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Landform planning: using science and economics to reduce operating costs and closure risk

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Abstract

Landforms of mined waste are the most obvious physical remnant of open pit mining operations. Reflecting this, they represent an important element of closure and relinquishment, and should be safe, stable, appropriately vegetated and represent minimal ongoing environmental risk. We review current issues and practice in the construction and closure of landforms, and then discuss the benefits of integrating enhanced understanding of mined wastes and soil materials with engineering and cost optimisation, to create landforms that will constitute low risk at closure.

The goal of landform planning should be to ensure that the right waste materials are put in the right place at the right time, in terms of the environment and the long-term land use, and also in terms of cost. Substantial cost savings can be achieved during construction and at closure by pursuing this goal. Poor outcomes of landform construction include excessive erosion which potentially compromises the integrity of cover layers, poor establishment of vegetation due to unfavourable material properties, poor vegetation development due to inadequate water holding capacity, nutrient deficiencies, or chemical toxicities, and longer term issues such as deep drainage through hostile stored material. Remediation of existing landforms to correct issues such as these is extremely costly.

The nature of the landform surface, in terms of slope configuration, and the nature of the materials themselves, directly affects critical long-term objectives such as resistance to erosion, integrity of encapsulation of hostile wastes, capacity to accept and store rainfall, and to support plant growth. Understanding the timing of material flow by type, and the preferred location for all materials are key elements in determining if a landform plan can be achieved. Formal audits should review landform development and rehabilitation in relation to the plan, and include updated information on waste types and volumes as mining progresses.

Developing a landform that minimises costs, both in operations and at closure, and that also represents the least risk to the surrounding environment can be achieved. Approaches using a block model approach to landform construction are a powerful tool for mine closure in that they create a practical interface for environmental constraints to be combined with, and influence, mining engineering and economics.

1 Introduction

Landforms of mined waste are the most obvious physical remnant of open pit mining operations. In many cases they represent a visually distinct, unnatural and high impact feature in the landscape and will remain a feature in perpetuity. Reflecting this, the landforms represent a significant element of closure and relinquishment, and it is important that they are safe, stable, non-polluting, appropriately vegetated and represent minimal ongoing environmental risk. However, in reality, in many cases development of landforms has involved only limited consideration of future closure requirements and at best has been based on known technologies of the day (Wright, 2006). The key design focus has typically been to minimise haulage cost. In addition, what in many cases may have been visually unattractive landforms, may

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now represent contaminant risks to mine closure planners who need to minimise long-term corporate liability.

The framework for considering and accepting landforms, in terms of an overall mine closure programme, is typically provided by closure criteria and associated standards, for example as mandated under the recent Western Australian mine closure guidelines (Nguyen, 2011). Typically, these criteria would support closure objectives such as:

- Landforms should be safe and stable.
- Potentially hostile materials are appropriately contained.
- Landform surfaces are capable of supporting appropriate vegetation.

Substantial supporting information may be required to convince stakeholders that potential liabilities of landforms at closed operations represent low and manageable risks, and to date there are few mining operations that have been successfully relinquished, compared to those under care and maintenance (Butler and Bentel, 2011). The inherent uncertainty of mine closure outcomes is an important factor, in terms of issues such as acid mine drainage from mined waste landforms, performance of engineered covers, drought, or fire (Butler and Bentel, 2011).

It is well established that it is far more cost-effective to design and construct landforms that will meet closure requirements during operations, than to superimpose these when mining has been completed (Biggs, 2003). Without planning, decisions made in the early stages of mine planning can significantly impact closure costs (Pulino et al., 2010). If an appropriate landform planning approach is applied, then the process is commonly a compromise between constraints such as the area of land available, the availability of the materials as determined by the mine schedule, and the cost of haulage. The challenge of working with these constraints and still achieving the best possible design outcome for the landform is most easily addressed early in the planning stages.

Mine closure is still a relatively recent phenomenon, Pulino et al. (2010) reported that Brazil's first closure regulation was published as recently as 2001, and closer to home, formal closure legislation only came into effect in Western Australia in 2010 (Nguyen, 2011). Prior to this recent, dedicated focus on mine closure, backed by regulations and increasingly by internal company policies and standards, there was generally substantial separation between personnel responsible for day-to-day management of a profitable mining operation, and those responsible for closure. There is an overwhelming benefit from those responsible for mining operations being cognisant of the potential impact of operational decisions on subsequent closure works, costs and environmental outcomes. The transition to this increasing awareness is an extension of that already achieved in day-to-day mining operations where there is generally good awareness of the potential environmental impacts.

In this paper, the authors review current issues and practice in construction and closure of landforms, and then discuss progress in landform planning and the benefits of integrating enhanced understanding of mined wastes and soil materials with engineering and cost optimisation, to create landforms that will constitute low risk at closure. A process of closure-focussed landform planning that realises immediate operational cost-savings, as well as minimising closure liabilities, is preferred to a process that is driven simply in response to regulation.

2 Current issues in landform planning and construction

As demonstrated in the proceedings of previous Mine Closure Conferences, a typical mine closure experience is about dealing with shortcomings and risks that have arisen as a result of actions, or inaction, during operations, for example, where insufficient attention was given to properties of waste materials and their appropriate long-term management for closure. The need for re-working and repair is not surprising, given that expectations of regulators and other stakeholders, together with awareness of mine operators, has become increasingly sophisticated, particularly in recent years. However, the need for remedial mine closure work will continue for some time across the mining industry to deal with existing legacies. A feature of this will be substantial and expensive effort directed at developing solutions for hostile or difficult materials that are not suited to the position in which they were placed. There is an obligation for us to learn quickly from these experiences and to integrate them into future waste management.

The potential financial benefits from developing solutions for managing mined waste that anticipate closure, combined with optimising waste scheduling during landform construction, are not as easily quantified as the direct costs of retro-fitting a solution at the end of mine life. A contributing factor is the sometimes substantial separation in time between operations and eventual closure. However, resolving issues in landform construction at closure is indisputably more expensive than the approach of developing an early understanding of the materials and their properties in relation to end-land use and closure design.

By applying a landform construction scheduling and optimisation tool, it is also possible to generate immediate savings from optimal placement of mined waste. The goal should be to use landform planning to ensure that the right waste material are put in the right place at the right time (Russell, 2008), in terms of the environment and the long-term land use of the site, and also in terms of cost. The ‘right material’ can only be determined as an intersection between material properties (physical, chemical) and, the expectation placed on them in terms of their position in the landform and the final land use.

2.1 Scale of the activity

Disposing of mined wastes on landforms represents a substantial proportion of the cost of mining. Typically, haul trucks can spend more time on the landform than in the open pit (Russell, 2008). It is our experience that by optimising the landform plan, cost savings can be of the order of 15 cents per bank cubic metre through strategic transport and placement of waste material. In that context, it is worth considering the volumes of mine waste that are planned at some operations. For example, over the first forty years of operation of the Olympic Dam Expansion, it is proposed that 11,600 million tonnes (Mt) of waste and low grade ore will be mined and placed into a rock storage facility (BHP Billiton, 2009). While at Boddington, one of Australia’s largest gold mines, 820 Mt of waste rock are planned to be mined in the current approved operation (De Sousa and Amoah, 2012). Most operations are substantially smaller in scale but in relative terms, the cost savings remain important. When it is considered that there are in excess of 500 commercial mineral projects in Western Australia alone (Nguyen, 2011), then the industry scale can be appreciated.

The substantial incentives for landform planning from a cost perspective become even more powerful if management principles for the waste can be incorporated into the plan. A critical step in reducing costs and risks at closure through improved landform planning is by facilitating a team approach between those focussed on excellent environmental outcomes and those responsible for efficient and cost-effective mining operations. Landform planning tools that incorporate both engineering and environmental considerations can be a critical common language for communications at this interface.

2.2 Closure risks associated with landforms

The issues presented by landforms at closure may be visually obvious, such as those due to erosion or lack of appropriate vegetation cover, or largely unseen but with long-term implications, such as potential release of metals into the environment as a result of oxidation of mined wastes. A common cause is the incorrect placement of materials, due to:

- Failure to identify early the strategic vision or ‘closure strategy’ for the landform, particularly in regard to water management (Lacy, 1998).
- Failure to characterise and identify the potential of material to generate an impact directly on the receiving environment, or its capacity to support establishment and development of a target ecosystem.
- Failure to plan for material placement that is appropriate for the specific material properties.

- Failure to manage materials during placement.

Some examples of poor outcomes are as follows, considered in sequence of immediate effects through to potential longer term effects:

- Erosion due to inappropriate landform design, or to materials that do not match the characteristics of the slope. Typically repair work is costly, and often not successful over the long term. Erosion may also result in exposure of chemically-hostile materials, by compromising the integrity of cover layers.
- Poor establishment of vegetation on landforms due to unfavourable surface material properties, such as soil salinity or extremes in pH, either due to the inherent properties of the materials or to weathering of freshly-exposed wastes. Physical constraints may also be an issue, such as hard-setting or lack of fine-textured material to support seed germination.
- Poor vegetation development due to the presence of materials deeper in the soil profile, which may have unfavourable properties such as inadequate water holding capacity, nutrient deficiencies or chemical toxicities, leading to limited root exploration or limited access to water or nutrients.
- Longer term issues such as uncontrolled infiltration into the landform leading to seepage, which, depending on the contained material, could have unfavourable properties for the receiving environment.

Repairs, re-shaping and remediation of existing landforms are extremely costly and therefore unattractive to most mining operations. It is critical to invest sufficiently in the ‘front-end’ to achieve the best possible outcome in terms of the physical landform, because it is going to have an overwhelming influence on closure risk and long-term successful environmental outcomes.

3 Integrating material properties and engineering constraints in a cost optimisation framework

An important advantage in achieving landform design that has the best possible environmental values is to link the design and construction as closely as possible to the mine plan. This can be done by integrating environmental constraints within cost-optimisation software, which allows detailed scheduling of waste dumping to achieve the best environmental outcome, at least cost (Jasper et al., 2006). Key factors that need to be integrated in a landform design include: climate and environment, waste material attributes, surface requirements, locations, mining economics, and waste scheduling (Russell, 2008).

3.1 Climate and environment

In considering landform design, the natural context is a useful reference and often will provide the most aesthetically acceptable outcome. However, McKenna et al. (2011) emphasised that the natural appearance of undisturbed landscapes is the product of complex interactions between the bedrock and surficial deposits, with historic effects of groundwater, climatic events, and larger scale geological processes. By attempting to model constructed landforms on local landscapes, we are effectively attempting to recreate the outcomes of long-term natural processes by mechanical means with materials that may have different properties, but at the same time ensuring that the processes themselves do not occur at an unacceptable rate (McKenna et al., 2011). Telfer operations in Western Australia provide a well-advanced current example of learning from local landscape processes and climatic factors through research such as that proposed by Hinz et al. (2006) to optimise landform construction (Mifsud et al., 2010).

In recognition that the natural landscape has developed over millennia and reflects the interaction between climate and geology, then this is the timeframe and context in which to consider the principles of landform construction. While long-term performance is an important principle, the most sensitive period is during and immediately after construction. During construction, the materials are exposed to the environment without any of the planned controls. Oxidation of mineralised wastes can commence, and it is vulnerable to accumulation of water into the mass of the landform, and erosion. Immediately after construction, vegetation establishment may just be commencing and its potential ameliorating effects, such as protection of the soil surface from rainfall impact, and the use of stored soil moisture, is not substantial. Therefore, ensuring that the design accounts for extreme precipitation events is a critical element. Resistance to erosion, appropriate management and disposal of excess water during storm events, storing potential infiltration while minimising impacts from deep drainage, and ensuring the availability of soil moisture for vegetation, are all critical to effective landform function and to meeting completion criteria.

3.2 Nature of the mined wastes

During planning for effective landform construction, some critical information is required in relation to mined wastes, including:

- The volume of material to form the landform.
- The physical and chemical characteristics of the materials (as detailed further in the following sections).
- Preferred material positioning in the landform to accommodate material characteristics, e.g. those materials that may be suited to placement near the surface, and those that may be best contained deep within the body of the landform.
- The sequence and timing of different materials being made available via the mining schedule.

At the planning stage it is not possible to have a complete understanding of each of these aspects. In terms of the geology, understandably the focus of geological investigations tends to concentrate on the orebody rather than the surrounding waste units. An additional issue in estimating waste volumes is in applying a swell factor, which may vary between geological units. A ‘single’ swell factor may misrepresent waste rock composition and behaviour. Finally, the design of a waste landform should take account of the timing of the waste material flow, particularly in relation to individual waste units. The typical approach of designs based solely on the anticipated final volume constrains the capacity to plan to manage specific units. A further complication may be the need to accommodate storage of low-grade ore. This needs to be at least cost, but access needs to be maintained for potential future processing, typically at the end of mine life. At many sites, the geochemistry of this low-grade ore will often represent the same or greater risks as the associated waste units, and therefore encapsulation may be desirable, but this may be in conflict with the requirement to maintain access for processing.

3.2.1 Characterising mined wastes

Characterising waste materials before constructing the landform, is a key step to maximise the likelihood that the final landform will satisfy stakeholder expectations. A key outcome of developing an understanding of the properties of the waste materials is to allow the optimal placement of wastes to be recommended. In recognition of the diversity of issues that may relate to the behaviour of mine wastes in constructed landforms, initial characterisation needs to address a suite of physical and chemical parameters (Table 1).

Physical properties such as particle size distribution, soil structural stability and hard-setting influence the capacity of the material to accept rainfall infiltration, and to store water for plant uptake. Water retention is also a critical factor in minimising deep drainage into potentially hostile wastes, such as those with acid-forming potential. The chemical properties of wastes are integral in considering the potential for acid formation, or release of metals, through to potential influence on plant growth through soil pH, salinity, nutrient deficiencies and toxicities (Table 1).

Many of the chemical and physical characteristics of mine wastes are intrinsic properties that cannot be practically ameliorated. Therefore, the most effective outcome from waste characterisation is to identify from the outset the position in the landscape to which the materials are most suited, whether it is to form a stable outer surface that will support vegetation establishment and growth, or those whose hostile properties require them to be placed inside the landform.

Table 1 Summary of physical and chemical properties of soils and mined wastes, and their importance in terms of the overall stability and function of a constructed landform (adapted from Jasper and Braimbridge, 2006)

Property	Soil Properties Influenced
Physical	
Particle size distribution, and % coarse material	Water retention, erodibility, hard-setting tendencies, Cation exchange capacity (CEC)
Bulk density	Plant growth, water retention, erodibility
Soil structural stability	Soil structure, erodibility, bulk density, plant growth
Soil strength: Penetrometer resistance, modulus of rupture (MOR)	Plant emergence, root proliferation, soil structure, erodibility
Soil permeability and infiltration	Erodibility, water retention, plant growth
Water retention characteristics	Plant growth (available water), deep drainage, implications for soil profile reconstruction / waste covers
Erodibility	Landform integrity, plant growth, downstream water quality, rehabilitation sustainability
Chemical	
Soil pH	Plant growth, water quality, nutrient availability
Electrical conductivity (salinity)	Plant growth, water quality
Available nutrients (N, P, K, S, Ca, Mg and micro-nutrients)	Plant growth
Cation exchange capacity (CEC)	Nutrient status, plant growth
Sodicity: Exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR)	Structural stability, erodibility
Acid-forming potential	Water quality
Mineralogy	Weathering products, including potentially acid-forming materials, CEC
Organic carbon	Structural stability, CEC, nutrient status, microbiological activity

In terms of materials placed in the rooting zone on landform surfaces, the key functions of this growth medium are to capture, store, and release resources such as water and nutrients, for uptake and use by plants. In any constructed or natural landscape, there are four functions of soil which are integral to soil quality and thus vegetation performance:

1. Accommodating water entry.
2. Retaining and supplying water to plants.
3. Resisting degradation.
4. Supporting plant growth (Karlen et al., 1994).

The capacity of a soil to fulfil each of these four functions is determined by its physical, chemical and biological properties. An additional element is matching the soil properties to the requirements of the plant species to be used in revegetating the landform. In undisturbed native ecosystems, the make-up of plant communities is strongly linked to soil type and landscape position. Therefore, to achieve the best revegetation outcomes, soil properties should be defined prior to rehabilitation. Vegetation communities are typically one of the most visible outcomes of mine rehabilitation, and thus are a logical focus of rehabilitation planning, but success in their establishment depends on creating an appropriate soil environment.

3.2.1.1 Water retention properties and soil covers on landforms

The capacity of surface materials on a landform to accept and store rainfall and make it available to plant growth is integral to establishing a sustainable vegetation community. For most perennial vegetation, the water retention properties of materials to several metres depth are relevant.

A specific application of water retention characteristics is in designing cover layers, for example, over acid forming waste material which may need to be protected from water infiltration. This has two aspects, firstly, incident rainfall must be held within the cover layers, minimising deep drainage into the potentially hostile materials. Secondly, the subsequent drying of the cover will often depend on transpiration by vegetation. For vegetation to be effective in using soil moisture over the long-term, the cover layers must therefore also have appropriate properties to support plant growth, including allowing root exploration and providing essential nutrients. If vegetation fails because of inappropriate soil properties, then a critical function of ‘store-and-release’ covers may not be achieved.

3.2.1.2 Salinity

The presence of high concentration of salts in the landform surface can affect vegetation directly, or saline drainage can have off-landform impacts. Excessive soil salinity is therefore a key measure for soils and mine wastes. Salinity of surface materials on landforms can be affected if they are overlying saline materials, as salts may rise to the soil surface over time via capillarity. Definition of the saline properties of wastes, as part of the landform planning process, will allow their impact to be minimised, through deep burial or by placing appropriate coarse material immediately above the saline layer, to act as a capillary break.

3.2.1.3 Nutrients and availability to plants

There is a range of elements that are essential for plant growth, include six macro-nutrients (N, P, K, S, Ca, Mg) and seven micro-nutrients (Fe, Cu, Mn, Zn, Mo, Cl, B) (Marschner, 1989). Most commonly, mine wastes can be expected to be low in macro-nutrients, but high levels of micro-nutrients are often experienced, consistent with the occurrence of mineralised orebodies, and may be released through weathering of exposed waste material. A self-sustaining natural ecosystem needs to have accumulated sufficient nutrient capital, and those nutrients need to be cycled so that adequate amounts are available for vegetative growth (Ward and Koch, 1996). Topsoil and plant biomass represent the most important reserves of nutrients in Australian ecosystems. Therefore, it is important that topsoil is salvaged before mining and is part of the landform construction process.

3.3 Surface requirements

The surface of the waste landform, in terms of slope configuration and the nature of the materials, is one of the most critical aspects in landform construction. The nature of the landform surface directly affects critical long term objectives such as resistance to erosion, integrity of encapsulation of hostile wastes, capacity to accept and store rainfall, and to support plant growth. Ultimately, slope configuration, and the nature of surface material on those slopes, should be inter-dependent, with slope angle being constrained by the relative capacity of the material to resist erosion.

Key drivers in landform construction, such as cost and available land area, can create pressures that conflict with an ideal outcome in landform design. Achieving the best outcome within the site constraints depends on having the best possible knowledge of material properties (Section 3.2), and the eventual outcome that is required in terms of vegetation and end land use.

If water does not need to be excluded from the mass of the landform, then the design of the surface layer can focus solely on vegetation requirements and erosion management. If water does need to be excluded, then several factors need to be considered, including slope configurations, managing runoff water, capacity of surface materials to accept and store rainfall, evaporation and transpiration, preferential flow paths and geotechnical stability.

In terms of geotechnical stability, the slope characteristics and landform hydrology are important. Some key considerations are that mining operations will not generate a uniform blend of wastes and so the properties of the worst material need to be considered, surface layers are generally finer materials with poor mechanical strength, and in addition to common slope failure mechanisms, tunnel erosion from crests or berms is an additional likelihood for many oxide wastes (Russell, 2008).

3.4 Potential locations of the landform

The nature of the site and the degree to which there is choice for the location of the waste landform, makes every landform unique. If possible, it is important to consider the footprint location ahead of that of infrastructure placement as the location of the landform can have multi-million dollar implications. Critical factors in location include:

- Proximity to the open pit exit or exits.
- Gradient of the footprint area, both for direction of drainage from the landform and the implications for dumping costs.
- Placement in relation to natural drainage and, where possible, avoiding blocking natural surface flow or accommodating drainage beneath the landform.
- Footprint constraints, e.g. tenement leases, future orebodies, priority flora and fauna, infrastructure, current and future.
- Topography, consideration of visual impact and opportunity to complement the local landscape.
- Stability of underlying material.

3.5 Cost

The key principles in relation to the economics of developing a waste landform are to minimise both the cost of construction and the cost of closure, by getting it right first time. Critical elements of construction cost are waste haulage economics, land area costs associated with pre- and post-construction tasks, and ancillary equipment costs associated with allowing haul trucks to operate on the landform safely and efficiently.

Reducing haulage costs will have operational benefits of reducing truck resources required for waste dumping, and benefits from reduced fuel use and a concomitant reduction in generation of greenhouse gases. Optimising the cost of landform construction needs to happen in the planning phase, and to be supported by regular reviews during construction. An important element in optimising haulage costs is balancing the vertical versus horizontal elements of truck movements.

3.6 Scheduling

In the same way that an open pit would not be operated without scheduling, the same approach is recommended for a waste landform. Optimisation software that operates on the basis that each successive block is placed in order of increasing haulage cost also allows the preferred end location of specific wastes to be designated (Journet, 2008). Understanding the timing of material flow by type, and the preferred location for all materials are key elements in determining if a landform plan can be achieved. Wastes that require encapsulation are more likely to be encountered at depth and the nature of open pit mining dictates that these will be mined towards the end of operations. A detailed understanding of the dumping schedule will allow specific planning to reserve space in the landform and to set aside materials for the encapsulation.

3.7 Review and refinement of the landform plan

Pre-mining information about the nature and volume of wastes to be mined is typically based on a sampling and characterisation programme that is constrained by the practicalities of drilling, and therefore has inherent uncertainty. In addition, the specific nature of the wastes and their behaviour when placed in a landform can only be broadly predicted. Reflecting these uncertainties, it is imperative that landform plans are re-visited regularly during the mining phase. Mine sites are dynamic in terms of planning and ongoing involvement is critical, particularly as new conditions or constraints are encountered. Added to this is movement of staff and potential loss of corporate memory about the programme. Formal audits should review landform development and rehabilitation in relation to the plan, and include updated information on waste types and volumes that becomes available as mining progresses.

An important complement to reviewing elements of the waste dumping schedule is to commence testing waste management and rehabilitation strategies as early as possible. Establishing and monitoring best-bet rehabilitation approaches allows evaluation of behaviour of hostile wastes, effectiveness of soil covers, methods for slope configuration, soil depths and placement and vegetation performance. Testing and evaluating all elements of the landform plan provides confidence, both for the operations in terms of the ongoing investment in the landform, and for stakeholders who are relying on an excellent environmental outcome.

4 Conclusions

Developing a landform that minimises costs in operations and at closure, and that also represents the least risk to the surrounding environment can be achieved. Planning is the key, but an effective plan relies on quality information and a commitment by the mine operations to achieving the plan during the life of the operations. Some key information inputs for planning and constructing mine landforms are:

- The end land use, and thus the rehabilitation outcome that is required for the landform.
- The nature of the mined wastes in terms of geochemistry, physical properties and their capacity to support plant growth.
- The schedule of production of each waste type.

Approaches using a block model approach to landform construction are a powerful tool for mine closure in that they create a practical interface for environmental constraints to be combined with and influence mining engineering and economics.

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