Report on:

COMPARISON OF THE EROSIONAL PERFORMANCE OF ALTERNATIVE SLOPE GEOMETRIES

Prepared for

KALGOORLIE CONSOLIDATED GOLD MINES PTY LTD

PROJECT NO. 343-002
REPORT NO. 01/09

SEPTEMBER 2009

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Environmental Engineers (Australia) Pty Ltd

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COMPARISON OF THE EROSIONAL PERFORMANCE OF ALTERNATIVE SLOPE GEOMETRIES

1 INTRODUCTION

Kalgoorlie Consolidated Gold Mines Pty Ltd (KCGM) requested Metago Environmental Engineers Ltd to develop a scope for the evaluation of waste rock dump design and management strategies. At the meeting held on 10 August 2009 at the offices of Kalgoorlie Consolidated Gold Mines Pty Ltd (KCGM) it was agreed to carry out erosion modelling as an essential part of project work. The erosion modelling work would include:

- Initial SIBERIA[1] modelling of potential slope and batter arrangements using generic erosion modelling parameters representative of the Kalgoorlie area. The results will be used to guide outer slope specifications to be used in the first stage of Dumpsolver modelling.
- Development of KCGM-specific erosion modelling parameters for cover materials based on survey data for historic rehabilitation and trial areas.
- Detailed SIBERIA modelling and refining of waste landform designs generated by Dumpsolver and with application of the KCGM-specific parameters.

As a precursor to the initial Siberia erosion modelling the erodability of five potential cross sections was compared. A review of these results led to the identification of three slope potential slope geometries further, more detailed, erosion assessment

[1] SIBERIA is a long-term erosion model developed in 1991 to simulate 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. These models are based on commonly accepted erosion physics specifically relationships between catchment area and runoff rate.

Erosion simulations with two sets of erosion parameters representing anticipated upper and lower bound parameters have been conducted for periods of 50 and 250 years. The results of the modelling have been analysed, compared and, from these, conclusions drawn as to the erosion performance of final dump landform.

Meteorological data indicates that the area around the KCGM mine site receives on average 264 mm of precipitation a year mainly in the form of short-term storms. While this is relatively low, saline, dispersive materials perform poorly in terms of a growth medium for the dump slopes and these materials are highly erosive. Therefore hard rock cover mixed with available topsoil is considered the most practical a means to maximise erosion protection of dump slopes. This conclusion has guided the selection of erosion parameters for the initial erosion assessment documented in this report.

It is important to note that the estimation of erosion parameters has been carried using available information on the physical and chemical properties of the dump materials and has drawn on previous erosion modelling work at other similar sites. No specific erosion testing has been carried out at KCGM. It is, however, the intention to derive erosion parameters from site specific data in later stages of this project as indicated above.

2 TERMS OF REFERENCE

The terms of reference for the modelling and assessments documented in this report are as follows:

1. Model a number of dump slope geometries as part of an initial erosion modelling programme and make use of erosion parameters representative of the dump materials located in the Kalgoorlie area.
2. Conduct long term (250 year) erosion simulations on three alternative dump slope geometries.
3. Compare the erosion performance of the alternative slope geometries...
4. Document the above in a report.

3 SIBERIA EROSION MODEL

3.1 Description of SIBERIA

Erosion modelling has been undertaken using the SIBERIA landform evolution model. SIBERIA is a long term erosion model developed by Willgoose et al. 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.

These models are 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, A is the catchment area and m_3 is a coefficient. 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:

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

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 unlikely to be the case for the surface materials at KCGM and may therefore be discarded.

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

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

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.

Over an extended period the parameters β_3 and m_3 remain essentially constant. It is therefore possible to write equation (3) as:

$$Q_s = \beta_1^{'} A^{m_1 m_3} S^{n_1} - \qquad (4)$$

Where

$$\beta_1^{'} = \beta_1 \beta_3^{m_3} - \qquad (5)$$

Where calibrations are conducted using surveys of dumps over an extended period, and where the rainfall that occurred over that period can be regarded as representative of the long term average and incorporates unseasonably high as well as low rainfall periods, it is possible to carry out the calibration to determine $\beta_1^{'}$ directly without the need to consider and specifically account for the rainfall-related parameters β_3 and m_3.

3.2 Erosion parameters

It is the intention to develop KCGM-specific erosion parameters through back analysis of erosion as measured from historical aerial surveys. This will be carried out once survey data becomes available. To facilitate on-going planning in the mean time it is appropriate to carry out the modelling using a range of erosion parameters that will represent upper and lower bounds of the parameters.

To establish the upper and lower bounds the physical properties of dump materials have been considered. Average rainfall mainly caused by short intensive storms at Kalgoorlie has also been taken into account.

Table 1 below indicates the two sets of erosion parameters that have been selected.

Table 1: Upper bound and lower bound erosion parameters

Parameter	Upper bound	Lower bound
β_1'	0.046	0.017
M_1	1.36	1.36
N_1	2	2

3.3 Incorporation of contour ripping

The surface of a slope at the end of construction will show undulations and irregularities as a result of vehicle tracks, construction tolerances, and material variability. These undulations and irregularities act as seed points for the onset of erosion. Similarly deep contour ripping to promote the establishment of vegetation presents a roughened surface parts of which will act as seed points for erosion as the rips overtop at low points.

To representatively simulate erosional behaviour it is essential to incorporate these into the starting surface.

To achieve this, an initial digital terrain model has been created using a "Random Surface" function in Land Desktop in which:

- Berm crest and toe variations have been simulated by incorporating a typical horizontal variation of ±0.1m in the horizontal plane and ±0.05 m in the vertical plane the crest.
- Deep rips have been simulated by incorporating contour channels 1m wide and an average of 0.3m deep.

4 ALTERNATIVE SLOPE GEOMETRIES

As a precursor to this assessment five alternative slope profiles were simulated so as to obtain guidelines for defining slope profile options. It was apparent from these simulations that:

- It is vital to prevent any runoff from the top surface of the dump from overtopping the uppermost crest.
- A stepped profile where runoff over tops the crests of the benches forming each step erodes significantly higher than a single concave slope. It is therefore essential, if a stepped profile is to be adopted, that each bench be shaped so as to prevent inter-bench runoff.

- A concave profile performs significantly better than a uniform slope profile.

It is a practical dump truck-based safety requirement that any benches be 40m wide.

Armed with these points the following slope profiles were selected by the project team for initial evaluation.

4.1 Option 1: Single concave slope

Option 1 slope surface geometry is based on a concave slope derived from the long term eroded profile of 20° slope 80m in height. The principle is that by constructing a slope at the anticipated long term profile from the outset the volume of material that will be eroded in the ensuing 250 years will be significantly reduced. To determine the long term eroded profile Siberia simulations have been conducted based on upper bound parameters to determine 1000 year erosion profile as indicated in Figure 1.

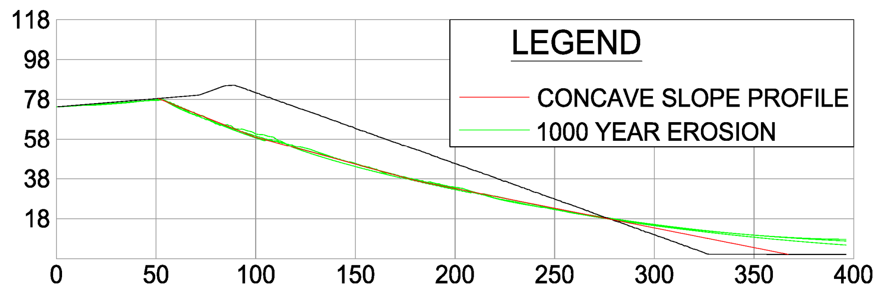

Figure 1: Eroded profile of 20° and 240m long slope

Figure 2 shows how the 1000 year eroded slope profile can be approximated by a series of straight slopes.

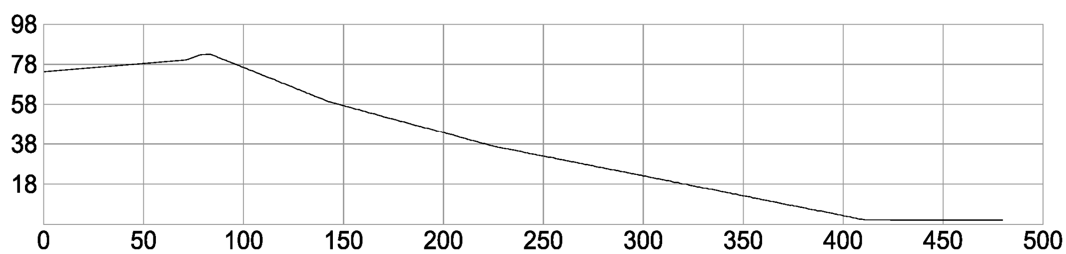

Figure 2: Option 1 slope - 80m high dump with single concave slope made out of 22°, 15.5° and 11.1° slopes with deep ripping and 5° back slopes

Figure 3 shows an isometric of Option 1 with a width of 350m and indicates deep ripping and undulations and irregularities generated on the slope surface.

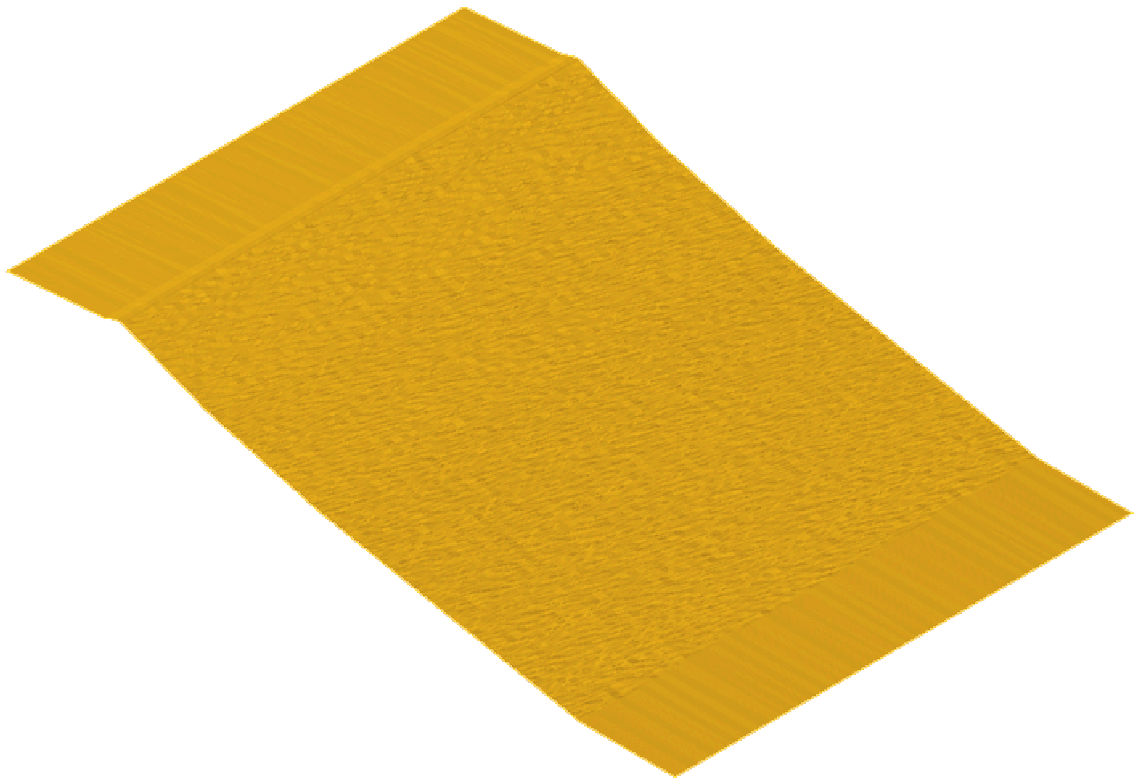

Figure 3: Option 1 slope isometric view

4.2 Option 2: Multiple stepped concave slopes with crest embankments

Figure 4 shows slope profile for Option 2 which comprises four 20m benches with concave inter-bench slopes where the concavity has been derived from the 1000 year eroded profile in a manner similar to Option 1. Each bench is constructed with a 5˚ back slope. Crest bunds 3m high are provided. Each crest bund has a crest width of 5m and the crest slopes inwards at 5˚. The objective in setting the crest bund height is to provide sufficient storage volume on each bench to retain the material eroded from the slope above the bench. The crest bund height has been determined from a series of erosion simulations with bunds of various heights.

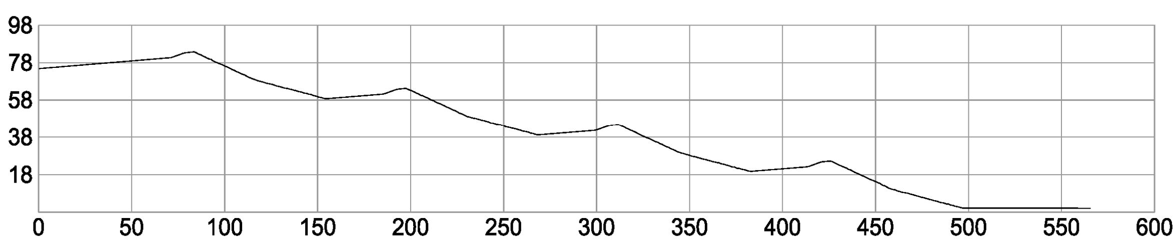

Figure 4: Option 2 - 80m high dump with three bund-protected 30m wide terraces, dual 25° and 15° slopes in between, 5° back slopes and deep ripping of slope surface

Figure 5 shows an isometric view of Option 2 with a width of 350m and indicates deep ripping and undulations and irregularities generated on the slope surface.

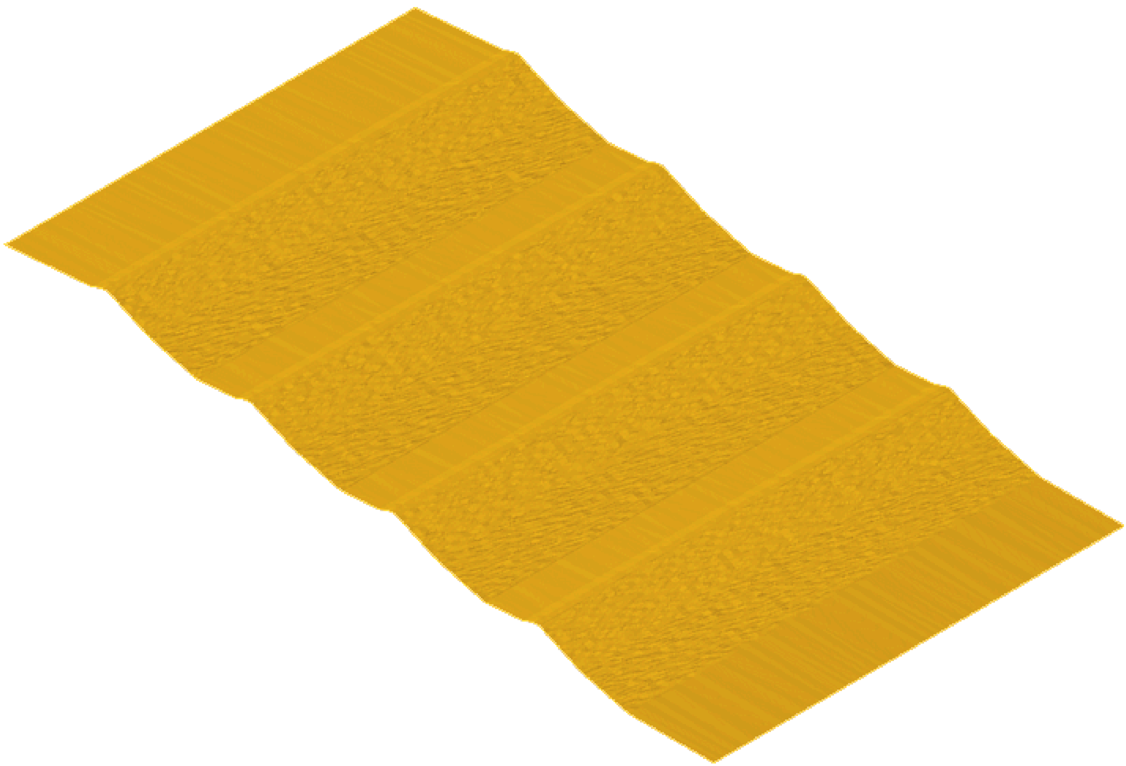

Figure 5: Option 2 slope isometric view

4.3 Option 3: Stepped slope with no crest embankments

Figure 6 shows Option 3 slope profile which comprises three equal benches over a total slope height of 80m. The slope between each of the benches is concave with the concavity derived from 1000 year modelling conducted similarly to Option 1. Each bench is constructed with a 5˚ back slope. No crest bunds are provided.

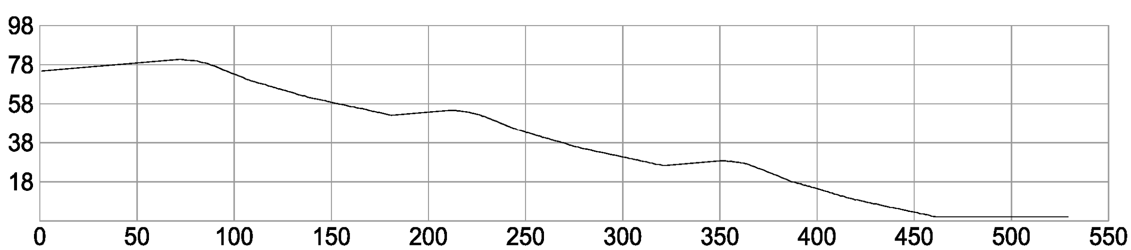

Figure 6: Option 3 - 80m high dump with three 30m wide terraces, rounded crests, triple 22° ,16° and 12° slopes in between, 5° back slopes and deep ripping of slope surface

Figure 7 shows an isometric of Option 3 with a width of 350m slope and indicates deep ripping and undulations and irregularities generated on the slope surface.

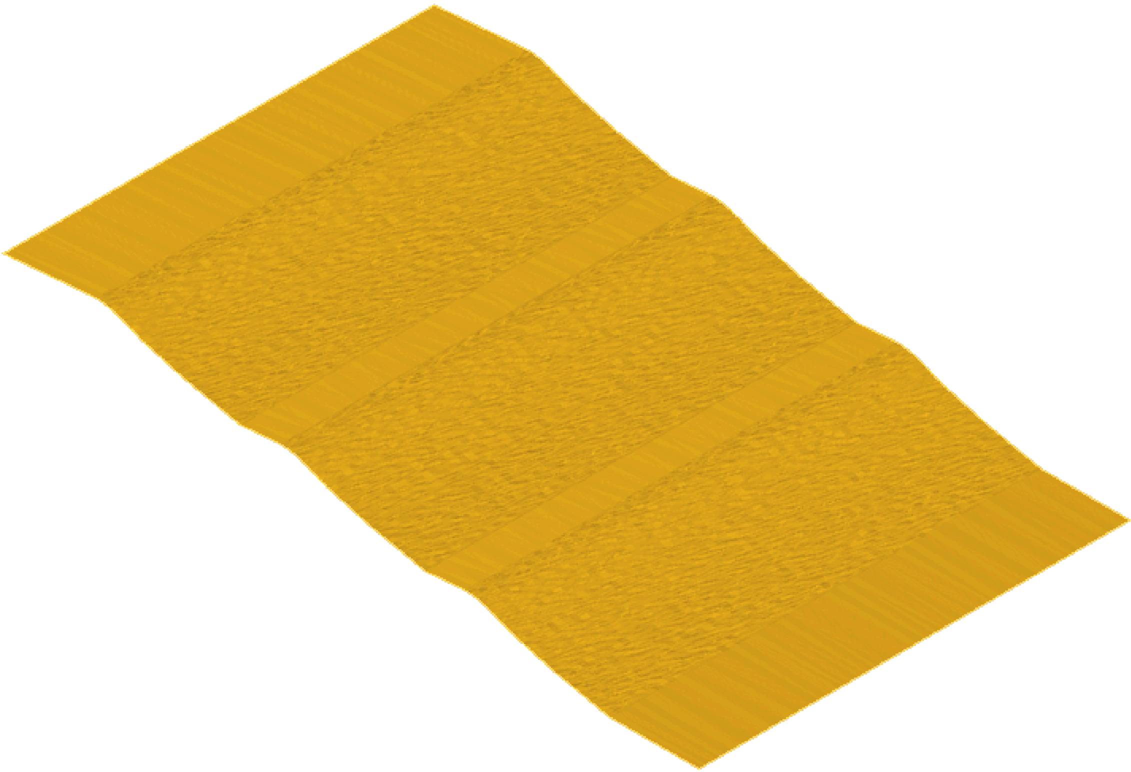

Figure 7: Option 3 slope isometric view

The sections below describe the erosion modelling results for the slope sections Options 1 to 3. The results of simulations using the lower bound erosion parameters are discussed first followed by the results of simulations for upper bound parameters.

5 EROSION MODELLING RESULTS

5.1 Option 1: Lower bound erosion parameters

Simulations have been conducted using erosion parameters that would yield lower bound estimates of erosion. Typical sections through Option 1 slope section are shown below in Figure 8.

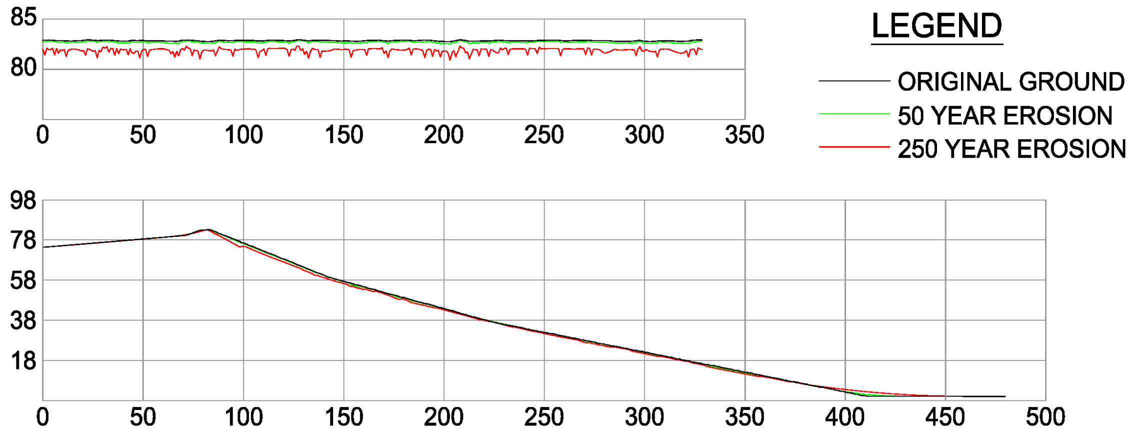

Figure 8: Typical cross section at the crest area of the dump and typical long section

Rendered results of erosion modelling for Option 1 slope section are shown below in Figures 9 and 10. These apply to years 50 and 250.

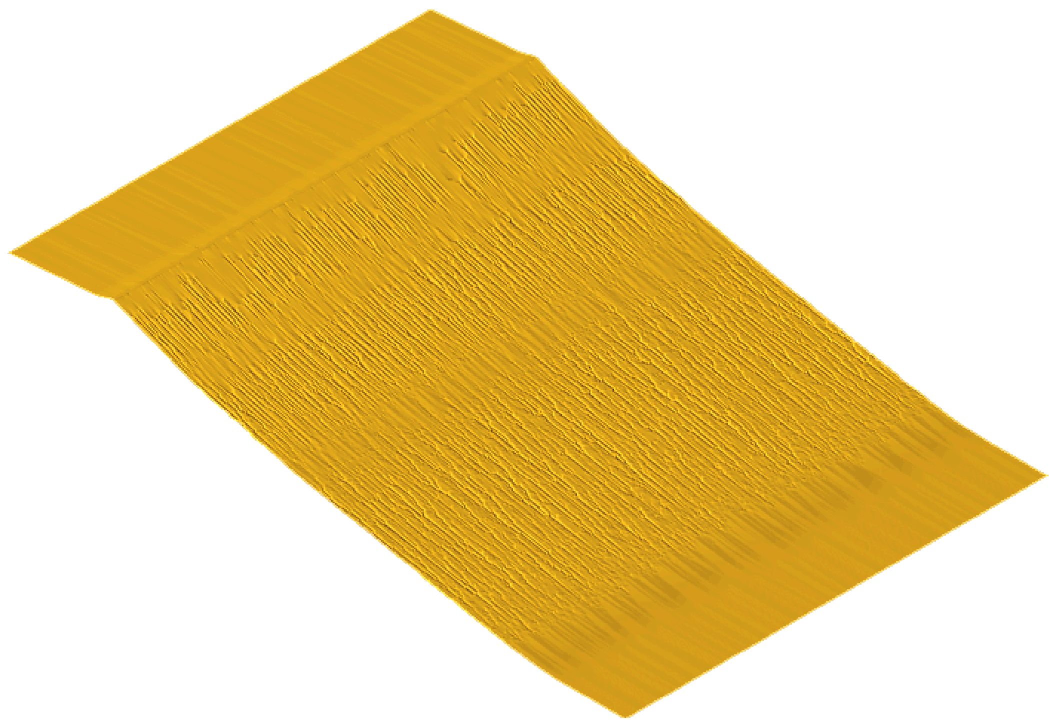

Figure 9: Option 1 slope section after 50 year erosion (lower bound)

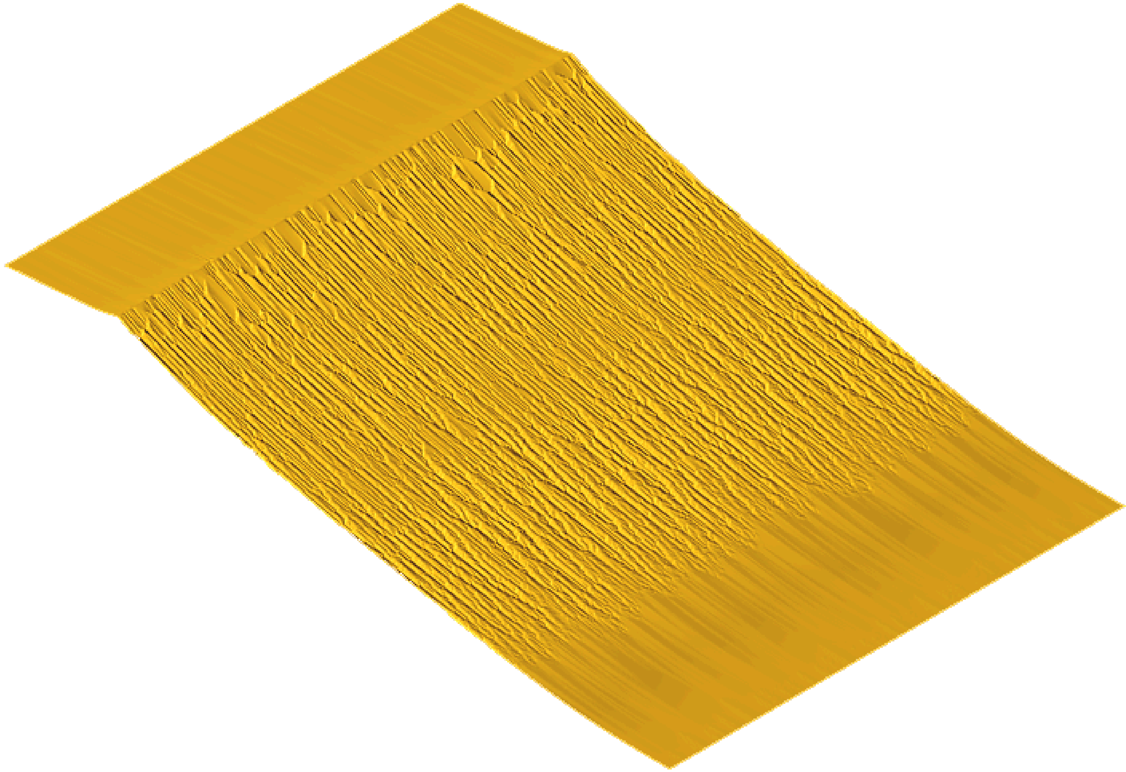

Figure 10: Option 1 slope section after 250 year erosion (lower bound)

5.2 Option 1: Upper bound erosion parameters

Simulations have been conducted using erosion parameters that would yield upper bound estimates of erosion. Typical sections through Option 1 slope section are shown below in Figure 11.

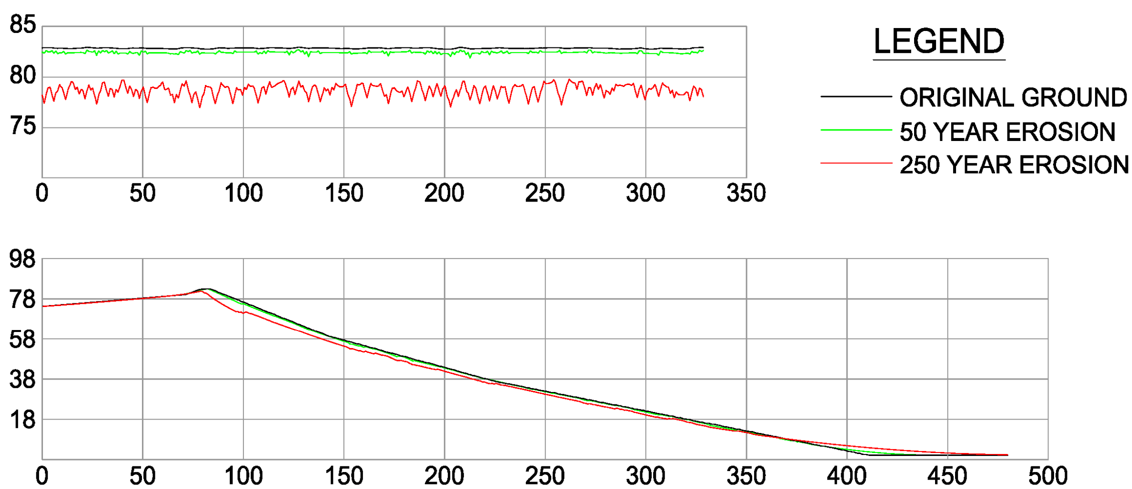

Figure 11: Typical cross section at the crest area of the dump and typical long section

Rendered results of erosion modelling for Option 1 slope section are shown below in Figures 12 and 13. These apply to years 50 and 250.

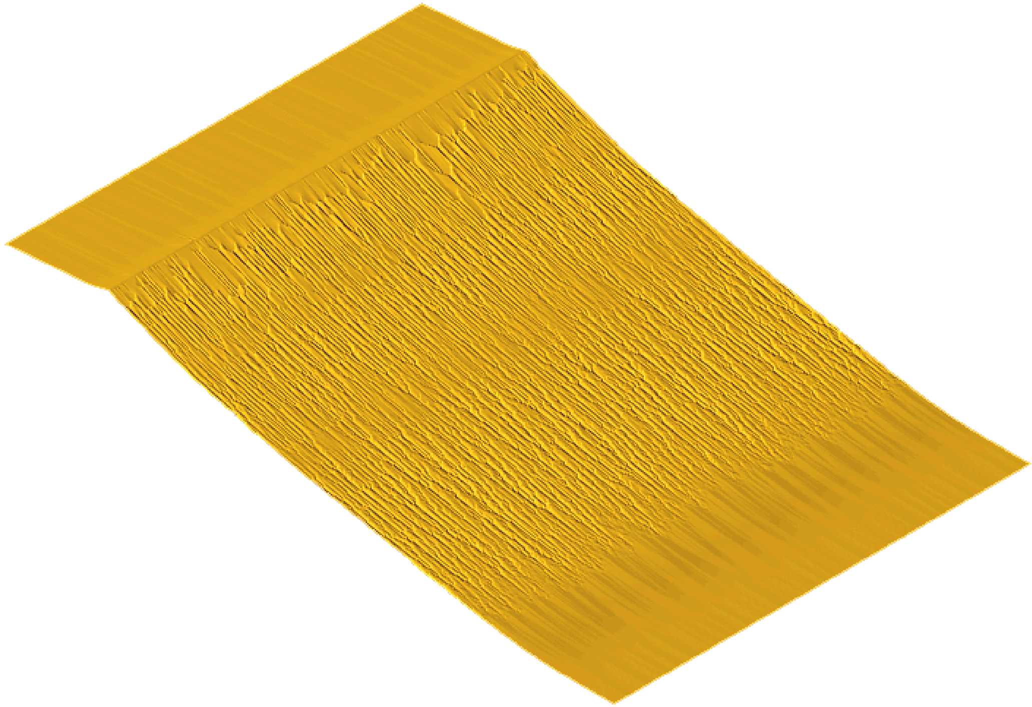

Figure 12: Option 1 slope section after 50 year erosion (upper bound)

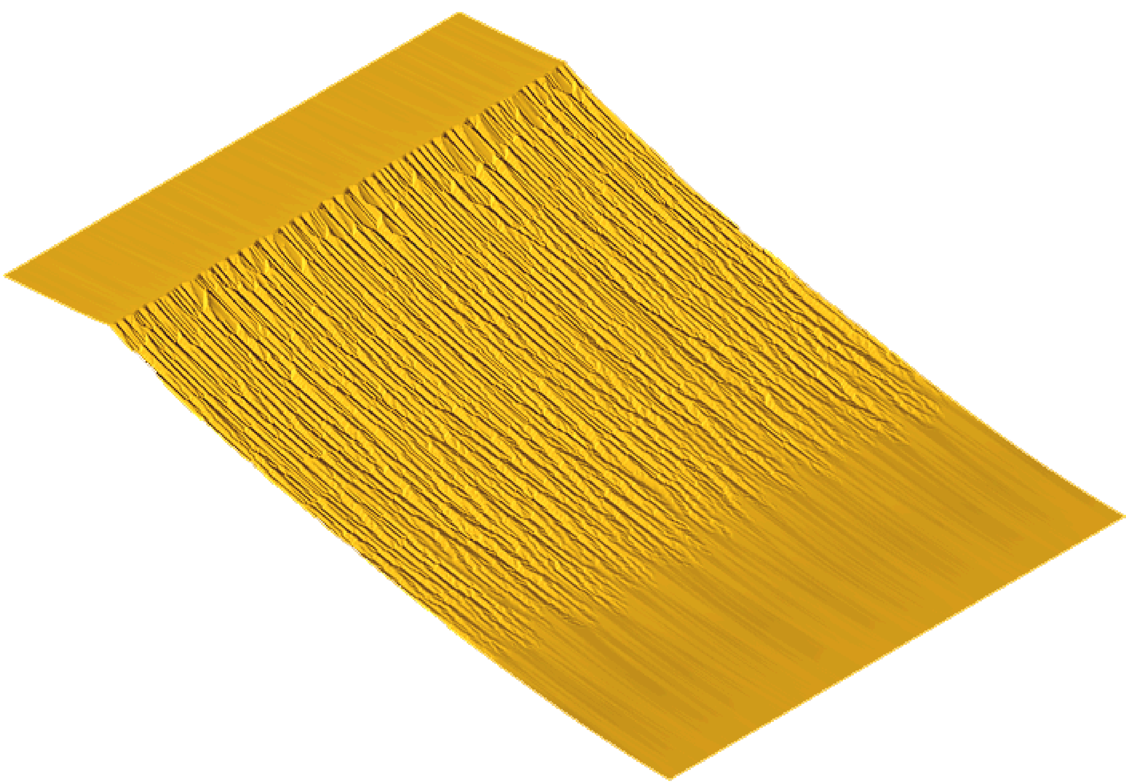

Figure 13: Option 1 slope section after 250 year erosion (upper bound)

5.3 Option 2: Lower bound erosion parameters

Simulations have been conducted using erosion parameters that would yield lower bound estimates of erosion. Typical sections through Option 2 slope section are shown below in Figure 14.

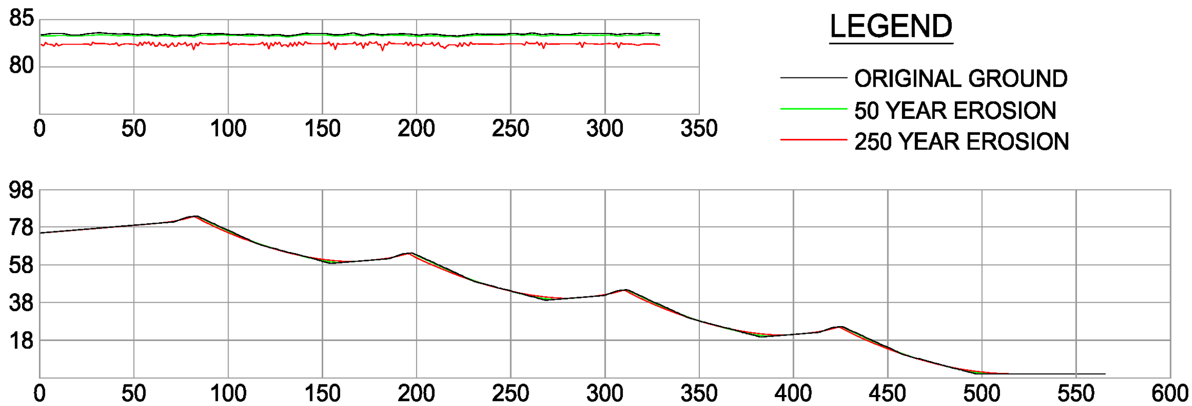

Figure 14: Typical cross section at the crest area of the dump and typical long section

Rendered results of erosion modelling for Option 2 slope section are shown below in Figures 15 and 16. These apply to years 50 and 250.

Figure 15: Option 2 slope section after 50 year erosion (lower bound)

Figure 16: Option 2 slope section after 250 year erosion (lower bound)

5.4 Option 2: Upper bound erosion parameters

Simulations have been conducted using erosion parameters that would yield upper bound estimates of erosion. Typical sections through Option 2 slope section are shown below in Figure 17.

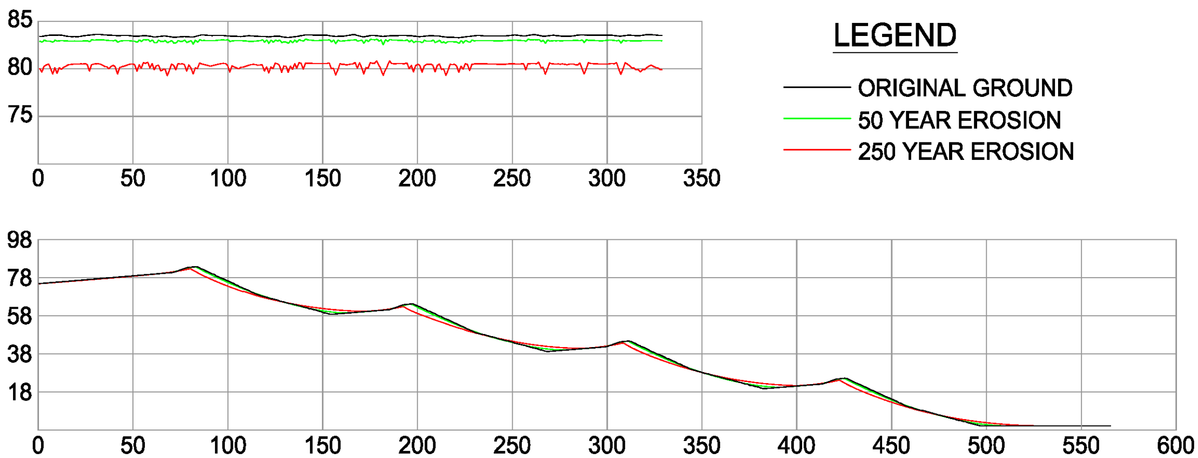

Figure 17: Typical cross section at the crest area of the dump and typical long section

Rendered results of erosion modelling for Option 2 slope section are shown below in Figures 18 and 19. These apply to years 50 and 250.

Figure 18: Option 2 slope section after 50 year erosion (upper bound)

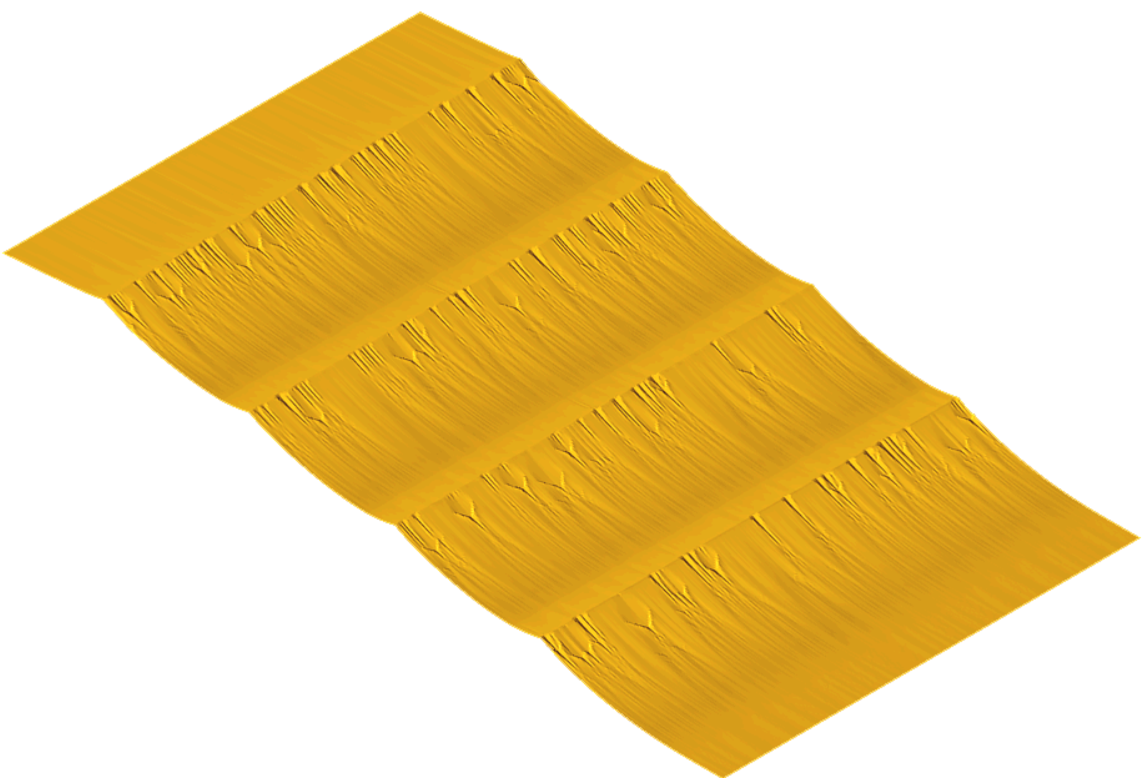

Figure 19: Option 2 slope section after 250 year erosion (upper bound)

5.5 Option 3: Lower bound erosion parameters

Simulations have been conducted using erosion parameters that would yield lower bound estimates of erosion. Typical sections through Option 3 slope section are shown below in Figure 20.

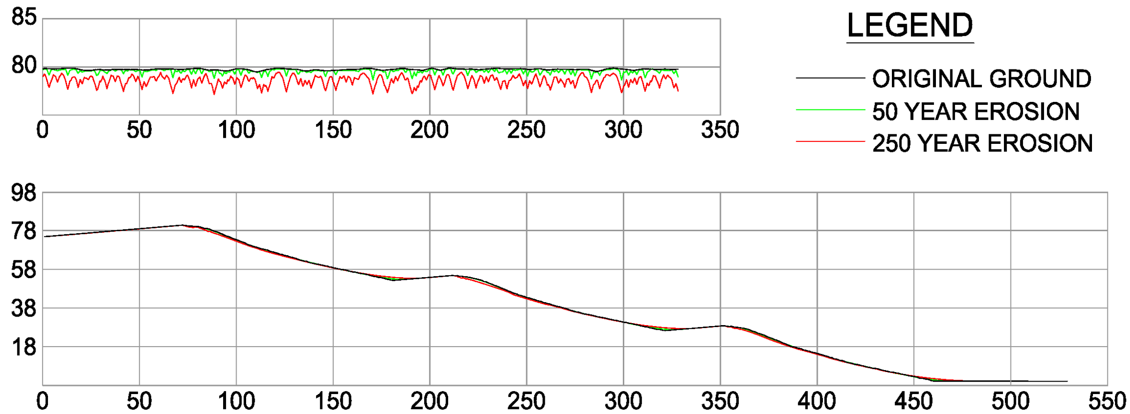

Figure 20: Typical cross section at the crest area of the dump and typical long section

Rendered results of erosion modelling for Option 3 slope section are shown below in Figures 21 and 22. These apply to years 50 and 250.

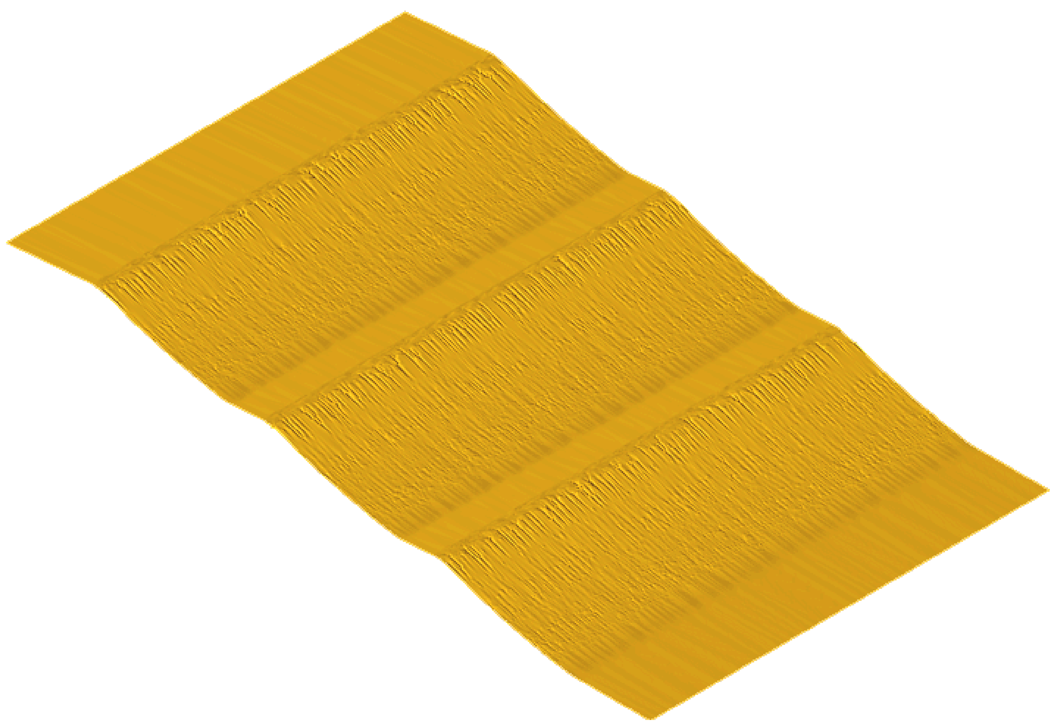

Figure 21: Option 3 slope section after 50 year erosion (lower bound)

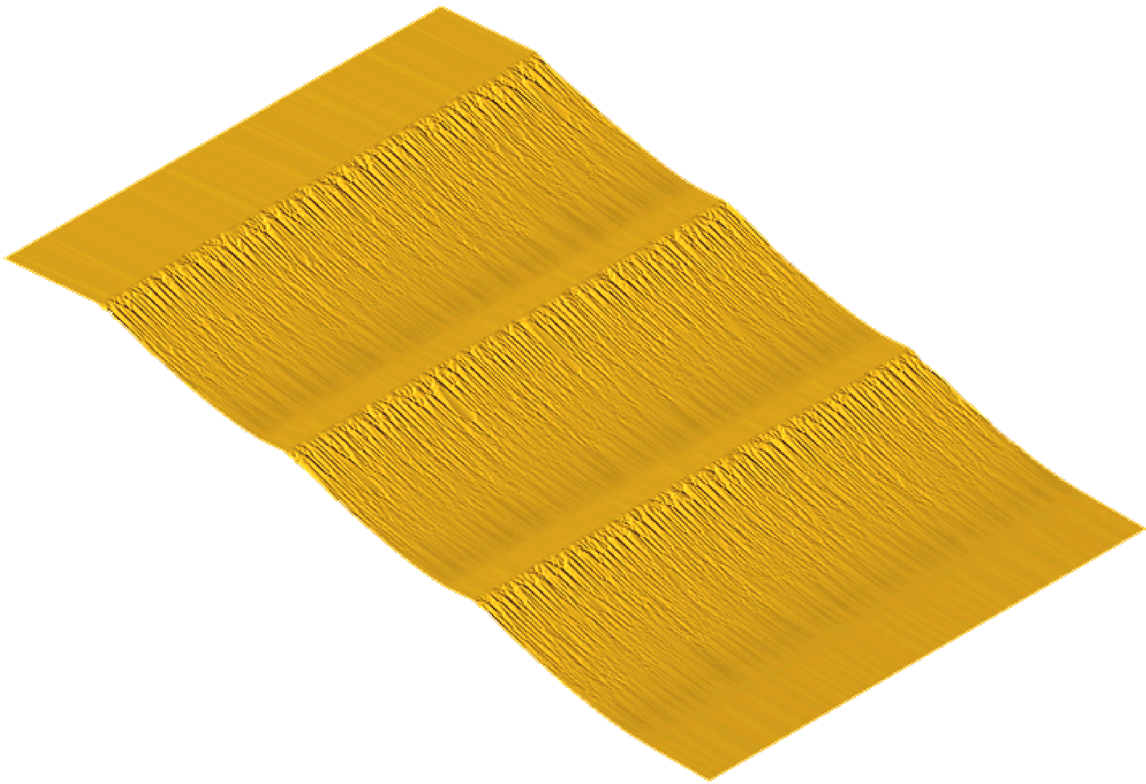

Figure 22: Option 3 slope section after 250 year erosion (lower bound)

5.6 Option 3: Upper bound erosion parameters

Simulations have been conducted using erosion parameters that would yield upper bound estimates of erosion. Typical sections through Option 3 slope section are shown below in Figure 23.

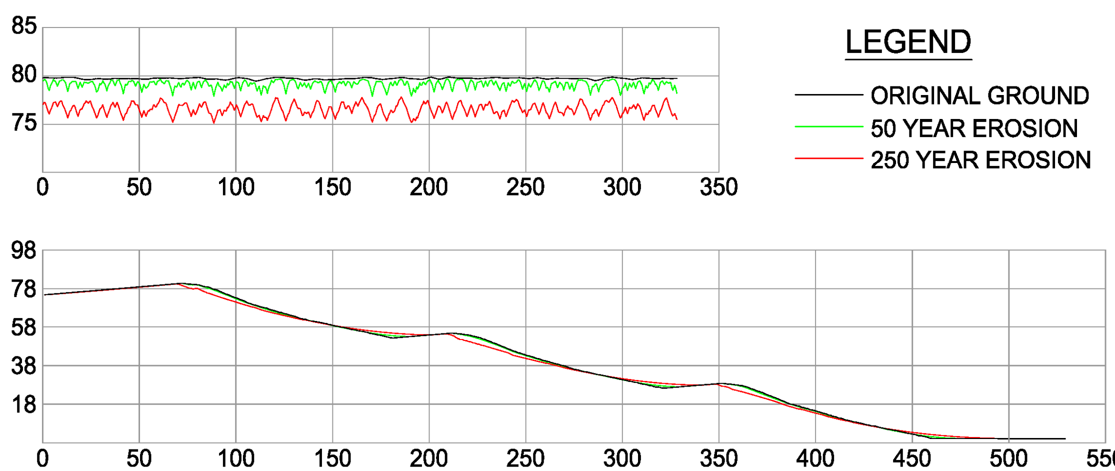

Figure 23: Typical cross section at the crest area of the dump and typical long section

Rendered results of erosion modelling for Option 3 slope section are shown below in Figures 24 and 25. These apply to years 50 and 250.

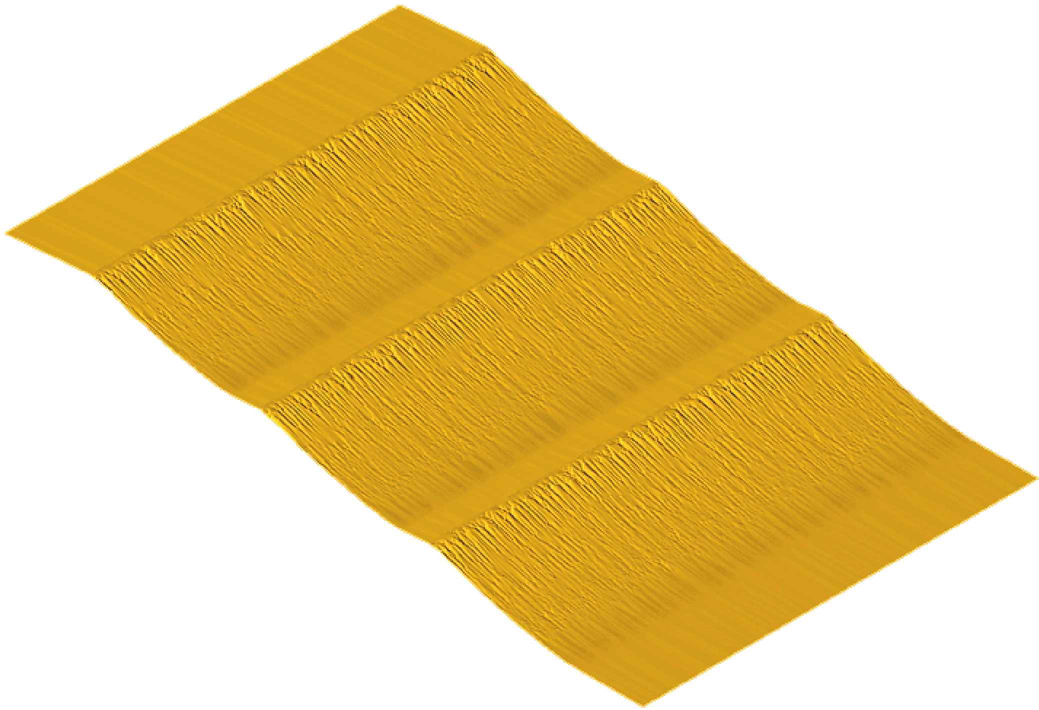

Figure 24: Option 3 slope section after 50 year erosion (upper bound)

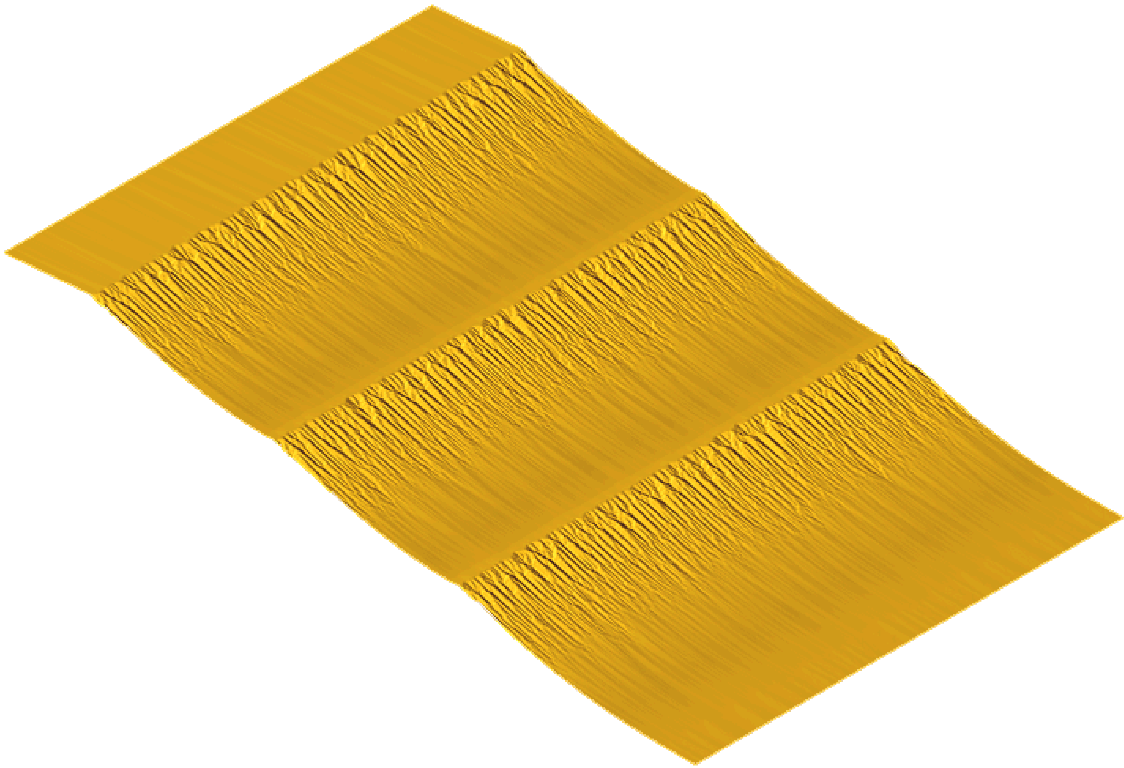

Figure 25: Option 3 slope section after 250 year erosion (upper bound)

6 SUMMARY OF EROSION SIMULATION RESULTS

In total six SIBERIA erosion simulations were completed for Options 1 to 3. The results were input into Land Desktop and converted into terrain models. These, in turn, enabled the production of rendered images as well as data on volumes of eroded material. A summary of the volumes of eroded material is provided below in Tables 2 and 3.

Table 2: Eroded volumes based on lower bound erosion parameters

Options	Eroded Volume (m^3/ha)			Percent compared to Option 1
	From year 0 to year 50	*From year 50 to year 250*	*Total*	
1	1,066	4,427	5,493	100 %
2	770	2,137	2,907	53 %
3	676	2,483	3,159	58 %

Table 3: Eroded volumes based on upper bound erosion parameters

Options	Eroded Volume (m^3/ha)	Percent

	From year 0 to year 50	*From year 50 to year 250*	*Total*	**compared to Option 1**
1	2,849	11,143	13,992	100 %
2	1,689	4,790	6,479	53 %
3	1,706	6,091	7,797	58 %

In reviewing the above results it is important to note that, in neither of the two stepped slope options, did runoff flow over the crests of any of the benches or from the top of the dump. It is also important to note that in none of the options was runoff from the top surface area of the dump allowed to flow down the slope.

Commonly the deepest erosion gullies are formed close to the dump crest areas. Cross sections taken through crest areas of slope Options 1 to 3 indicate that gullies of up to 6m deep can be formed there after 250 years of erosion. Table 4 below shows maximum and average gully depths for each Option.

Table 4: Maximum and average gully depths

Options	Lower bound erosion parameters		Upper bound erosion parameters	
	Maximum gully depths, m	***Average gully depths, m***	***Maximum gully depths, m***	***Average gully depths, m***
1	2.03	1.33	5.90	4.52
2	1.90	1.43	4.30	3.56
3	2.66	1.55	4.75	3.40

7 CONCLUSIONS

The erosion simulation results indicate that provided runoff and eroded material can be retained on each bench a stepped profile with concave inter-bench slopes will generate less erosion over the long term than a single concave slope. Options 2 and 3 meet this criterion.

A stepped profile with four benches performs marginally better than a stepped profile with three benches. It may therefore be feasible to consider inter-bench heights of 30m and thereby reduce the total length of the slope.

8 RECOMMENDATIONS

It is recommended that:

1. Calibration of erosion parameters from aerial survey data be carried out as is presently the intention.
2. Consideration be given to further optimising between the slope options using calibrated erosion parameters for the KCGM materials so as to determine the slope profile that best addresses the constraints of erosion performance, practicality of dump operation and available real estate.

Dr G I McPHAIL MIEAust CPEng **Dr N Nazarov**

For and on behalf of

Metago Environmental Engineers (Australia) Pty Ltd

REFERENCES:

Ref 1: Waste Rock Dump Closure Design, Metago Environmental Engineers Pty Ltd, December 2007

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