EROSION CONTROL, HOW PRACTICAL IS IT – REALLY?

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ABSTRACT

It is said that erosion, like death and taxes, is inevitable and unavoidable. Even the best attempts at armouring, re-profiling and vegetating slopes, at best, only slow the process down - hopefully long enough to get sign-off. But there are smarter ways to address erosion control such that the inevitable long term liabilities of nuisance and negligence are minimised.

This paper evaluates the efficacy of a range of erosion control strategies using erosion modelling and provides an indication of the extent to which long term liability is reduced through each strategy. To achieve this, a number of typical examples of eroding structures are modelled and conclusions are drawn on lessons that should be learned. Potential remedial measures entailing armouring, re-shaping and containment are applied, erosion re-modelled, and conclusions drawn as to the most practical and effective erosion control alternatives. Finally, the lessons learned are applied under a "greenfields scenario" in which certain of the structures are re-formed from scratch to ideal profiles and geometry. Erosion modelling is again applied to evaluate erosion performance. A comparison is made between the "greenfields" and the "brownfields" example and, from this comparison, a number of guidelines on effective ways to control and reduce erosion over the long term are developed.

INTRODUCTION

By its nature mining exposes largely innocuous, stable materials, breaks them down and stores them as close to the mining operations as possible but at surface. Inevitably the erodability of the material increases not only because the rock has been broken down in to smaller, more mobile particle sizes, but also because the most convenient geometry for the surface dumps is not usually the optimum geometry to minimise erosion. Design of erosion protection measures has traditionally been based on experience, common sense and a desire to do what every body else does as this reduces risk if the measures fail. The problem is that closure represents a considerably longer time frame than the time frame on which experience-based design is based. The simple truth is that a lot of the measures implemented by the mining industry are sub-optimal and likely to incur cost and liability down the line.

But there is hope. Erosion modelling capabilities that make it possible to project into the long term have improved. It is possible to link erosion modelling programs such as SIBERIA to digital terrain modelling software and carry out engineering optimisation.

This paper evaluates a range of mining-generated structures and to assess comparative erosional performance. The potential effectiveness of erosion mitigation measures is evaluated as well as the potential scale of benefits if appropriate landform design is implemented from the start of operations.

SIBERIA

The modelling and predictions documented in this paper have been carried out using the progam SIBERIA. SIBERIA is a long term erosion model developed by Willgoose et al [1] 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. 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 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:

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

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 in the range of 1.5 to 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 applies to armoured slopes of clean (no fines) or bound materials which is not the case for run of mine or crusher-run rockfill such as that anticipated at St Ives.

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

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

Since n_1 is larger than m_1, and S is a number less than 1, Q_s is considerably more sensitive to the slope gradient than the slope length. Within commonly encountered ranges of slope length and gradient, therefore, a long flat slope will erode less than a short steep slope of the same height and material.

EROSION MODEL PARAMETERS

Erosion modelling documented in this paper has been carried out using SIBERIA. Erosion parameters have been estimated from a range of methods that involve one of flume testing, short term rainfall and runoff testing insitu or calibration of erosion from two sets of aerial survey. The actual parameters vary depending on the materials but are not the central focus of the paper. Instead the focus is the engineering comparison and design to reduce and control erosion and the evaluation of alternative erosion reduction and control measures.

LONG TERM EROSION OF VARIOUS STRUCTURES

The erosional performance of a number of structures is considered below. These structures are typical and while a number of them are based on actual structures in order to make the analyses as realistic as possible the location and exact status of the structures is not relevant to the focus of this paper. All structures should therefore be regarded as purely hypothetical but realistic nonetheless.

Tailings Storage Facilities

Tailings storage structures, or TSFs as they are usually referred to in Australia, take a number of forms in today's mining. Figure 1 shows four typical configurations on an exaggerated vertical scale of 5 to 1. Two configurations represent tailings deposition at conventional thickened slurry consistencies and indicate beaching from the main embankment up-contour as well as beaching from the high ground to the main embankment such that the pond forms against the embankment. The lower two configurations are for high density thickened discharge, one being a central thickened discharge configuration and the other being an advancing cone configuration.

Closure of the TSFs needs to take into account management of surface runoff on the top surface and down the sides. In conventional TSFs the water on the top surface would drain to the pond area from where it would need to be routed to ground level. Typically a channel at low gradient to ensure sub-critical flow would be constructed. This is illustrated in Figure 2. Also indicated in Figure 2 is the potential eroded form of the conventional tailings structure. It is evident that severe erosion could occur not only of the relatively steep side slopes of the main embankment with severe gulleying, but also of the sides of the drainage channel. These issues are kernel to the design of erosion control measures.

The lower two images in Figure 2 show the eroded forms of the CTD and the advancing cone configurations. By their form these configurations are naturally shedding so there is no need for a drainage channel. The erosion parameters in all of the eroded images are identical. It is evident that the erosion on the CTD and advancing cone configurations is significantly lower than for the conventional configuration. This is ascribed to two factors:

- The low slope angles that characterise CTD and advancing cone tailings structures.
- The "spreading" nature of the slope as a result of the conical geometry.

It is evident from Figure 2 that erosion control measures would likely be required on the slopes and options in this regard are considered later in this paper.

Rock Dumps

Figure 3 shows a typical waste rock dump associated with an adjacent open cast operation. Waste rock has been trammed up the open pit ramps directly onto the dump and the dump formed through a combination of paddock dumping and end tipping. Part of the dump has been terraced in line with guidelines. The remainder of the dump is still active.

Figure 4 shows the potentially eroded dump if it were closed in its current form. From Figure 4 the extent of potential gulleying through the slope terraces is evident and concerning. It is apparent that once sufficient inter-berm erosion has occurred that water is able to cascade from one berm to the next the slope rapidly gullies and significant volumes of material are eroded.

Also of significance is the potential erosion from the top surface if water is able to flow from the top down the side slopes. Dentritic drainage channel formation is evident on the top surface close to the slope crest. Indeed examination of intermediate time step outputs from SIBERIA indicates that as soon as the top surface of the dump contributes flow to a side slope the rate of erosion increases exponentially.

Erosion of the intermediate slopes that drain onto the top surface is of significance as the eroded material will gradually accumulate on the top surface and change the drainage patterns. Once these drainage patterns change to allow water to flow from the top surface down the side slope the rate of erosion of the side slope will increase exponentially. Options to address the issues highlighted by the erosion simulations are addressed later in this paper.

Heap Leach Pads

A typical heap leach pad is indicated in Figure 5. Geometric configurations for heap leach pads vary depending on site topography. In the case illustrated the pad is developed in stages. Figure 5 indicates the potential state of the pad at closure. The top surface has been dished so as to ensure that there is a low probability of runoff accumulating on the surface draining down the side slopes. A particular characteristic of heap leach pads is the fact that the cost of developing a heap leach pad, which requires large preparatory earthworks to ensure appropriate drainage gradients over which liners and extensive drainage systems are constructed, is high relative to the tonnage of rock that may be placed on the pad. Consequently the desire to form steep side slopes benched only to accommodate slope stability constraints is high. The pad indicated in Figure 5 has therefore been assigned relatively steep, benched side slopes as indicated in Figure 6.

Figure 7 shows the potential eroded form of the pad and Figure 8 the cross sections that emerge from SIBERIA simulations at various periods after closure. It is evident from Figure 7 that gulleying of the slope may be anticipated notwithstanding the fact that there is now run off down the slope face from the top surface of the pad. Figure 8 indicates that the berms are eroded away relatively rapidly potentially within a period of 10 years depending on the erosion parameters.

Dumps of Dispersive Materials

Figure 9 shows a typical dump comprising paleochannel material excavated from the adjacent open pit. Paleochannel material is commonly dispersive as are a significant proportion of dump materials in the coal mining areas in Queensland. Dispersive materials are characterised by their poor cation bonding which renders the material liable to break down into colloidal fraction on contact with water. Consequently not only are erosion rates high but any ponding of water on the dump materials even for the shortest duration commonly results in the formation of “rat holes” and erosion tunnels.

Also indicated on Figure 9 is the potential eroded form of the dump with time. It is evident that the high erosion characteristics result in rapid and deep gulley formation with materials being transported well beyond the confines of the dump as well as into the adjacent pit. Experience with the closure of dumps of dispersive materials has shown that it is practically impossible to eliminate tunnel formation and gulleying on these structures. Options to address this experience are evaluated later in the paper.

MITIGATION ALTERNATIVES

Some might argue that erosion, like death and taxes, is inevitable so why fight it. Accept it and live with it. This argument is usually backed up with statements to the effect that the mining operations are remote and the areas around the mines unpopulated. However the erosion simulations described above clearly indicate that, depending on the geometry and nature of the materials, erosion can be extensive and questions of duty of care, nuisance, and negligence can arise particularly if the mining operation is close to people or sensitive environments. Often the materials concerned have contamination potential as a result of sulfide minerals or other potentially mobile contaminants. In these cases erosion mitigation and control measures are essential when closing mining-related dumps and tailings storage facilities. But which alternatives work best and how should they be deployed so as to ensure maximal benefit per dollar of expenditure on mitigation? The sections below evaluate the common approaches in relation to the structures described above.

Generally erosion mitigation options can be classified into the following broad approaches:

- Armouring to reduce the rate of erosion
- Re-shaping to form a less erosion-prone landform
- Containment of erosion within the confines of the dump or TSF

In this paper we will present a fourth alternative which is not commonly used. This relates to the promotion of erosion of a dump into an adjacent pit through formation of a landform that maximises erosion.

Commonly combinations of the above would be applied. However, to illustrate the relative effectiveness and considerations pertinent to the mitigation approaches they are considered one at a time and singularly in the sections below.

Armouring

While most materials have a natural armouring ability, for finer grained materials this is insignificant unless there is an element of cementation as a result of the chemical make up of the material. Indeed other than for dumps comprising large hard rock materials such as quartzite it is usual for waste dumps also to experience extensive erosion notwithstanding its natural armouring ability. This is because of the variability of the material and therefore the variability of the extent of potential natural armouring.

So armouring usually involves trucking in erosion resistant materials and covering the dump or TSF. However, landform and topographic geometry continue to be important considerations. The mere act of placing rock over a TSF is no guarantee that erosion will be sufficiently reduced. The armouring layer itself is subject to erosive forces and itself has limits. As importantly is the size compatibility between the armouring layer and the material being armoured. Coarse rocks with minimal fines placed on the slope of a TSF is unlikely to slow down erosion significantly. This is because the water flows at the contact between the tailings and the waste rock where the residual area of tailings surface exposed to the runoff may still be as much as 50%. Flow velocities are slowed due to the tortuosity of flowing around and between rocks but so are the erosion eddys and consequently the tailings will be mobile notwithstanding the rock cover.

Figure 10 shows the conventional TSF in Figure 2 simulated with armouring-related erosion parameters. It is evident that the armouring has significantly reduced the erosion of the slopes compared with the bare tailings. Figure 11 shows the results of a sensitivity analysis carried out to evaluate the impact of reducing erodability on the dump indicated in Figure 9.. While time scales are dependent on the actual erosion parameters what Figure 11 does indicate is the relative erosion rates. A number of interesting points emerge from the results in Figure 11, notably:

- While the erosion rates change significantly with changes in the principle erosion parameter, β_1, erosion is not eliminated.
- Erosion rates per year (dotted lines) tail off with time. This is because during the first few years of erosion gradients from the crest of the dump to ground level are at a maximum. Flow from the top surface is moving to the crest areas and down the slopes. With time, as the slopes erode and the crests effectively rill back into the dump, the gradients reduce and consequently the erosion rates peak and then drop off.
- Over the long term the higher erosion parameters result in lower annual erosion. It is considered that this is again related to the flattening of the erosion gradient and the rate at which this occurs but this may also simply be a function of the particular dump geometry.

Issues that form the basis of an assessment into armouring may be grouped as follows:

- Availability of suitable materials
- Construction access conditions and general constructability eg high steep slopes
- Segregation of the cover materials during construction
- The need to layer the armouring in high flow and critical areas so as to improve the effectiveness of the armouring. As a rule the provision of an intermediate gravel layer between tailings and coarse waste rock significantly improves the effectiveness of the armouring layer in reducing erosion of the tailings.
- Cost, the old leveller. This is likely to be high.

Re-shaping

Re-shaping of the dump or TSF to eliminate runoff from the top surface down the side slopes, to reduce flow gradients and to remove excess runoff can be very effective in improving erosion performance. This is illustrated in Figure 12 where the application of the above re-shaping approaches to the rock dump from Figure 3 is indicated. Specifically:

- The top surface has been re-graded so as to route runoff to the central area of the dump and then down the access ramp and into the pit. Gradients have been maintained such that these are well below critical flow gradients.
- A crest berm has been provided to the crest to further ensure that water will not drain from the surface onto the slope faces.
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Figure 13 shows the eroded dump in comparison with the original based on the same erosion parameters and time period. The improvement in erosion performance is clearly evident. Even then, there is still room for further optimisation to the re-shaping measures.

Considerations in evaluating re-shaping approaches include:

- Constructability – it is vital to fully account for the implications in dozing down a slope that has been formed at or close to natural angle of repose. Usually this entails gradual working down of the slope and involves repeated dozing and re-dozing of approximately 40% of the slope material.
- Cost. Loading, hauling and dozing requires a significant equipment commitment. It is probably most cost effective to provide for this construction using mining equipment at the time of closure rather than employ a contractor for this work.

Control of Eroded Material

Since erosion is inevitable it is likely that some form of containment along the toe of the dump or TSF will be required in order to reduce long term risks of nuisance and negligence. Methods for simulating long term erosion performance are improving rapidly but there remains a large residual uncertainty in respect of actual performance when specifying erosion mitigation measures. On the other hand, containment by means of trenches and external bunds formed of material excavated from the trenches provides a useful means of preventing public access to the dump while at the same time providing additional assurance that liabilities are being contained.

Figure 14 indicates the dump from Figure 9 equipped with a trench and bund around the rear side (non-pit side) of the dump. The trench is graded so that water will drain to the pit thereby encouraging the transport of eroded material from the back slope to the pit. The external bund is sized to contain the majority of the anticipated erosion. Figure 16 shows the results of an erosion simulation using the same erosion parameters and time period (up to 150 years) as for Figure 9. The following points are noteworthy in respect of Figure 16:

- The bund and trench are indeed effective in containing eroded material. This is evidenced by the fact that the bund remains prominent above the eroded material for the majority of the time period simulated.
- There is scope to refine the bund sizing by increasing its height or moving the bund further away from the side slopes at each end of the dump.

Bunding around the toe of the dump clearly has significant potential to reduce liability risks arising from duty of care. Moreover, the bunding principle is in line with current approaches to pit isolation in respect of long term liability. In the case illustrated it is simply a matter of extending the pit bund around the dump as well.

Promotion of erosion into pits

An approach that is not commonly considered is illustrated in Figures 16 to 19. This entails carrying out just enough re-shaping to the dump of dispersive material as referenced in Figure 9 as to promote erosion of the dump material into the pit. Measures that have been simulated using the same erosion parameters as for Figure 9 throughout are as follows:

- Figure 16 – re-grading the top surface of the dump such that runoff on the top surface is directed to the crest adjacent to the pit and encouraged to erode down the slope face
- Figure 17 – re-grading as per Figure 16 but providing three “starter” gulleys into which flow will be confined and therefore erosion rates increased.
- Figure 18 – as per Figure 17 but with six smaller gulleys

Figure 19 shows a comparison of the results. The following points are evident from Figure 19:

- The option indicated by Figure 18 has the highest erosion rate
- In all options including the do nothing option erosion rates increase over the first few years and then tail off. This is ascribed to the initial high flow high gradient conditions down the slope after which, as the slope erodes and gradients flatten, erosion rates reduce even though the runoff volumes are unchanged.
- While the potential erosion enhancement measures do significantly increase erosion rates the increase is a maximum of 20% to 30% rather than 3 to five orders as was hoped for. On the other hand the measures that were proposed are not extensive and would serve to reduce erosion on the back slope by eliminating flow from the top surface down that slope.
- The times for erosion of the dump are significantly longer than 10 to 20 years which means that as a closure strategy on its own this approach is unlikely to be acceptable as it does not preclude injury to a member of the public should they access the site after closure. If, however, it were to be considered in conjunction with other

strategies, in particular bunding around the toe to effect isolation of the dump and the pit as a combined unit the combined strategy would have considerable merit and be very practical.

GREENFIELDS EXAMPLES

This paper has indicated that where erosion of dumps and TSFs are likely to prove problematic over the long term it is possible to implement effective mitigation measures albeit at significant cost. The question begs, however, as to what could be done prior to and during dump or TSF formation that will reduce closure expenditure.

Consider, for example, the dump of dispersive material evaluated in the previous section. What if we had our time over and could re-form the dump all over again. Our previous simulations show us that gradient is the prime controller of erosion. The erosion gradient is determined by the slope from the base of the pit to the rear crest of the dump so if we are able to maximise this gradient we should be able to accelerate erosion. Under this scenario we would also make the side slopes of the dump as steep as possible. Figure 20 illustrates such a dump. It is formed along the pit rim as close as stability may allow. Frontage on the pit is maximised along the length of the pit on the up-contour side. The top surface of the dump is sloped towards the pit. Figure 21 shows the simulated result at the same time periods as before. Erosion rates are considerably increased – by a factor of 2 to 3 as opposed to the 20% to 30% increase through modifying the existing dump. Notwithstanding the scale of this improvement it would still be prudent to provide a suitably sized bund and trench around the rear of the dump so as to minimise long term liability as Figure 21 shows dispersion of solids beyond the confines of the dump and pit.

A number of guidelines may be abstracted from the other examples evaluated above. These may be summarised as:

- Form continuous slopes that approximate the long term eroded slope profile. This will reduce the total volume of material eroded even if it won't eliminate erosion altogether.
- Ensure that runoff accumulating on the top surface is routed off the dump or TSF using gentle gradients
- Ensure that no runoff accumulating on the top surface flows down a slope face
- Aim for a contiguous top surface topography ie avoid the formation of sub-dumps within the main dump area.

To illustrate the effectiveness of the first point noted above, namely formation of a continuous slope that approximates the long term eroded profile consider Figure 22 which shows a stepped profile that is practical for formation in the course of dumping operations either by end tipping and stepping back or by paddock dumping. Also indicated on Figure 22 is the desired final slope profile. Since the steps or benches in the slope have been positioned appropriately formation of the continuous slope entails only "knocking the tops off the slope crests". This represents a considerable reduction in dozing effort and cost.

But is it worth the effort? Consider the heap leach pad previously evaluated. Assume that a new stage of pad development is planned but that a decision has been made to ensure that the slope should be constructed so as to minimise long term erosion. Figure 23 shows a potential extension to the dump as well as a two-slope profile for the new area. This profile is based on an averaging out of the long term eroded profile as indicated in the insert. The eroded dump slopes are indicated in Figure 23. Figure 24 shows comparative performance of the two slopes and Figure 25 shows comparative sections. Comparison of the total volume of erosion at each year indicates that erosion is reduced by an average of 40%. This reduction is likely to significantly reduce the extent and therefore the cost of closure works and is indeed worth the effort.

CONCLUSIONS

Erosion in mining has, and continues to be, a significant problem and intractable problem. However, there are now tools that enable progression beyond mere analysis of the volume of erosion to the engineering and comparison of less erodable landforms. These tools are yielding useful results that provide guidance on closure design. This paper has considered a range of erodable mining-related structures and evaluated their comparative erosion performance. This has been shown to be poor for typical dump or tailings storage structures. The paper has gone on to assess the beneficial impact of a range of commonly applied erosion mitigation measures of armouring, re-shaping and containment, and reviewed issues that need to be considered when evaluating these measures. It is evident that, to ensure that erosion-related closure measures minimise long term liabilities arising from nuisance and negligence, it will be necessary to implement combinations of the mitigation measures. The paper has gone on to evaluate two examples of “doing it smarter” from the beginning of dump formation and has shown that the benefits are potentially very significant both in terms of reliability and as well as cost. It is shown, however, that even then it will be necessary to implement one or more of the mitigatory measures albeit on a much smaller scale. Typically an erosion containment bund around the dump or TSF will be required. Such a bund will also be effective in discouraging public access after closure in the same way that pit bunds are used to discourage access to open pits. Where the dumps or TSFs are in close proximity to the pit there would be merit in extending the pit bund around the dump or TSF to create a contiguous barrier.

REFERENCES

1. Willgoose, G. R. and Riley, S. J. *Application of a catchment evolution model to the prediction of long term erosion on the spoil heap at Ranger Uranium Mines: Initial analysis.* 1998. Canberra, Australian Government Publishing Service. Supervising Scientist Report 132.

Figure 1: Typical TSF configurations

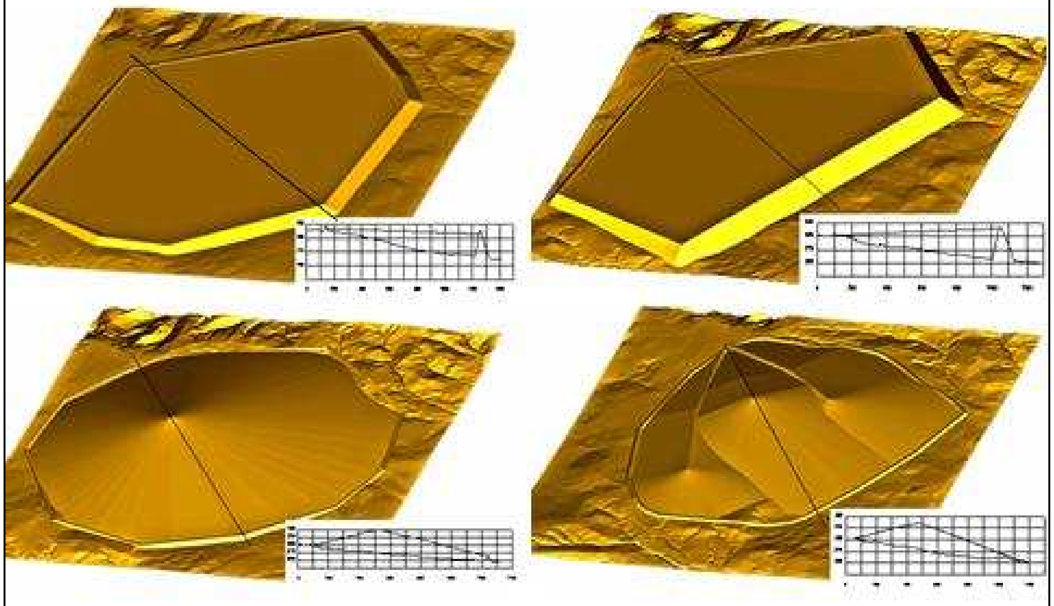
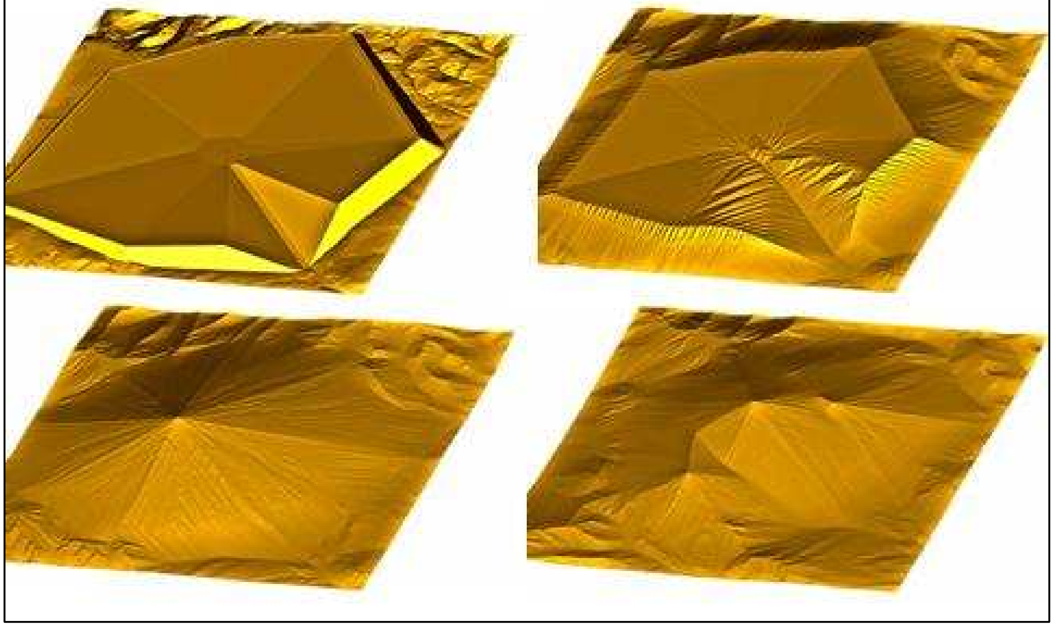


Figure 2: Typical long term erosion



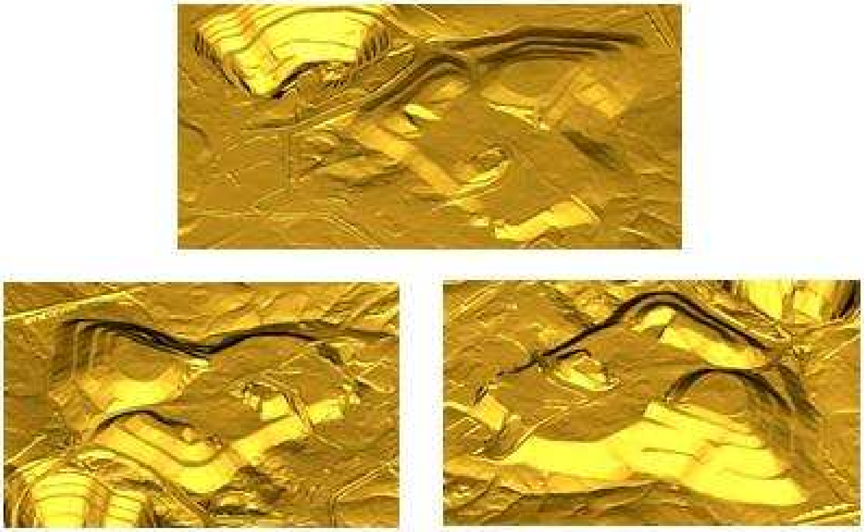


Figure 3: Typical dump

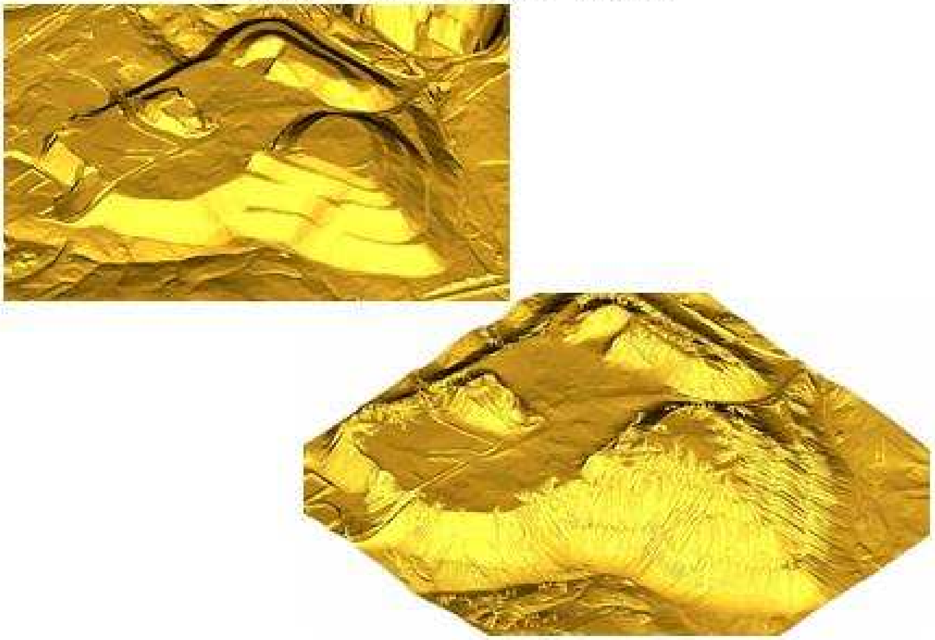


Figure 4: Eroded dump

Figure 5:Typical Heap leach pad

Figure 6: Typical projected profile to maximise capacity

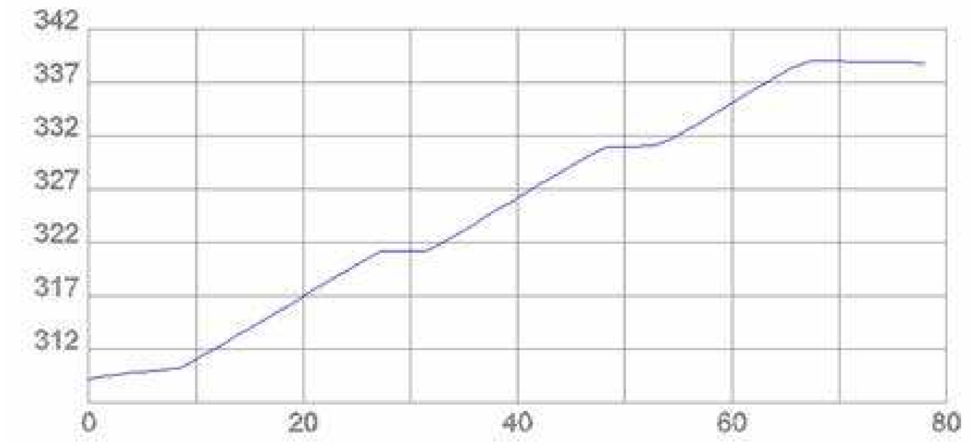
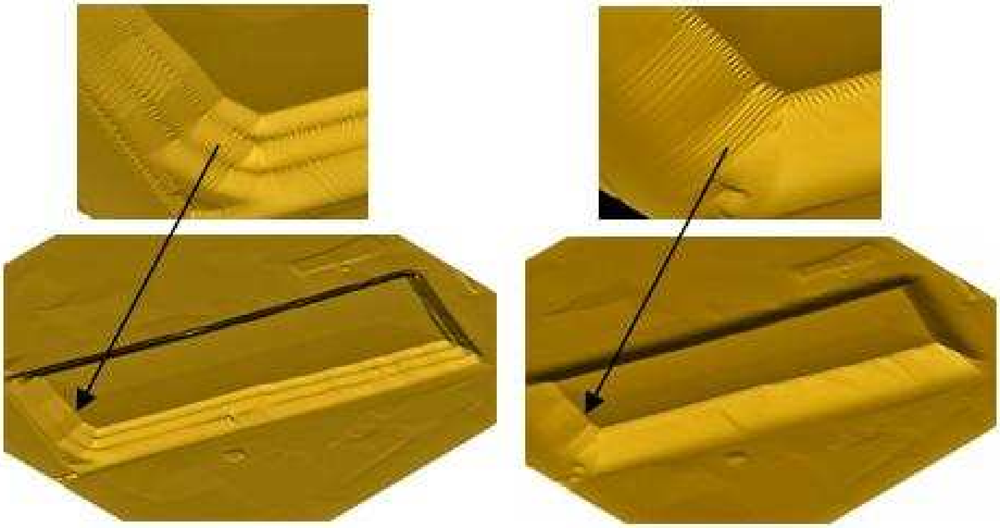


Figure 7: Erosion of typical heap leach pad



10 years

100 years

Figure 8: Sections showing erosion of typical heap leach pad

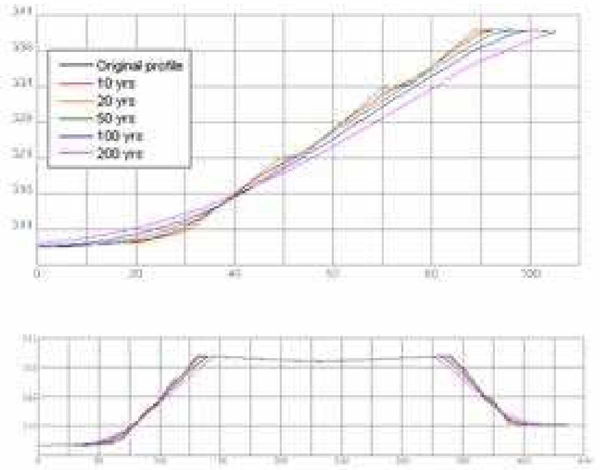


Figure 9: Erosion of dump of dispersive materials

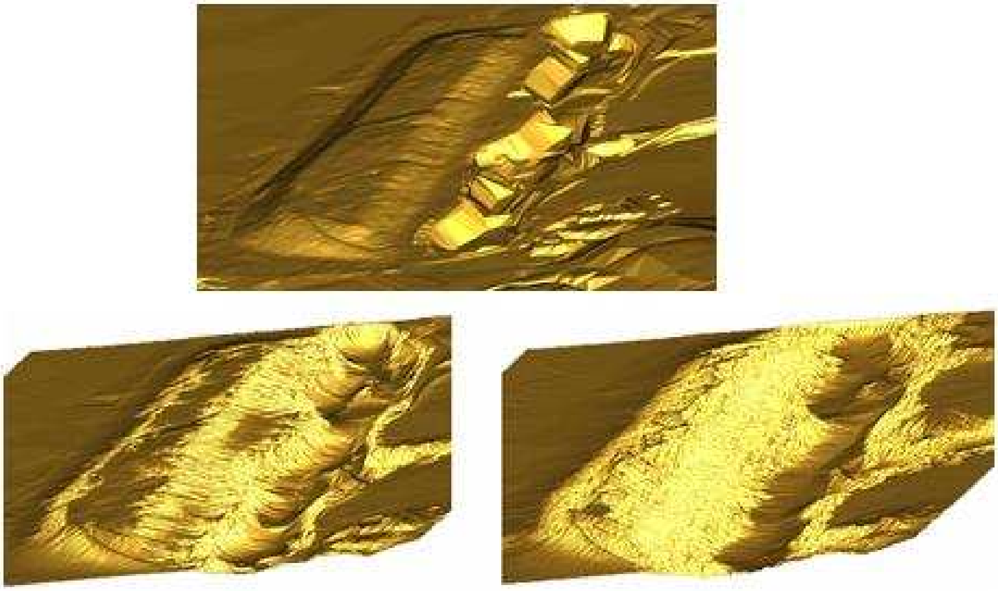
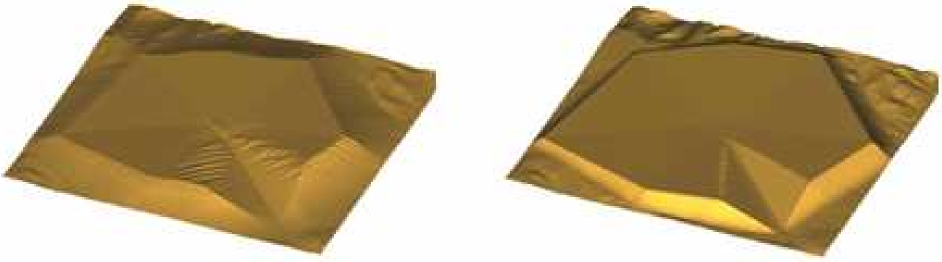


Figure10: Armouring on tailings storage facilities



200 years un-armoured

200 years armoured

Figure 11: Influence of armouring - reduced erosion parameters

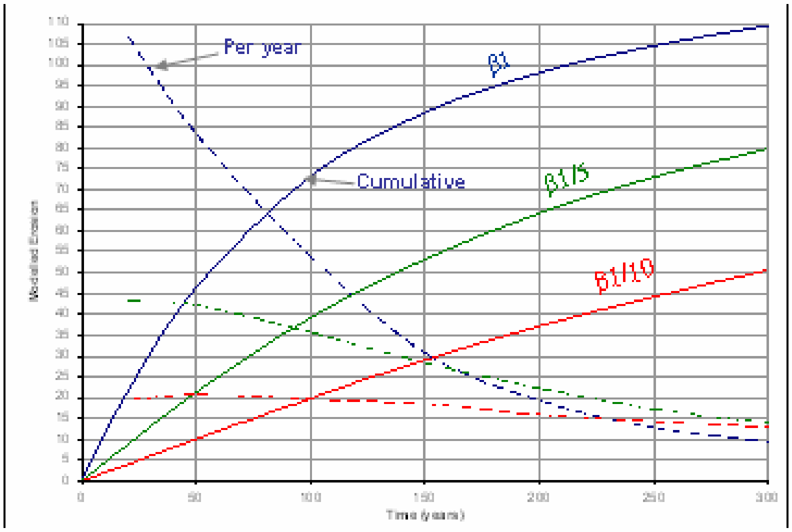


Figure 12: Re-shaped rock dump

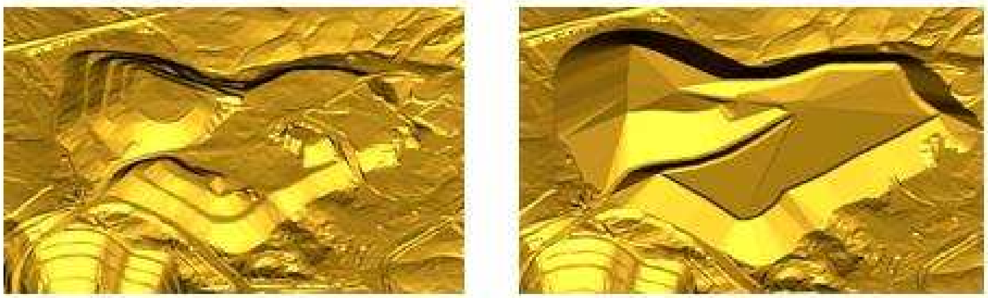


Figure 13: Comparison of dump erosion

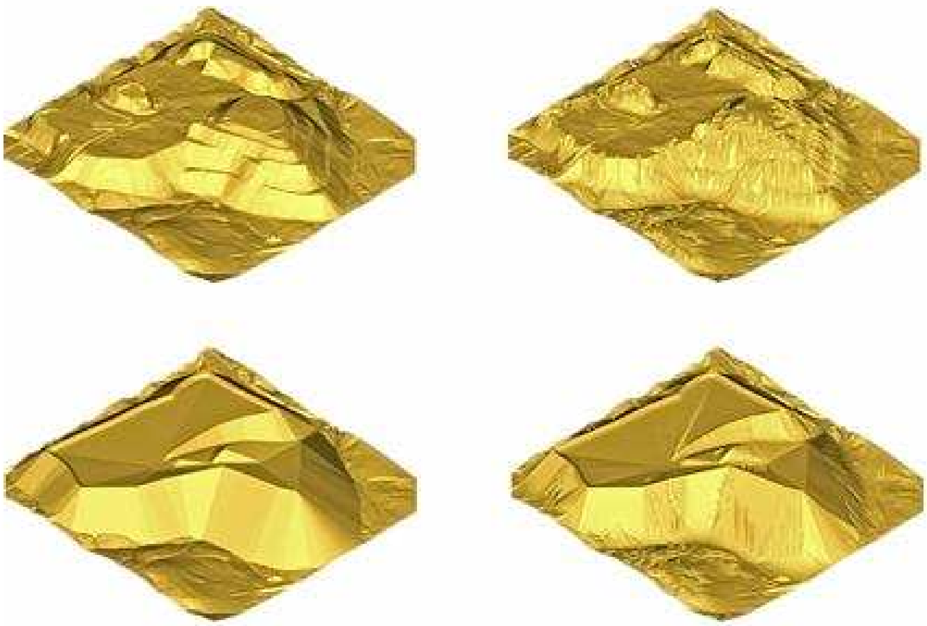


Figure 14: Containment bund and sediment diversion trench

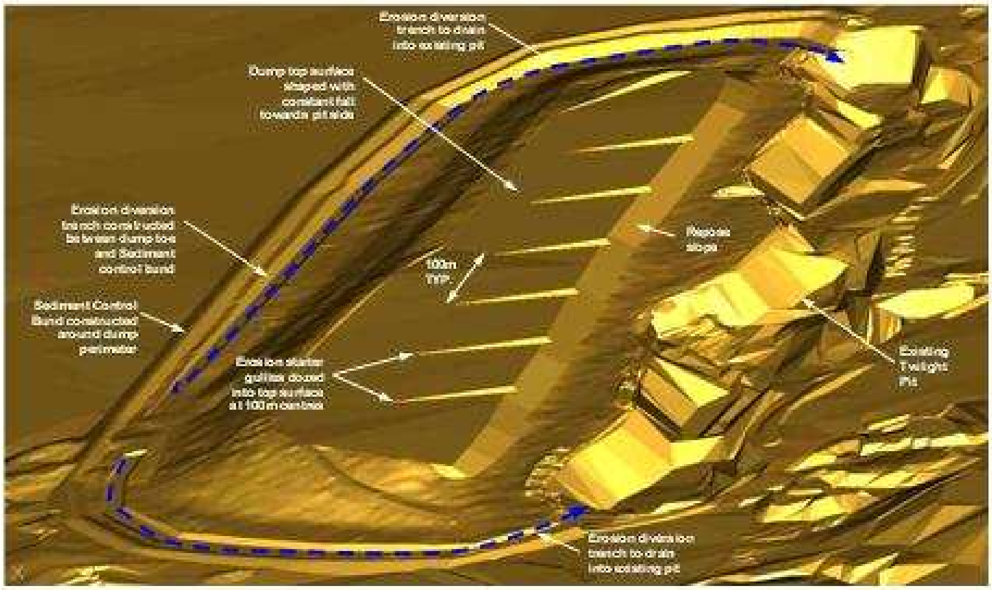


Figure 15: Dump view from rear showing erosion containment

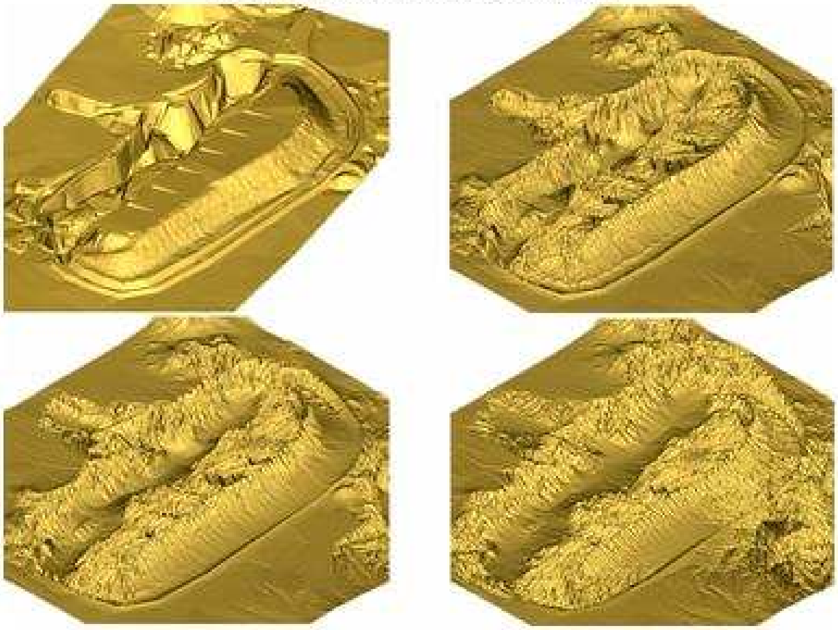


Figure 16: Sloping the top surface

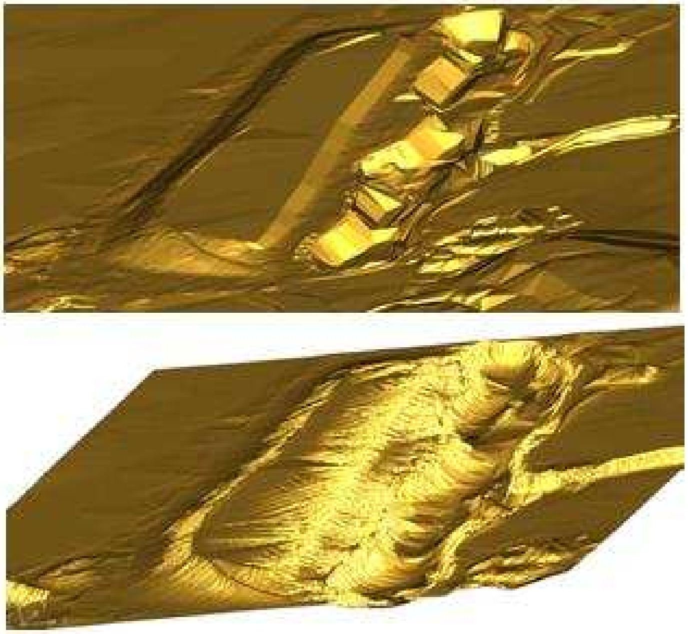


Figure 17: Sloping and gulleying of the top surface

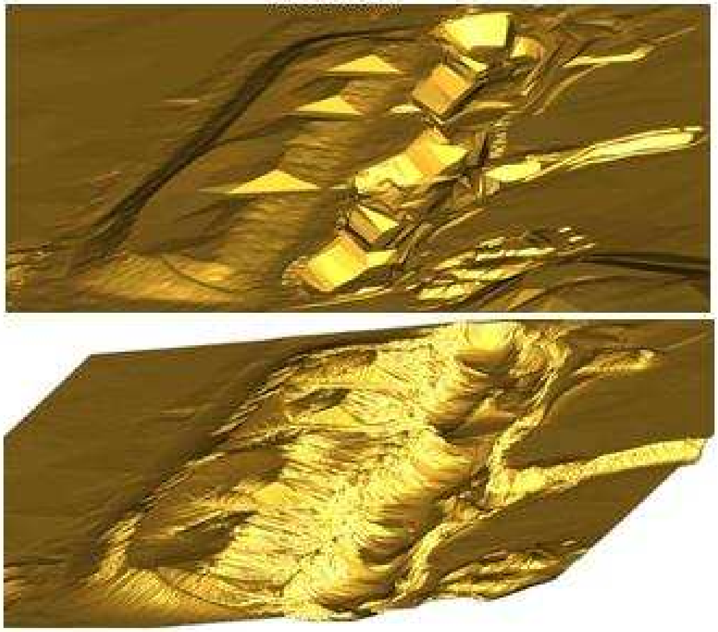


Figure 18: Further gulleying on the top surface

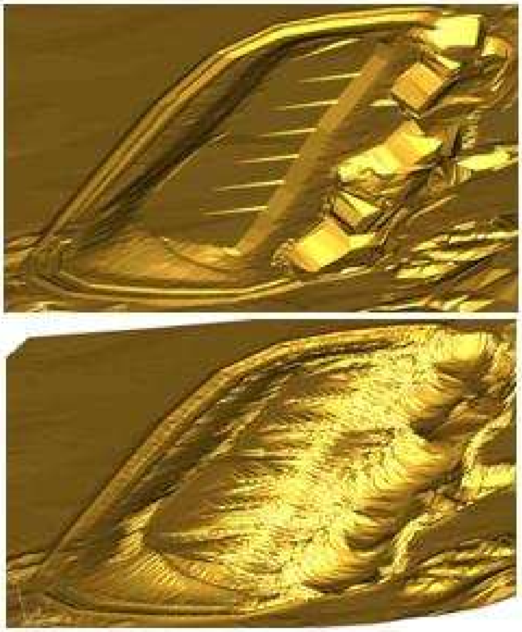


Figure 19: Comparison of erosion enhancement approaches

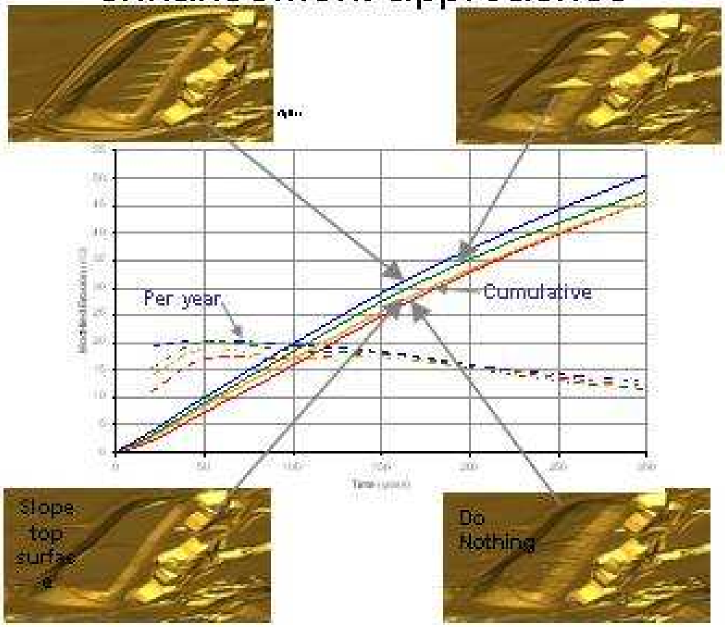


Figure 20: Starting over

Figure 21: Starting over erosion result

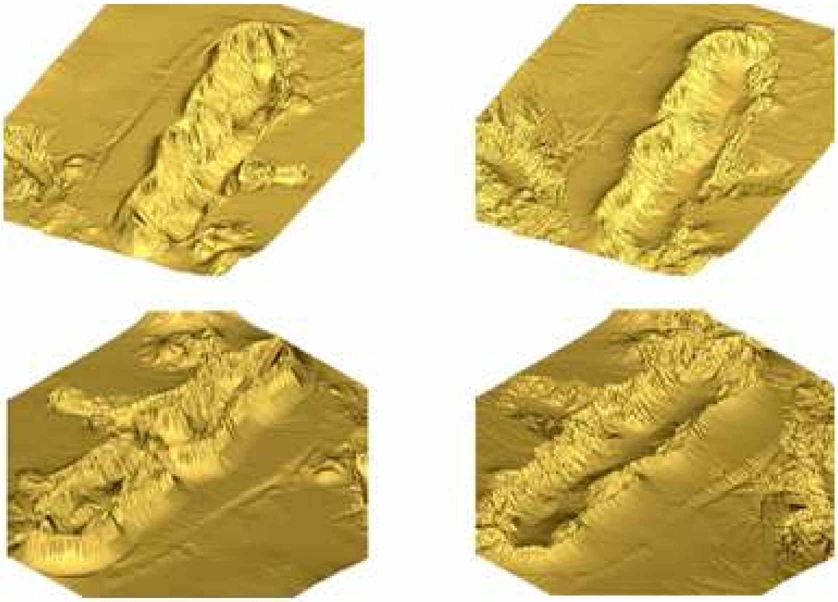


Figure 22: Stepped profile to achieve concave profile with minimum dozing

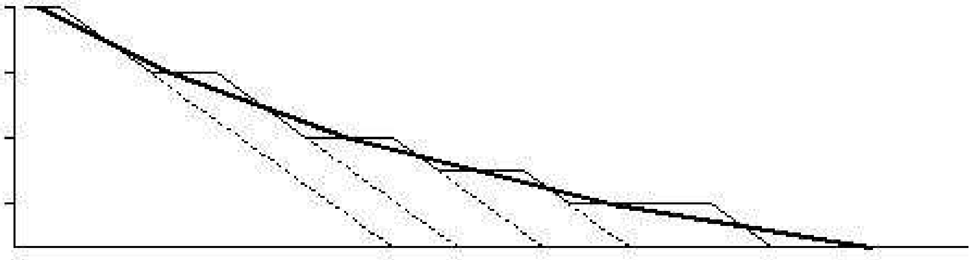


Figure 23: Development of a two-slope concave profile

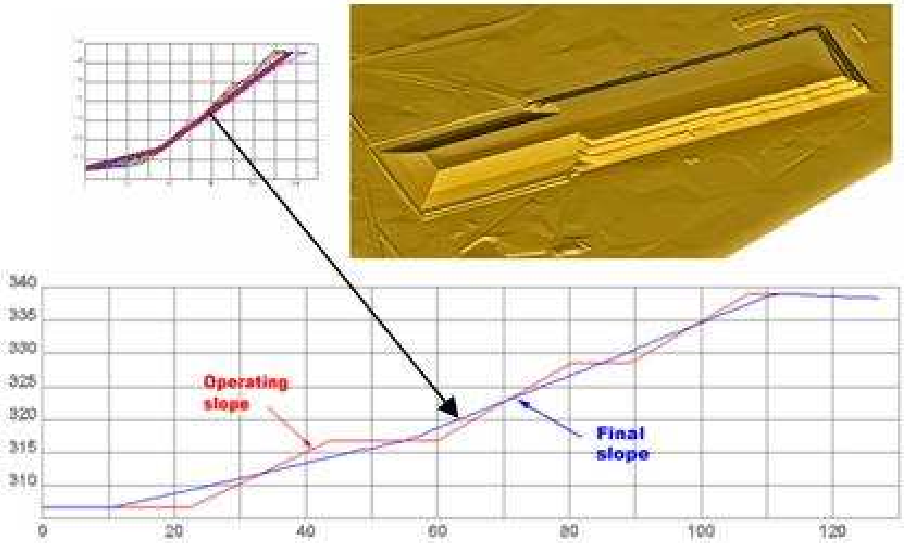


Figure 24: Performance of a two-slope profile

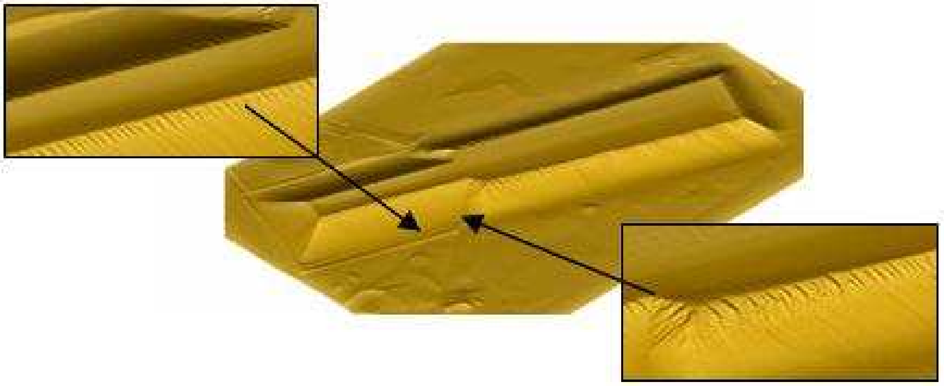
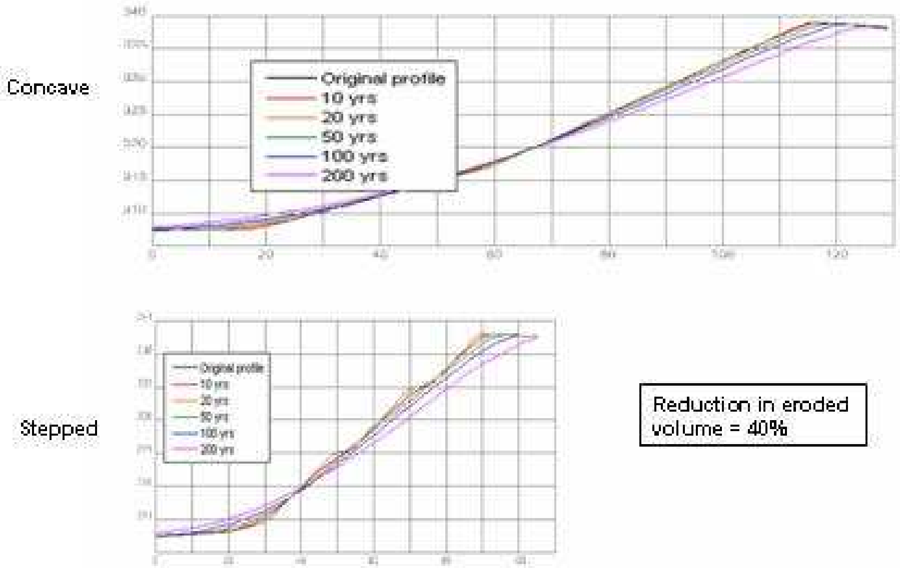


Figure 25: Comparison of erosion from a concave vs stepped slope



Reduction in eroded volume = 40%