WASTE ROCK DUMP DECOMMISSIONING AT MINES IN NORTHERN WESTERN AUSTRALIA

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ABSTRACT

Mine waste rock dumps in northern Western Australia are frequently some 400 m high with bench faces of up to 60 m in height. The dumps are located in a region susceptible to tropical cyclones and regularly experience high intensity rainfall events over the wet season. The majority of the dumps are highly erodable and at the same time experience large consolidation settlements. Moreover, frequently, minerals such as pyrite, talc and chlorite present in the waste rock materials release hydroxides and inorganic salts such as Ca SO_4 and $MgSO_4$ which are mobilised by infiltrating water and are released as seepage at the toe of the dumps. The resulting contamination, together with large scale erosion issues, poses significant long term decommissioning challenges. A range of decommissioning alternatives that address infiltration, erosion, settlement, and storm control issues to varying degrees have been conceptualised and evaluated on the basis of practicality, effectiveness, cost and reliability. This paper describes the evaluations with an emphasis on the key issue of erosion management and control.

INTRODUCTION

Decommissioning of mine waste structures in northern Western Australia, a region susceptible to cyclone events, presents specific problems associated with erosion control as well as dispersion of leached salts through infiltration and seepage. Even where the waste comprises blasted waste rock the intensity of rainfall and associated runoff is sufficient to erode significant tonnages of rock from the slopes of the dump. This erosion is exacerbated if there are fines in the waste rock since the fines reduce infiltration and increase runoff. Slope erosion, and the subsequent deposition of eroded material on benched or terraced areas of waste rock dumps, results in re-profiling of the benches or terraces with time with the result that over time water ponds increasingly closer to the outer crest of the bench or terrace raising the probability of breaching crest walls. Once flow over the outer crest begins to occur slope erosion increases exponentially because the catchment area suddenly includes the bench or terrace area.

Mining economics frequently dictate that waste rock be dumped in a series of terraces so as to minimise the haul distances and gradients. More specifically, where, waste stripping is carried out at higher elevations, the tendency is for waste rock to be dumped along the natural slope in a series of benches. The benches are tied in to lower terraced areas and frequently result in effective waste rock dump heights of 400 m.

Figure 1 below indicates a typical waste rock dump in the Kimberley region of Western Australia. High elevation benches are evident together with lower elevation terraced areas.

Figure 1: View of a waste rock dump in northern Western Australia

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. The issues are further complicated by the scale on which dumps from open cast mines are generated. Not only are these high and terraced, but they are also extensive in area due to the waste stripping ratios inherent to this form of mining. Figure 2 shows the projected layout of the dumps indicated in Figure 1. The crest of the dump will advance some 700 m from that indicated in Figure 1.

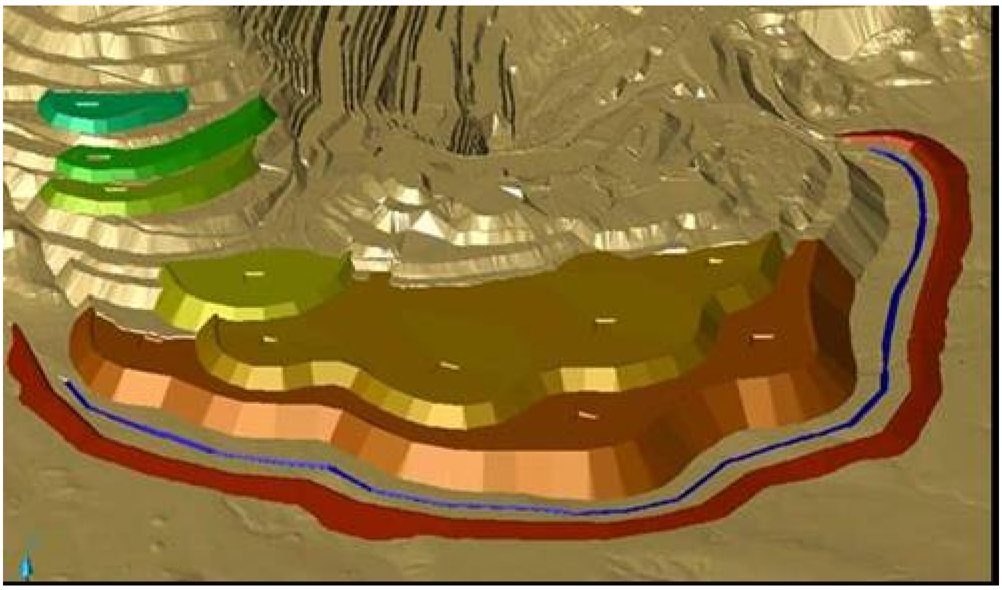


Figure 2: View of the waste rock dump as at the end of mining

This paper describes assessments carried out on a number of decommissioning concepts for a dump such as indicated in Figure 2. Each concept has been developed to reduce erosion and infiltration. The advantages and disadvantages are set out and a conclusions drawn as to the merits of a novel approach that would take advantage of specific waste rock types to simultaneously address both the infiltration as well the erosion issues.

CONCEPTS EVALUATED

Stepped profile concept

It has been well established by Willgoose and other researchers [1] and [2] that over the long term slopes erode to a concave profile where the eroded slope gradient is steeper at the upper reaches of the slope and flatter at the lower. It is therefore logical that if the slope profile is constructed as close as practical to the anticipated long term concave profile the total erosion would be minimised. Figure 3 below illustrates a stepped profile for a waste rock dump constructed on steeply sloping ground. The bench heights of the terrace are maintained constant and the terrace widths are widened in the lower parts of the slope to achieve the concave profile.

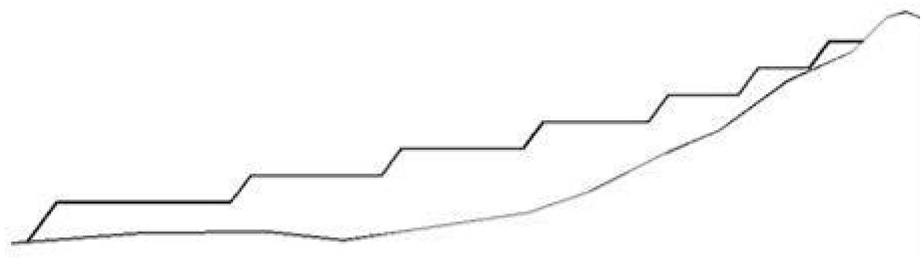


Figure 3: Schematic of a stepped profile for a waste rock dump

A number of drawbacks to the stepped profile concept become evident the moment the concept is considered in detail. These are:

- The profile can be costly to construct in as the bulk of the waste rock is placed in the wider terraces which are at low elevation and are also furthest from the source.
- While dozing of the slope faces between the benches would further improve the approximation to the long term eroded profile it would be costly and, seeing as nature would achieve the same end naturally, probably unnecessary. However, regulators are reluctant to allow residual slopes at natural angle of repose even on terraces and it will be necessary to doze these down to a slope of 20 to 25 degrees. Given the number and lengths of the slopes, dozing costs are likely to be high.
- The concept does little to reduce infiltration and therefore does not address leaching problems that may be associated with acid rock drainage products and the like.

Surface drainage concept

Controlled discharge from the waste rock dump is a concept frequently considered. Figure 4 below illustrates a surface drainage concept in an application of a terraced waste rock dump of large area.

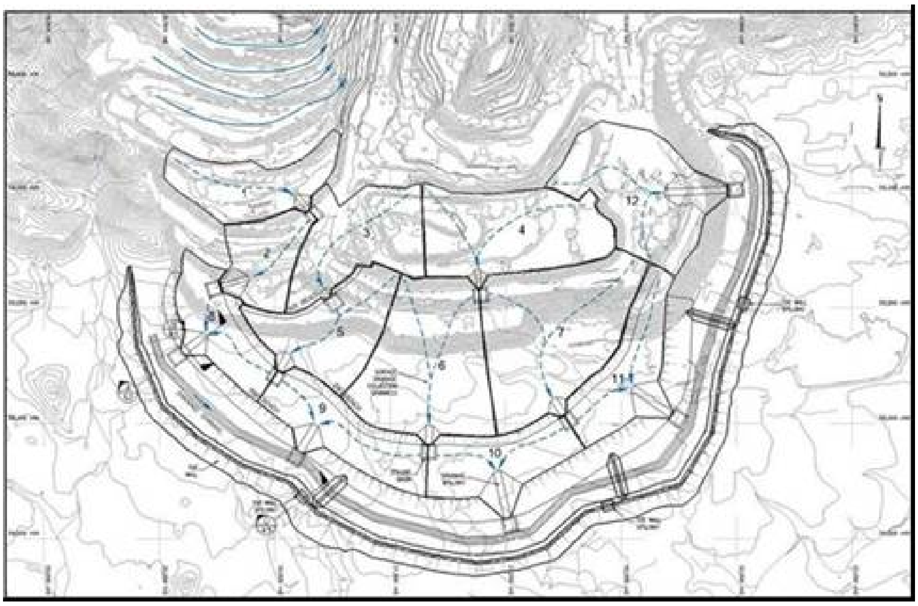


Figure 4: Surface drainage concept applied to a waste rock dump of large area

Notable features of the concept as illustrated are:

- Provision of discharge channels to transfer the water from one terrace level to the next as well as the provision of stilling basins with each discharge channel.
- Formation of drainage trenches on the surface to direct runoff to the discharge channels. These would be lined to reduce infiltration
- Paddocking off of the surface into controllable areas and shaping to encourage flow to controlled areas with minimal infiltration
- Provision of a toe bund to capture material eroded from the slopes.

Issues that emerge from detailed evaluation of this concept in the context of long term rainfall patterns are as follows:

- Flow rates down the drainage channels range from 10 to 15m^3/s and velocities are above 4m/s making it necessary to line the channels
- The channel linings need to be flexible as the rock will settle differentially after construction. This implies the use of gabion and reno mattress structures as liners and even then these are close to their limit at velocities of 4m/s..
- Differential settlements in the channels will cause localised concentration of flow and therefore localised velocities in excess of 6m/s which will considerably increase the risk of failure of the gabions and reno mattresses.
- The channels are costly to construct and costlier still to line. In the example illustrated costs were of the order of $15 million.
- Differential settlement of the terraces which may cause changes in surface drainage and thereby increase infiltration

Sub-surface drainage concept

A sub-surface drainage concept would make use of the fact that certain of the waste rock types on a mine may have lower fines and be inert. Typically zones of a benign hard rock such as quartzite could be interbedded with other materials and could be used to provide preferential drainage routes through the rock dump. The concept is illustrated in Figure 5 below.

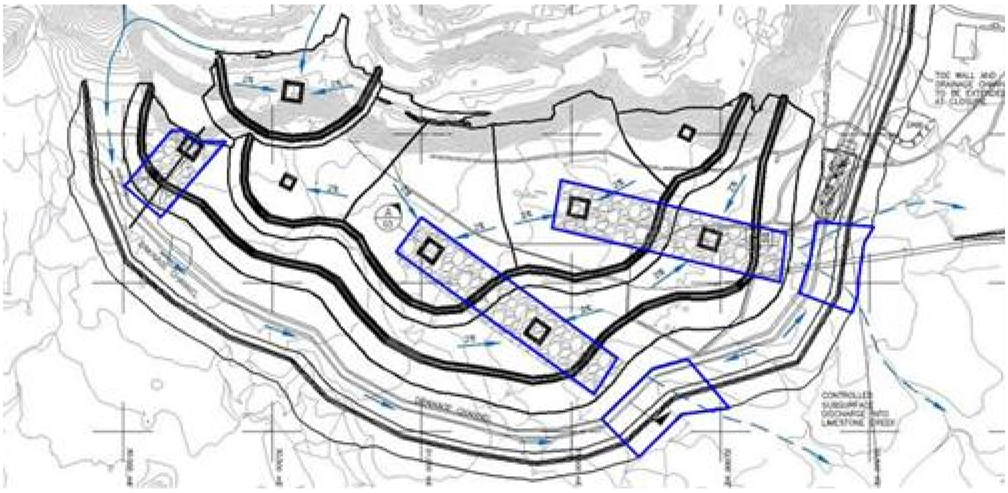


Figure 5: Sub-surface drainage concept

Notable features of the concept are:

- Placement, as part of routine mining operations, of zones of quartzitic material 200 m wide and 30 m high aligned with natural drainage channels in the original topography
- The formation of sumps which connect the quartzitic zones. The sumps would capture surface runoff directed to the sumps via drainage trenches as per the surface drainage concept described above and then allow infiltration to the toe area via the quartzitic zone. This is illustrated in Figure 5 below. Drainage in the sumps would be predominantly from the side slopes as the base of the pit would be sealed by sediments drawn into the sumps. This is illustrated in Figure 6 below.

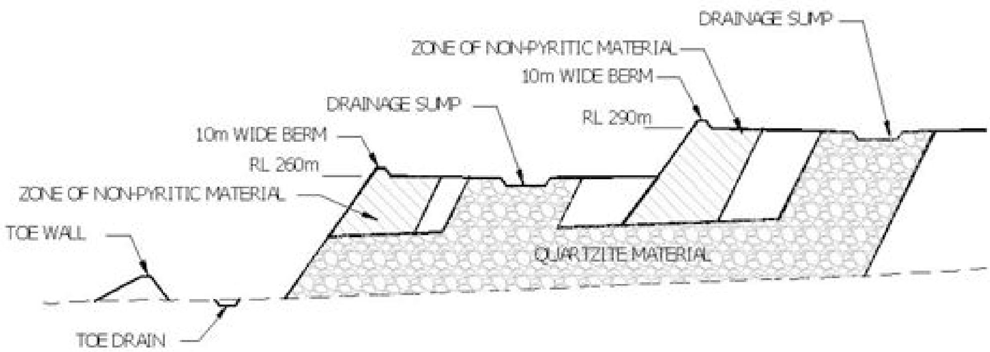


Figure 6: Typical section through quartzitic rock preferential drainage zones

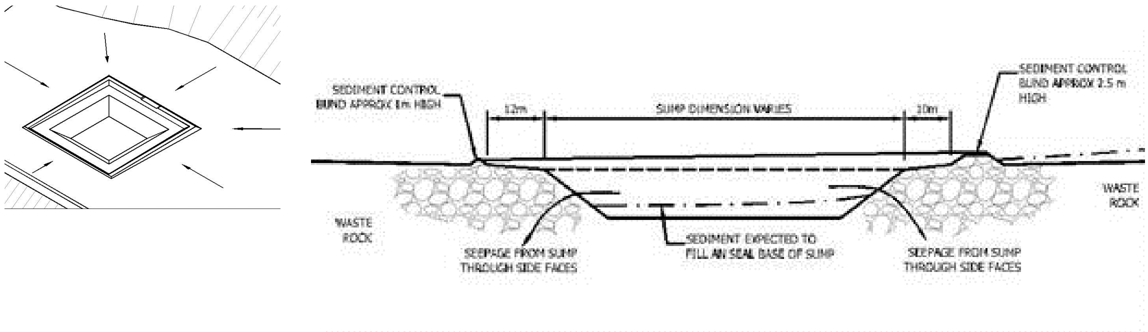


Figure 7: Typical section through an excavated pit.

Issues of concern relating to the above sub-surface drainage concept are :

- The reliability of the sumps in terms of long term drainage rate and rate of filling with sediments
- Blinding of the quartzitic zone by sediments drawn from the sumps
- Differential settlement of the terraces which may cause changes in surface drainage and thereby increase infiltration
- Reliability of construction given the vagaries of mining conditions and difficulty of controlling construction.

Store and release concept

A typical store and release concept as applied to waste rock dumps would entail the following :

- Paddocking off of the dumps as in the surface and sub-surface concepts
- Placement of a 0.5m compacted clay layer or layer containing sufficient clay materials to form a plastic seal to the rock surface as well as sufficient clay to prevent migration of the clay during seepage
- Placement of a 2m zone of waste rock with fines. This zone is paddock dumped and flattened without introducing compaction. Vegetation is established in this zone (hence the reason for fines).

The store and release concept operates by trapping and storing rainfall runoff in a perched zone above the clay liner and within the loose waste rock zone during the wet season. Over the year this water is evapo-transpirated by the vegetation established in the uncompacted waste rock zone. The clay layer reduces infiltration to a minimum during the store and release cycle.

Issues of concern in regard to this concept are:

- Availability of suitable clay materials. These would need to come from disturbed areas and would have to be stockpiled until the dump is completed. Substitution of the clay materials with low permeability silty materials or even benign tailings would increase the risk of erosion of the layer into the waste rock and subsequent rat-holing.

- Differential settlements will cause cracking in the clay liner and possibly vertical displacements. These will reduce the effectiveness of the liner and concentrate flows into the rock fill.
- Double handling of the clay materials combined with strict control of clay placement and compaction will be costly. Over a 300 ha dump area the clay liner would cost of the order of $10 million.

WHICH CONCEPT IS APPROPRIATE ?

Selection between the concepts will be dependent on specific site conditions and waste dump geometries. With the exception of the sub-surface drainage concept all of the other concepts have been applied in northern Western Australia with varying degrees of success. None of these concepts have been in place longer than 10 years.

The sub-surface drainage concept is untried but has considerable merit. Unlike the stepped profile it is able to address the issue of infiltration and has the potential to limit erosion rates to a greater extent. Unlike the surface drainage and the store and release concepts it is low cost provided the mining schedules allow placement of the preferential drainage zone as part of routine mining. There are increased costs for the mining of the drainage zone material but volumes are limited and costs relate only to the extra over haulage rate.

Since the sub-surface drainage concept has not been explored to the same extent as the other three, and it has specific merit in a number of operations, this paper goes on to describe evaluations relating to sedimentation of the sumps as well as to overall erosion performance. The hydraulic and hydrological assessments follow routine and established techniques well documented in the literature and therefore do not require in-depth exploration in this paper.

EROSION ASSESSMENTS FOR THE SUB-SURFACE DRAINAGE CONCEPT

Since the primary issue of concern relates to sedimentation of the sumps and this sedimentation will occur as a result of erosion from terrace slopes above the sumps it was decided to carry out erosion simulations using SIBERIA as set out below.

SIBERIA Model

SIBERIA is a long term erosion model developed by Willgoose [3] in 1989 to explore the linkages between the time evolving geomorphic form of natural landscapes and the hydrology and erosion processes occurring on them, and how these processes, in turn, determine the future evolution of the natural landform. SIBERIA works with a gridded digital terrain model which evolves in time in response to runoff and erosion derived from physically based erosion models. SIBERIA is the only commercially available erosion simulation software that is able to model gulley development as well as overall erosion rates.

SIBERIA is based on commonly accepted erosion physics specifically relationships between catchment area and runoff rate such as that typically used in regional flood frequency analysis :

$$Q = \beta_3 A^{m_3} \qquad (1)$$

where Q is the characteristic discharge out of the catchment, β_3 is the runoff rate and A is the catchment area. The characteristic discharge is the mean peak discharge.
The erosion model is similar to that used in traditional agricultural sediment transport models where the rate of sediment transport is related to discharge, slope and a transport threshold :

$$Q_s = \beta_1 Q^{m_1} S^{n_1} \text{ - } threshold \qquad (2)$$

where Q_s is the mean annual sedimentation rate, β_1 is the erodability (including the material erodability, vegetation cover factor and any cropping practice factors (USLE terminology)), S the slope and m_1 and n_1 are parameters to be calibrated for the erosion process. The erosion is relatively insensitive to the exponent n_1 which is commonly taken as 2. The exponent m_1 is modified during calibration to ensure that the concavity of the modelled slope is similar to the prototype. Commonly m_1 is in the range 1 to 1.5. The threshold is a simple allowance for shear stress mobilisation of the material.
The threshold term applies to armoured slopes of clean (no fines) or bound materials which is not the case for the surface materials at Osborne and may therefore be discarded.

Equations (1) and (2) may be combined to yield equation 3 below :

$$Q_s = \beta_1 \ \beta_3^{m_1} A^{m_1 m_3} S^{n_1} \text{ - } \qquad (3)$$

Solution of the above two equations by finite elements at each grid point is effected by Siberia to derive the eroded position of the grid point at the end of each time step. The eroded topography is therefore being continuously updated thus enabling the simulation of gulley formation.

Model calibration

A number of methods for obtaining the erosion parameters for SIBERIA exist :

- Rainfall and runoff testing using rainfall simulators on test areas of 10 m by 2m. This testing is routinely carried out within Australia and involves the calibration of erosion rates using WEPP and translation of these erosion rates to SIBERIA by calibrating erosion over the test area. Dr Rob Loch [3] has been a leader in this form of testing.
- Controlled flow through a series of flumes constructed on the sides of dumps and tailings dams. This method does not simulate rainfall runoff but allows the impact of high flow rates on a range of armouring methods to be assessed.
- Calibration of erosion rates from digital mapping of eroded slopes.

In the assessments described below the approach of calibrating erosion rates from digital mapping has been carried out.

Figure 8 below shows a slope comprising waste rock materials in northern Western Australia where, other than for reinstatement of the crest of the slope, no significant dumping has taken place over 7 years. This slope has been mapped, initially from aerial photography and later using laser mapping techniques. The slope as at 1996 has been set up as an initial surface within SIBERIA and a series of simulations over a 7 year period carried out with a range of parameters and the predicted and actual eroded surfaces compared on the basis of hypsometry and overall eroded surface. Figure 9 shows a section along the slope and indicates the initial surface (blue) the final surface (red) and the calibrated surface (green). It should be noted that a specific flood event occurred in 2001/2 that caused overtopping of the crest wall and the erosion of a number of deep gulleys. It is has not been possible to simulate these deep gulleys. SIBERIA is not suited to modelling of specific flood events. However, the calibration on the long term surface in matching overall erosion depth and gulley spacing is good.

The parameters derived from the calibration are considered reasonable for long term simulation because it is evident from assessment of the slope area characteristics of the long term gulleys that they have eroded to depths characteristic of the natural armouring of the rock. Over the long term, therefore, while there will be continued erosion of the slope, gulley depths will remain relatively consistent for cases for cases where slopes erode due to runoff only from the slope i.e. not from an areas above the slope.

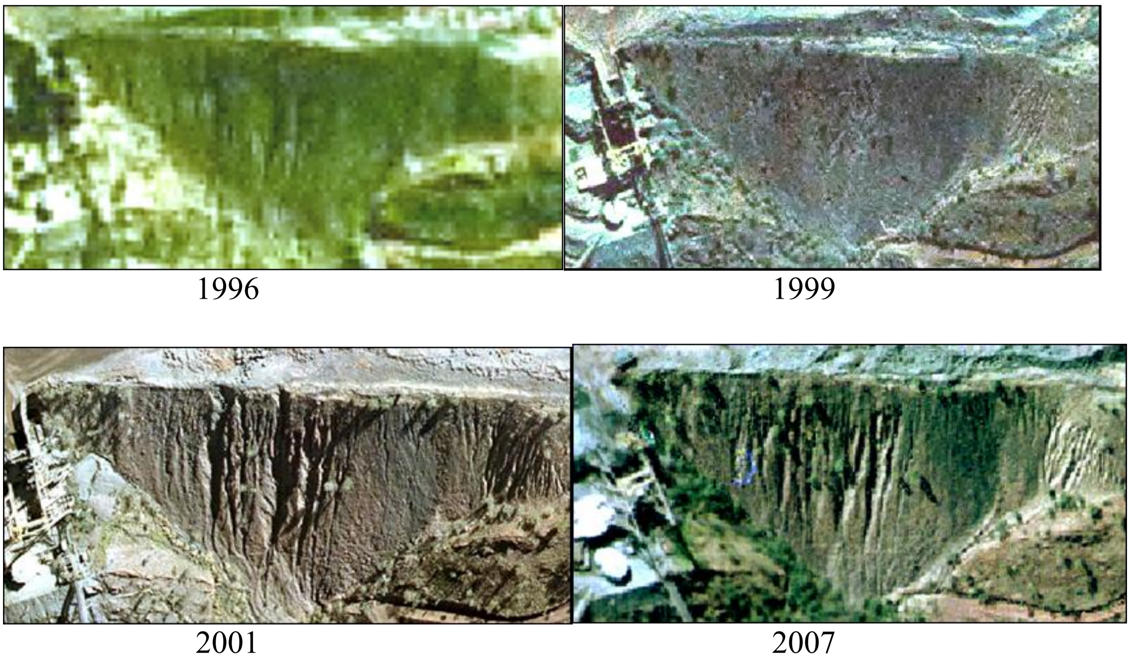


Figure 8: Aerial photos of a slope subject to erosion over 7 years

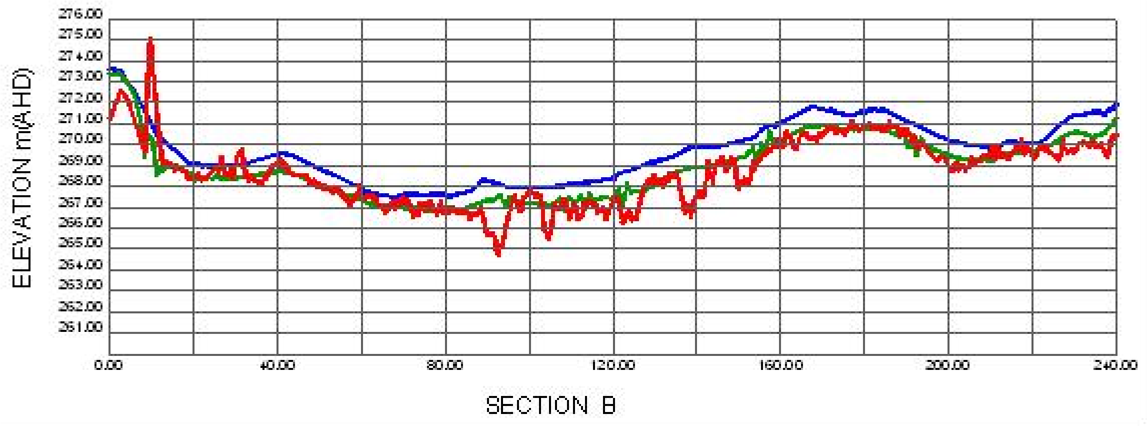


Figure 9: Section through eroded slope showing the initial and final surveyed surfaces as well as the calibrated surface

Erosion rates are significantly reduced where vegetation is established on a slope. In this respect the slope in Figure 8 provided useful calibration information as, other than for the large gulleys, the remainder of the slope has some vegetation cover.

Overall dump erosion

Based on the above parameters, SIBERIA has been used to simulate erosion of the waste rock dump indicated in Figure 2. It was found in initial simulations based on the pit layout indicated in Figure 5 that the sumps filled with sediment within 50 years. This was clearly unacceptable so the layout in Figure 5 was modified to that indicated in the initial dump in Figure 10. Figure 11 shows the geometry of the main terrace.

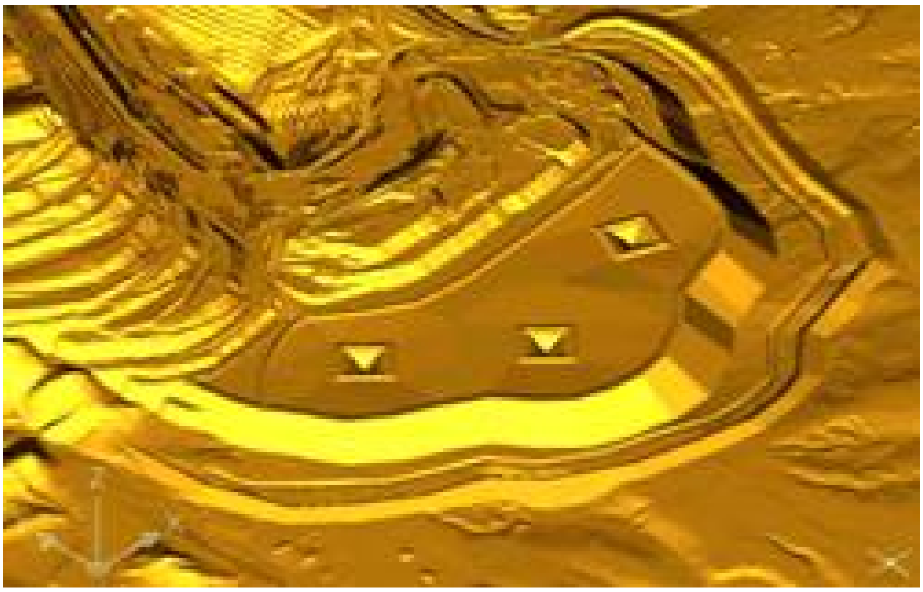


Figure 10 : Modified layout of sumps in sub-surface drainage concept

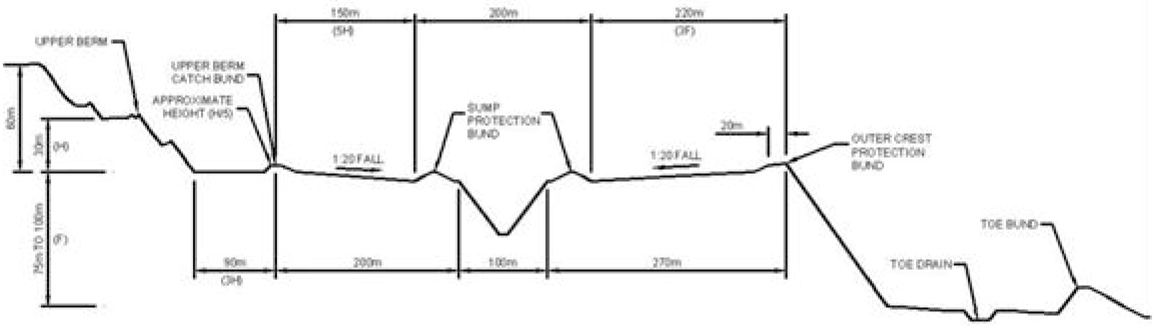
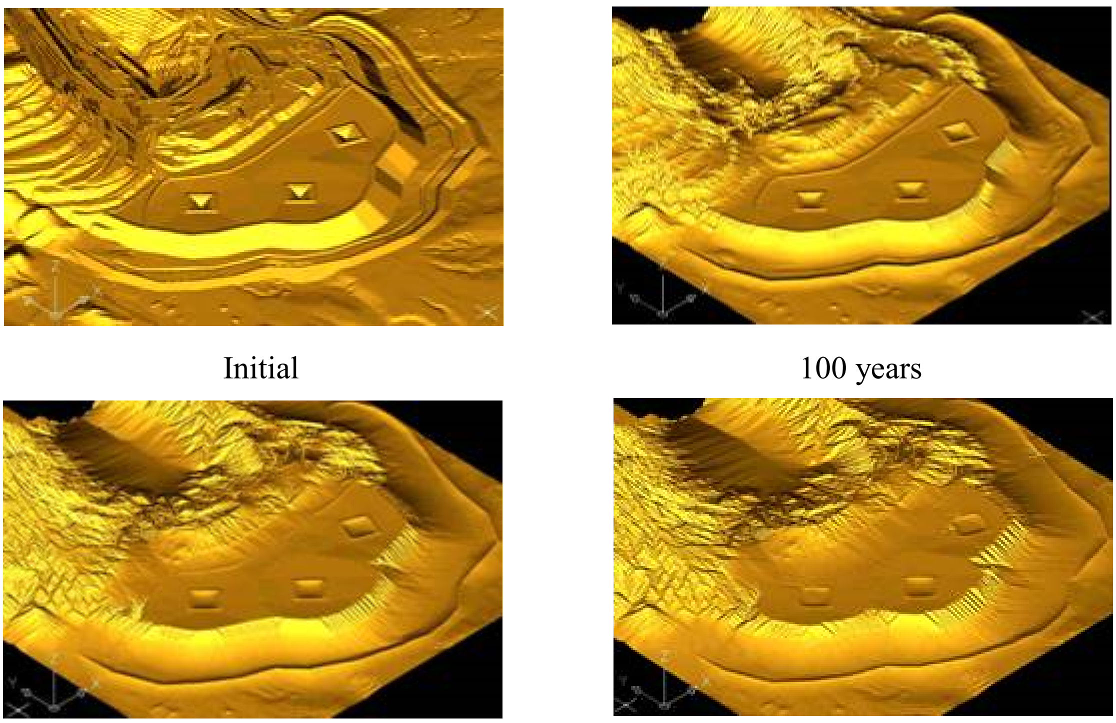


Figure 11: Preferred terrace geometry from SIBERIA simulations

Features of Figures 10 and 11 that are note worthy are :

- The application of a waste rock bund along the back of the main terrace. The purpose of this bund is to retain the majority of the sediments eroded from the slope and terrace above. Because the bund is constructed of waste rock, runoff would permeate through to the main terrace.
- The use of deeper sumps protected by waste rock bunds around the crest of each pit. Pit numbers have been reduced and the pit areas increased accordingly. The increased pit depth arises from controlled dumping of the waste rock and makes it unnecessary to do any excavation.
- The elimination of the front terrace which, it was found, overtopped within 100 years due to erosion from the slope above.

Figure 12 below shows the eroded dump at 100, 300 and 500 years.



Initial 100 years

300 years 500 years

Figure 12 : Results of SIBERIA erosion simulations

From a design perspective, two aspects are immediately apparent from the results indicated in Figure 12. These are :

- The toe confining bund can be lowered over most of its length i.e. the initial assumptions are conservative.
- The bund along the back of the main terrace should be raised. This will provide additional sediment holding capacity and protect the sumps to a greater extent.

Figure 13 below shows the eroded profiles along a section through the main terrace at intervals up to 1000 years. It is interesting to note that by 1,000 years the main terrace has overtopped and the terrace as a whole begins to erode.

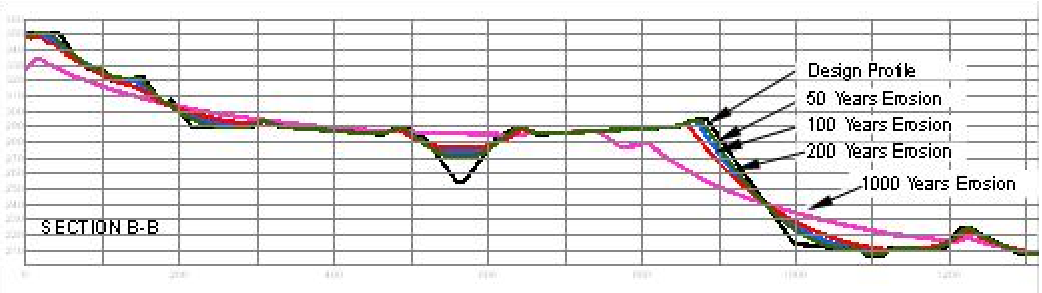


Figure 13: Section through the main terrace showing eroded profiles

Figure 14 below shows a section along the slope of the main terrace and indicates erosion depths and gulley formation.

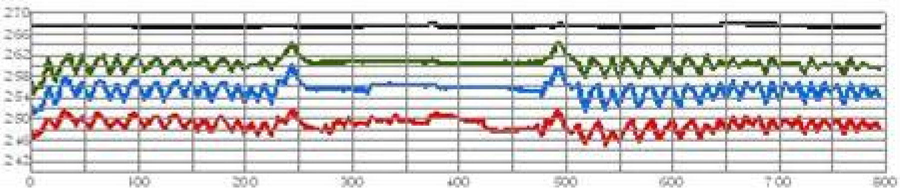


Figure 14: Section along the slope of the main terrace showing eroded depths and gulleys

A key question that could be raised at this stage is that of reliability of erosion predictions. Clearly these are influenced by parameter selection and the extrapolation of the parameters derived from a 7 year calibration over 1,000 years. This is entirely valid but the fact is that there is no way of being able to improve reliability without a more extensive record. However, the value of the simulations lies primarily use in comparing design concepts. In the final analysis whether the predicted erosion profile occurs in 200 years instead of 300 years is largely immaterial provided the design is robust enough.

Side slopes

The erosion simulations described in the previous section were based on a single slope at natural angle of repose. The simulations indicated the extent of erosion of this slope which could be taken as the worst case or maximum erosion scenario. Figure 15 below shows the eroded profiles in the slope face at 500 and 1,000 years. Figure 16 shows the 500 year eroded profile for a 20 degree slope after simulation in SIBERIA and Figure 17 the 500 year eroded profile of a stepped slope.

Table 1 shows a comparison of the eroded volumes for a range of potential profiles

Table 1: Comparison of total eroded volumes for a range of slope profiles

Case	Description	Eroded volume as a percentage of the volume for a natural angle of repose slope
Base	Erosion of natural angle of repose slope	100%
1	Slope dozed to constant 20 degrees	85%
2	Optimal stepped profile (based on construction constraints)	72%
3	Theoretical profile dozed initially to 500 year natural angle of repose eroded profile	50%

Table 1 shows that even if the slope is dozed to the projected 500 year profile for the natural angle of repose, it is unlikely that the total erosion after 500 years will be less than 50% of that for the natural angle of repose. Further optimisation of the stepped profile has shown that it could be reduced to 68% but this will require an impractical number of benches.

Figure 15: Eroded profiles for slope at natural angle of repose

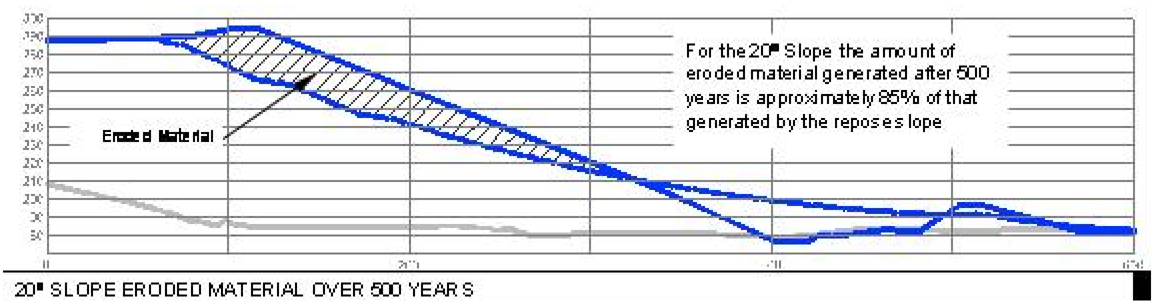


Figure 16: Eroded profile at 500 years for slope at an initial slope of 20 degrees

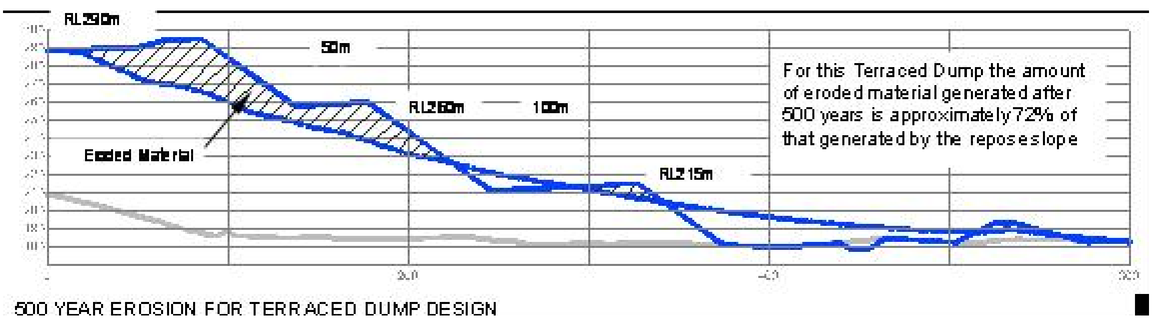


Figure 17: Eroded profile at 500 years for a stepped profile

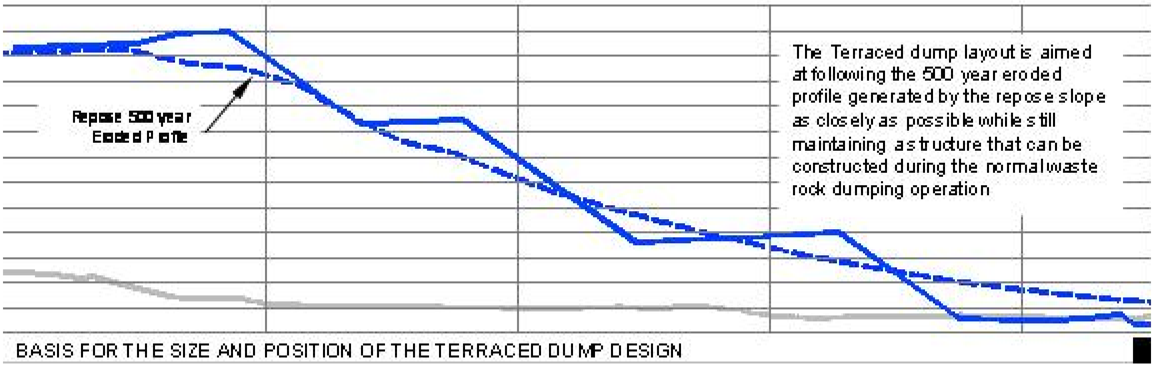


Figure 18: Optimised stepped profile.

It should be noted that in Western Australia, the regulators take the viewpoint that no slope should be left at natural angle of repose for reasons of safety of the public who may chose to go climbing up the slopes. This is not a stability criterion but one based on issue of public liability. To meat this stipulation it would be best to create the stepped profile and doze individual benches down such that the final dozed profile is as close to the 500 year profile as practicable.

Figure 19 below shows the waste rock dump with the optimised stepped profile.

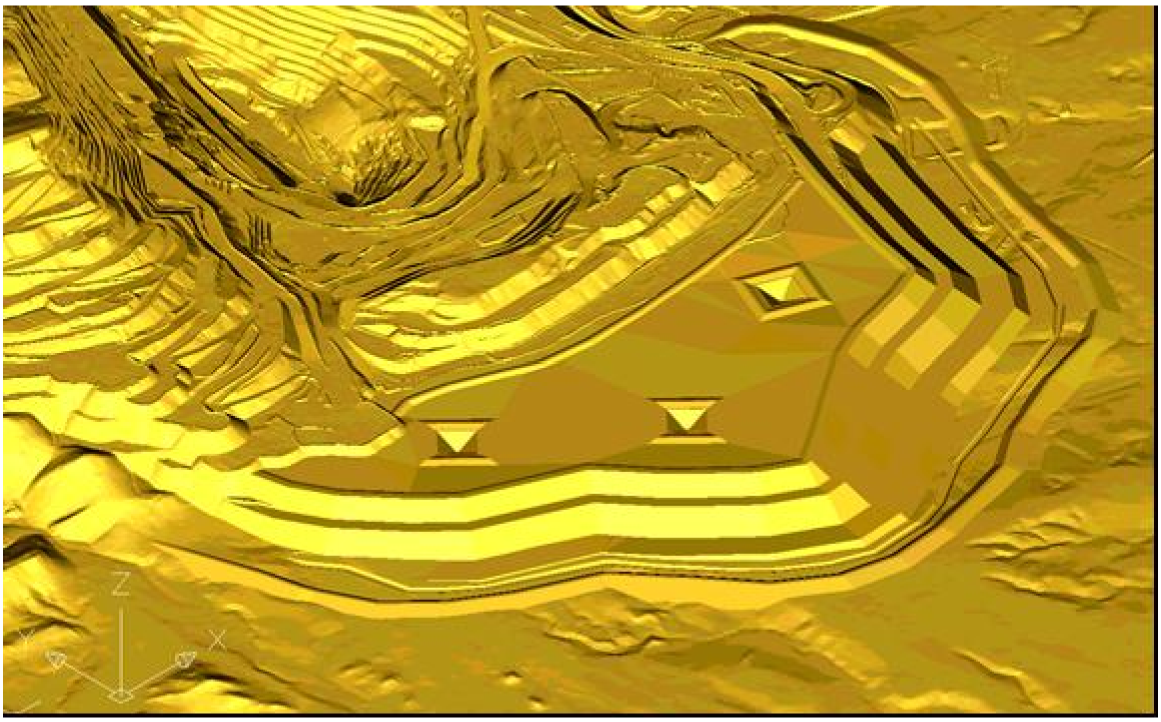


Figure 19: Isometric showing dump with optimised stepped profile.

CONCLUSIONS

The following conclusions are drawn :

- There three erosion and infiltration control concepts that are generally being applied to the decommissioning of waste rock dumps, namely the construction of a concave, stepped profile that approximates the final predicted erosion profile, surface drainage control and shedding, and store and release. None of these has an extended track record in Western Australia and each has a number of issues that require detailed consideration. Selection between these will be a function of specific site conditions.

- A fourth concept of creating drainage sumps on the top surface of the dump and providing preferential drainage zones that enable water collected in the sumps to discharge at the toe via sub-surface flow has been described. Like the other three the efficacy of this approach is dependent on specific site conditions.
- Of the concepts evaluated all but that involving the creation of a stepped profile over the full dump height consider the issue of minimisation of infiltration, an important issue where infiltrated water will become contanminated with salts generated within the dump and then released as seepage at the toe.
- A key issue to be addressed in assessing the sub-surface drainage concept relates to reliability of the sump operation and most specifically to sedimentation of the sumps. This paper has shown that there are methods to assess this using SIBERIA to simulate long term erosion.
- Like all modelling the results are only as good as the input data and for this reason a method of calibration that takes account of natural armouring as well as the effects of vegetation by using historical survey data of an established eroding slope has been demonstrated.
- Erosion modelling provides a method for optimising between and within design options.

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