A RELOOK AT THE SLOPE GEOMETRY OF MINE RESIDUE DEPOSITS IN TERMS OF EROSION, SOIL FORMATION, VEGETATION COVER AND WATER QUALITY

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ABSTRACT

The most common historic method in the design of mine residue deposits (MRDs) outer slopes has been to provide the maximum airspace over the smallest footprint area possible, and constructing the embankment to form an outer slope which comprises a series of steep slopes (typically 1-in-~2) separated by terraces or benches at approximately 10m vertical intervals. These residue deposits are then either vegetated directly or protected in some other way (such as through the application of waste rock cover) to reduce wind and water erosion rates. The side slopes of these historical MRDs can be described as compound, consisting of terraces and steep intermediate slopes.

This paper questions the validity of this approach in terms of satisfying a broad range of closure objectives and suggests that more focus needs to be placed on the selection of geometry, cover systems and vegetation strategies at design stage, in order to provide self-sustaining and cost effective closure solutions.

To illustrate the shortcomings of the traditional slope geometry, and highlight the benefits of an alternative (geomorphic) approach, use is made of a simple but recognised soil erosion model and landscape evolution modelling software.

A design approach is proposed which could potentially improve the quality of the runoff from the side slopes and surrounding areas. This could even enable runoff from the side slopes and catchment paddocks to be discharged directly to the environment without a significant negative impact on downstream users.

The implications of the proposed approach in terms of the design and operation of the facility (and hence the impact on risk and cost) is also discussed, with a new skill set being incorporated into the design phase in order to truly “design for closure”. This paper also suggests ways in which geomorphic features can be incorporated into the design of the MRD in order to improve long term stability.

1. HISTORIC APPROACH TO MINE RESIDUE DISPOSAL SLOPE CONFIGURATION

In the authors opinion, historically, the main focus in the selection of the side slope geometry for mine residue deposit (MRD) facilities in Southern Africa was on:

- Providing maximum airspace for waste over the smallest footprint area.
- Where possible, adopting deposition techniques that provide a means to construct the outer embankment or slope using the mine waste material itself to provide the confining structure and exposed outer surface.
- Ensuring adequate physical stability against a slope failure and liquefaction, although minimal attention has been given to physical stability in terms of erosion.
- Ensuring adequate freeboard to limit the risk of overtopping.

Terraces at regular intervals of 7 to 10m measured vertically were constructed on most tailings dams and waste rock dump side slopes. These were generally motivated by one or more of the following:

- The practical limitations of the construction method (e.g. the ring dyke system employed on gold dams, or the end tipping method employed on rock dumps).
- The belief that it was better to limit the slope length from an erosion point of view, by having intermediate terraces, with each terrace provided with a “reliable engineered” means of getting stormwater from the terrace to the bottom of the facility. The relative importance of slope length and slope angle were not considered.
- The need to create access to various points on the otherwise steep slopes.

The intermediate slopes were generally steep, often varying between the angle of repose of the material (typically 1-in-1.3 to 1-in-1.8) in the case of waste rock, or 1-in-1.5 to 1-in-2.7 in the case of tailings materials. According to Blight and Amponash-Da Costa (1999), the pessimum angle for erosion of silt sized particles is 1-in-1.5. The average slope measured from the top crest to the toe was typically in the region of 1-in-3.

The primary historical objective of vegetation cover on MRDs was dust control, and not closure based on ecological criteria (Thatcher, 1979). Vegetation was often aimed at the establishment of pasture grasses, which was a result of the fact that pasture grass seeds are readily available on the market and can be rapidly established on ameliorated slimes (Chamber of Mines, 1968; 1979). The use of ecologically sound approaches and tolerant, native plant species that offered more sustainable solutions has been recognised since the 1950's (Bradshaw, 1970; Bradshaw and Chadwick, 1980), and has been well defined for South African gold MRDs (Weiersbye and Witkowski, 1998; Weiersbye et al., 2003; 2006; 2009).

Previously, limited consideration was given locally to factors such as:

- the resilience of the vegetation types to events such as fires or droughts,
- the tolerance of the vegetation to the geochemical environment of the tailings,
- soil forming properties of the vegetation selected,
- the root structures and their ability to physically bind the soil, and
- the ability of the vegetation to consume rainwater and mitigate seepage (Witkowski and Weiersbye, 1998).

However, exactly how to achieve the appropriate slope geometry in order to mimic a shallow and concave natural hill-slope remains a challenge. On existing steep-sided MRDs, slopes are reduced using expensive cut and fill methods. Although the reduction of an experimental MRD slope to ~16 degrees resulted in a significant reduction in erosion (Tongway, 2008a; Weiersbye et al., 2009), mechanised methods of slope reduction at the end of a mines life fails to demonstrate that the approach is self sustaining and that sufficient funds have been set aside for the post closure period. This makes the award of a closure certificate risky for the Authorities if the closure is applied for within a few decades of cessation of mining operations. Therefore the construction of new MRDs with shallower slopes in the first place is in the authors opinion a preferred solution. In addition to substrate geometry, vegetation for closure also relies upon a suitable geotechnical foundation, and this must also be addressed at the design stage (Tongway and Ludwig, 2006; Tongway, 2008b).

The management of terraces is relatively straightforward, during the operational life of the dam, when there is plenty of equipment and resources available, but inwards-sloping terraces consistently pond and present a significant problem in the post operational phase. In the post operational phase, ponding, or the combination of high erosion from the slope above the terrace, and the deposition of material on the flat terrace logically results in the overtopping of the terrace at some point leading to massive gully formation and failure at that point as illustrated in Figure 1 which shows a tailings dam that has been closed for some time.

Engineered structures to remove water from the terraces using an approach of engineered chutes or penstocks has also in the authors opinion, proved unsuccessful in most cases, often resulting in complete wash aways of concrete chutes or erosion and flow below the chutes.

Figure 1. Gully Formation on a Terrace of a Disused Tailings Dam

Dust emissions from fine MRDs such as tailings dams have, particularly in the semi arid to arid regions, also been found to increase after decommissioning of the dams. This is as a result of not only the top surface drying out but also as a result of the aerodynamics of the tailings dam surface (Blight, 1991). The sharp crests along each terrace and along the top crest of the dam, in combination with the die back of grass on the slopes and top of the MRD, contribute to increased dust emissions. Although grassing of the MRD results in rapid dust control (Annegarn et al., 1991), this is temporary and the South African approach to pasture grassing of MRDs has been criticised for many decades (Halliday, 1978; Bradshaw and Chadwick, 1980; Weiersbye et al., 2006). Similar methods used elsewhere in the world fell into disfavour in the 1980's. It is known that most of the pasture species used on tailings dams are intolerant to the conditions, and this is addressed through extensive amelioration (liming, fertilization, and irrigation or leaching) of the substrate (Chamber of Mines, 1976; Thatcher, 1979).

Weiersbye and Witkowski (1998) measured substrate biogeochemistry and vegetation on 56 gold slimes dam sites across the Witwatersrand Basin ranging in age from 3 to ~50 years since planting. They found a significant decline in aerial cover for grasses after amelioration ceased (i.e. irrigation, liming, fertilization), with on average less than 50% of the original cover remaining 6 years after ceasing (equivalent to 8 to 9 years post-planting). This was attributable to the combined effects of steep slope, intolerant plant species and ecologically unsound methods. On the majority of steep slimes dam slopes, there was less than 10% of aerial cover by 15 years after amelioration had ceased. Although this low density of grass cover comprised tolerant plants and appeared to be relatively persistent (Weiersbye et al., 2006), it played a negligible role in mitigating erosion, gully-formation, run-off and seepage. This ultimately leads to the need to re-establish vegetation on the slopes. Even on a well-leached and heavily ameliorated gold MRD, where grass has survived for decades and aerial cover is relatively high (53%), this is still significantly lower than aerial cover on equivalent natural (and less erosion-prone) slopes in the region, and the substrate condition remains poor (Rossouw et al., 2009). In contrast, aerial cover on the more sheltered and flatter berms initially declines as the less tolerant pasture grasses die off, and then shows a slow increase over long time periods as more tolerant native grass species start to colonise (Weiersbye and Witkowski, 1998).

From a water quality perspective, the runoff from the side slopes has typically been contained in “leaky” catchment paddocks which were designed to function as sediment traps, but essentially also function as evaporation / seepage structures. The high silt loads ultimately lead to either overtopping of these structures, or the need for continual de-silting. High runoff and erosion rates on the surface and sub-surface (pipe gullies) of side slopes leads to the depletion of resources necessary for soil formation and hence plant growth (including water, nutrients, microbes and plant litter) which in turn leads to further die back of vegetation and subsequent further accelerated erosion. In the case of acid generating tailings, the accelerated erosion due to high runoff rates exposes salt and acid generating materials. The salinity and oxidation products result in poor runoff quality and further die back of vegetation in cases where the plants are not tolerant to these conditions (Weiersbye et al., 2006).

High runoff rates also imply lower infiltration rates, which means that in areas of high net evaporation, salts tend to rise and accumulate on the surface. These salts are then washed from the surface with each successive storm event, resulting in poor runoff quality. The runoff from the side slopes of MRDs in the semi arid to moderate rainfall environments (i.e. 400 to 800 mm), which dominate throughout most of the Southern African mining regions, is thus typically of a poor quality and may continue to deteriorate for many decades after cessation of active deposition on the MRD.

The end result is that there exists a large number of MRDs that cannot be closed in an effective near self sustaining manner, given their current geometry. Maintenance of the MRD tops and slopes requires ongoing maintenance or regular re-vegetation, or significant end of life re-engineering by, for example, flattening the slopes and removing the terraces, and applying soil covers to the facilities as has been done for several MRDs such as the Pering (Metago 2005), Daggafontein and Brakpan MRDs (AngloGold Ashanti Ltd., 2007).

In this paper, the authors propose that the MRD designers need to reconsider the manner in which MRDs are designed and constructed. While the traditional focus areas of MRD design, including issues such as materials handling, slope stability, freeboard and liquefaction risk, will always be significant factors in the design process, these factors do not necessarily control the selection of the final slope geometry, particularly if we are to be realistic about the often quoted commitment to “design for closure”.

It is recognised that rainfall is the main driver of erosion on MRDs (Hinz et al., 2006), and that landscape geomorphology (Sawatsky et al., 2008; Jones, 2008), and surface heterogeneity (Tongway, 2008a; 2008b) are mitigating factors. Design for closure therefore implies consideration of a range of additional issues, which to date typically receive scant attention at design stage.

2. DESIGN FOR CLOSURE

Designing for closure implies that the final landform has to be stable over a much longer time period than the operational phase. For the purpose of this paper, ‘closure’ is interpreted as a state for which it is possible to demonstrate that key parameters do not deteriorate with time, i.e. the key parameters should be stable or demonstrate an improvement with time, and be resilient to stressors to which the MRD can reasonably be expected to be subjected over a period of several hundred years. In the Southern African context, this would include droughts, floods, fire, seismic events, etc.

If we ignore for the moment the fact that the MRD itself should ideally provide resources to the environment and the society after closure, and focus purely on designing the facility to prevent negative impacts on surrounding communities and the environment, then the key long term performance parameters that we would select could be limited to those mentioned in Table 1 below:

Table 1. Performance Parameters of the MRD

Key Performance Objectives for Closure Design	**Key Performance Indicator**
Dust fallout rates around the facility.	To achieve a specified compliance standard in terms of dust emissions considering nuisance dust, ingestible and inhalable size fractions (PM_{10}'s), toxicity or radiological dose.
The quality of runoff from the facility.	A sustainable closure solution inevitably requires that runoff and seepage is environmentally neutral, with concentrations of contaminants that do not exceed average environmental backgrounds in order to avoid detrimental impacts.
The quality of groundwater in the vicinity of the facility.	At closure, the magnitude and extent of contaminant plumes should indicate a static temporal trend of improvement with time.
Where relevant, radiological and toxicological doses to receptors based on the various contaminant pathways.	Radiological and toxicological doses attributable to the facility should be within acceptable levels. Radiological and toxicological doses to consider all primary and secondary pathways including dust, surface water, groundwater, soil, sediment, vegetation, etc.
Sediment loads.	Sediment loads should be at levels that do not impact on aquatic and terrestrial ecosystems and downstream users.
Phreatic Surface.	The phreatic surface should not daylight anywhere on the side slope surface as it could degrade runoff quality and lead to accelerated erosion.

It would be necessary to add to the above list if key performance objectives were set for issues such as carbon sequestration, revenue generation potential, habitat creation, etc., but for the purpose of this paper we will simplify the design objectives to those listed in the table above.

The design solution may incorporate a number of features to achieve the desired results in terms one or more of the key performance areas listed above. With respect to the side slopes, vegetation most commonly plays a key role in terms of achieving the desired targets for one or more of the key performance areas.

For vegetation to be self-sustaining, leading eventually to soil formation and mitigation of acid generation, it is crucial that:

- Although complex to measure, in principle, the rate of soil formation must at least equal the rate of erosion, and
- the vegetation cover and roughness, together with the aerodynamic shape of the facility should be chosen to effectively prevent upliftment of dust particles from the surface.

In the case of acid generating tailings, there are two additional key performance indicators, namely:

- The average rate of erosion (mm/yr) from the slope must be less than the average rate of downward migration of the acid front (mm/yr), and
- the oxidation rate should be as low as possible, or oxidation products mitigated .

Each of these objectives is described in the proceeding sections in greater detail.

3. KEY PERFORMANCE OBJECTIVES FOR SLOPE DESIGN, PERFORMANCE PREDICTION AND VERIFICATION

Aerodynamics and Surface Roughness

The greater the heterogeneity of the surface and sub-surface, the better it will attenuate erosive forces. Although homogenous grass covers do effectively prevent all dust emissions from MRD, these covers tend to be non-lasting and are far less effective in attenuating run-off, sub-surface flows, infiltration and seepage. In contrast, a MRD with heterogeneous surface micro-topography that includes run-on and run-off zones, and structurally diverse cover (stones, brush, shrubs, grasses, trees etc.) can function more effectively in attenuating erosive forces even without a high level of basal cover (the run-off zones are generally bare except for cryptogam crusts), simply because the micro-contouring and larger and more extensively rooted plants are effective in terms of reducing wind speeds, in attenuating sub-surface flows, and in consuming infiltration, whereas the smaller, low-growing plants such as grasses and ground-covers are effective in capturing and retaining surface transported particles and litter (Tongway, 2008a; Weiersbye et al., 2009).

The traditional terraces found on the side slopes of most MRDs, present a problem from an aerodynamic point of view. The sharp crest of the terrace provides a point of low pressure, which results in dust upliftment. In general, smooth slopes (without sharp crests) will outperform terraced slopes in terms of dust emissions.

Although grass-cover does significantly mitigate dust emissions from MRDs, they tend to be non-lasting on steep slopes and do little to mitigate sub-surface erosion or seepage. Therefore more tolerant and higher evapotranspiration (ET) vegetation covers on MRDs (i.e. mixtures of shrubs and other plants as well as tolerant perennial grasses) will improve performance (Weiersbye et al., 2006).

It should be borne in mind that dust emissions are believed to contribute up to 50% of the total erosion from surfaces of tailings dams (Blight, 1991). This is significant in terms of water quality, since much of this dust is deposited outside of the perimeter of the catchment paddocks, and therefore has a detrimental impact in terms of runoff quality from the cleaner catchments of the surrounding land.

From a dust generation point of view, it is therefore preferable to eliminate terraces and ramps to the extent practical, and to provide a vegetation cover that includes woody plants as well as perennial grass species.

Vegetation cover, types and function is measurable using a range of ecological techniques.

Rate of Development of the Oxidised Zone > Erosion Rate

If the material on the side slope erodes away at such a rate that material containing significant residual sulphides (unoxidised materials) is continually exposed on surface, the water quality key performance indicators are unlikely to be met.

The prediction of the performance of a side slope against this objective requires the capacity to predict the general rate of acid production (or oxidation products) with time and the rate of erosion. Both of these parameters are significantly influenced by vegetation, although this is complex to model. The prediction of the erosion rate is discussed in proceeding sections.

Several geochemical tools exist to predict oxygen flux and hence the acid front migration rate, all of which have their own limitations. Despite the limitations and complexity of these models and techniques, they are useful at design stage for prediction of the order of magnitude of the rate of oxidation, and the rate of development of the oxidised zone beneath the surface.

In the end, verification that the depth to the base of the oxidised zone is greater than the erosion rate is reliant on field data collected over several years or even decades. Verification could comprise measuring the sulphide content at depth over time on vertical profiles beneath the surface of the slope.

In terms of this key performance indicator, a slope that results in a low erosion rate is more likely to succeed than one which erodes rapidly or which forms deep gullies on the side slopes. Since gully formation is so commonly associated with the level narrow terraces typical of traditional MRD side slopes, a side slope without terraces is likely to outperform one with terraces in terms of this criteria. The relationship between erosion rate and slope length and slope angle is discussed in this paper. Slopes with vegetation types and surfaces that reduce the runoff volume and rate are likely to outperform those that result in rapid runoff and associated high erosion rates. Increasing infiltration beyond a certain point may mobilise the products of acid generation and to this end vegetation combinations that ensure that the MRD is maintained in an overall water deficit, and/or absorb the products of acid generation would further contribute to protection of water resources.

Minimise the Acid Production Rate

A mine residue facility that becomes effectively leached of its pollutants over a period of 100 years presents a far greater pollution threat than one which is leached over a period of 100 000 years. It should be borne in mind that in arid and semi arid environments with high net evaporation, leaching products can migrate both upwards towards the surface in dry seasons, and downwards during rainfall events, as well as exhibiting mass diffusion. All have the capacity to impact negatively on run-off, groundwater and surface water resource quality via various pathways.

The net acid generation rate in most sulphide MRDs, with the exception of those that have very high air permeability, is primarily controlled by the oxygen flux through the macro pore spaces (Cathles and Schlitt, (1980); Scharer et al. (1991). The former is in turn is largely controlled by the inter-particle air permeability of the material, together with the presence of “mass oxygen transport routes” provided by fissures, cracks and roots within the material. The air permeability in turn is inversely dependent on the degree of saturation or moisture content of the material. Materials at or near saturation exhibit very low air permeabilities compared to dry materials, hence the position of the phreatic surface largely dictates the limit of the oxidation depth.

Inert soil covers can potentially reduce the concentration of oxygen reaching the acid generating materials below the soil, whereas in contrast plant roots facilitate increased oxidation of sulphides at depth below the surface. Again, notwithstanding the effect of the mass transport routes provided by fissures, cracks and roots, the oxygen flux is also dependent on the distance from surface to the particle sites at which sulphide oxidation is occurring.

The requirement for self-sustaining vegetation and reduced oxidation rate therefore appear to be mutually incompatible, unless the actual ameliorative functions of root products and organic matter, and the controls exerted by infiltration, ET and plant physiology are built into the equation, as well as a distinction drawn between the different types of ‘salts’. For example, plants are far more tolerant to sulphate salinity than chloride salinity at the same osmotic potentials.

In general, the vegetation and soil formed on the slope potentially provides four key functions in terms of managing surface runoff quality, namely:

- The oxidised zone is slowly converted to a growing medium (soil) and the oxidation products may be consumed, immobilised, neutralised, or cycled in the vegetation litter and root zones.
- Fissures, cracks, holes (caused by animals), biopores and roots provide pathways to get oxygen to deeper zones below surface, which means that even in fine materials the sulphide oxidation "front" occurs over a wider depth range. Since the depth from which salts can be brought to surface through capillary rise is generally limited by the maximum suction pressures that can practically develop in a particular material, it follows that the distribution of oxidation products over a broader depth range below surface assists in limiting the upward salt flux through capillary rise.
- It increases the rainfall infiltration rate by virtue of the surface roughness and vegetation type, which in turn increases moisture content, reduces the oxygen permeability and hence the oxygen flux into the acid generating waste and assists in distributing oxidation products downwards during seasonal wetting fronts, reducing the availability of salts in the near surface horizons, which would otherwise be readily brought to surface through capillary rise.
- It removes stored water from the substrate via the root system, with certain oxidation products and other contaminants either remaining behind in the soil (precipitated or adsorbed on organic materials), or consumed by vegetation. This implies less oxidation products migrating to the surface as a result of capillary rise.

The selection of the right vegetation types is critical to the functioning of the ET cover in order to reduce seepage from the MRD to the groundwater. The selection of shrubs with dimorphic roots enables the plants to consume rainwater, as well as potentially access shallow phreatic surfaces within the MRD. The flatter the side slope, the greater the interception of rainfall and infiltration, but also the greater the chance of roots consuming this and intercepting the phreatic surface.

Roots and micro-organisms play a significant role in tying the soil together and reducing erosion. On MRDs, woody and semi-woody plant species tend to be more tolerant to the conditions (Weiersbye et al., 2006), provide considerably better soil forming properties than grass species (Weiersbye et al., 2009; Rossouw et al., 2009) and contribute more to ET than grasses (which are largely dormant in winter on the Highveld) (Dye et al., 2008). However, the inclusion of a diversity of both is important to ecosystem function.

For all of the above reasons mentioned in this paragraph, the focus in future on MRD rehabilitation should be on heterogeneous and perennial native vegetation (shrubs, perennial grasses, trees etc) such as shrublands and 'pseudo-savannahs', instead of pastures comprising a few grass species (Weiersbye, 2007).

There are a number of considerations that need to be taken into account by the designer as follows:

- Apart from the impact of slope angle on erosion, the flatter and the rougher the slope, the greater the infiltration. Higher moisture contents in fine wastes imply lower air permeability and hence a lower oxidation rate.
- The presence of organic matter allows vegetation to tolerate higher soil acidity (i.e. aluminium availability). In general, shrubs and trees provide more litter, and higher quality litter, around their base than do grasses, so again a slope that includes shrubs as well as grasses would generally outperform a grass covered slope. However, if the erosion rate is such that there is a net loss of these resources from the slope, this function cannot be achieved (Tongway and Ludwig, 2006).
- The lower the air permeability of the waste, the lower the oxygen flux into the acid generating waste and hence the slow the development of the oxidised zone.
- A slope with extensive and deep rooted vegetation would outperform a slope with only shallow rooted vegetation since the deep root systems are capable of broadening the oxidation front. The runoff and seepage as a percentage of the rainfall can be established through monitoring techniques (e.g. using a trial slope with vegetation cover, and in situ instrumentation).

One of the best indicators of the acid production rate is provided by the underdrainage seepage quality . This needs to be combined with information drawn from various other geochemical tests.

Erosion Rate Less than the Soil Formation Rate

A rate of erosion that exceeds the rate of soil formation results in a net loss of resources necessary for vegetation growth and topsoil development, which in turn results in a net die back of vegetation and hence accelerated erosion. Resources in this context refer to plant litter, water, microbes, fungi, nutrients, etc. The use of terraces on MRDs is often justified in order to limit slope lengths, however, by using a terrace, the intermediate slopes are made steeper than they need be, for a given air space provided. From the discussion above it is evident that the erosion rate is a significant issue in determining how a MRD side slope will perform in terms of the closure design objectives. The remainder of this paper explores the relationship between slope length and slope angle in terms of potential erosion rates, in an attempt to guide the design process towards achieving the closure objectives by getting an appropriate slope geometry in the first place.

4. THE RELATIVE SIGNIFICANCE OF SLOPE LENGTH AND SLOPE ANGLE

Unfortunately many of the erosion models developed to date have focused on agricultural applications for shallow slopes with a diverse particle size range, and generally have not been calibrated or verified for the steeper slopes of relatively homogenous particle sizes associated with MRDs. The erosion model would also need to be parameterised for cohesion factors associated with the mine waste particles - cohesion is negligible for most tailings and this limits the use of parameters derived from natural soils. Notwithstanding this significant limitation, for the purpose of this paper, use has been made of a fairly simple model, namely the Revised Universal Soil Loss Equation (RUSLE) (United States Department of Agriculture, 1997), to illustrate the relative significance of slope length and slope gradient. The RUSLE is the most widely used model to predict soil loss, from shallow slopes, and is an enhanced version of the earlier Universal Soil Loss Equation (USLE).

Alternative soil modelling techniques are more suitable for the steeper slopes, but the RUSLE has been chosen in this paper due to its simplicity. It is considered satisfactory for the purpose of illustrating the relationship between slope length and slope angle. Note that the RUSLE is generally not regarded as being valid for slopes steeper than 25 percent (1-in-4 or 14 degrees) (Blight, 1989).

Both the USLE and the RUSLE were developed in the United States of America, but are generally applicable, and work has been done in South Africa (Haylett 1960 and Smith 1999) to obtain localised input values.

The RUSLE was developed to take cognisance of what were considered to be the governing parameters, and is presented below.

$$A = R \bullet K \bullet L \bullet S \bullet C \bullet P$$

Where:

A is the temporal average annual soil loss (tonnes per hectare per year).
R is the rainfall-runoff erosivity factor.
K is the soil erodibility factor for a standard plot 22.1 m in length of 9% slope.
L is the slope length factor.
S is the steepness factor.
C is the cover management factor.
P is the support practice factor.

In order to obtain a realistic prediction of the likely range of erosion rates from MRD slopes, it was necessary to model the potential range of input parameter values to take cognisance of the variability and uncertainty associated with these values. A Monte Carlo simulation process was applied using Microsoft Excel, together with the @Risk add-in, to take cognisance of the above. This process takes random values from user specified distributions for the input parameters and calculates the erosion rate for the generated combination of properties.

In the example presented below, the slope angle was kept constant at 1-in-5 and the height of the facility was varied to determine the effect of slope length on erosion. The example is intended to represent a large gold tailings dam located in the Highveld region of South Africa. The input parameters are summarised in table 2 below:

Table 2. RUSLE Input Parameters

Parameter	**Units**	**Range (Min)**	**Range (Max)**	**Probability Distribution Applied**	**Source**
Rainfall-runoff erosivity factor (R)	$MJ.ha^{-1}.mm.hr^{-1}$	200	250	Uniform	Garland, *et al*, 1999
Soil erodibilty factor (K)	$t.ha.hr.ha^{-1}.MJ^{-1}.mm^{-1}$	0.0158	0.0474	Uniform	USDA Agricultural Handbook 703
Slope length factor (L)	N/A	Dependent on slope length		N/A	USDA Agricultural Handbook 703
Steepness factor (S)	N/A	2.795		N/A	USDA Agricultural Handbook 703
Cover management factor (C)	N/A	0.19*	0.42*	Uniform	le Roux, J. J., 2005
Support practice factor (P)	N/A	0.68*		N/A	le Roux, J. J., 2005

*Personal communication with I.M. Weiersbye and P.J. Dye, 27 May 2009, with regards to selecting the correct range from the literature.

The distributions of the predicted erosion rates for various trial slope lengths can be seen in Figure 2.

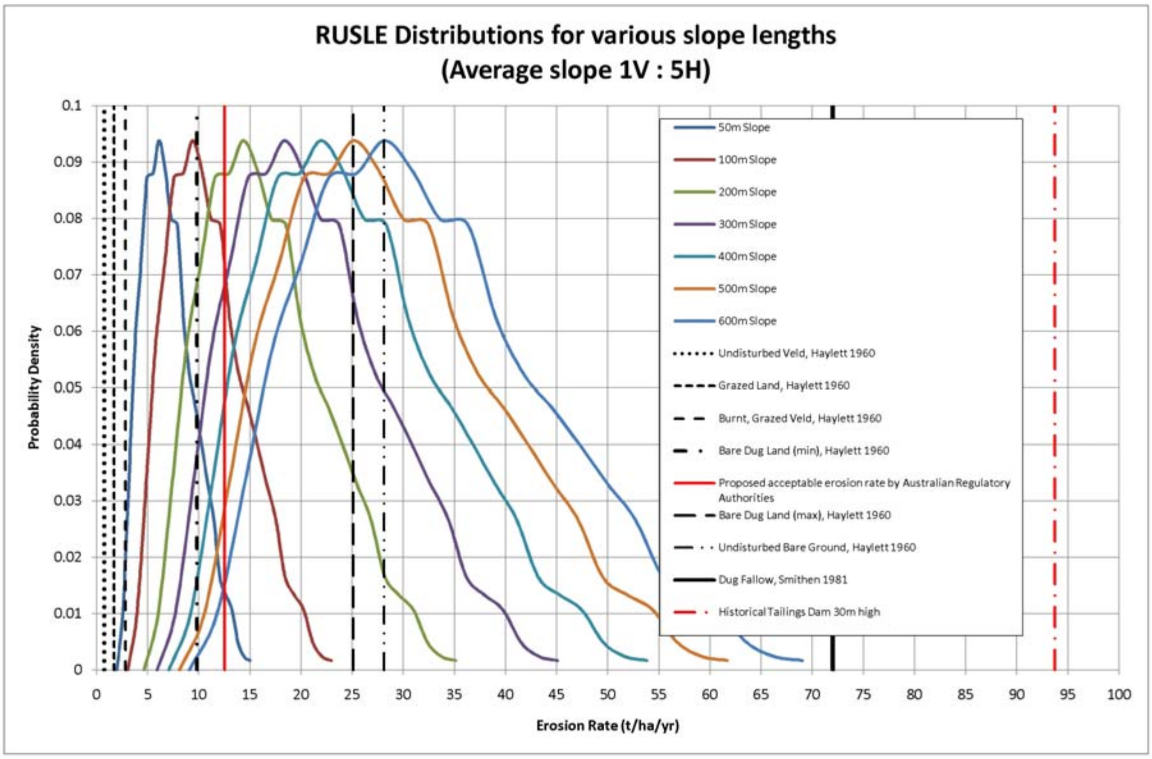

Figure 2. RUSLE Distributions

It should be noted that the predicted erosion rate using the RUSLE for the conventional gold tailings dam side slope geometry, based on an average side slope of approximately 1-in-2.5 and 30m total vertical height is also shown on the graph. This is directly comparable with a slope length of 150m. The RUSLE predicts an expected erosion rate of 12.5t/ha/yr for the 1-in-5 slope compared to 93.7t/ha/yr for the conventional profile.

It can be seen from the graphical results above that the flatter slope of 1-in-5 results in a 7.5 fold reduction in the erosion rate, and probably a corresponding reduction in the average rate of loss of critical resources necessary to sustain vegetation cover.

From Figure 2, it is concluded that the erosion rates achieved using the flatter but longer slopes (by eliminating terraces), are a significant improvement on the erosion rates predicted for the traditional slope profile. However, it is not possible to state that the erosion rates achieved by flattening the side slopes alone, will be sufficiently low to satisfy the key requirement that they should be lower than the soil formation rate.

Although the flatter side slope is expected to result in a significant reduction in erosion rates compared to the traditional profile, the predicted erosion rates are in most cases still greater than the erosion rates for regional natural slopes depicted in Figure 2 as dotted or dashed vertical lines. Since soil formation is a long-term process, it is necessary to assume that the erosion rate on sustainable natural slopes is less than or equal to the accretion rate (i.e. litter, particulates, transported sediment) on these slopes. The Australian Regulatory Authorities have proposed a erosion rate value of 12.5t/ha/yr (So et al, 2002), (<1mm/yr on average) as the acceptable upperbound limit for MRDs in the region. Clearly, this value is not necessarily appropriate for all substrata, conditions, vegetation types or climates, but it does provide a general estimate of the target erosion rate which the design needs to achieve.

It should however be noted that the RUSLE predicts significantly lower erosion rates than the rates reported in literature for conventional similar tailings dam slopes which can be as high as 500t/ha/yr from uncovered tailings dam slopes, and 200t/ha/yr for sparsely grassed slopes (Blight, 1989). Naturally, for the limitations discussed above, the RUSLE may under predict erosion rates for all slope lengths presented even for the 1-in-5 slope.

The RUSLE model was run with the same input parameters used to develop Figure 2, but for a range of slope angles. Clearly, flattening the slope results in an increased total height of facility for a given footprint area. This has been considered in developing Table 3 which shows that despite increasing height and hence slope length, erosion rates decrease with a decrease in slope angle for the range of values considered. The result presented below is for a MRD which has an airspace of 450 million m^3. Slopes much steeper than 1-in-3 are generally not practical from a slope stability point of view and slopes that are flatter than 1-in-7 will often require much larger footprints to provide sufficient airspace, or will tend to intercept the phreatic surface resulting in seepage along the slope.

Table 3. Effect of Slope Angle on the Overall Erosion Rate

Slope	Slope Angle (degrees)	Slope (percent)	Height of MRD (m)	Slope Area (ha)	Erosion Rate (t/ha/yr)	Erosion (t/yr)
1 : 3	18.4	33%	96	147	40.5	5,975
1 : 5	11.3	20%	102	242	28.0	6,759
1 : 7	8.1	14%	113	681	19.9	13,542

This flattening of the outer slope and increase in height results in the area of the side slopes increasing dramatically, which results in the total erosion mass per year being greater for the flatter slopes (Column 7 of Table 3).

This is however not really the issue, as the real issue is the erosion rate per hectare per year (Column 6) which has practically halved by flattening the slope from 1-in-3 to 1-in-7.

From the above calculations using the RUSLE, it can be concluded that MRDs designed with slopes of 1-in-5 to 1-in-7 are going to significantly outperform the historic designs which are generally between 1-in-2.2 and 1-in-3, despite the increased slope length. The issue still remains however, whether these slopes will be sustainable as the erosion rates are still not within the supposed ballpark of 12.5 t/ha/yr.

5. FURTHER POSSIBLE MEASURES TO ACHIEVE THE KEY PERFORMANCE OBJECTIVES FOR CLOSURE DESIGN

The following list suggests a number of further measures, which acting either in isolation or in combination have been shown to reduce the rate of erosion and lead to the required development of a growth media, or ‘soil’ (Jones, 2008; Sawatsky et al., 2008; Tongway, 2008; Weiersbye and Witkowski, 1998; Witkowski and Weiersbye, 1998; Weiersbye et al., 2006; 2009).

- Selection of an appropriate vegetation cover with more emphasis placed on root structure and provision of litter which accelerates soil formation;
- Strategic placement of roughness elements on the surface. This could include a ‘Gravel-mulched surface’ which was found to be effective by Blight (1989), or brush packing which is a well-established technique for erosion control and was found to be effective on MRDs;
- Placement of subsurface roughness elements to increase infiltration and flow path length;
- Placement of natural soil cover which will be naturally less erosive than tailings;
- Possible selective placement of gravelly soils towards the lower end of slopes;
- Use of non-dispersive soils where a soil cover is utilised. The outer slope of uncovered historical MRDs, which are generally characterised by high silt, fine sand and relatively low clay contents has been determined to be one of the most erodible materials available (Matthee and Van Schalkwyk, 1984). Unfortunately, most milled mineralogical process wastes fall into this category;
- Mimic geomorphology of a natural hill – using the concept of spurs and valleys to reduce the flow path length without increasing the slope length. The valleys are protected with suitable materials vegetation and runoff attenuation features;
- Use of concave slopes, steeper at the final crest and flatter near the toe;
- Use of very broad gently sloping terraces which are wide enough to provide a substantial crest berm (typically 25m wide as a minimum) and steep enough to prevent significant sedimentation.

Micro, and to a limited extent macro, scale roughness features may be added to reduce the erosion potential of the side slopes. These features could include “bowls” of brush or other organic matter to aid in the establishment of vegetation or patterned roughness elements.

Banded vegetation (Valentin et al., 1999; Tongway et al., 2001), can significantly reduce the rate of erosion by reducing the kinematic energy of the runoff, and provide rougher patches which encourage deposition of the eroded material to retain essential resources. It was further shown that wind-blown material around isolated plants might act as a nucleus for the development of vegetation arcs. Incorporating subsurface roughness elements such as rocks, old bricks, inert building rubble, etc., would also increase the surface’s erosion resistance.

6. PREDICTON OF THE LONG TERM LANDSCAPE EVOLUTION

Geomorphological evolution models, e.g. SIBERIA, are particularly useful to designers in assessing the long term performance of a particular mine residue facility design. Such models clearly illustrate the rapid deterioration of slopes adjacent to slope changes in geometry, such as crests and terraces, as can be seen in Figure 3 and Figure 4 and allow the designer to test alternative systems and provide data on the relative performance of alternative designs.

Figure 3. Mine Residue Deposit as Designed – Without Erosion

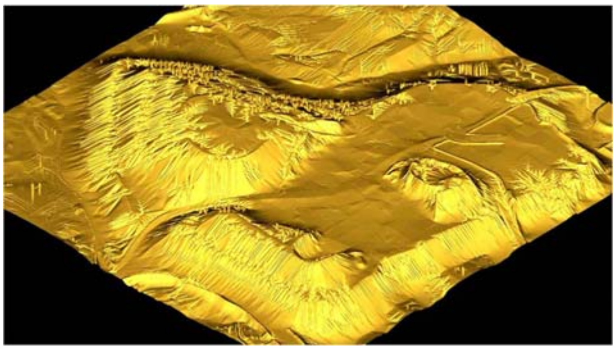

Figure 4. Mine Residue Deposit after Running SIBERIA to Simulate Several Decades of Erosion

Often nature itself provides some of the keys to the design of slopes as natural analogues can be used to understand how a particular geometry is likely to perform in the long term. For example water will move down-gradient on the steepest path and any man-made attempt to divert it will generally be unsuccessful in the context of a closed facility. Biological approaches to control runoff water are more sophisticated as they rely on a variety of different mechanisms, and may be more appropriate, cost effective and reliable in the long term.

7. DESIGN VERIFICATION

Having decided on a slope profile and approach to soil cladding, vegetation, roughness elements, etc., as described above, and implemented in the design, the next stage is to verify that the approach works.

In order to determine whether the approach achieves the key closure performance objectives for the MRD, it is necessary to monitor the performance of the slope over a prolonged time period. Typically to judge whether the slope is potentially self-sustaining, it is necessary to measure a range of variables that describe different biological attributes and can be related to function. The use of landscape indicator values concerned with ecosystem development is well established for natural rangelands, but is still being tested for applicability on different types of MRDs. A constraint to interpretation is that there are no true natural analogues for MRDs as they are currently constructed. However, according to Tongway et al. (1997), adequate vegetation cover (governed by the biogeochemical potential and climate) and plant litter is a common feature in all highly functional landscapes. Conversely, on dysfunctional landscapes, a lack of adequate vegetation at ground level causes litter and other resources to be transported by wind or water and lost from the system, and inadequate infiltration of water. Initially on constructing the slope, it is the geometric and geotechnical design of the slope that provides the initial physical stability, but over time biological development should dominate.

Unfortunately, this time period can be tens to hundreds of years. This means that for slopes that are engineered for closure at the end of the mines operational life, there could still be 30 to 50 years of monitoring required to demonstrate that the solution is on a rehabilitation trajectory that indicates it will be self-sustaining. On the other hand, solutions that are implemented concurrently with operations as the dam crest level rises, will have more time to allow refinement of the design.

For this reason, a solution involving concurrent final rehabilitation (rather than end of life rehabilitation) should always be favoured and called for by shareholders, government authorities and affected communities alike, as concurrent final rehabilitation solutions are associated with significantly less risk and more accurate aftercare cost estimates.

Landscape function analysis (LFA) is a well established indicators-based technique for monitoring the condition of rangelands and more recently mine lands (including soil-clad rock dumps and rehabilitated strip mine land). It is useful to verify whether designed slopes shows a net depletion or accumulation of resources (Tongway and Ludwig, 2006), and may prove useful for assessing gold MRDs (Rossouw et al., 2009). The analysis is carried out along a gradsect and involves measuring landscape organisation and soil surface indicators, from which indices are derived for stability, infiltration and nutrient-cycling (Tongway, 2008). Measurements must be repeated at regular time intervals over many years to establish temporal trends. In the event that resources are depleting with time, it can be concluded that the erosion rate is too high. If the slope indicates accumulation of resources at a rate faster than or equal to the average depletion rate, it can be concluded that the accretion rate (a precursor of soil development, which also includes factors such as decomposition) will generally equal the erosion rate. Vegetation is then likely to exhibit succession to more stable (perennial) communities, i.e. transform over time from one set of species to another, but is not likely to die off as experienced on most of the MRDs in arid to semi arid mining regions of Southern Africa.

8. CONCLUSIONS

To truly design for closure, MRD designers need to broaden the scope of the design to include not only the more traditional key focus areas associated with the operational phase, namely stability, liquefaction, freeboard and the tailings deposition method, but also consider and assign equal importance to the key performance objectives associated with closure of the facility.

While there are a number of tools available to provide designers with methods to assess and verify the extent to which design alternatives achieve these objectives, they tend to be simplistic and there is a need for empirical data to calibrate mathematical design tools to aid in the design process. While engineers have excellent tools and methods for determining slope stability, liquefaction potential and, even to an extent, beach angles, the availability and reliability of design tools to determine erosion and accretion rates on MRD slopes and soil formation is limited.

Verification of a design in terms of its ability to satisfy the key performance closure objectives generally takes several decades and for this reason, concurrent pollution control and rehabilitation methods are preferred over end of operational life solutions. The slope has to be tested and endure events to which it can reasonably be expected to be exposed including physical disturbance, fire, drought and floods. A sustainable solution should enable the slope to tolerate / be resilient to such events without an increase in emissions to the environment (including dust, radiological and toxicological impacts, surface water quality or seepage quality), and with minimal active intervention from people.

In this paper it is argued that MRDs with flatter slopes (typically 1-in-4 to 1-in-7) and preferably minimal terraces and ramps, stand a significantly better chance of achieving the closure objectives than those with steep slopes (typically around 1-in-3) that have been used in the past. This is despite a probable increase in slope length and final height of the facility (provided that slope length is attenuated by roughness and aggregate stability elements) Flattening the slope improves the chances of achieving a sustainable solution for a number of reasons including:

- Enhanced infiltration,
- Reduced erosion rate and gully formation,
- Reduced capillary rise,
- Improved vegetation cover,
- Reduced exposure of acid generating materials or products of acid generation on surface and hence
- Improved runoff quality.

While flatter design slopes are likely to result in significant improvements to surface runoff quality, there is insufficient evidence at this stage to suggest that this alone can achieve the requirement that the soil formation rate (measured as the accretion rate) must at least equal the erosion rate. The little data available suggests that reducing the erosion rate further, or increasing the soil formation rate, requires additional measures over and above slope reduction.

It is argued that vegetation selection should in future focus more on tolerant perennial species, including woody plants, with dimorphic (surface and tap), and fibrous root systems. Such vegetation types offer advantages in terms of:

- Reduced wind and water velocities at surface and hence reduced dust emissions and run-off,
- Sub-surface erosion control,
- Enhanced evapotranspiration to reduce seepage,
- The provision of pathways to get oxygen to deeper layers to broaden the oxidation front,
- Formation of stable aggregates by roots and micro-organisms to bind the mine residue, and
- Longevity and tolerance to adverse conditions

A number of other measures are proposed that could be considered to further reduce the erosion rate on a MRD slope. A combination of these measures, together with flattening of the slope may well prove to provide a sustainable closure approach, together with improved runoff quality and reduced seepage.

It should be noted that the closure design objectives may significantly alter the method of tailings deposition in future as traditional approaches such as the common daywall system used in South Africa are impractical on shallow slopes. However, as with all design, the method of construction should be adapted to suit the desired outcome and not the desired outcome adapted to suit the method of construction. Innovative construction methods will be called for to meet the desired outcome.

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