Assessment of Concave and Linear Hillslopes for Post-Mining Landscapes

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ABSTRACT

In nature, hillslopes have an upper convex and a lower concave profile. Therefore, concave slopes offer an alternative design for rehabilitated landscapes. However, concave hillslopes for rehabilitated landscapes must be justified in terms of long-term erosional stability and cost, because of the popularity of linear slopes.

Concave and linear hillslopes with different slope gradients were examined for generic small and large waste stockpiles in three climates to evaluate long-term stability. The hillslopes were evaluated for long-term erosional stability using the SIBERIA model.

The highest and lowest erosion were observed in linear and natural concave slopes respectively, for all simulations. Over the range of slopes and climate simulated, the natural concave slopes had a two- to three-fold sediment reduction when compared to corresponding linear slopes. The modelling illustrated that concave slopes made of linear segments can be as effective as the natural concave slopes in reducing sediment loss. The climate, stockpile size, and vegetation did not affect the predicted erosion pattern between linear and concave slopes.

The initial cost of rehabilitating a waste stockpile with slopes at angle of repose is slightly more compared to a linear slope; however, if reducing long-term maintenance liability for the stockpile is a closure objective, then the cost difference is insignificant. Where new waste stockpiles are being constructed, the cost of forming a concave slope should be no greater than for a linear slope.

Additional Key Words: Landform evolution, SIBERIA, erosion, mine rehabilitation.

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INTRODUCTION

Final post-mining landscapes should be hydrologically, geomorphologically and visually compatible with the surrounding area and should remain stable over a long period of time (Ayres et al., 2006). Nature provides analogues for rehabilitated mine landscapes in terms of hillslope forms and gradients. In nature, hillslopes have a convex upper profile with a concave profile lower down the slope. Therefore, concave slopes for rehabilitated landscapes offer an alternative design approach for post-mining hillslope profiles. However, linear slopes are more popular for post-mining reclaimed landforms due in large part to simplicity in design, construction and the failure to consider long-term performance. As such, efforts are needed to understand and justify the suitability of concave hillslopes for rehabilitated mine landscapes in terms of reduced sediment loss to the surrounding environment and cost effectiveness over the long term.

Hancock et al. (2003) studied a series of linear and concave landforms on mine spoil in northwest Western Australia. This study demonstrated that over the range of slopes and slope lengths examined, concave slopes can reduce sediment loss by up to five times that of linear slopes. However, in this study, long-term cost effectiveness of concave slopes over conventional slope designs and maximum slope angle that dozers can safely operate along contour were not considered. Further, research has not addressed the suitability of concave slopes in more temperate climates for both small waste stockpiles and large waste stockpiles.

Concave and linear hillslopes with different slope lengths and gradients for both small and large stockpiles are examined in this paper, and compared in terms of sediment loss to evaluate the feasibility of concave slopes for post-mining landform designs in three different climates. The constructed concave slopes are evaluated for long-term erosional stability against a series of linear and natural concave slopes. SIBERIA, a three-dimensional fluvial erosion and landform evolution model, is used to evaluate a range of linear and concave waste storage facility designs for long-term erosional stability over a 1000-year period in three different climates.

The objective of this paper is to offer quantitative evidence that (given assumed climatic and material erodibility conditions for different locations), concave slopes provide a more stable landform as compared to linear slopes. Discussion on whether one slope design over the other provides acceptable erosion rates is a site-specific issue, and beyond the scope of this paper. However, it is fundamental to note that the appropriate approach is to develop site-specific closure objectives, and from that, closure design criteria, of which, for example, includes acceptable erosion rates for rehabilitated mine waste landforms. Following this basic first component required for developing a site-specific closure plan, would be, for example, a quantitative assessment of erosion rates for alternative rehabilitated landforms to determine which landform meets the closure design criteria.

EROSION MODELLING PROGRAMME

Rehabilitation design configurations

In this study, a series of linear and concave slopes were developed for a small and a large waste stockpile to evaluate long-term erosional stability and cost effectiveness (see Table 1 and Figures 1 and 2). An order of magnitude difference exists between the height and width of the simulated small and large stockpiles. Slope gradients for these linear and concave slopes were selected based on the feasibility of constructing the slope configurations with overall rehabilitation costs in mind. The concave slopes were constructed using a series of linear
segments whose slope gradients are below the maximum slope gradient (20) that dozers can safely operate along contour.

In addition to these slope designs, natural concave slopes with overall gradients of 25% and 30% were constructed for both small and large stockpiles to compare results. The area-slope relationship with $\alpha = 0.40$ as described in Hancock et al. (2003) was used to construct concave slopes with continuous curvature. However, in practice, it is difficult to construct concave slopes with continual curvature on waste dump slopes, particularly for larger waste storage facilities. Therefore, natural concave slopes were simulated primarily for comparison purposes to other slope designs.

Table 1. Characteristics of landform designs for the simulated small and large stockpile.

<table>
<thead>
<tr>
<th>Slope Type</th>
<th>Overall Slope (crest to toe)</th>
<th>Slope Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percent</td>
<td>Angle</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>Linear</td>
<td>36%</td>
<td>19°</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>17°</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>14°</td>
</tr>
<tr>
<td>Concave – 2 or 3 linear segments</td>
<td>30%</td>
<td>17°</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>14°</td>
</tr>
<tr>
<td>Concave – 4 or 6 linear segments</td>
<td>30%</td>
<td>17°</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>14°</td>
</tr>
<tr>
<td>Natural concave ($\alpha = 0.4$)</td>
<td>30%</td>
<td>17°</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>14°</td>
</tr>
</tbody>
</table>

*Height = 30 m; width = 50 m. †Height = 300 m; width = 500 m.

**Erosion and landform evolution model (SIBERIA)**

SIBERIA is a physically-based model that simulates geomorphic evolution of landforms subjected to fluvial erosion and mass transport processes (Willgoose et al., 1991a-c), and links widely accepted hydrology and erosion models under the action of runoff and erosion over variable-time scales. The physics of runoff and erosion that are included in the model are broadly similar to the well understood WEPP model (Flanagan and Livingston, 1995); the main difference being that SIBERIA allows the landform to evolve in response to erosion (Hancock, 2004). The SIBERIA erosion model has been evaluated for erosion assessment of post-mining landforms (Boggs et al., 2000, 2001; Evans et al., 2000; Evans and Willgoose, 2000; Hancock et al., 2000, 2002).

The sediment transport equation of SIBERIA consists of two terms:

$$q_s = q_{sf} + q_{sd}$$

where $q_s$ is the sediment transport rate per unit width ($m^3/s/m$ width), $q_{sf}$ is the fluvial sediment transport term, and $q_{sd}$ is the diffusive transport term (both $m^3/s/m$ width). The fluvial sediment transport term is based on the Einstein-Brown model which is:

$$q_{sf} = \beta_1 Q^{m_s} S^{n_s}$$
Figure 1. Profile characteristics of multi-linear concave slopes for the small stockpile.

Figure 2. Profile characteristics of multi-linear concave slopes for the large stockpile.
where $Q$ is the discharge per unit width ($\text{m}^3/\text{s/m width}$), $S$ the slope (m/m) in the steepest downslope direction and $\beta_1$, $m_1$ and $n_1$ are constant one-dimensional parameters which require calibration for a particular site. The diffusive transport term is expressed as:

$$q_{st} = DS$$

(3)

where $D$ ($\text{m}^3/\text{s/m}$) is diffusivity. The diffusive term can model creep, rain splash and land sliding.

SIBERIA does not directly model discharge but uses a sub-grid effective parameterization based on empirical observations, and justified by theoretical analysis, which conceptually relates discharge to area ($A$, $\text{m}^2$/m width) draining through a point as:

$$Q = \beta_3 A^{m_3}$$

(4)

where $\beta_3$ is the runoff rate constant and $m_3$ is the exponent of area, both of which require calibration for a particular field site.

For long-term elevation changes, it is convenient to model the average effect of these processes over time. Accordingly, individual events are not normally modelled, but rather the average effect of many aggregated events over time is modelled (Hancock, 2004). The sophistication of SIBERIA lies in its use of digital terrain models for the determination of geomorphology of a drainage area, as well as its ability to efficiently adjust the landform with time in response to the erosion that is predicted to occur on the landform.

**SIBERIA parameters and simulations**

Three climate regimes were considered to examine long-term stability of linear and concave slopes for rehabilitation of mine waste stockpiles: (1) arid climate with mean annual rainfall of 160 mm and annual potential evaporation (PE) of 1385 mm; (2) seasonally wet/dry tropical climate with mean annual rainfall of 1400 mm (mostly falling in the wet season as high intensity short duration rainfall events) and annual PE of 2700 mm; and (3) moderate continental climate with mean annual rainfall of 870 mm with 30% as snowfall and annual PE of 600 mm.

Erosion parameters used for these climates are indicative of soil and rock material with relatively high erodability (see Table 2). A series of simulations were carried out to assess the erosional stability of the various final slope configurations. The initial simulation was carried out using parameters for a surface “with no vegetation” to represent a “worst-case” scenario. This scenario is plausible in the event of complete vegetation loss due to brush fires, pest attack in monocultures, and severe drought conditions. A second simulation used parameters with vegetation after some initial growth period. This simulation was included to examine the effect of temporally changing erosion parameters because of vegetation development. Time to establish complete vegetative cover on slope surfaces varied with each climate.

The hillslope profiles detailed in Table 1 and Figures 1 and 2 were converted into digital elevation models with regular grid spacing (1 m and 5 m for small and large stockpiles respectively). The SIBERIA model simulations were completed for a period of 1000 years to evaluate long-term erosional stability of the slopes considered. This time period is considered to be sufficiently long to provide information as to the long-term behaviour of slopes.

In post-mining landscapes, the majority of erosion occurs by gullying caused by fluvial erosion (Hancock et al., 2000). Consequently, the authors are only concerned with fluvial erosion for the purposes of this paper. Erosion caused by rain splash is considered to be insignificant when compared to fluvial erosion on post-mining landscapes.
Table 2. SIBERIA parameters for “no vegetation” and “with vegetation” on slope surfaces.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Scenario</th>
<th>Duration</th>
<th>$\beta_1$</th>
<th>$m_1$</th>
<th>$n_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid climate</td>
<td>No vegetation</td>
<td>0 – 1000 yrs</td>
<td>0.00075</td>
<td>1.5</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>With vegetation</td>
<td>0 – 50 yrs</td>
<td>0.00075</td>
<td>1.5</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 – 1000 yrs</td>
<td>0.000075</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Seasonally wet/dry tropical climate</td>
<td>No vegetation</td>
<td>0 – 1000 yrs</td>
<td>0.0032</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>With vegetation</td>
<td>0 – 15 yrs</td>
<td>0.0032</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 – 1000 yrs</td>
<td>0.000032</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Moderate continental climate</td>
<td>No vegetation</td>
<td>0 – 1000 yrs</td>
<td>0.00142</td>
<td>1.52</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>With vegetation</td>
<td>0 – 5 yrs</td>
<td>0.00142</td>
<td>1.52</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 – 1000 yrs</td>
<td>0.0000142</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

PRESENTATION OF MODELLING RESULTS
Simulation results are presented to (1) compare erosional stability of concave slopes versus linear slopes, (2) examine the influence of climate and stockpile size on sediment loss, and (3) assess the affect of vegetation on long-term erosional stability of linear and concave slopes. Comparisons between linear and concave slopes of small and large waste stockpiles are made using average annual soil loss rates.

Sediment loss from linear and concave slopes
Figure 3 shows the general pattern of average erosion rates predicted for linear and concave slopes with no vegetation on the surface. Sediment loss increases with increasing slope gradient in each slope category. Maximum erosion occurs from linear slopes, while minimum erosion occurs from concave slopes with continual curvature for both 25% and 30% slope gradients after 1,000 years. There is approximately 50% erosion reduction with concave slopes with continual curvature compared to corresponding linear slopes. Concave slopes made of two linear segments do not greatly reduce erosion when compared with linear slopes. However, a concave slope made of four linear segments greatly reduces sediment loss from hillslopes compared to a linear slope with an overall gradient of 25%. The average annual erosion rate decreases with increasing concavity of the concave slopes. The SIBERIA model predicts concave slopes to be more stable than linear slopes, particularly as the overall concavity of the concave slope increases.

Results of SIBERIA simulations predict that over a 1000-year simulation period, linear slopes have the highest erosion while concave slopes with continual curvature have the lowest erosion. A comparison of sediment loss for linear and concave slopes demonstrates that over the range of slopes and slope lengths examined, a concave slope with continual curvature is much better in terms of reduced sediment loss from a reclaimed hillslope.

Influence of climate type and stockpile size
Figure 4 shows the general pattern of average erosion rates predicted for linear and concave slopes with no vegetation for the simulated small and large stockpiles in three different climates. The maximum erosion from the small stockpile occurs in the seasonally wet/dry tropical climate, while the minimum erosion occurs in the simulated arid climate as expected; however, for the large stockpile, predicted erosion rates in the arid climate are greater than or approximately
similar to the erosion in the seasonally wet/dry tropical climate. It was hypothesized that the large stockpile should have a similar pattern of erosion between climates as predicted for the small stockpile; however, this was not predicted by the simulations using the model inputs presented in this paper.

Figure 3. Average erosion rate predicted for linear and concave slopes with no vegetation.

Figure 4. Influence of climate type and stockpile size on predicted average erosion rate.
The important observation from Figure 4 is the consistent pattern of average annual erosion predicted between linear and concave slopes for each climate. Maximum erosion occurs from linear slopes while minimum erosion occurs from concave slopes with continual curvature. Concave slopes made of two linear segments do not greatly reduce erosion when compared with linear slopes. However, concave slopes made of four linear segments greatly reduce sediment loss from hillslopes compared to linear slopes. For the simulated small stockpile, both a 25% concave slope with continual curvature and a 25% concave slope made of four linear segments produce approximately equal sediment loss in each climate.

Climate and the size of the waste stockpile do change the amount of erosion from each slope type. However, the greater erosional stability observed in concave slopes compared to linear slopes is not influenced by the size of the stockpile and type of climate.

**Influence of vegetation**

SIBERIA simulations demonstrate that, as expected, landforms with vegetation greatly reduce erosion compared to slopes with the bare surfaces (see Figure 5). The modelling conducted for this study further indicates that vegetation does not influence the pattern of erosion predicted for linear and concave slopes for the vegetation conditions modelled. Sediment loss increases with increasing slope gradient in each slope category for both the small and large stockpile with and without vegetation on the slope surfaces. For the small stockpile with and without vegetation, maximum erosion occurs from linear slopes while minimum erosion occurs from concave slopes with continual curvature for a 30% overall slope gradient. For a 25% overall slope gradient, minimum erosion occurs from concave slopes made of four linear segments. For the large stockpile with and without vegetation, minimum erosion occurs from concave slopes with continual curvature for both 25% and 30% overall slope gradients. The concave slopes with greater concavity greatly reduce erosion from hillslopes compared to linear slopes in both small and large stockpiles with and without vegetation.

![Figure 5](image-url). Influence of vegetation on predicted average erosion rate.
The key point resulting from the simulations that considered vegetation is that over the long term (e.g. the 1000 years modelled), it may not be appropriate to simply rely upon vegetation to reduce erosion rates on linear slopes. Furthermore, while it can be argued that maintenance can be undertaken on linear slopes that do undergo erosion, this must only be considered a short-term management approach. Erosion and geomorphologic processes require long-term considerations, of which maintenance cannot be considered as being a viable alternative. Finally, as discussed later in this paper, constructing a slope with a configuration that is more stable (i.e. with concavity) does not imply a higher cost for construction.

**DISCUSSION OF MODELLING RESULTS**

Concave slopes produce a rapid drop in elevation in upper reaches of the profiles, where catchment area is small and runoff is minimal. As the catchment area increases, slope decreases reducing the velocity of runoff and erosive influence. In contrast, linear slopes allow accumulation of runoff in the down slope direction with no velocity reduction. This increases the erosion from a linear slope as compared to a concave slope with the same overall gradient. Climatic and vegetation conditions influence the amount of sediment loss from each slope, but do not change the erosion pattern predicted for linear and concave slopes due to the rationale provided above. The type of climate and vegetation on the slope surfaces determine the amount of runoff, which influences the amount of fluvial erosion.

The results of this study provide strong evidence that concave slopes can greatly reduce sediment loss as compared to linear slopes for rehabilitated mine landforms in a variety of climatic regimes. It has been further demonstrated that concave slopes with larger concavity perform better in terms of erosion than those with shallow concavity, particularly for steeper overall slope gradients. This is a result of higher concavity slopes losing elevation more rapidly in the upper reaches of the profiles where runoff volumes are lower, and having a lower slope gradient in the lower reaches of the profile where runoff volumes are higher. This study also demonstrates that concave slopes constructed with 4-6 linear segments are as effective in reducing fluvial erosion from hillslopes as compared to natural concave slopes with continual curvature of 0.4.

**COMPARATIVE COST ANALYSIS**

It is fundamental to consider closure and performance criteria necessary to meet closure objectives when considering costs of rehabilitating a waste storage facility. It is common to lose sight of these key facets of closure planning during the process of seeking the lowest construction/operating cost. Costs for constructing concave slopes can vary depending on the circumstances, in particular when retrofitting them to linear slope landforms. Where new mine waste stockpiles are being constructed, the cost of forming concave slopes should be no greater than for a linear slope. There will be some minor additional costs for survey control and supervision during construction, but within the overall cost of site closure, these should be insignificant.

In the case of retrofitting concave slopes to existing linear slopes many variables will come into consideration, most of them being site-specific. In general however, the cost will have a strong relationship to the overall height of the landform and whether the stockpile slopes are currently angle of repose or at some other linear slope configuration. Typically, reshaping is achieved by pushing down slope with dozers, ideally with a balanced “cut to fill” operation. This is only applicable to a certain point, after which the push distances become uneconomical for
dozers, and a re-mining operation should then be considered; this will be the case particularly for large mine waste landforms with angle of repose slopes. Another constraint on retrofitting hillslopes is where the footprint of the landform cannot be increased; this will prevent pushing down and require cutting back instead.

Table 3 compares the cut-fill volumes, toe extension distance and average dozer push distance for the various small stockpile final slope designs for both 25% and 30% overall slopes. These comparisons are based on retrofitting to an existing angle of repose slope (37°). Recontouring costs increase with increasing dozer push distance; however, there is not a considerable difference in average dozer push distances between the slopes considered in this study. The key points based on data presented in Table 3 are:

- retrofitting to the natural concave slope considered in this study is most costly from an earthmoving perspective, and would also require the greatest amount of survey control;
- the greater the concavity in the slope profile, the greater the toe has to be pushed out;

Table 3. Comparison of re-contouring efforts estimated for the small stockpile final designs.

<table>
<thead>
<tr>
<th>Slope Profile</th>
<th>Cut-Fill Volume</th>
<th>Toe Extension Distance</th>
<th>Avg. Dozer Push Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³/m</td>
<td>% Diff. from Linear</td>
<td>m</td>
</tr>
<tr>
<td><strong>25% Overall Slope Gradient</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>305</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>Concave – 2 Linear Segments</td>
<td>315</td>
<td>3.3%</td>
<td>43</td>
</tr>
<tr>
<td>Concave – 4 Linear Segments</td>
<td>250</td>
<td>-18.0%</td>
<td>47</td>
</tr>
<tr>
<td>Concave – Natural</td>
<td>340</td>
<td>11.5%</td>
<td>54</td>
</tr>
<tr>
<td><strong>30% Overall Slope Gradient</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>220</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>Concave – 2 Linear Segments</td>
<td>230</td>
<td>4.5%</td>
<td>32</td>
</tr>
<tr>
<td>Concave – 4 Linear Segments</td>
<td>220</td>
<td>0%</td>
<td>33</td>
</tr>
<tr>
<td>Concave – Natural</td>
<td>245</td>
<td>11.4%</td>
<td>43</td>
</tr>
</tbody>
</table>
• retrofitting to a concave slope comprised of four linear segments costs the same or less compared to a linear slope, with perhaps minor additional costs for survey control for the multi-linear concave slope design;

• the concave slope comprised of two linear segments is only marginally more costly than a linear slope with the same overall gradient; however, when reduced erosion and thus lower maintenance costs post-closure are factored in, the initial higher rehabilitation cost is insignificant; and

• if the site has a limited footprint or some geological structure that prevents pushing out the toe, then a linear slope may be a better option; however, this will have more long-term maintenance costs compared to re-mining the material and forming a concave slope.

SUMMARY AND CONCLUSIONS
Concave and linear slopes with different slope length and gradient were examined and compared in terms of sediment loss to evaluate the long-term feasibility of concave slopes for post-mining landform designs. A series of linear segments were used to construct concave slopes. These concave slopes were evaluated for long-term erosional stability using the SIBERIA model against a series of linear slopes and natural concave slopes.

Results of simulations demonstrate that over a 1000-year simulation period, linear slopes have the highest erosion while natural concave slopes have the lowest erosion for each stockpile size and climate regime simulated. A comparison of sediment loss for linear and concave slopes clearly demonstrates that over the range of slopes, slope lengths and climate simulated, the natural concave slopes greatly reduce sediment loss from the hillslopes for both small and large waste stockpiles. For both the small and large stockpiles modelled, a two- to three-fold reduction in sediment loss in each climate condition modelled was predicted for the natural concave slopes, as compared with corresponding linear slopes. The modelling conducted predicts that concave slopes consisting of a series of linear segments are as effective as concave slopes with continual curvature in terms of sediment loss reduction. The climate and the size of the stockpile do not change the erosion pattern observed between linear and concave slopes.

The simulations conducted as part of this study also illustrate the fallacy of simply relying on vegetation and maintenance to control erosion on linear slopes. Stability of a mine waste landform is a long-term consideration, while maintenance of any gullies and rills that develop must be considered as being a comparatively short-term approach. During the early stages of vegetation development, it may not be possible to simply rely on vegetation to control erosion. Furthermore, under drought, or other processes that will affect vegetation ground coverage and viability, the landform will not have the benefit of vegetation to ensure stability.

Costs for constructing concave slopes can vary depending on the circumstances, in particular when retrofitting them to pre-existing linear slopes. In the case of retrofitting concave slopes to existing linear slopes many variables will come into consideration, most of them being site-specific. Where new mine waste stockpiles are being constructed, the cost of forming a concave slope should be no greater than for a linear slope except some minor additional costs for survey control and supervision during construction.
Finally, it must be emphasized that while beyond the scope of this paper, the first fundamental step in this process is determining site-specific closure objectives, from which site-specific, and even landform specific, closure design criteria are developed. Following this fundamental step in developing a site’s closure plan, would be a program that incorporates the approach outlined in this paper to quantify erosion rates for alternative landform designs.

REFERENCES


