INCORPORATION OF NATURAL SLOPE FEATURES INTO THE DESIGN OF FINAL LANDFORMS FOR WASTE ROCK STOCKPILES[1]

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Abstract. Historically, final landforms for waste rock stockpiles consist of linear (in plan), planar slope surfaces with unvarying gradients and angular slope intersections. Slope drainage structures are generally oriented along contours and are highly engineered, while revegetation efforts follow artificial configurations. By contrast most natural slopes are characterized by a variety of shapes (typically concave), and drainage systems follow natural drop lines with catchment sizes defined by undulating relief on the slope. Vegetation on natural slopes grows in discrete vegetation units that are adjusted to hillside hydrogeology, incident solar radiation, and other microclimate effects.

This paper reviews the key elements of natural slopes and proposes methodologies for improved design of final landforms, and in particular, methodologies for the reclaimed slopes of waste rock stockpiles. Two case studies are included to demonstrate that natural slope configurations are more stable than highly engineered landforms over the long term. The design methodologies and supporting discussions presented in this paper are also applicable to any above-ground waste storage facility with topographic relief.

Additional Key Words: Landform evolution, geomorphology, SIBERIA, WEPP, mine rehabilitation

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[1] Paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

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7th International Conference on Acid Rock Drainage, 2006 pp 59-75
DOI: 10.21000/JASMR06020059

https://doi.org/10.21000/JASMR0602

Introduction

The mining industry has an illustrious reputation for changing landscapes. At one time, this was an accepted product of industrialization; towers of rock were testaments to how mankind can conquer the earth (McKenna, 2002). Today, however, regulations and public expectations have changed and now the massive landscape changes that occur during mining must be tempered, such that post-mining landscapes conform to the final land use objectives required by stakeholders and regulators.

Often waste rock stockpiles resulting from open pit mining operations require extensive regrading prior to site closure because the rehabilitated final landform was not addressed during the stockpile construction phase. Angle-of-repose slopes are generally flattened due to long-term geotechnical stability, erosion and safety concerns, and in many cases, to facilitate placement of a topsoil / growth medium layer or an engineered cover system. Historically, rehabilitated stockpile landforms possess uniform slopes conforming to neat lines and grades. This lends itself to uniformity of design and construction, but does not necessarily achieve the mine closure objectives of minimum erosion and long-term sustainability (Sawatsky et al., 2000).

Uniform landforms represent immature topography, and are poised to evolve to lower energy states by shallow slope failures or accelerated erosion. In contrast, the development of a sustainable landscape for mine closure involves the development of landforms that replicate natural landscapes. The replication of mature and relatively stable natural systems reduces the rate and risk of accelerated erosion. It also encourages replication of the self-healing erosion control systems that help preserve the stability of the natural analogue (Sawatsky et al., 2000).

The objectives of this paper are to review the key elements of natural slopes and propose methodologies for improved design of final landforms, and in particular, methodologies for the reclaimed slopes of waste rock stockpiles. Two case studies are included to demonstrate that natural slope configurations are more stable than highly engineered landforms over the long term. Although the focus of this paper is reclaimed slopes / final landforms for waste rock stockpiles, the design methodologies and supporting discussions presented in this paper are also applicable to any above-ground waste storage facility with topographic relief.

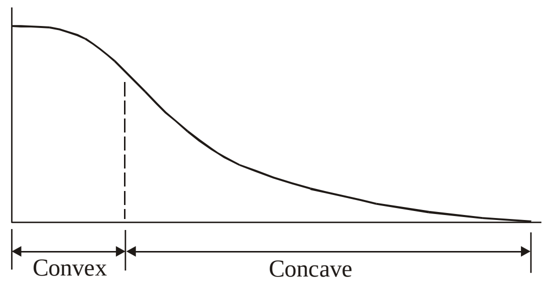
Background

Key Elements of Natural Slopes

Natural slopes are a reflection of a balance between driving forces in geomorphic systems and the resistance of materials on the slopes (Toy and Hadley, 1987). The forces that act on landscapes can be summarized into those due to climate (precipitation, evaporation, wind), gravitational forces causing mass land movements, and weathering processes that encompass chemical and biological changes to the materials. The resistance of the material derives from the physical properties of soils and the added structural stability contributed from biomass such as roots and surface debris (Toy and Hadley, 1987).

Most slopes in nature are characterized by a variety of shapes including convex and concave forms interspersed with ridges (spur ends) and swales (hollows) (Fig. 1a). Carson and Kirkby (1972) compiled data on a large number of hillslopes, and determined that the majority of hillslopes possess rounded convex summits and have shallow concave elements at the base (Fig. 1b). Drainage systems generally follow natural drop lines in the slope, with catchment sizes defined by undulating relief on the slope.

(a)



(b)

Figure 1. (a) Photograph showing key features of a natural hillslope (near Salt Lake City, UT) and (b) profile of a natural hillslope in a soil-mantled landscape.

Vegetation on natural slopes grows in discrete vegetation units that are adjusted to hillside hydrogeology, incident solar radiation, and other microclimate effects. Trees and shrubs are concentrated in concave areas, where moisture conditions are higher, while grasses / legumes generally dominate the drier convex portions.

Examination of analogues like Mount Wilkinson near Wiluna, Western Australia shows there is little vegetation or topsoil to be found on the upper sections of natural slopes. It is only once the slope flattens out in the lower third of the slope that vegetation approaches the density of the surrounding flats and that topsoil is found. The upper two-thirds of the slope are characterized by surfaces that are well armored and consist of coarse particles, any fines are found below this layer of coarse material.

<u>Historic Construction and Reclamation of Waste Rock Stockpiles</u>

Waste materials at most historic mining operations were generally stockpiled in the most cost-effective method, with no concern for rehabilitation. Haigh (2000) discusses historical reclamation methods and outlines the "cosmetic" approach where temporary measures such as thin topsoil layers and temporary erosion controls were used to mask the disturbance. The landscapes created were still fragile and would often succumb to extreme erosion, or biological and chemical processes such as those producing acid rock drainage. Often revegetation was used synonymously with reclamation in the common perception of effective reclamation.

Historically, final landforms for waste rock stockpiles consist of linear (in plan), planar slope surfaces with unvarying gradients and angular slope intersections. The slopes of many historic stockpiles remain at angle-of-repose (typically 37° or ~1.3H:1V), making them susceptible to excessive gully erosion and nearly impossible to revegetate. In general, most reclaimed stockpile slopes are not steeper than 20° (2.75H:1V), because this is the maximum angle for safe operation on the contour by a dozer. Flattening steep slopes by dozing from the top downwards can also result in slopes with a convex profile unless closely supervised.

Revegetation efforts typically follow random or artificial configurations (Fig. 2a), while slope drainage structures are generally oriented along contours and are highly engineered (Fig. 2b). For example, mine rehabilitation guidelines for the construction of hillslopes in Australia requires that benches be cut into the reconstructed slope at spacings determined by slope length and angle (AMIC, 1989). The benches capture runoff, thus reducing velocity and volume moving down the slope facet and ultimately erosion in the short term. However, over the long term, benches and contour banks are prone to failure, and once failure has occurred they channel water in concentrated flow paths, leading to severe gullying (Hancock et al., 2003).

(a) (b)

Figure 2. Photographs illustrating historical reclamation practices for waste rock stockpiles.

Need for Improved Methodologies for Designing Waste Stockpile Final Landforms

Following a tour of 57 abandoned and partially reclaimed operating mines, McKenna and Dawson (1997) created an inventory of mine closure practices, physical performance of reclaimed areas, and environmental impacts of reclaimed and abandoned mines. The inventory shows that the greatest physical risk to the landscapes is associated with gully erosion and re-established surface water drainage courses. Gully erosion poses the greatest environmental threat to covered waste storage facilities containing hazardous materials such as acid-generating or radioactive materials. In addition, methods to reduce and control infiltration and leaching of acid drainage products or metals from minerals often work against measures to reduce erosion, which would rather promote infiltration and reduce runoff.

It is well known that steep unarmored slopes will flatten, planar slopes will gully, straight drainage courses will start to meander, and linear or convex slopes will become concave. Unplanned, rapid changes in the reclaimed landscape could result in unacceptably high sediment loading of streams, gully scarring, and landslides (Keys et al., 1995). The incorporation of natural slope features into the final landform design for stockpiles not only improves aesthetics, but also emulates slopes that are in equilibrium with local conditions of rainfall, soil type and vegetation cover. The relatively small increase in costs for engineering and construction for creating natural landforms are more than offset by improved aesthetic impact, decreased slope maintenance costs, and improved long-term stability. Schor and Gray (1995) reported design and engineering costs for landform grading increase approximately 1 to 3%, and surveying 1 to 5% over conventional methods.

Rehabilitation practices of the mining industry need to become increasingly sophisticated as new methods and the environmental impacts of mining become better understood (Hancock et al., 2003). This requires that post-mining landforms be designed according to best practice technology. With the time and resources now available, mining companies are able to develop complex plans to restore the landscapes they disturb, and to meld this process into their mining activities to minimize the resources required and maximize efficiency. In addition, the ability to demonstrate successful reclamation has become a competitive advantage in the mining industry, particularly in the oil sands region of northern Alberta, Canada (Barbour et al., 2004).

Proposed Methodology for Designing Waste Rock Stockpile Final Landforms

A generalized approach and guidelines are proposed below for developing a sustainable final landform design for future and existing waste rock stockpiles. Two software packages for predicting erosion and landform evolution are also reviewed, followed by a case study.

Design Approach

The consideration of geomorphic principles is fundamental when designing a stable landform. Reclamation failure can usually be traced to violation of geomorphic principles, most fundamentally having too great a disparity between force and resistance (Toy and Hadley, 1987). Examples of this are having a hillslope that is too steep or too uniform, channel gradients that are too steep, drainage courses with sharp angles (in plan), or too large of drainage basins. Hancock et al. (2003) show that an understanding of landscape geomorphological properties and the use of erosion models can greatly assist in the design of post-mining landforms.

Landform design for rehabilitation also requires a holistic view of mining operations, where each operational stage and each component of the mine is part of a plan that considers the end-use of the site as much as the immediate need (Environment Australia, 1998). This plan, which needs to be flexible to accommodate changes in methods and/or technology, is about optimizing post-mining land capability, minimizing the costs in achieving optimal land use, and limiting long-term maintenance liabilities.

The following generalized approach is proposed for developing a sustainable final landform design for future waste rock stockpiles:

1) Determine the final land use for the rehabilitated site through consultation with all stakeholders, and an assessment of potential geologic or structural control elements for the landform;

2) Observe and collect data on the natural landscape prior to mining, such as hillslope forms and gradients, soil and vegetation types, drainage density, and watershed characteristics;

3) Determine the long-term eroded profile for the various slopes of the future final landform through erosion and landform evolution numerical modeling, to aid in the design / construction of the stockpile during mine operation;

4) Determine a suitable footprint design for construction of the stockpile based on the contours of natural landforms for post-mining visual blending and consideration for potential enlargement of the footprint following construction of the final landform;
5) Design a surface water management system to safely convey meteoric water off the final landform, and ensure runoff reaches final discharge points in volumes and at velocities that will not cause unacceptable erosion or sedimentation;
6) Develop a waste management plan / stockpile design that takes into consideration the storage of reactive and non-reactive waste materials (e.g. encapsulation of reactive waste with inert waste as described in Waters and O'Kane (2003)), and the findings of completing Steps 3 to 5 inclusive;
7) Develop a revegetation plan suitable for the swales and ridges in the final landform based on data collected in Step 2; and
8) Review the final landform design with key stakeholders for general acceptance prior to implementation.

It is proposed that the above design approach can be applied to existing waste rock stockpiles with modifications to steps 2, 3, 4, and 6 as follows:

2) Observe and collect data on a nearby natural landscape (a natural analogue) to determine hillslope forms and gradients, soil and vegetation types, drainage density, and watershed characteristics;
3) Determine the long-term eroded profile for the various slopes of the existing stockpile through erosion and landform evolution numerical modeling;
4) Based on the maximum slope length and gradient as determined from Steps 2 and 3, design a methodology for reshaping the existing stockpile to conform to these requirements (a horseshoe-shaped landform, which creates a small well-defined catchment, can be effective in reducing slope length and gradients without changing the footprint of an existing stockpile); and
6) Develop a final landform design following completion of Steps 2 to 5 inclusive, taking into consideration the long-term safe storage of reactive or hazardous materials.

Various aspects of the final landform for a waste rock stockpile should be tracked or monitored following construction, such as revegetation and erosion developments, defining the water balance, and evolution of cover soils. This enables as-built performance to be compared to predicted performance of the new landscape, and particularly for large sites where progressive reclamation occurs, provides feedback to adjust future landform designs. A watershed is the ideal unit size of a landform to evaluate the behavior of a landscape (Barbour et al., 2004). A description of monitoring methods for watershed-scale performance monitoring can be found in MEND (2006).

<u>Design Guidelines</u>

The most appropriate design for a waste stockpile final landform will vary from site to site, depending on a range of factors including climate, geology, soils, local hydrological patterns, topography, and the adopted final land use (Environment Australia, 1998). The following guidelines are proposed to aid in the development of a sustainable final landform design for waste rock stockpiles.

- Design the final landform using natural analogues as described in Keys et al. (1995). The reclaimed landscape can be no more stable than the adjacent undisturbed landscape; therefore, the designer can assume that the reclaimed area will be less stable and design accordingly, with gentler slopes, higher density drainage and smaller drainage basins.
- Maintain the final landform height and slope angles for stockpiles in areas of low relief as low as possible. Where slopes compatible with the surrounding landscape cannot be achieved, an attempt should be made to visually soften steeper areas by avoiding straight "engineered" ridges and sharp changes of angle, and by careful planting of trees to break up views of the horizon (Environment Australia, 1998).
- The preferred reclaimed slope design is a "spur-end" slope plan with a concave or complex (convex-concave) profile. The use of terraces or contour banks should be avoided. It is very difficult in practice, particularly for stockpiles with long slopes, to construct concave slopes with continual curvature on a waste rock stockpile. However, hillslope curvature can be obtained using a series of linear slopes or slope facets as shown in Fig. 3. Hancock et al. (2003) demonstrated through simulations with a landform evolution model that there is minimal difference in sediment loss between a hillslope constructed of linear facets and that constructed from continual curvature.
- Erosion and subsequent evolution of the proposed final landform design(s) should be predicted over a period of at least 100 years using state-of-the-art software packages.
- The thickness of earthen covers designed to minimize the entry of atmospheric oxygen and/or meteoric water to reactive or hazardous material should not only be based on soil-atmosphere numeric simulations, but should also take into consideration the predicted long-term erosion from the final landform (e.g. see Ayres et al. (2005)).
- The design of surface water drainage courses should be based on the discharge and sediment load of the receiving stream(s). Drainage channels used to convey surface water off the top of the landform should follow the slope gradient of the final landform as much as possible. The use of imported substrate as well as man-made materials such as pipes, gabions, and concrete should be avoided whenever possible.

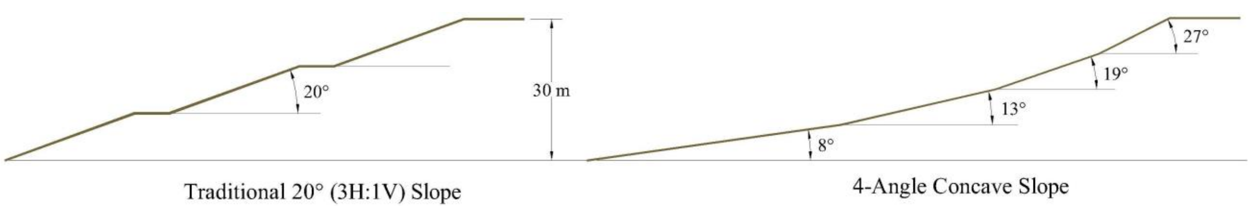


Figure 3. Schematic showing traditional and concave slope designs for reclaimed waste rock stockpiles.

- Design conservatively to account for excessive erosion resulting from extreme climatic events and differential settlement in the reclaimed landform.

- Reclamation of large waste storage facilities should include the construction of small lakes and wetlands upstream of final surface water discharge points, provided they are geomorphically compatible and stable. Such features will attenuate surface runoff to reduce peak flows and increase sedimentation prior to reaching receiving streams (Sawatsky, 2004).

<u>Numeric Analyses of Erosion / Landform Evolution</u>

Numeric analyses of erosion / landform evolution allow an assessment of current and future landscape designs without the problems associated with field studies. Much of the available literature investigates erosion on long flat slopes (e.g. agricultural sites), with little available for steeper slopes common to waste rock stockpiles. Steeper slopes tend to rill dramatically, something that traditional erosion models (e.g. Universal Soil Loss Equation, USLE) have not been able to satisfactorily address. The development of the Water Erosion Prediction Project (WEPP) (Laflen et al., 1991; Flanagan and Livingston, 1995) and SIBERIA (Willgoose et al., 1991; Willgoose, 2000) models has begun to address this numeric analysis deficiency.

The WEPP model is a process-based program that was developed in the late 1980's and early 1990's by the United States Department of Agriculture (USDA). It is best suited for detailed considerations of short-term (up to 100 years) impacts of slope length, gradient, and management on erosion rates. The appropriate scales for application are tens of meters for hillslope profiles, and up to hundreds of meters for small watersheds (Flanagan and Livingston, 1995). The model explicitly considers rill and interrill erosion and is therefore better able to consider interactions of slope length and gradient than other models. WEPP estimates net soil loss for an entire hillslope or for each point on a slope profile on a daily, monthly, or average annual basis. Basic inputs required for the WEPP model include climate data, slope configuration, soil properties, and soil management (vegetation) properties.

The WEPP model provides a detailed description of the susceptibility of soils and spoils to rill initiation and transport. This aspect makes the model especially applicable to situations where soil erodibility is measured in the laboratory, and to consideration of materials (such as rocky spoils) for which erosion responses to slope length and gradient differ greatly from those of agricultural soils. However, being an agriculturally-based model, WEPP does not consider potential effects of erosion and deposition on landform development, nor does it deal specifically with gully development.

SIBERIA is a physically-based model for simulating the evolution of landforms over geomorphic timescales developed by Dr. Garry Willgoose at the University of Newcastle, Australia. It simulates runoff and erosion from a landform that evolves in response to predicted erosion and deposition. It is a three-dimensional topographic evolution model, which predicts the long-term evolution of channels and hillslopes in a catchment on the basis of runoff and erosion. The location and speed with which gullies develop are controlled by a channelization function that is related to runoff and soil erodibility (Willgoose et al., 1991). The model solves for two variables; elevation, from which slope geometries are determined, and an indicator function that determines where channels exist. An activation threshold governs channel growth. A surface may commence with no gullies, but when the activation threshold, which depends on discharge and slope gradient, is exceeded, a channel develops.

The SIBERIA model needs to be calibrated before evaluating whether it correctly models the observed evolution of rehabilitated mine landforms. The model has been calibrated to rainfall and runoff data from the ERA Ranger Mine (ERARM) in the Northern Territory, Australia, and used to predict the possible erosion over 1,000 years for ERARM rehabilitation proposals (Evans and Willgoose, 2000). Hancock et al. (2000) demonstrated that SIBERIA is an appropriate model for assessment of erosional stability of rehabilitated mine sites over time spans of around 50 years. The following methods can be used for obtaining erosion parameters required for input to the SIBERIA model:

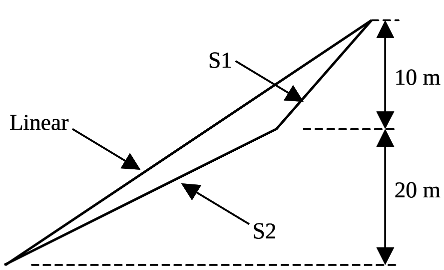
- Collect erosion data from rainfall and runoff testing using rainfall simulators as described by Loch et al. (2001), and subsequently use a model such as WEPP to determine erosion rates for each soil type;
- Measure controlled flow through a series of flumes constructed on the hillslope; this method does not simulate rainfall / runoff but allows assessment of the impact of high flow rates on a range of armoring methods; and
- Determine erosion rates from digital mapping of slopes actively being eroded.

Case Study #1 – Generic Site in Midwestern USA

The WEPP model was used to estimate the rate of erosion from various slope profiles for two waste rock stockpiles on a generic mine site situated in mid-western USA. Fig. 4 details the stockpile slope designs examined in the erosion modeling program. A large stockpile with a vertical height of 300 m as well as a smaller 30 m high stockpile was considered in the analysis.

Small Stockpile Landform Alternatives

Linear	1.3H:1V 3.0H:1V 4.0H:1V 5.0H:1V
Concave #1	S1 – 3.0H:1V S2 – 4.0H:1V
Concave #2	S1 – 3.0H:1V S2 – 5.0H:1V



Large Stockpile Landform Alternatives

Linear	1.3H:1V 2.75H:1V 3.0H:1V
Concave #1	S3 – 2.5H:1V S4 – 3.0H:1V
Concave #2	S3 – 2.5H:1V S5 – 3.0H:1V S6 – 3.5H:1V

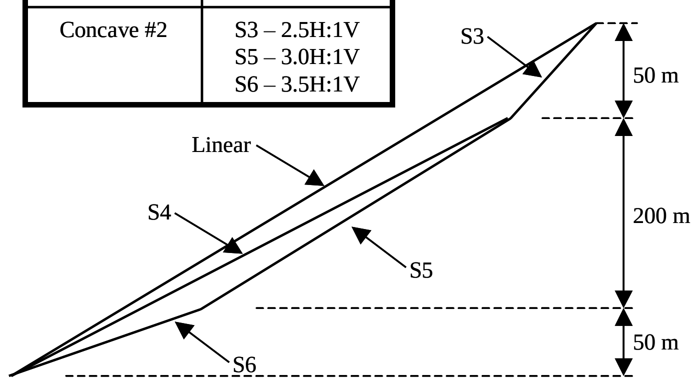


Figure 4. Slope profile designs examined in the erosion modeling program for the small and large waste rock stockpile at the case study #1 site.

Both linear slopes, ranging from angle-of-repose (~37° or 1.3H:1V) to 11.3° (5H:1V) for the small stockpile, and concave slopes comprised of two or three linear slope facets were evaluated. Additional inputs used for this numeric modeling exercise are summarized as follows:

- The total precipitation for the simulated year is approximately 600 mm, with approximately 30% occurring as snowfall, and a large portion of the rain falling during short, intense summer thunderstorms;
- The particle size distribution of the near surface material on slopes of both stockpiles is the same, comprised of 12% silt and clay, 28% sand, and 60% gravel based on the USDA classification system; and

Two different soil management practices were investigated; a bare surface and a rangeland short grass with 28% surface coverage.

Table 1 summarizes the erosion rates predicted for the small stockpile with a height of 30 m. The predicted erosion rate for the 3H:1V bare slope decreases by 22% compared to that predicted for the angle-of-repose bare slope. This is not a significant improvement in reduced erosion considering the large difference between a 3H:1V and an angle-of-repose slope. The predicted erosion rate continues to decrease as the linear slope is reduced to 4H:1V (74 Mg/ha/yr) and 5H:1V (65 Mg/ha/yr). The addition of the short prairie rangeland grass significantly reduces the predicted erosion for each slope configuration examined (more than halved compared to the bare surface condition). The predicted erosion rates for the concave slopes are slightly lower compared to their corresponding linear slopes.

Table 1. Predicted erosion rates from various slope configurations for the small waste rock stockpile at the case study #1 site.

Simulation	Slope Profile	Slope Gradient	Soil Management	Soil Loss Rate (Mg/ha/yr)
SS-1	Linear #1	1.3H:1V	Bare surface	113
SS-2	Linear #2	3H:1V	Bare surface	88
SS-3			Rangeland grass	37
SS-4	Linear #3	4H:1V	Bare surface	74
SS-5			Rangeland grass	32
SS-6	Linear #4	5H:1V	Bare surface	65
SS-7			Rangeland grass	28
SS-8	Concave #1	Upper 3H:1V Lower 4H:1V	Bare surface	68
SS-9			Rangeland grass	30
SS-10	Concave #2	Upper 3H:1V Lower 5H:1V	Bare surface	59
SS-11			Rangeland grass	26

Table 2 summarizes the erosion rates predicted for the large stockpile with a height of 300 m. The erosion rates for the larger stockpile are higher compared to the smaller stockpile, especially for the angle-of-repose slope where the computed erosion rate is double that predicted for the 30 m high slope. The 3H:1V slopes are more comparable as the slope length is not great enough to produce a large difference in the predicted erosion rate.

The modeling program found a significant difference in the erosion rates for the angle-of-repose and the 2.75H:1V slope for the large stockpile; the predicted erosion for the flatter slope is 52% of the steeper slope. Erosion rates for the concave slopes are predicted to be slightly lower compared to those for the linear slopes. Comparison of simulation results for LS-4 and LS-8 show that the concave slope should produce approximately 16% less erosion compared to the linear slope for the same 900 m slope footprint.

The findings of this case study illustrate that concave slopes are more stable than linear slopes, particularly for large waste stockpiles, and even a moderate grass cover can significantly reduce rates of soil loss from reclaimed slopes.

Table 2. Predicted erosion rates from various slope configurations for the large waste rock stockpile at the case study #1 site.

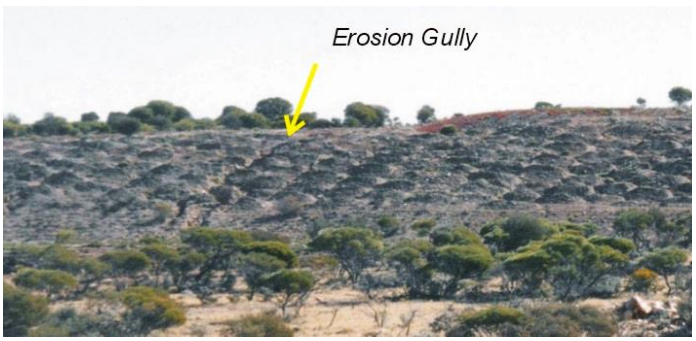
Simulation	Slope Profile	Slope Gradient	Soil Management	Soil Loss Rate (Mg/ha/yr)
LS-1	Linear #1	1.3H:1V	Bare surface	226
LS-2	Linear #2	2.75H:1V	Bare surface	117
LS-3			Rangeland grass	52
LS-4	Linear #3	3H:1V	Bare surface	107
LS-5			Rangeland grass	42
LS-6	Concave #1	Upper 2.5H:1V Lower 3H:1V	Bare surface	100
LS-7			Rangeland grass	39
LS-8	Concave #2	Upper 2.5H:1V Middle 3H:1V Lower 3.5H:1V	Bare surface	90
LS-9			Rangeland grass	36

Short-term versus Long-term Landform Stability

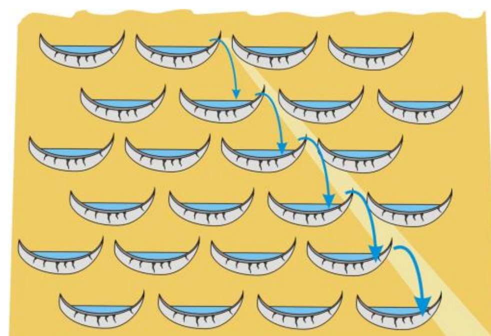
Various measures can and have been used in the reclamation of waste rock stockpiles that provide short-term stability, but are generally not a suitable means for long-term landform stability. These include terracing or contour banks, cross-slope or contour ripping of the surface, dozer basins or “moonscaping” (see below), and placement of erosion control blankets in drainage channels. Provided these measures are properly implemented, they reduce erosion rates as a result of higher infiltration (i.e. lower runoff) and/or greater roughness on the surface (i.e. surface resistance). These techniques are prone to failure over the short term (i.e. 1 to 10 years), which explains why none of these measures are found on natural slopes. However, this time frame may be sufficient to allow a good stand of grasses and legumes to establish, thereby aiding in the long-term stability of a reclaimed slope.

Moonscaping has been trialed on a number of waste rock stockpile slopes in Australia as a potential method of slope stabilization; however, it has been of limited success and is not advised as a long-term surface treatment. Moonscaping is where the slopes are formed into rows of basins intended to contain all water within their individual catchments. Each row of basins is offset half a basin width from the rows above and below to ensure all water is intercepted (Fig. 5a). The limiting factors to moonscaping are:

- Cost – it requires very precise earthmoving to create;
- Sizing of basins to contain all water;
- Leaking from basins downslope through the uncompacted outer edge;
- Slumping and failure of the outer edge leading to a cascading failure;
- Overtopping of basins leading to cascading failure (Fig. 5b);
- Basins sedimenting up over time and losing storage capacity; and
- High visual impact.



(a)



(b)

Figure 5. (a) Photograph showing a moonscaped surface on the side of waste rock stockpile with evidence of gully erosion and (b) schematic of the failure mode for most moonscaped surfaces.

<u>Case Study #2 – Whistle Mine Backfilled Pit Cover System, Canada</u>

Erosion and landform evolution numerical modeling was conducted to design a runoff management system and final landform for the backfilled open pit at Whistle Mine near Sudbury, ON, Canada (Ayres et al., 2005). The cover system consists of nominally 0.45 m of compacted clay overlain by a minimum of 1.2 m of sand and gravel, with 0.08 m of topsoil admixed to the cover surface to increase nutrient levels for revegetation efforts. The surface of the backfilled pit, which covers an area of approximately 10 ha, has an average slope of 17% over a maximum length of 125 m as a result of natural relief in the area.

The WEPP model was used to estimate erosion rates from the cover surface, while the SIBERIA model was used to predict the evolution of the final landforms. A 100-year climate database was developed for the site based on historical data collected from a nearby meteorological station. The surface of the cover system was assumed to be bare of vegetation for all WEPP simulations, which is reasonable for short-term and probably somewhat conservative for long-term predictions of erosion rates. WEPP output data were used to generate parameters for the SIBERIA landform evolution model.

The first landform alternative examined consists of a highly engineered system to manage runoff generated from spring snowmelt and rainfall events. The landform has contour banks to capture runoff water and divert it laterally to one of two collection channels oriented parallel to the slope. A perspective view of this landform design is shown in Fig. 6. Output from the SIBERIA model showing the evolved nature of this landform design after running the 100-year climate file is presented in Fig. 7. The model output shows breaching of the contour banks, development of gullies and rills, and in general, failure of the landform over a 100-year period. The gullies may armor over the longer term, but acting against this possibility is the relatively large contributing area that will feed some of the gullies. In addition, if the cover material weathers over time and runoff rates increase, gully erosion of this landform will be significant.

The second alternative and ultimate landform design implemented for the backfilled pit cover system consists of a number of catchments oriented parallel to the slope with a "swale and ridge" pattern (Fig. 8). This micro-topography is beneficial for revegetation efforts because snow accumulates in the troughs, thereby increasing soil moisture levels, and wind velocities are reduced across the ground surface, thus reducing potential erosion of topsoil and grass seeds. The size and geometry of the catchments are based on the results of WEPP modeling, which takes into consideration acceptable erosion rates for the cover system and sediment loading that will be delivered to the runoff collection system. The SIBERIA model was not used to predict the long-term evolution of the second landform design.

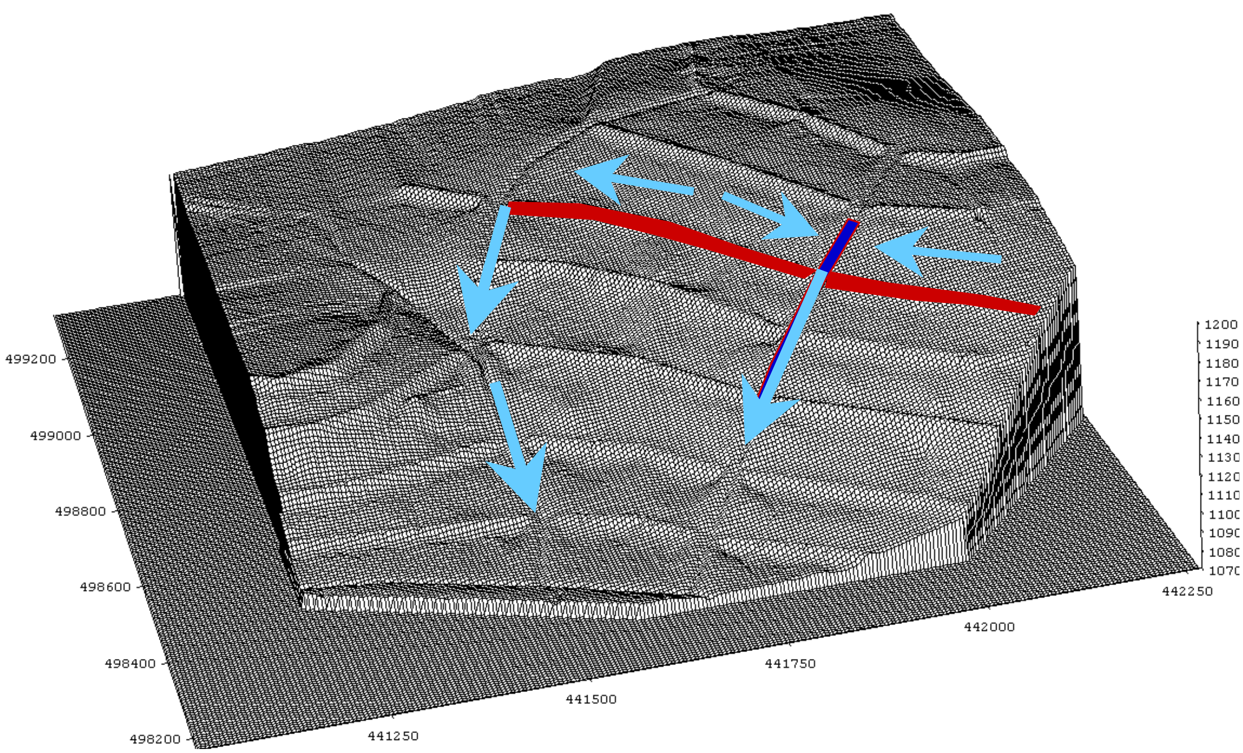


Figure 6. Surface contours (vertically enhanced) for the first landform alternative evaluated for the Whistle Mine backfilled pit cover system (from Ayres et al., 2005).

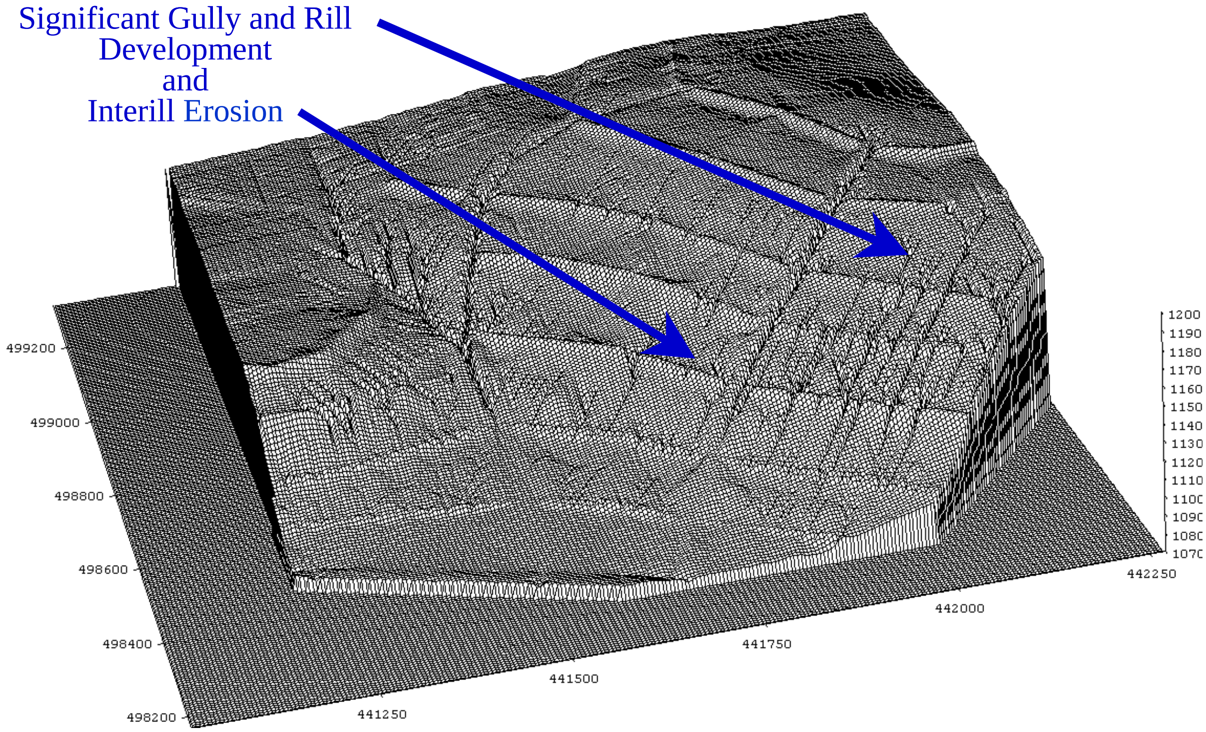


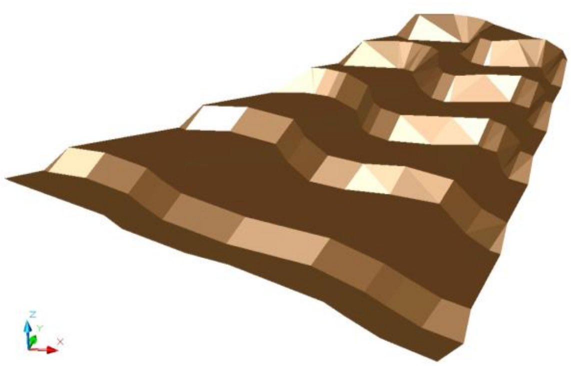
Figure 7. Predicted landform evolution of the first landform alternative for the Whistle Mine backfilled pit cover system after 100 years (from Ayres et al., 2005).

Figure 8. Second alternative and ultimate landform design implemented for the Whistle Mine backfilled pit cover system (from Ayres et al., 2005).

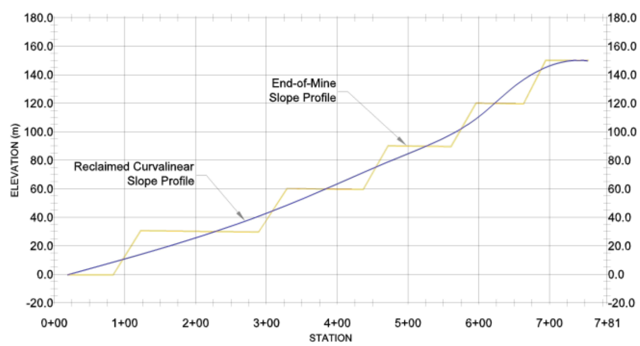
Alternative Construction Technique for Waste Stockpiles with Closure in Mind

A proposed alternate construction technique for waste rock stockpiles with closure in mind is shown in Fig. 9 (referred to as "contour-terraced" construction). The height of each bench is the same but the width of each terrace narrows in the upper reaches of the stockpile to achieve the concave profile. The width of each terrace and the ultimate stepped profile is based on the desired slope of the final rehabilitated landform. Ideally, landform evolution modeling will have been completed in advance of stockpile construction. This way, individual benches can be dozed such that the final dozed profile is as close to the long-term profile as practicable. In addition, the footprint contour for each bench becomes increasingly sinuous with height, which favors the creation of swales and ridges during final grading without having to move excessive amounts of waste material. Another positive aspect of this design compared to conventional stockpiles constructed with long angle-of-repose slopes is that the overall erosion from the slopes will be reduced during the life of the mine, which may be significant for large mining operations.

An issue that requires discussion is the fact that concave slopes have less volume than linear slopes. If concave slopes are desired in the final landform design, then careful planning is required to minimize the volume of waste rock that will have to be rehabilitated by other means. Increasing the footprint of the reclaimed final landform is one way of handling excess material, but this may not be possible in all cases. Ultimately, the use of concave slopes in the stockpile final landform requires better mine planning so that waste rock is correctly positioned from the start of the operation.



(a)



(b)

Figure 9. (a) Perspective view and (b) slope profiles for a contour-terraced waste rock stockpile.

Summary

Historically, rehabilitated waste rock stockpile landforms possess uniform slopes conforming to neat or "engineered" lines and grades. This lends itself to uniformity of design and construction, but does not necessarily achieve the mine closure objectives of minimum erosion, long-term sustainability, and limiting long-term maintenance liabilities. The incorporation of natural slope features into the final landform design for stockpiles not only improves aesthetics, but also emulates slopes that are in equilibrium with local conditions of rainfall, soil type and vegetation cover.

The use of geomorphic principles and a holistic view of mining operations are critical to the design of rehabilitated landforms for waste rock stockpiles. The most appropriate landform design for a stockpile will vary from site to site, depending on a range of factors including climate, geology, soils, local hydrological patterns, topography, slope aspect, and the adopted final land use. Design guidelines have been proposed to aid in the development of a sustainable final landform for waste rock stockpiles. The WEPP and SIBERIA models are valuable tools for evaluating the long-term erosion and landform evolution of various landscape designs. The construction of a "contour-terraced" waste rock stockpile during mining operations is far better suited to the development of sustainable final landform, and can significantly reduce rehabilitation costs.

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