call & Nicholas:

<table>
<thead>
<tr>
<th>% finer</th>
<th>d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>55</td>
</tr>
<tr>
<td>10</td>
<td>64</td>
</tr>
<tr>
<td>20</td>
<td>94</td>
</tr>
<tr>
<td>30</td>
<td>122</td>
</tr>
<tr>
<td>40</td>
<td>152</td>
</tr>
<tr>
<td>50</td>
<td>183</td>
</tr>
<tr>
<td>60</td>
<td>229</td>
</tr>
<tr>
<td>70</td>
<td>268</td>
</tr>
<tr>
<td>80</td>
<td>335</td>
</tr>
<tr>
<td>90</td>
<td>457</td>
</tr>
<tr>
<td>95</td>
<td>671</td>
</tr>
<tr>
<td>100</td>
<td>945</td>
</tr>
</tbody>
</table>
Read from Graph:

\[ D_{50} = 183 \text{ mm} \]
\[ D_{90} = 457 \text{ mm} \]

\[ \text{finer} := \text{data}_k^{(\phi)} \quad \text{size} := \text{data}_k^{(\psi)} \quad i := 1 .. 12 \]

Input Parameters

Case := 3

\[ D := \begin{cases} 
0.015 \text{ m} & \text{if Case = 1} \\
0.025 \text{ m} & \text{if Case = 2} \\
0.035 \text{ m} & \text{otherwise} 
\end{cases} \]

\[ D = 0.035 \text{ m} \]

\[ S := \begin{cases} 
0.5 & \text{if Case = 1} \\
0.347 & \text{if Case = 2} \\
0.245 & \text{otherwise} 
\end{cases} \]

\[ S = 0.245 \]

Case = 1 if slope length = 500ft
Case = 2 if slope length = 1000ft
Case = 3 if slope length = 1500ft

Flow Depth at 500ft, 1000ft, and 1500ft slope lengths

Bed slope
\[ \gamma_s := \frac{25700 \text{ N}}{\text{m}^3} \text{ Specific weight of particles} \]

\[ \gamma := \frac{9800 \text{ N}}{\text{m}^3} \text{ Specific weight of water} \]

\[ \rho := 1000 \frac{\text{kg}}{\text{m}^3} \text{ Density of water} \]

\[ \nu := 0.00000131 \frac{\text{m}^2}{\text{s}} \text{ Kinematic viscosity of water} \]

\[ g = 9.807 \text{ m} \cdot \text{s}^{-2} \text{ Acceleration due to gravity} \]

**Shear Stress Calculations**

\[ R_b := D \text{ Hydraulic radius assumed equal to flow depth for shallow flow conditions} \]

\[ \tau_b := \gamma \cdot R_b \cdot S \] Bed shear stress

\[ \tau_b = 84.035 \frac{\text{N}}{\text{m}^2} \]

\[ u_b := \sqrt{\frac{\tau_b}{\rho}} \text{ Shear velocity, measure of the intensity of turbulent fluctuations.} \]

\[ u_b = 0.29 \frac{\text{m}}{\text{s}} \]

\[ r := 1 \ldots 11 \]

\[ d_{avg r} := \frac{\text{size}_r + \text{size}_{r-1}}{2} \cdot \text{mm} \text{ Average grain sizes for gradation} \]

\[ \text{Re}_r := \frac{u_b \cdot d_{avg r}}{\nu} \text{ Reynold's Number for each size fraction in gradation} \]
Below are equations that define of Shield's Diagram piecewise ($\tau_{s1} - \tau_{s6}$) and $\tau_{s6}$ is an "if statement" to determine which portion of the diagram applies to a given Re value:

\[
\tau_{s1} = .115 \left( \frac{Re}{r} \right)^{.79279}
\]

\[
\tau_{s2} = -2.65633 \times 10^{-5} \left( \frac{Re}{r} \right)^6 + 7.84922 \times 10^{-4} \left( \frac{Re}{r} \right)^5 - 9.23733 \times 10^{-3} \left( \frac{Re}{r} \right)^4 \ldots
\]

\[
\quad + 5.47343 \times 10^{-2} \left( \frac{Re}{r} \right)^3 - 1.67934 \times 10^{-1} \left( \frac{Re}{r} \right)^2 + 2.35315 \times 10^{-1} \left( \frac{Re}{r} \right) \quad \ldots
\]

\[
\tau_{s3} = .032
\]

\[
\tau_{s4} = \left[ 4.84921665018181 \times 10^{-9} \left( \frac{Re}{r} \right)^3 - 2.36934036367859 \times 10^{-6} \left( \frac{Re}{r} \right)^2 + 3.80480495638856 \times 10^{-4} \quad \ldots
\]

\[
\quad + 2.5449950466873 \times 10^{-2} \right]
\]

\[
\tau_{s5} = .046
\]

\[
\tau_{s6} = .047
\]

\[
\tau_{s6} = \text{if } \left[ Re < 2, \tau_{s1}, \text{if } \left( Re < 8, \tau_{s2}, \text{if } \left( Re < 19, \tau_{s3}, \text{if } \left( Re < 217, \tau_{s4}, \text{if } \left( Re < 397, \tau_{s5}, .047 \right) \right) \right) \right) \right]
\]

<table>
<thead>
<tr>
<th>$dav_{fr}$ =</th>
<th>$Re_{fr}$ =</th>
<th>$\tau_{star_{fr}}$ =</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>$1.317 \times 10^4$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.079</td>
<td>$1.748 \times 10^4$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.108</td>
<td>$2.39 \times 10^4$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.137</td>
<td>$3.032 \times 10^4$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.168</td>
<td>$3.707 \times 10^4$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.206</td>
<td>$4.559 \times 10^4$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.248</td>
<td>$5.499 \times 10^4$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.301</td>
<td>$6.672 \times 10^4$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.396</td>
<td>$8.763 \times 10^4$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.564</td>
<td>$1.248 \times 10^5$</td>
<td>0.047</td>
</tr>
<tr>
<td>0.808</td>
<td>$1.788 \times 10^5$</td>
<td>0.047</td>
</tr>
</tbody>
</table>

\[
\tau_c = \tau_{star_{fr}} \cdot d_{fr} \cdot \left( \gamma_s - \gamma \right)
\]

Critical shear stress for each size fraction in gradation

\[
\tau_{fr} = \frac{\tau_c}{\tau_{fr}}
\]

Ratio of critical shear stress of each size fraction to average shear stress in river

---

Rosemont Mine Landforming 4 February 2010
Theoretical Armor Layer Calculations

Probability that a grain of given size will not erode, fit from Gessler plot of q versus \( \frac{\tau_c}{\tau_b} \):

\[
q_r := \begin{cases} 
  \tau_{r-1} < 2.8, & \left[ 0.0716545194773488 \left( \frac{\tau_r}{\tau_{r-1}} \right)^4 - 0.496929374396984 \left( \frac{\tau_r}{\tau_{r-1}} \right)^3 \ldots \right] + 0.987737827575074 \left( \frac{\tau_r}{\tau_{r-1}} \right)^2 - 0.104758490295694 \tau_{r-1} \ldots \\
  \tau_{r-1} \geq 2.8, & 1.0
\end{cases}
\]

\[
q\Delta P_r := q_r \left( \text{finer}_r - \text{finer}_{r-1} \right)
\]

Intermediate calculation for armor layer gradation

\[
q\Delta P_r := (1 - q_r) \left( \text{finer}_r - \text{finer}_{r-1} \right)
\]

Intermediate calculation for eroded particle gradation

<table>
<thead>
<tr>
<th>( \tau_{c_r} )</th>
<th>( d_{avgr} )</th>
<th>( \tau_{r-1} )</th>
<th>( q_r )</th>
<th>( q\Delta P_r )</th>
<th>( q\Delta P_r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06 m Pa</td>
<td>0.06 m Pa</td>
<td>0.079 m Pa</td>
<td>0.108 m Pa</td>
<td>0.137 m Pa</td>
<td>0.168 m Pa</td>
</tr>
<tr>
<td>59.037 Pa</td>
<td>0.079 m Pa</td>
<td>0.703 m Pa</td>
<td>0.96 m Pa</td>
<td>1.218 m Pa</td>
<td>1.49 m Pa</td>
</tr>
<tr>
<td>80.708 Pa</td>
<td>0.703 m Pa</td>
<td>0.312 m Pa</td>
<td>0.484 m Pa</td>
<td>0.65 m Pa</td>
<td>0.799 m Pa</td>
</tr>
<tr>
<td>102.38 Pa</td>
<td>0.96 m Pa</td>
<td>0.484 m Pa</td>
<td>4.84 m Pa</td>
<td>5.16 m Pa</td>
<td>6.505 m Pa</td>
</tr>
<tr>
<td>125.173 Pa</td>
<td>1.218 m Pa</td>
<td>0.65 m Pa</td>
<td>5.16 m Pa</td>
<td>6.882 m Pa</td>
<td>3.495 m Pa</td>
</tr>
<tr>
<td>153.944 Pa</td>
<td>2.21 m Pa</td>
<td>1.0 m Pa</td>
<td>10 m Pa</td>
<td>23.125 m Pa</td>
<td>8 m Pa</td>
</tr>
<tr>
<td>185.704 Pa</td>
<td>2.681 m Pa</td>
<td>1 m Pa</td>
<td>10 m Pa</td>
<td>71.875 m Pa</td>
<td>8 m Pa</td>
</tr>
<tr>
<td>225.311 Pa</td>
<td>3.522 m Pa</td>
<td>1 m Pa</td>
<td>10 m Pa</td>
<td>71.875 m Pa</td>
<td>8 m Pa</td>
</tr>
<tr>
<td>295.931 Pa</td>
<td>5.015 m Pa</td>
<td>1 m Pa</td>
<td>10 m Pa</td>
<td>71.875 m Pa</td>
<td>8 m Pa</td>
</tr>
<tr>
<td>421.477 Pa</td>
<td>7.185 m Pa</td>
<td>1 m Pa</td>
<td>10 m Pa</td>
<td>71.875 m Pa</td>
<td>8 m Pa</td>
</tr>
<tr>
<td>603.818 Pa</td>
<td>7.185 m Pa</td>
<td>1 m Pa</td>
<td>10 m Pa</td>
<td>71.875 m Pa</td>
<td>8 m Pa</td>
</tr>
</tbody>
</table>

\[
\Sigma q\Delta P := \sum_{r=1}^{11} q\Delta P_r \quad \Sigma q\Delta P = 71.875 \quad \text{Summation of all } q\Delta P\text{ terms for use in determining } \Delta P_A.
\]

\[
\Sigma q\Delta P := \sum_{r=1}^{11} q\Delta P_r \quad \Sigma q\Delta P = 23.125 \quad \text{Same but for eroded particle gradation}
\]

\[
\Delta P_{A_r} := \frac{q\Delta P_r}{\Sigma q\Delta P} \quad \text{Incremental probability function of armoring layer (missing probability = 0 for finest grain size)}.
\]
\[ \Delta P_{1A_r} := \frac{q1 \Delta P_r}{\Sigma q1 \Delta P} \] 

Same but for eroded particle gradation

\[ PA_{incomplete_r} := \sum_{r = 1}^{r} \Delta P_{A_r} \] 
Cummulative probability function of armoring layer (missing probability = 0 for finest grain size).

\[ P1A_{incomplete_r} := \sum_{r = 1}^{r} \Delta P1A_{r} \] 
Same but for eroded particle gradation

\[ r := 0..11 \] 
Increase counter variable to account for entire set of grain sizes given initially.

\[ PA_r := \left( \text{if}(r = 0, 0, PA_{incomplete_r}) \right) \cdot 100 \] 
Add initial probability = 0 for finest grain size in armor layer distribution--COMPLETE ARMOR LAYER DISTRIBUTION expressed in percent.

\[ P1A_r := \left( \text{if}(r = 0, 0, P1A_{incomplete_r}) \right) \cdot 100 \] 
Same but for eroded particle gradation.

**Resulting Armor Layer Particle Size Distribution**

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>PA_r</th>
<th>P1A_r</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.055</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.064</td>
<td>0.367</td>
<td>20.48</td>
</tr>
<tr>
<td>0.094</td>
<td>4.706</td>
<td>50.238</td>
</tr>
<tr>
<td>0.122</td>
<td>11.44</td>
<td>72.552</td>
</tr>
<tr>
<td>0.152</td>
<td>20.49</td>
<td>87.665</td>
</tr>
<tr>
<td>0.183</td>
<td>31.602</td>
<td>96.37</td>
</tr>
<tr>
<td>0.229</td>
<td>44.508</td>
<td>99.5</td>
</tr>
<tr>
<td>0.268</td>
<td>58.296</td>
<td>99.891</td>
</tr>
<tr>
<td>0.335</td>
<td>72.174</td>
<td>100</td>
</tr>
<tr>
<td>0.457</td>
<td>86.087</td>
<td>100</td>
</tr>
<tr>
<td>0.671</td>
<td>93.043</td>
<td>100</td>
</tr>
<tr>
<td>0.945</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Armored Particle Size Distributions

\[
\begin{array}{c|c|c|c}
\text{Size (m)} & \text{P}_{500} & \text{P}_{1000} & \text{P}_{1500} \\
\hline
0.055 & (0.347, 5.327, 12.897, 22.773, 34.456, 47.353, 60.501, 73.667, 86.834, 93.417, 100) & (0.369, 4.657, 11.322, 20.3, 31.355, 44.246, 58.077, 72.028, 86.014, 93.007, 100) & (0.367, 4.706, 11.44, 20.49, 31.602, 44.508, 58.296, 72.174, 86.087, 93.043, 100) \\
\end{array}
\]

Eroded Particle Size Distributions

\[
\begin{array}{c|c|c|c}
\text{Size (m)} & \text{P}_{e500} & \text{P}_{e1000} & \text{P}_{e1500} \\
\hline
0.229 & (24.862, 57.503, 79.815, 92.936, 98.849, 99.925, 100) & (20.155, 49.662, 71.938, 87.176, 96.095, 99.426, 100) & (20.48, 50.238, 72.552, 87.665, 96.37, 99.5, 100) \\
\end{array}
\]
Stability

*Original Gradation*

\[
q_2 \Delta P := \sum_{r = 1}^{10} \left( q_r \right)^2 \left( \text{finer}_r - \text{finer}_{r-1} \right)
\]

stability := \frac{q_2 \Delta P}{\Sigma q \Delta P}

*Armored Gradation*

\[
\Sigma q_2 \Delta P_A := \sum_{r = 0}^{10} \left( q_r \right)^2 \Delta P A_r
\]

\[
\Sigma q \Delta P_A := \sum_{r = 0}^{10} \left( q_r \cdot \Delta P A_r \right)
\]

stability_A := \frac{\Sigma q_2 \Delta P_A}{\Sigma q \Delta P_A}

stability_A = 0.906

**NOTE:** For the calculated armor layer to be stable, the stability factor must be > 0.5

<table>
<thead>
<tr>
<th>Case</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.923</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.904</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.906</td>
</tr>
</tbody>
</table>
Depth of Degradation to Armor Layer Formation

from Julien, River Mechanics (2002)

\[ d_{sc} := 183 \text{mm} \quad \text{Stable particle is assumed to be the D50.} \]

\[ P\%(x) := \text{interp(size-mm, finer\%, x)} \quad \text{Linear interpolation of input gradation curve.} \]

\[ \text{Determines percent finer for a given grain size.} \]

\[ \Delta p_c(x) := 1 - P\%(x) \quad \text{Determines fraction of gradation larger than critical particle size.} \]

\[ \Delta z(x) := 2 \cdot d_{sc} \left( \frac{1}{\Delta p_c(x)} - 1 \right) \quad \text{Degradation depth required to form an armor layer twice the thickness of the critical particle size} \]

\[ \Delta z(d_{sc}) = 14.409 \text{-in} \]

\[ \Delta p_c(183\text{mm}) = 0.5 \]
APPENDIX C
ADDITIONAL STABLE SLOPE PROFILE RESULTS
Basin Geometry - Planar Concave Slope

Stable Slope vs. Horizontal Dist.

Stable Slope Profile

Stable Slope vs. Slope Length

[Slope vs. Horizontal Distance graph]

[Slope vs. Slope Length graph]
Basin Geometry - Expanding Concave Slope, $\eta_0 = 10$ ft

Stable Slope vs. Horizontal Dist.

Stable Slope Profile

Stable Slope vs. Slope Length

Rosemont Mine Landforming
Basin Geometry - Expanding Concave Slope, \( t_0 = 50 \text{ ft} \)

**Stable Slope vs. Horizontal Dist.**

- \( \theta_0 = 50 \text{ ft} \)
- D50 = 1m
- D50 = 2m
- D50 = 3m
- D50 = 4m
- D50 = 5m
- D50 = 6m
- D50 = 7m

**Stable Slope Profile**

- \( \theta_0 = 50 \text{ ft} \)
- D50 = 1m
- D50 = 2m
- D50 = 3m
- D50 = 4m
- D50 = 5m
- D50 = 6m
- D50 = 7m

**Stable Slope vs. Slope Length**

- \( \theta_0 = 50 \text{ ft} \)
- D50 = 1m
- D50 = 2m
- D50 = 3m
- D50 = 4m
- D50 = 5m
- D50 = 6m
- D50 = 7m

---

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Basin Geometry - Expanding Concave Slope, $\eta_0 = 100$ ft

Stable Slope vs. Horizontal Dist.

Stable Slope Profile

Stable Slope vs. Slope Length
Basin Geometry - Expanding Concave Slope, $q_0 = 150$ ft

Stable Slope vs. Horizontal Dist.

Stable Slope Profile

Stable Slope vs. Slope Length
Basin Geometry - Expanding Concave Slope, $q_0 = 200$ ft

Stable Slope vs. Horizontal Dist.

Stable Slope Profile

Stable Slope vs. Slope Length

Rosemont Mine Landforming
Basin Geometry - Expanding Concave Slope, $r_0 = 250$ ft

**Stable Slope vs. Horizontal Dist**

$\tau_0 = 250$ ft

<table>
<thead>
<tr>
<th>$D_{50}$</th>
<th>Slope (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m</td>
<td>0.8</td>
</tr>
<tr>
<td>2m</td>
<td>0.6</td>
</tr>
<tr>
<td>3m</td>
<td>0.4</td>
</tr>
<tr>
<td>4m</td>
<td>0.2</td>
</tr>
<tr>
<td>5m</td>
<td>0.0</td>
</tr>
<tr>
<td>6m</td>
<td>0.0</td>
</tr>
<tr>
<td>7m</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Stable Slope Profile**

$\tau_0 = 250$ ft

**Stable Slope vs. Slope Length**

$\tau_0 = 250$ ft

<table>
<thead>
<tr>
<th>$D_{50}$</th>
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</thead>
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<tr>
<td>4m</td>
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</tr>
<tr>
<td>5m</td>
<td>0.0</td>
</tr>
<tr>
<td>6m</td>
<td>0.0</td>
</tr>
<tr>
<td>7m</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Basin Geometry - Expanding Concave Slope, $r_0 = 300\text{ ft}$

Stable Slope vs. Horizontal Dist

Stable Slope Profile

Stable Slope vs. Slope Length

Rosemont Mine Landforming
Basin Geometry - Expanding Concave Slope, $\eta_0 = 350$ ft

Stable Slope vs. Horizontal Dist.

Stable Slope Profile

Stable Slope vs. Slope Length

Rosemont Mine Landforming
Basin Geometry - Expanding Concave Slope, \( r_0 = 400 \text{ ft} \)

**Stable Slope vs. Horizontal Dist.**

- \( r_0 = 400 \text{ ft} \)
- \( D50 = 1\text{ in} \)
- \( D50 = 2\text{ in} \)
- \( D50 = 3\text{ in} \)
- \( D50 = 4\text{ in} \)
- \( D50 = 5\text{ in} \)
- \( D50 = 6\text{ in} \)
- \( D50 = 7\text{ in} \)

**Stable Slope Profile**

- \( r_0 = 400 \text{ ft} \)
- \( D50 = 1\text{ in} \)
- \( D50 = 2\text{ in} \)
- \( D50 = 3\text{ in} \)
- \( D50 = 4\text{ in} \)
- \( D50 = 5\text{ in} \)
- \( D50 = 6\text{ in} \)
- \( D50 = 7\text{ in} \)

**Stable Slope vs. Slope Length**

- \( r_0 = 400 \text{ ft} \)
- \( D50 = 1\text{ in} \)
- \( D50 = 2\text{ in} \)
- \( D50 = 3\text{ in} \)
- \( D50 = 4\text{ in} \)
- \( D50 = 5\text{ in} \)
- \( D50 = 6\text{ in} \)
- \( D50 = 7\text{ in} \)
Basin Geometry - Concentrating Concave Slope, $\eta_0 = 200$ ft

Stable Slope vs. Horizontal Dist.

Stable Slope Profile

Stable Slope vs. Slope Length

Rosemont Mine Landforming
Basin Geometry - Concentrating Concave Slope, \( q_0 = 300 \) ft

**Stable Slope vs. Horizontal Dist.**

- \( q_0 = 300 \) ft
- \( D50 = 1 \) m
- \( D50 = 2 \) m
- \( D50 = 3 \) m
- \( D50 = 4 \) m
- \( D50 = 5 \) m
- \( D50 = 6 \) m
- \( D50 = 7 \) m

**Stable Slope vs. Slope Length**

- \( q_0 = 300 \) ft
- \( D50 = 1 \) m
- \( D50 = 2 \) m
- \( D50 = 3 \) m
- \( D50 = 4 \) m
- \( D50 = 5 \) m
- \( D50 = 6 \) m
- \( D50 = 7 \) m
Basin Geometry - Concentrating Concave Slope, $r_0 = 400$ ft

**Stable Slope vs. Horizontal Dist.**

- $r_0 = 400$ ft
- L50 = 1m
- L50 = 2m
- L50 = 3m
- L50 = 4m
- L50 = 5m
- L50 = 6m
- L50 = 7m

**Stable Slope Profile**

- $r_0 = 400$ ft
- L50 = 1m
- L50 = 2m
- L50 = 3m
- L50 = 4m
- L50 = 5m
- L50 = 6m
- L50 = 7m

**Stable Slope vs. Slope Length**

- $r_0 = 400$ ft
- L50 = 1m
- L50 = 2m
- L50 = 3m
- L50 = 4m
- L50 = 5m
- L50 = 6m
- L50 = 7m
Basin Geometry - Concentrating Concave Slope, $\theta_0 = 600^\circ$

**Stable Slope vs. Horizontal Dist.**

- $\theta_0 = 600^\circ$
- $D50 = 1m$
- $D50 = 2m$
- $D50 = 3m$
- $D50 = 4m$
- $D50 = 5m$
- $D50 = 6m$
- $D50 = 7m$

**Stable Slope Profile**

- $\theta_0 = 600^\circ$
- $D50 = 1m$
- $D50 = 2m$
- $D50 = 3m$
- $D50 = 4m$
- $D50 = 5m$
- $D50 = 6m$
- $D50 = 7m$

**Stable Slope vs. Slope Length**

- $\theta_0 = 600^\circ$
- $D50 = 1m$
- $D50 = 2m$
- $D50 = 3m$
- $D50 = 4m$
- $D50 = 5m$
- $D50 = 6m$
- $D50 = 7m$
Basin Geometry - Concentrating Concave Slope, $t_0 = 700$ ft

**Stable Slope vs. Horizontal Dist.**

- $t_0 = 700$ ft
- $D_50 = 1\text{ in}$
- $D_50 = 2\text{ in}$
- $D_50 = 3\text{ in}$
- $D_50 = 4\text{ in}$
- $D_50 = 5\text{ in}$
- $D_50 = 6\text{ in}$
- $D_50 = 7\text{ in}$

**Stable Slope Profile**

- $t_0 = 700$ ft
- $D_50 = 1\text{ in}$
- $D_50 = 2\text{ in}$
- $D_50 = 3\text{ in}$
- $D_50 = 4\text{ in}$
- $D_50 = 5\text{ in}$
- $D_50 = 6\text{ in}$
- $D_50 = 7\text{ in}$

**Stable Slope vs. Slope Length**

- $t_0 = 700$ ft
- $D_50 = 1\text{ in}$
- $D_50 = 2\text{ in}$
- $D_50 = 3\text{ in}$
- $D_50 = 4\text{ in}$
- $D_50 = 5\text{ in}$
- $D_50 = 6\text{ in}$
- $D_50 = 7\text{ in}$

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Basin Geometry - Concentrating Concave Slope, $\theta_0 = 300^\circ$.