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KEYNOTE ADDRESSES
The importance of failure in mine closures

F von Bismarck  Joint Governmental Agency for Coal Mine Rehabilitation, Germany

Abstract

When delegates from companies present papers at conferences, the word most frequently cited is success. This is very understandable but an important aspect of being successful is the ability to look honestly at failure. Failure is often stigmatised; rarely is it talked about in the open.

The major challenge in mine closure is – and this is something that probably holds true for everybody involved in the process – finding the optimal path that runs between overestimating or underestimating risks. Taking a closer look at failures helps us to find that path. Planners and engineers, even the most well-regarded experts and regulators, are human. Their preconceptions may be mistaken, leading them to the wrong conclusions. Sometimes such assumptions are long-standing beliefs, their true worth hidden until failure reveals them to be false.

In his famous 1948 work ‘Cybernetics: Or Control and Communication in the Animal and the Machine’, Norbert Wiener laid the foundations for controlling systems and ensuring reliable communication by explaining the essential role of negative feedback in a self-educating system. Mine closure can be considered as such a system. Our attempts to self-educate, such as at international conferences, require negative feedback, or, in other words, an honest assessment of our mistakes.

Many success stories could be told about the German Government’s EUR 10 billion, 25-year coal mine rehabilitation programme in the former East Germany. But those involved in the project encountered significant failings, too. In this paper, I present some of those failures in the field of geomechanics and what we have been able to learn from them.

For decades, engineers relied on formulas based on established geomechanical models to determine the stability of dumped and levelled waste material. The results of these model calculations were accepted by regulators as no better methods were available. Since 2009, several ground-breaks have proved that these models are incomplete and the process has not yet been fully understood. The long-standing assumption that dumped waste material settles slowly and evenly was evidently untrue. Additionally, the belief that only exogenous forces can trigger a ground-break was found to be false.

These mistaken assumptions had severe consequences. As the areas had been deemed stable, the land had already been sold by the mining company and had been in use for several years for activities, including agriculture and forestry. It is truly fortunate that the ground-breaks did not cause any casualties.

In the wake of these ground-breaks, all areas of dumped waste were re-evaluated. Access to thousands of hectares of land was barred as a precautionary measure, which in turn delayed the rehabilitation process and necessitated compensation costs for farmers and forest owners. At the same time, more investment became necessary for further research and development (R&D) to come to a better understanding of the process and to develop new and specialised stabilisation measures.

This re-evaluation of the waste dumps would pinpoint areas with potential stability deficits, where new technologies such as gentle-blast-compaction have now been applied. These lessons had to be learned the hard way.
Ecological research needed to manage risk and meet rising standards in mining rehabilitation

B Miller  Botanic Gardens and Parks Authority, Kings Park, Australia

Abstract

Ecological sciences can assist mine planning and management on the way to effective rehabilitation and closure in a number of distinct ways. The identification of likely environmental impacts is a routine application that aids planning. Extending this to assessing the likely complexity of rehabilitation needs may be an equally valuable aid for risk-identification and mitigation, but is not at all routine. The identification of reference target ecosystems, the design of approaches to sample, assess and define these, and then to monitor rehabilitation trajectory towards them are elements of best practice. While these can significantly improve rehabilitation planning and effectiveness, they are often not applied in a way that enables this potential. Lastly, improving technical capacity to deliver required rehabilitation outcomes is the broadest area of potential benefit to closure management. Investing in environmental science may seem counterintuitive for a mining company but there are many potential benefits.
The eye of the beholder — utility and beauty in mine closure

BE Harvey  The University of Queensland, Australia

Abstract

Maximising sustainable mine closure outcomes requires a business-connected approach that takes full advantage of ongoing human and economic occupation of former mine sites. This is evidenced in the majority of successful mine closures around the world, particularly in well-populated regions. Flying in the face of this experience, current mine closure regulation, planning and implementation frequently focuses on the minutiae of environmental remediation. These two perspectives are laced with inherent tensions and contradictions that, left unresolved, will lead to suboptimal mine closure plans that will be difficult to reset when new ideas and economic options emerge. Companies, communities and regulators faced with mine closure scenarios should explicitly place future economic occupation of mine sites at the forefront of mine closure visioning and leave open future options for creative human enterprise.
What lesson for mine closure we can learn from unassisted soil and ecosystem development

J Frouz  Charles University, Czech Republic

Abstract

We used chronosequences of post-mining sites combined with long-term observation of individual sites to compare soil and ecosystem development in post-mining sites undergoing unassisted ecosystem development, and sites reclaimed by various reclamation technologies in different climatic conditions. Using these approaches that allow comparison of individual trials over long periods of time is essential, as in many cases early stage ecosystem development may not be a good indicator of long-term trends. Here, the overview of major mechanisms that determine soil formation and ecosystem development in various climatic conditions are given. We also explore soil formation under various restoration technologies. In suitable climatic conditions, on no toxic overburden, spontaneous processes have the potential to produce valuable ecosystems. In many types of landscapes, namely those with intensive agriculture such as the many parts of Europe, spontaneous recovery of post-mining sites brings a unique opportunity to restore natural habitats. Post-mining landscapes have very high potential for soil carbon sequestration, and in suitable situations, soil formation can be rapid, resulting in development of 10 cm deep A horizon in several decades. Studies of spontaneous processes can be useful for improving reclamation technologies, namely the selection of proper target vegetation and reconsidering or modification of some operations during reclamation.
Extended ecosystem function analysis — the next step for mine rehabilitation appraisals

RN Humphries  Blakemere Consultants Ltd, UK

Abstract

Ecosystem Function Analysis/Landscape Function Analysis (LFA/EFA) is a long established and well received science-based monitoring and assessment technique for rehabilitated mines sites in Australia. It provides keystone evidence for the re-establishment of ecosystem function in the form of soil condition across a range of mine substrates and climatic conditions.

LFA/EFA, in its current form is less concerned with subsequent ecosystem type and development in terms of vegetation composition and structural formation by which communities are recognised and characterised. Similarly, LFA/EFA is not concerned with their condition and, in particular, life-cycle states and dynamics which constitute the key foundation of sustainable ecosystems.

The purpose of this paper is to consider whether there is scope for extending the LFA/EFA methodology for assessing revegetation success and ecosystem sustainability. Having examined the methodology and the ability to integrate an index-based assessment of composition, structure and condition, it is concluded that the LFA/EFA methodology can be extended. Hence, it is recommended that the suggested modifications are considered further and developed as necessary to enhance the current LFA/EFA methodology and also to meet biodiversity enhancement expectations.
Store and release cover water balance for the south waste rock dump at Century mine

TK Rohde  EMM Consulting Pty Limited, Australia
PL Defferrard  MMG Limited, Australia
M Lord  MMG Limited, Australia

Abstract
In 2010 a store and release cover (the cover) was constructed on the south waste rock dump (SWRD) at Century mine (the mine). The purpose of the cover is to reduce seepage (percolation) into the potentially acid forming (PAF) waste rock by maintaining a compacted reduced permeability layer (RPL) at near-saturated conditions. This is achieved by overlaying the RPL with a 1.5 to 2 m thickness of dolomite rock and soil-mulch (the soil-mulch). The RPL is the trafficked surface of the SWRD. The soil-mulch has a hummocky final surface that captures rainfall so it does not runoff, allowing it in part to infiltrate, with excess water removed by evaporation and transpiration. The unsaturated behaviour of the cover is being monitored by instrumentation including volumetric water content sensors and a weather station capable of estimating potential evapotranspiration. The instrumentation allows for the calculation of storage of rainfall in the cover, seepage (or percolation) through the base of the cover and in situ soil water characteristic curves (SWCC). The paper presents the results of three years of monitoring. It shows that seepage is about 6% of the total rainfall over the monitoring period and that the majority of the infiltration is going into storage within the cover before being removed by evapotranspiration. The paper presents a preliminary water balance for the cover by calibrating a Vadose/w model (the model) using in situ SWCCs and calculating actual evapotranspiration.
LANDFORM DESIGN AND REHABILITATION
Hydrological function of berms within a waste landform design

B Roddy Landloch Pty Ltd, Australia
E Howard Landloch Pty Ltd, Australia

Abstract

Berms remain a persistent feature in waste dump landform designs as they are perceived to provide the benefits of reduced slope length, protection against future batter erosion by partitioning the slope with level or backsloping berms, and reduced flow velocity. Underpinning this rationale is the belief that the berms will be a permanent and unchanging feature that controls erosion over the long term. These assumptions are not true. Berms begin to evolve immediately after their construction by trapping sediment and having a beneficial effect over the short to medium term. Longer term, berms fill with sediment and overtop. The time it takes to overtop depends on the material, the size of the berm, and the climate. Once a berm is breached, previously hydraulically disconnected batter sections become a connected flow network that delivers large volumes of runoff from upper slopes to lower slopes that were never designed to withstand them. This process can be caused, or contributed to, by poor quality construction techniques.
Waste dump steep slope construction learnings

WT Moore  Newmont Asia Pacific, Australia
P Garneau  O’Kane Consultants, Australia

Abstract

Optimising and testing final waste dump batter slope parameters prior to reclamation is a valuable step within the mine closure planning process. The aim of the testing is to increase knowledge of site specific characteristics, verify performance against the closure criteria, and assist in revising what are often high level closure costs.

Newmont Boddington Gold (Boddington) is owned and operated by Newmont Asia Pacific and is located approximately 130 km southeast of Perth in Western Australia. The operations consist of two large hard rock open pits, with a current mine life until 2029, with processing of stockpiled material until 2032. The expected final footprint of the waste rock dumps is 811 hectares.

In late 2014, Boddington constructed a rehabilitation trial on an outer slope of Waste Rock Dump 7 (WRD07). The primary goals of the trial were to: i) construct and verify if a steeper than currently approved slope can remain safe and stable whilst meeting closure criteria, and ii) understand the water balance of the slope. Key variables tested within the trial include a 22 degree batter angle, and three surface treatments each with varying ratios of rock armouring within the two metre oxide cover. The same prescribed gravel and topsoil materials were applied to the three surface treatments.

If the trial can demonstrate that a safe and stable slope can be constructed, expected benefits to mine closure planning and execution includes a reduction in dozer pushing costs, better designed surface water drainage system, and more accurate prediction of the volume of leachate that will be required to be managed.

Assessment of the slope’s performance is monitored through water balance measurements, erosion assessment and vegetation growth assessment. Monitoring equipment installed within the trial includes a lysimeter, six soil sensory nests, and a runoff/interflow collection system.

This paper presents a case study of the construction of the trial. The information obtained from the project will be highly valuable in assessing the current closure plans and performance against closure criteria.
Slope stability in landform design

R Knutsson  Luleå University of Technology, Sweden
A Bjelkevik  Tailings Consultants Scandinavia AB, Sweden
S Knutsson  Luleå University of Technology, Sweden

Abstract

Tailings storage facilities (TSFs) will, after closure of the mine, have to be stable in a long-term perspective (e.g. 1,000 years or more). In many cases, due to the characteristics of the tailings, a high phreatic surface is required to keep the tailings saturated in order to prevent, or minimise, the process of oxidation. Due to this the slope stability of the embankment, or the land form slope, is critical as any material exposed to a hydraulic gradient is exposed to a load. So, the question is:

Is the embankment, or landfill slope, that is exposed to a hydraulic gradient safe in the long term with respect to the actual design and material properties?

In order to answer that question, an understanding of the structure, its stability and level of actual safety during operation is necessary. This paper will therefore discuss slope stability for embankments during operation and the long-term perspective and how the factor of safety (FS) can be verified. Practice today for dam stability is that a certain FS is required, i.e. a safety margin (in Sweden FS>1.5), and for that condition we design the embankment. The design includes the geometry of the structure, material properties, water management/water levels and requirements for compatibility between different materials, as well as for construction and operation. The FS can, however, not be physically measured on, or in, the actual embankment. What can be measured is seepage, pore pressure and movement (vertical and horizontal displacements). But how can the readings be used to verify the actual FS? In order to illustrate this, an example from a TSF in northern Sweden is presented where readings have been taken through numerical modelling (PLAXIS), comprehensive geotechnical investigations, lab testing and inclinometers.

In order to predict how an embankment, or landform slope, will behave in the long-term phase and what the actual FS will be, the authors believe it is necessary to understand the behaviour of the structure during operation. The method used for the example illustrated in this paper shows a method to gain an understanding for a structure, which is absolutely crucial for understanding the actual FS and for the possibility to predict the level of safety in the long term.
Integrating the use of natural analogues and erosion modelling in landform design for closure

I Kelder  Jacobs, Australia
CG Waygood  Jacobs, Australia
T Willis  Emergent Ecology, Australia (formerly Mangoola Open Cut)

Abstract

Landform design methodologies as applied in Australia use primarily one of three methods: Linear and empirical designs that consider primarily materials movement, Landform Evolution Models (such as WEPP or SIBERIA) to assess long-term erodibility of specific material within landforms, and hydrological models that use stable alluvial natural analogues in the local environment as a template for a stable unconsolidated landform shaped by water (typically Geofluv™ or similar).

This paper is a case study on the use of elements of all three of these methods on Mangoola Open Cut, a large open cut coal mine in New South Wales, Australia, with a primary focus on the outcomes of an erosion modelling assessment of a Geofluv™ designed landform adapted to meet the site specific requirements.

Construction of the landform commenced in 2012, and the performance to date has been encouraging, based on the short-term, prior to the establishment of vegetation.

Short-term SIBERIA modelling was undertaken to inform the management of erosion risks in the short and long term, and in turn, facilitate ongoing flexibility for the construction of the landform. The modelling will also guide some aspects of revegetation. The modelling predicts that the average overall erosion rate in the long term (500 years) will be similar to the erosion rates of natural landforms in the general area.
Cover system performance — using numerical modelling to optimise monitoring systems

P Garneau O’Kane Consultants, Australia
K Albano O’Kane Consultants, Australia
WT Moore Newmont Asia Pacific, Australia

Abstract

Lysimeters are widely used in the mining and waste industries to directly measure the performance of cover systems installed for rehabilitation of containment facilities (the facility) to restrict net percolation (deep infiltration) and oxygen flux. As lysimeters are conceptually simple, stakeholders place significant emphasis on performance measured by these systems, which adds to the importance of obtaining representative net percolation values. However, the design of lysimeters for cover system monitoring programs in the mining industry often does not consider fundamental aspects of lysimeter design, leading to inaccurate measurement of percolation. Lysimeters also require complementary soil monitoring equipment in order to measure multiple parameters of a cover system’s water balance, and thus its overall performance.

Newmont Boddington Gold Mine, located in Western Australia, implemented rehabilitation field trials for assessing the performance of an updated closure strategy for its Waste Rock Dumps (WRD). The extensive monitoring required for assessment of the cover system performance included the design and installation of a lysimeter to measure percolation. Sizing, that is the depth and area dimensions of the lysimeter, was completed through numerical modelling. Numerical modelling is used to ensure that the lysimeter performs to expectations under a wide range of conditions encountered during the life of the facility.

O’Kane Consultants completed an integrated numerical assessment to develop the monitoring system design for performance monitoring of the WRD cover system. Completion of a performance analysis was required for selection of the optimal lysimeter design whilst considering installation and cost. Numerical modelling was undertaken to simulate and compare the relative performance of various lysimeter configurations. Geostudio’s VADOSE/W and SEEP/W, two commercially available software packages, were coupled to simulate long-term percolation through the cover system and seepage rates through the lysimeter’s base. This paper presents the methodology utilised, results of numerical simulations of lysimeter designs and final design of the performance monitoring system.
The importance of revisiting landform design after key decision-making events

K Knight  AECOM Australia Pty Ltd, Australia

Abstract

URS Australia Pty Ltd (now AECOM Australia Pty Ltd) was commissioned to prepare technical specifications and oversee remediation works to construct a containment cell for the encapsulation of lead tailings at the Northampton State Lead Battery site in Western Australia. The design and construction works were conducted between September 2009 and January 2010 with the objective to reduce residual risks and long-term liabilities associated with a safe, stable and non-polluting site. Design of the containment cell was to encapsulate an approximate volume of 20,000 m³ lead tailings. As the onsite work progressed, 14,000 m³ of additional buried tailings materials were identified and, due to a lack of other suitable options, it was determined by the client and other relevant stakeholders that the additional volume of tailings had to be encapsulated within the same footprint. This altered the design of the cell significantly, which subsequently affected the desired rehabilitation outcomes. The scope did not allow for an alteration of rehabilitation methodology and consequently, three years post construction works, the landform showed signs of instability and the landform surface would not sustain vegetation. In 2013 a refocussed effort was made to promote achievable rehabilitation outcomes. Despite various technical challenges such as steep batters, lack of growth medium, and challenging climatic conditions, these rehabilitation efforts have been successful; the landform is currently safe, stable, non-polluting, and is on a path towards hosting self-sustaining vegetation. As a result, a collaborative technical approach, inclusive of engineers, hydrologists, geotechnical and rehabilitation specialists has become an important component of all URS remediation projects.
Managing the waste rock storage design — can we build a waste rock dump that works?

R Barritt  O’Kane Consultants, Australia
P Scott  O’Kane Consultants, Australia
I Taylor  O’Kane Consultants, Australia

Abstract

For a waste rock dump to be managed both during operations and at closure, a thorough understanding of the composition of the waste is an important requirement. A comprehensive block model should be prepared, with an appropriate materials management and placement plan developed in conjunction with the mining schedule. However, a waste rock dump’s success is hinged on such compositional elements being regularly updated through ongoing materials characterisation over the life-of-mine. Failure to undertake this may potentially result in inappropriate material placement and classification for environmental purposes, and unnecessary costs to the mine and surrounding environment. A revised cover system and landform design was undertaken for a base metal mine in northern Australia following reclassification of its waste. The original permitted landform design comprised an extensive protective cover system of non-acid forming waste rock (88% of overall waste), encapsulating the small potentially acid forming waste volume (12% of overall waste). Additional geochemical studies indicated that these ratios were incorrect and as such, the total volume of clean non-acid forming waste available for the facility was further decreased to a fraction of the initial value. A cover system incorporating both the barrier and moisture ‘store-and-release’ concepts was proposed to limit net percolation into the reactive potentially acid forming waste. In addition, a landform design and extensive surface water management plan was prepared to manage both the high intensity wet season rainfall received at site and the naturally erosive materials available for landform construction. This paper presents the issues encountered during the design stage, which included: a tropical climate; geochemically reactive waste materials; and a surface water management system design, which was to be maintenance free and similar to natural systems in the long term.
Waste landform cover system and geometrical design — integration with waste placement and landform optimisation approach

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Abstract

One of the foremost challenges in mine landform design is the design of stable waste landforms that provide geochemical and geotechnical stability that resist long-term erosion and degradation of cover systems. Surface instability can expose reactive waste and lead to acid and metalliferous drainage, increased sedimentation of downstream waters, cause poor revegetation or related environmental impacts.

The landform surfaces are the interface between the mine landform and the surrounding environment and therefore affect long-term environmental impact. This paper focuses on practical design guidance from early concept development through to the quantitative assessments required for detailed design. This extends to discussion on overall geometry of landforms, veneer stability, cover system design and the selection of cover system materials. These factors should be considered together and integrated with internal waste landform design to provide confidence in design, and improve closure outcomes.

Surface water is intrinsically linked with surface (in)stability and the landform features, such as cover system selection, plateau grading, selection of embankment profiles and drainage structures, require an integrated approach to ensure that the design meets the stability objectives. Landform cover systems are commonly adopted for closure to manage water and oxygen ingress. In many instances the cover system forms a critical component of the closure solution to limit/mitigate the impacts of acid metalliferous drainage, and to enable rehabilitation success. Cover systems are most effective when developed in unison with the landform construction and geometry to improve the stability of the cover system, to accommodate surface water management features, and to realise efficiency in materials scheduling.

Embankment stability is affected by geometry, including slope lengths, gradients and catchments. Longer, shallower slopes have larger catchments and potentially more runoff, whilst shorter steeper slopes have less catchment but (owing to the steep grade) require less energy to mobilise waste. A balance needs to be reached for best performance which is unique for the specific material types and hydrological setting.
SOILS FOR MINE CLOSURE
Genomic studies of biological soil crusts — successional dynamics for the rehabilitation of mine tailings facilities

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Abstract

Biological Soil Crusts (BSCs) are complex communities that include primary producers and multiple levels of consumers in the dependent food web generally consisting of hundreds of species. BSCs can increase porosity, enhance aggregate stability and improve physical structure of soils. Furthermore, BSCs protect soils from wind and water erosion, and they have been used in desertification control. Cyanobacteria are the principal live component of BSCs and provide most of the cohesive characteristics of the BSCs in arid and semi-arid lands by the production and secretion of polysaccharides that allow the chelation and bioavailability of nutrients for other organisms such as algae, fungi and other bacteria species. The microorganisms that are present in the BSCs are not easy to grow using traditional methods; hence, studies using molecular techniques can help to examine the wide range of microorganisms present in the communities. Due to the environmental features of the BSCs, it has been suggested that they can be used to bioremediate degraded soils for rehabilitation purposes. We conducted the first study carried out in Chile in order to develop a methodology for the use of biocrusts as the primary stabilisation means for both soil stockpiles and rehabilitated soil. The phylogenetic and diversity characterisation of BSCs through genomic analysis and bioinformatic tools will allow the development of a suitable methodology to culture and then to inoculate the communities of microorganisms on soils for mine site reclamation.
Appropriate thickness and medium of covering soil on land reclamation in a coal mining subsidence area

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Abstract
Coal mining impacts land resources and lowers the environmental quality which has led to a focus on ecological reclamation in mining areas. This study aimed to find a new method for land reclamation of mining subsidence areas and also provide a reference for land reclamation in these mining areas. The study method initially conducted an eco-geological survey at the mining subsidence area in Zoucheng city. Data collected from the survey was used to link plants and their underground habitats. Data was collected through stringent ecological procedures. The appropriate thickness and medium characteristics of covering soil were determined by the theory of plant below-ground habitat. The study results showed that the appropriate thickness of covering soil in the Zoucheng coal mining subsidence area was 30 cm for herbages; 50 cm for emergent aquatic plants; 70 cm for moisture-proof trees; and 90 cm for drought-proof trees. Furthermore, surface soils with depth of 0–30 cm were suitable cover mediums, and local subsoil could be used as a cover medium after applying artificial fertilisers.
Selected properties of the incipient soils developing on coal mining wastes, Bowen Basin, Australia

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Abstract

The limited amounts of available good quality, fully developed soil frequently constrain the success of rehabilitation works. Consequently, the minesoils that develop spontaneously on spoil materials and their transported erosion products in post-mining landscapes must be used as alternative growing media in achieving rehabilitation objectives. The minesoils developing on spoils derived from open cut coal mining in four Bowen Basin mines are defined and selected properties contrasted with those of local, fully-developed soils. These diverse materials reflect the variety of parent materials present and are developing in immature, geomorphologically active landscapes where they are undergoing substantial physical weathering and, in some places, chemical weathering associated with pyrite oxidation. Important physical limitations as growing media include elevated dispersivity, a high tendency towards crust formation and a very limited development of biologically based structure. Minesoil pH, salinity and sodicity range widely and are used to define twelve classes of materials that reflect their potential limitations as growing media and in substrate stability. Extremes are seen as common and major constraints to soil and ecosystem development. Profile development is largely limited to the surface 50 millimetres. For minesoils to develop eventually into soils in approximate equilibrium with contemporary environments and to provide the ecosystem goods and services necessary to support natural patterns of biodiversity, productivity and water quality, their long-term development pathways need to be better understood.
Ecological and soil development of 19th Century iron and coal mine wastes at Bryn Defaid, South Wales

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M Pawlett Cranfield University, UK
M Tibbett University of Reading, UK

Abstract

Prior to modern regulatory control, mine wastes were typically abandoned and left with minimal disturbance or improvement at the former mine site. Bryn Defaid is one such example and is located on the western slopes of Aberdare Mountain, Rhondda Cynon Taff, Wales, where spoil materials from iron and coal mining were deposited from the mid-1800s. In this study, we investigated the relationship between varied extents of floristic development (including mosses, heather, acidophil grasses and diverse communities of lichens), and the development of incipient soils after 150 years of pedogenesis. We hypothesised that observable categorical changes in the floristic development would be reflected in differential soil development and in its associated microbiota. Ecological development was classified into six floristically defined categories: Bare ground, Primary colonisation, Lichen dominant, Moss-lichen mix, Moss-vascular plant mix and Moss-heather mix.

Soil chemistry showed no significant effect of floristic development on pH (ca.4.5–5.0) and basic cations but a significant effect on soil organic matter and total nitrogen and phosphorus. These higher concentrations were typically found in the moss dominated sites. Soil microbial biomass was also high under mosses, particularly the moss-heather community. Abiotic and biotic conditions under lichen communities were not significantly different to those under later floristic communities, suggesting that other factors (potentially spoil stability) are affecting the development of lichen communities. Overall, there was a relationship between some key soil properties and the extent and stage of floristic development. We conclude that plant-soil feedbacks may play an important role in controlling the development of post-mining plant ecology and related pedogenesis.
STAKEHOLDERS AND COMMUNITIES
Town resource cluster analysis — understanding and quantifying your operation’s social and economic linkages at local, regional and state levels

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Abstract

This paper demonstrates an applied approach to assessing the socio-economic impacts of mine closure using the application of Town Resource Cluster (TRC) analysis; a methodology developed in Australia for application within a natural resource management and development planning context. The methodology provides opportunity to examine the linkages between a resource operation and social systems, and affords quantification of economic and social contribution at local, regional and state levels to guide operational planning and decision-making at various phases of an operation’s lifecycle.

In the context of mine closure planning, TRC analysis delineates the social and economic associations between a mine and its local and regional communities based on a number of factors, including: employee (and family) place of residence; use of services; annual household expenditure; employee involvement; and participation in local community life. Data relating to supplier linkages can also be demonstrated and quantified.

This paper illustrates that by using TRC analysis, an operational site can obtain an understanding of both the positive contribution that its operation is presently making, as well as identifying and quantifying the potential impacts on local towns and communities as the mine closure process commences. Such a process ensures no surprises and affords the effective management of change at local and regional levels.

The technique is presented further through discussion of a number of case studies where it has been practically applied.
Social closure planning: scoping, developing and implementing – a case study

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CD Grant  Anglo American, Australia  
M January  Anglo American, South Africa

Abstract

Social aspects often lag behind or are not factored into closure plans with the same rigour and levels of confidence as the physical and bio-physical aspects. Anglo American has a predominance of operations in developing countries where local communities become directly and indirectly dependent on the mining activities for their livelihoods. This emphasises the importance of proactive management of social aspects throughout the life-of-mine and at closure. Anglo American is of the opinion that a mine closure plan without concurrent social planning leaves a significant gap in the planning process, lowers the overall confidence in sustainable closure and increases post-closure residual risk as well as associated liabilities. The objective of this case study is to demonstrate how the Anglo American Mine Closure Team is assisting a coal mine in South Africa to develop its social closure plan and closure costs for the site. This is a significant departure from the norm where operations in the past have used external consultants. Using in-house resources ensures deeper ownership of the mine closure plan and thus a better chance that the plan will be executed as intended. The final social closure plan will address the needs and risks associated with employees and dependents, interested parties, affected parties and regulators. Understanding the needs and expectations of these stakeholders is essential to improve the confidence of the overall mine closure plan. The project to develop the social closure plan is split into three phases. The objective of phase one is to deliver a detailed scope of work, with actions, timelines, accountabilities and budgets, which will inform the development of the social closure plan component of the overall mine closure plan. The objective of phase two is to support the colliery with the execution of the actions identified in phase one to ensure the social closure plan is compiled to an acceptable level of confidence given the closure date for the colliery and that it is delivered within set timelines and budgets. The objective of phase three is to support the colliery to implement the social closure plan over the remaining life-of-mine and improve the level of confidence of the final closure plan, mainly through increased stakeholder engagement. Social closure criteria will be developed and included in the current stakeholder engagement platforms. The development of the social closure plan is managed as a project where gaps are identified, all required activities are mapped, resources assigned, critical paths identified and where the schedule is managed with rigour. Through this approach the challenge of involving a diverse array of internal and external stakeholders is much easier to manage. In addition, this multi-disciplinary approach allows for better integration and synergies between the social, physical, biophysical and financial closure planning.
Attractive nuisances and wicked solutions

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Abstract

Mine closure plans generally include the objective of creating sustainable conditions that provide for public health and safety and protect the environment. The mining industry has developed and implemented approaches and technologies to achieve this objective in a variety of contexts. However, some activities will inevitably result in post-mining conditions that become attractive nuisances — conditions that appeal to trespassers who may not understand or appreciate the safety risks to themselves and others.

During operations, controls can be implemented and monitored to reduce the risk of exposure to attractive nuisances, but after closure this becomes more difficult. Proactive stakeholder engagement can identify likely post-mining land uses and sustainable livelihoods. However, what happens when these are in conflict with mine closure goals? It is critical to understand the drivers for and context of future land use and livelihood development to mitigate and/or influence the potential impacts of both.

In addition, throughout the mine lifecycle (exploration through closure), the operation should support sustainable and responsible development at a community level. Yet, in some instances the social context can severely limit the options for and effectiveness of standard technical closure approaches. In extreme cases, the social context of a project may not lend itself to any solution that achieves the technical and socio-economic objectives of closure because of uncontrollable future use of the site. These challenges, along with the consequences of economic disturbance, and population displacement, inequality, and poverty — issues often referred to as a ‘wicked problem’ — are often inadequately addressed.

Within the context of closure, this paper compares the complex and multi-dimensional aspects of poverty with the constraints and opportunities posed by mining as a dominant single sector economy. Examples of integrated closure planning, stakeholder engagement, and land use and livelihood development are presented to illustrate successful approaches to avoiding or mitigating attractive nuisances after closure. These successes are contrasted with situations where future land use and livelihood development are less controllable, potentially limiting the effectiveness of industry standard closure practices. In doing so, the authors propose an overarching wicked solution for social closure through livelihood restoration and socially and ecologically sustainable community development practices.
Abandoned mines — environmental, social and economic challenges

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Abstract

The environmental, social and economic problems associated with abandoned mine sites are serious and global. Abandoned mines may pose unique and complex challenges, often leaving negative impacts such as: safety and health hazards for people and animals, neglected mining heritage and other assets, in addition to economically-depressed communities.

Acid and metalliferous drainage (AMD), also known as acid mine drainage, is one of the negative environmental impacts on water quality that can result in a subsequent loss of biodiversity. AMD impacts can occur from underground workings, open pit mine faces, waste rock landforms, and tailings storage areas that were left exposed to the elements or inadequately rehabilitated, resulting in the contamination of water with dissolved metals and acidity.

Social and economic impacts on countries and individual communities can be due to issues such as: a loss of the productive land, loss or degradation of groundwater, pollution of surface water by sediments or salts, changes in river regimes, air pollution from dust or toxic gases or risk of falls into shafts or open pits.

Resources for cleaning up abandoned mines are very limited in most jurisdictions. A strong policy framework is required and, in order to be effective, primary policy elements must be embedded in the legislative framework. This paper explores the international dialogue that has taken place on abandoned mines, our improved understanding of legal liability, funding remediation and rehabilitation and the strategies that are in place to minimise the likelihood of more mines being abandoned.
DECOMMISSIONING OF TAILINGS DAMS
Towards closure — considerations in tailings storage design

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Abstract

This paper explores the relationship between geotechnical issues and drainage/water management in the design of tailings storages for closure, with an emphasis on high rainfall and tropical environments. Selection of the tailings system for a project will greatly influence the tailings geotechnical characteristics within the storage facility (i.e. tailings density and strength). Other influences include ore type, grind size etc. Options available include the use of high density thickened tailings or filtered tailings. Higher density and greater strength tailings should lead to reduced differential settlements, reduced risk of failure of tailings storage facility (TSF) cover drainage (water management) systems and hence better closure outcomes. Selection of the tailings system for the project can have other impacts on water management for the project, including water conservation (e.g. thickened or filtered tailings and greater return of water at the plant).
Capping of a surface slurried coal tailings storage facility

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Abstract
A completed, conventional, surface slurried coal tailings storage facility in Southeast Queensland, Australia, required capping to facilitate rehabilitation for grazing purposes. The facility had been closed for some years and the upper part of the tailings beach was well-desiccated, while residual ponds covered the low areas with the extent of ponding varying with rainfall. Prior to the commencement of capping, the tailings were tested using a field shear vane, the results of which were used to assess the safe trafficking of the dozer and placement of the initial capping layer. Both the peak and remoulded vane shear strengths were tested, the former representing small-strain loading and the latter representing bow-waving. An initial 1 to 2 m deep capping layer of coarse reject was placed using a D6 Swamp Dozer. Capping commenced from the strongest, highest elevation of the tailings beach, and extended towards the ponds. As the capping progressed, further vane shear testing was carried out to assess the shear strength of the tailings beyond the capping layer, and the strength gain over time in the already covered tailings, which would enable further capping material to be safely placed. The paper describes the capping approach and sequence adopted. The initial capping was followed by the placement of further coarse reject by D9 Dozer.
Centrifuge modelling of drawdown seepage in tailings storage facilities

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Abstract

Uncertainties surrounding seepage behaviour are a key issue raised in tailings storage facility (TSF) operation. Poor seepage management can result in negative environmental impacts, costly remediation or even embankment failure and, in the context of mine closure, long term liabilities and/or legacy site issues. In particular, recovery pumping rates must be maintained for sufficient time to capture seepage both during operation and after closure during reservoir drawdown.

Seepage analyses for TSF design commonly assume isotropic or, at best, anisotropic homogeneous material properties. However, layering during deposition, consolidation and swelling on drying and wetting create a seepage environment far more complex than these assumptions suggest. Improved modelling is required to increase analysis confidence.

Centrifuge modelling allows geotechnical phenomena to be investigated using scale models under representative stress conditions. However, precious few examples exist for seepage modelling using this technique. This paper briefly discusses modelling equipment development for use with The University of Western Australia (UWA) beam geotechnical centrifuge. Results for seepage during reservoir drawdown, simulating facility closure, are then presented for a layered, heterogeneous embankment model, as compared to predictions made by commercial analysis software. Findings are used to comment on the implication of simplifying analysis assumptions on drawdown time and flowrate calculations.
Leading practice store and release cover trials for a tailings storage facility at Century mine

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TK Rohde  EMM Consulting Pty Limited, Australia
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Abstract

A store and release cover that is designed (the cover) to limit the release of sulphate salts and metals (the potential contamination) from acid forming tailings is site specific; being a function, among other factors, of the borrow materials available, tailings deposition method, and the climatic setting. Three experimental cover trials, each a 75 x 75 m square were developed and constructed on the tailings storage facility at MMG (Minerals and Metals Group) Century mine in the semi-arid Northwest Queensland. The covers rely on the storage of rainfall during the wet season and its release during the dry season through evapotranspiration. Covers typically comprises of a compacted fine-grained reduced permeability layer (RPL) of compacted clay overlain by a significant thickness of loose rock and soil (rock mulch). At the mine there is a paucity of fine-grained material for the RPL, this may be overcome by using mixtures of coarse and fined grained soil and rock (the mixtures). The cover trials have been designed to test three potential RPL mixtures which include minus 10 mm crusher dust conditioned with bentonite, a geo-synthetic clay liner placed between an upper and lower layer of minus 10 mm crusher dust, and minus 10 mm crusher dust conditioned with an extra 15 to 30% fines (passing 0.075 mm). All three cover trials have been enhanced by the addition of a capillary break (CB) layer directly above the tailings. The purpose of the CB is to stop the vertical rise of potential contamination from reaching the top layer of the cover, which is rock mulch. The performance of the cover trials is being monitored by instrumentation, including volumetric water content and matric suction sensors, a weather station capable of estimating evapotranspiration and lysimeters to measure percolation (deep infiltration) through the base of the cover. The instrumentation allows for direct measurement of infiltration into the cover, storage of rainfall and percolation through the base of the cover. The paper describes the cover trials construction, instrumentation and monitoring data from the past two years.
CASE STUDIES:
LESSONS LEARNED
Lessons learned from closure of mine facilities

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Abstract

Mine facilities decommissioning, closure, and rehabilitation have been conducted at sites in the Western Hemisphere (in particularly the Western United States) for several decades. This time period has allowed the planning, permitting, closure, and post-closure performance to be evaluated. This paper outlines the primary lessons learned from involvement at a number of sites in various climate and topographical settings. From these examples, the primary closure issues discussed in the paper include: (1) post-closure property control and land use; (2) stakeholder relationships and commitments; (3) residual waste material management; (4) design period and post-closure maintenance; (5) water management (before, during, and after closure), and (6) socio-economic impacts.
Pitfalls of gold mine sites in care and maintenance

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MA Lund  *Edith Cowan University, Australia*

Abstract

Gold is a highly valued and volatile commodity which is subject to many external forces, such as price and availability. Global gold stocks are increasing but the supply is dwindling. Gold mining companies are always looking for novel methods to optimise extraction and processing thereby reducing operating costs and maximising profit. The extraction and processing of gold involves complex chemical processing which results in large volumes of waste, including toxic tailings, and damage to aquatic and terrestrial ecosystems. Our research indicates that gold mines in Western Australia regularly enter an operational phase known as ‘care and maintenance’ where active mining is not occurring but the site is not yet formally closed. It is a mode generally used to reduce operating costs and overheads, whilst maintaining the option to recommence mining in the future. Sites in care and maintenance are often neglected and minimal rehabilitation is undertaken resulting in massive environmental liabilities and social issues. In worst case scenarios, companies simply mothball the site and they become abandoned or legacy sites. We recently quantified the disturbance footprint and environmental legacies around a representative sample of gold mines in the West Australian Goldfields region. Our results suggest that sites in care and maintenance are a potential emerging problem for regulators left carrying the can for the costs of rehabilitation.
Key mine closure lessons still to be learned

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Abstract

The focus of mining project feasibility studies and operations is still on short-term profitability with little view to a post-closure landscape and liability. The faults of both the original and the operation’s mine planners are therefore vested upon the closure teams who must deal with these planning decisions. Following completion of operations, most mining companies that have not adequately prepared for mine closure will face an inability to relinquish their project leases as a result of closure planning process shortfalls. Following from our own closure project experiences and of recent international mine closure conferences, we propose seven key lessons still to be learned if successful mine closure is to be achieved.

Firstly, a paucity of baseline environmental monitoring data often incapacitates good closure planning from the outset with a failure to understand key closure risks and risk drivers for the site. Well-characterised environmental information prior to mining disturbance and monitored progressive rehabilitation is a great strategy to address this fault.

An insufficient understanding of the physical and chemical characteristics and volumes of waste materials is a second critical fault of closure processes.

A third significant issue is contaminated mine waters such as acid and metalliferous drainage (AMD). AMD is arguably one of the single biggest liabilities and management issue post-closure.

Failure to engage stakeholders in a documented process is a fourth prime failing often seen with the fifth of mine closure procrastination. Like all of these causes, this problem often arises from thinking mine closure is an activity at end of life-of-mine rather than as a process that begins with the initial mine plan and then regularly continues throughout mine life. Diligent attention to regular planning assessment and stakeholder consultation from an early operational phase may fend off later criticisms, lead to closure outcomes better directed by years of underpinning work and also reduce end of mine costs.

A sixth significant closure planning error is the failure to account for the long temporal scales that closure planning must accommodate, particularly so when costing closure. This failure is often due to closure views being short-term, to meet immediate regulatory and operational planning needs rather than focussed on the future.

A seventh lesson from historic closure planning is the simple failure to have clear closure objectives and approaches to identified outcomes. This may result in a focus on technical studies that fail to provide better closure understanding, whilst expending hard-won closure-aimed budgets. Driving closure planning by well-defined goals through corporate tools such as closure standards designed to meet both internal requirements and relevant closure guidelines is an ideal solution to avoiding wasted closure resources such as time and finances.

Whilst learning and addressing these key closure lessons is no guarantee of successful relinquishment, recognition of these issues and judicious planning to overcome them is more likely to present well-considered closure plans with greater chance of closure relinquishment in a sustainable socio-environmentally manner that maintains a company’s and the broader mining industry’s licence to operate into the future.
The use of satellite-based remote sensing methods to assess the changes in the environmental impacts from the Marcopper disaster on Marinduque Island, Philippines

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KG Mercer  Australian Centre for Geomechanics, The University of Western Australia, Australia  
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Abstract

The Marcopper Mining Disaster occurred between 1975 and 1996 on the Philippine island of Marinduque, a province of the Philippines. It remains one of the largest mining disasters in history and is almost completely un-rehabilitated. The Marcopper Mining Corporation mined the Mt. Tapian ore body followed afterwards by the San Antonio copper ore body, using open pit methods. Three separate environmental incidents occurred during this time which finally culminated in between 2 to 3 million tonnes of tailings which flowed from the Tapian in-pit tailings facility along a drainage tunnel into the 26 km long Boac River. Flooding isolated and buried some villages under 2 m of floodwater and tailings. Environmental impacts were considerable and the government declared the Boac River dead. Since 2002, despite two major studies which were completed in 2004 and 2005, no remediation efforts have been undertaken on any of the waste landforms or rivers to-date.

In order to understand the ongoing environmental changes taking place on the mine waste landforms, the Australian Centre of Geomechanics partnered with MacDonald, Dettwiler and Associates to undertake a preliminary review of the Marcopper waste landforms using products derived from historical radar and optical images collected over the island from the 1996 to 2014. This paper summarises the results of this study and makes recommendations for further remote sensing studies and ground-truthing activities.

Remote sensing challenges using historical data were significant and included persistent cloud cover or haze in regions, heavy vegetation in some areas, and localised steep terrain. Historical images were used to map the changes taking place on the waste landforms using a variety of remote sensing approaches including automated multi-date change detection algorithms, Normalised Difference Vegetation Index, terrain analysis and land cover mapping.

This study found that the Calancan Bay tailings outfall has retreated over 550 m since 1996 and that barren and steep-sloped regions are present near the mine pits and tailings dams. In addition, the size of both pit lakes has continued to increase. Nevertheless, the findings showed that within the vicinity of the open pits and mine waste landforms there has been gradual reestablishment of vegetation during the 18-year study period.
A comparative study of regulatory approaches to mine closure with a special emphasis on the current situation in the former Soviet Union

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Abstract

Successful mine closure or reclamation processes have various definitions in jurisdictions around the world. Setting criteria for a successful mine closure is required to measure progress towards achieving the objectives of closure. The majority of existing guidelines are based on processes – methods and procedures and techniques – the ‘means’ rather than the ‘ends’. Current debate argues that identification of end-use is good practice in mine closure methodology, seeking outcomes such as future use, performance and function. This paper examines aspects of these ‘good’ mine closure practices, identifying the objectives and criteria in the jurisdictions of Western Australia, Canada (BC), Chile and South Africa.

This paper then goes on to contrast these aspects with what is currently found in former Soviet Union (FSU) countries of Russia, Kazakhstan and Kyrgyzstan. It is apparent that these FSU countries have much to do to achieve good mine closure practices. The paper concludes with descriptions of planned future development of policies and trends in the FSU arena that could move towards targeting similar good practices.
When is it time to say enough is enough for historical mine rehabilitation and closure? A Pilbara case study

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Abstract

Mine rehabilitation and closure standards, and stakeholder expectations regarding these, have changed significantly over time. In particular, over the last 20 years, regulator, community and industry expectations on what constitutes acceptable rehabilitation and walk-away solutions have increased dramatically. This has improved rehabilitation and closure outcomes, but this has also raised the bar to an often unrealistic level for historical mine sites. It can increase closure costs, prolong (or even prevent) site relinquishment and damage stakeholder confidence in a company’s and the broader industry’s ability to undertake mining in a sustainable manner. Is it fair to expect a historical site to meet modern standards or are these expectations setting up operations and companies to fail?

The imposition of current or future closure standards on older operations is a major concern for industry. There is a need for a new approach and dialogue regarding the actual environmental and community risks associated with historical sites, and what rehabilitation and closure standards are practical and should apply. If there are no sensitive receptors and the risks have been contained or are being managed effectively, why go any further? This does not mean that mine operators should ignore their responsibilities and that new mines should not be expected to achieve higher standards or best practice, but decisions need to be made on the most practical, pragmatic and cost-effective way to utilise what are often limited resources in rehabilitating and closing historical mines. To adopt a new approach, it is important that stakeholders understand the standards that were applied when mining at a site commenced and/or when a mine was operational, and what closure outcomes are realistic. Perhaps there are alternative, and possibly better, environmental outcomes that can be achieved rather than trying to achieve the impossible on a site that was not set up to current-day standards?

This paper discusses the Blue Spec Shear Gold-Antimony Project near Nullagine, Western Australia, and draws on other examples, to trigger a conversation within industry, regulators and the community about whether historical sites can meet modern rehabilitation and closure standards, and if a new site relinquishment approach is required.
Dealing with mine closure planning liabilities, opportunities and lessons learned

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Ts Davaatseren  Erdenet Mining Corporation, Mongolia
Kh Vladimir  Erdenet Mining Corporation, Mongolia

Abstract

In 1978, Erdenet Mining Corporation (EMC or Erdenet) was established in accordance with a joint venture agreement between the governments of Mongolia and the former Soviet Union (51% and 49%, respectively). As one of the largest ore mining and processing operations in the world, the company produces approximately 530,000 tonnes of copper concentrate and 4,500 tonnes of molybdenum concentrates annually.

The company plans to expand its productivity from 26 mtpa to 32 mtpa due to declining ore grade, to retain competitiveness and also to hold revenue at a consistent level. Consequently, a number of issues became apparent that were not identified in the decision-making process for the expansion approval. What was initially thought to be a gradual process of developing and integrating mine closure plans (MCP) for the mine operations over the life-of-mine, this expansion now requires a MCP for the decommissioning of the old tailings storage facility (TSF) and a MCP incorporated into the design of the new TSF.

This paper examines a number of issues and opportunities that accompany expansion changes to a 37-year-old mine. Firstly, the MCP needs to be integrated into the company’s business plan. A mid-term business plan update (2016 to 2025) is in progress. The number of items were determined which were relevant to mine closure within this timespan. For example, the existing TSF is at approximately 60% of its initial design capacity; a new TSF will need to be constructed during the next 10–14 years. The old TSF will require a MCP to deal with drainage and groundwater contamination, existing dust issues, rehabilitation and ongoing monitoring and remediation. By contrast, the new TSF will include mine closure considerations during the design, construction and operation; an ideal opportunity to reduce post-closure monitoring, costs and ongoing liabilities.

Erdenet town was established in 1974 specifically for the mine and now has a population of around 110,000. Public participation will be adopted for the first time during the new TSF/MCP development process and for the old TSF closure. This paper will also touch on the changes in town dynamics since the mine’s conception and what this may mean to the mine closure process.
Engineering and reclamation of the Holden Legacy Mine — advancing the state-of-practice for mine closure

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Abstract

Rio Tinto is reclaiming an abandoned copper mine in one of the most isolated places in the continental U.S., located near Lake Chelan in the remote reaches of north-central Washington State. The Holden Mine was one of the largest operating underground copper mines in the U.S.; the mine was developed and operated between 1937 and 1957 and produced over 90,000 tonnes of copper, as well as zinc, silver and gold. Over the life of the mine, nearly 100 km of underground tunnels had been excavated and 7.6 million tonnes of mill tailings placed on U.S. National Forest lands near Railroad Creek. Although Rio Tinto never owned or operated the mine, they are managing and funding a several hundred million dollar clean-up to prevent future water and soil contamination and to restore the former mine site under the United States Environmental Protection Agency Superfund process. Adjacent to the mine is a former man camp, now home of the Holden Village Inc., a religious community that hosts 5,000 to 6,000 visitors each year. Engineering the Holden Mine remedial design required development of an integrated system of mine closure components including: infrastructure improvements, surface water and sediment management, slope stability improvements, surface and groundwater collection and treatment, mill demolition, and restoration to re-establish vegetation consistent with that of the surrounding forest. This paper addresses these topics and includes information on the design criteria and objectives, pre-design investigations and evaluations, and a summary of the design for each remedial component. The paper concludes with the project successes and lessons learned from engineering the remedial design. The first in a series of technical papers, this paper provides the mine closure community an overview of the innovative design and construction techniques that have been applied at the Holden Mine with the goal of further advancing the state-of-practice for mine closure and remediation at other sites.
Designer waste landform modelling and design — Rum Jungle Mine

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Abstract

Rum Jungle is a former uranium mine site near Batchelor in the Northern Territory. Historical mining activities at the site between 1952 and 1971 have led to ongoing and adverse impacts on the surrounding environment. Sulfidic mine waste is prevalent in the Main and Intermediate Waste Rock Dumps (WRDs) and consequently, Acid and Metalliferous Drainage (AMD) is a problem. Even though a technical assessment after rehabilitation determined that the engineering and environmental criteria were met, ongoing impacts have led to contemporary water quality standards not being met in the East Branch of the Finniss River and soils around the site, and led to poor vegetation establishment and coverage.

The Department of Mines and Energy (DME) is directing a collaborative, multi-phased rehabilitation planning process for the site. The Former Rum Jungle Mine Site Conceptual Rehabilitation Plan (CRP) (2013) outlines the objectives, the rehabilitation approach and preferred rehabilitation strategy for the mine site. Objectives for the site are to provide geotechnical and geochemical stability so as to allow for sustainable land uses by traditional Aboriginal owners of the site. To achieve these objectives, it is proposed to relocate all existing above ground WRDs, to either backfill the Main Pit void, or a single, stable and aesthetic waste storage facility (WSF) which will be constructed on site. Development of the strategic approach and detailed design of civil engineering works is currently underway to manage geochemically and radiologically active mine waste prevalent across the site.

O’Kane Consultants Pty. Ltd. (OKC) is preparing rehabilitation designs for the overall site, supported by various (ongoing) technical assessments for the WSF and Main Pit. The detailed numerical modelling includes a material balance assessment, waste placement and oxygen ingress modelling, waste wetting up and drain down modelling, cover system and landform evolution modelling. The control of surface water, seepage, and erosion in the long-term and during construction is central to achieving the rehabilitation objectives. As such, assessment of the proposed WSF geometric design methodology by the practical implementation of landform evolution models, including Water Erosion Prediction Project (WEPP), SIBERIA and CAESAR-Lisflood is being completed. These models are used in conjunction with sophisticated terrain modelling software (Civil 3D) to assess future stability based on surface materials and desired landform geometry. The assessment methodology is based on lab testing and observations of erosion on existing landforms, and the validation adds confidence to the assessment. This enables improved aesthetic design for the proposed WSF, an important design objective, and can provide confidence in stability of the landform over long time frames.

The results of the detailed assessments by OKC and other consultants are used to conduct ongoing detailed engineering designs for the overall site including the design of the WSF with appropriate waste placement specification, a natural shape and provide long-term surface stability. This paper discusses the overall approach and integration of the various technical studies and supporting numerical assessments.
Post-closure funding initiatives to facilitate custodial transfer and relinquishment of mining tenure

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Abstract

The aim of mine closure works is usually to minimise residual liability to enable the responsibility for land management to be transferred to a custodial authority. The accepted approach to relinquish mining tenure after closure works is to measure performance against agreed objectives and criteria over a period of time, to demonstrate success to key stakeholders. The relevant custodial authority may, however, be unwilling to inherit the responsibility for managing closed mines and ongoing closure liabilities in perpetuity.

There are very few examples in Western Australia where a closed mine has been relinquished to the State Government in a coordinated manner. There are examples, however, where Governments have inherited legacy mines and associated closure liabilities, where the mine operator has been unable to meet their closure obligations.

There are examples from around the world where mine operators have established long-term, self-perpetuating funding initiatives as a mechanism to facilitate custodial transfer of mining areas and coordinated relinquishment of mining tenure. Such initiatives can provide financial surety in the event of foreseen or unforeseen closure risks, provide for organisation and management of a custodial body, provide an ongoing benefit to the community or the environment, and can fund ongoing activities for a closed mine.

Self-perpetuating funds and other mechanisms that buffer the exposure that a custodial authority has to residual liabilities and risks, in concert with demonstrated closure success, may encourage Western Australian regulators to more readily consider relinquishment applications for mining tenure. This paper reports on some of the long term funding initiatives that have been applied globally.
WATER MANAGEMENT
Passive treatment of acid mine drainage at Vryheid Coronation Colliery, South Africa

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Abstract

A novel passive bio-neutralisation water treatment process has been applied to treat an acidic mine drainage decant emanating from a closed colliery in northern KwaZulu Natal, South Africa. The process has been implemented to treat 200 m³/day of water and incorporates the following components: a 3.2 km pipeline from the decant point to the water treatment site, a molasses dosing station, a 1,000 m³ bio-neutralisation reactor, three aeration cascades to oxidise sulphides, passive sulphide gas extraction to a bio-filter to oxidise sulphide gas, three limestone reactors for pH polishing, and an aerobic wetland to remove residual nutrients. The bio-neutralisation technology is a strictly biological process utilising bacterial processes to treat an influent with a pH as low as 2.8 to remove the acidity, iron and aluminium. The plant has already been constructed and commissioning commenced in August 2015.
Two-dimensional reactive transport modelling for waste management — aquifer injection case study

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Abstract

Mine closure projects are increasingly including consideration of detailed groundwater contaminant models that require inclusion of geochemical conditions, attenuation and plume development. To illustrate these concepts, modelling of a proposed borehole mining (BHM) trial, undertaken as part of a mineral sands development project, is provided as a case study. The BHM trial tests a proposed unconventional mining method, known as borehole mining, and trials the selective in situ removal of ore to reduce the need for overburden removal.

The ore is located within an aquifer which resides below the groundwater table and is associated with potentially acid forming (PAF) material. The BHM trial will extract mineralised sands/ore and separate fines (< 53 µm) from the sands. As part of the BHM trial, the fines, neutralised with excess limestone (CaCO₃), and a portion of the ore will be re-injected (with groundwater; 70/30, liquid/solids) back into the cavity space left from extraction.

Klohn Crippen Berger was commissioned to determine the likely water qualities resulting from the various scenarios of the borehole re-injection trial. This was assessed using the results of in-field, laboratory geochemical testing and hydrogeochemical modelling. The hydrogeochemical modelling was undertaken using the Geochemist’s Workbench (Bethke & Yeakel 2010) X2t module (2D reactive transport modelling). The models have incorporated the injectate composition (~70% groundwater and ~30% waste materials), aquifer water quality and simplified aquifer mineralogy. Aquifer hydraulic properties were included based on previous hydrogeological characterisation and groundwater modelling investigations.

A series of 2D reactive transport models were constructed to simulate two injection options and to undertake sensitivity analysis. This includes aquifer injection for a 5-day period (fines only) and 36-day period (fines and ore), followed by one year of migration under natural groundwater gradients. The purpose of the modelling is to provide confidence in the BHM trial, with the possibility of the results being used to assess contaminant trigger values from the point of injection. Resulting water qualities for the various scenarios were compared to Australian drinking water requirements to provide guidance on the preferred injection methodology, and to assess whether the proposed approach would result in significant water quality impacts in the receiving aquifer. The paper uses this case study to illustrate how reactive transport modelling can assist in mine close assessments.
Watercourse diversions relinquishment in Queensland – a risk-based approach to monitoring

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Abstract

Recent modifications to the model licence conditions for constructed watercourse diversions on operational mines in Queensland introduced an outcome-based approach to managing compliance of constructed diversions, as opposed to the previous prescriptive licence conditions. Watercourse diversion licences can now only be relinquished once they have proven a diversion has met the outcome-based conditions stipulated in the licence.

Many watercourse diversions constructed as part of resource activities in Queensland have been designed with no or little consideration for geomorphic processes, natural watercourse hydraulics and/or the local vegetation landscape. For this reason, a large number of licenced watercourse diversions are in poor to moderate condition and will not be able to meet the outcome-based licenced conditions without significant rectification or modification works. Additionally, previous licence conditions required licence holders to undertake monitoring for individual diversions at varying frequencies (annual, biennial or five-yearly). However, the current Department of Natural Resources and Mines (DNRM) model licence conditions do not specify a monitoring frequency. This leaves licence holders in a difficult situation in which they have a relinquishment liability and no formal guidance from the administering authority regarding acceptable monitoring activities and frequencies.

To assist a licence holder, we developed a risk-based method to inform watercourse diversion monitoring and evaluation programs, dictating monitoring frequencies and methodologies based on the diversion risk profile. The program also provided information about compliance liability against model licence conditions, developed management options for non-compliant watercourse diversions and prepared prioritised works programs to manage transition to compliance, particularly focussing on improving the likelihood of future relinquishment.
Adaptive, integrated water management designs and probabilistic modelling for mine waste facility closure and restoration

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Abstract

Closed Mine Waste Facilities (MWFs), both tailings and waste rock facilities, represent a potential hazard to the downgradient surface water and groundwater environment. Adaptive, integrated engineering designs at mine sites with short-term life–of-mine resources necessarily mean that closure should be factored into designs and mitigation measures very early in the project lifecycle. Not least, as key decision makers can see the finish line even before the first ore has been shipped. Also, there is emphasis on the importance of having a mechanism for providing a demonstrable analysis, which increases the confidence of the designer/owner, the regulatory authorities, and the public, that the solution is providing environmental protection.

The assessment of the long-term risks such facilities pose to the water environment is an important issue for mine closure, particularly when the potential for an impact on the water environment has been identified, necessitating the need to make financial provision for aftercare costs. In addition to the need for financial provision during aftercare, European and international regulatory frameworks require mitigation of potential impacts on the water environment in the long-term, necessitating assessments to account for long-term cover/cap and liner performance as well as changes in climate. This paper presents a case study describing the use of a series of modelling approaches, including probabilistic modelling, to evaluate design performance and risk associated with an Integrated Mine Waste Facility (IMWF) at Dundee Precious Metals Krumovgrad’s (DPMK’s) proposed mine site in Krumovgrad, Bulgaria. The case study illustrates the application of probabilistic modelling involving the use of probabilistic risk assessment to appraise differing closure and remediation strategies for the IMWF at the design stage based on available environmental data. In the case study presented, probabilistic modelling was successfully applied to quantify the nature of the risk to groundwater and surface water in closure, and the degree of amelioration afforded by differing management techniques (placement of a basal liner, installation of a groundwater capture system for a defined period, and capping of the site in closure). The ultimate decision that the site should move forward with a groundwater capture scheme to provide containment for the site during operation and early post-closure was supported by impact assessments demonstrating that the tailings and waste rock source would not pose a long-term risk to groundwater and surface water in closure.
Surface water assessments — critical for effective landform design

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Abstract

Surface water impacts can represent a significant long term mine closure risk in general and for landform design specifically, particularly in arid environments due to a range of factors including erosion, geotechnical instability and changes to geochemical conditions associated with water movement through landforms. Undertaking targeted surface water closure assessments during the landform design phase can provide an effective mechanism to define and manage drainage risks.

Surface water assessments utilise a hydrological model to determine the runoff generated from catchments under design rainfall conditions in order to develop a hydrograph as an input into a hydraulic model. The hydraulic model assesses the performance of the surface water controls under the modelled conditions. The surface water assessment should be informed by the critical return period for any given site. Effective waste rock characterisation provides inputs for modelling the as-constructed hydraulic properties and an indication of how these properties may change over time.

Surface water assessments are critical to develop closure designs that minimise the need for ongoing maintenance, are geared towards the achievement of long term closure objectives and are better able to meet stakeholder expectations. These assessments can provide key information to the landform design process, including drainage controls, storage features, slope configuration, upstream runoff management and armouring specifications.

This paper explores the technical aspects of undertaking surface water assessments and provides practical working examples.
Establishing closure targets for discharge to temporary waters — a review

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Abstract

Temporary waters include intermittent and ephemeral streams, lakes, pools and wetlands and are found throughout the world, largely in arid and semi-arid environments. The development of resource projects near temporary waters requires the determination of potential impacts pre, during and post mining which is often difficult to quantify and monitor due to the highly variable nature of the systems. In Australia, the current water quality guidelines for the protection of aquatic ecosystems are unsuitable for application in temporary waters and it is acknowledged that there is a need to develop guidance for these waters. A review of international practice finds a similar issue where current policies for protection and assessment and management guidelines generally are found to be lacking. A rigorous scientific approach for defining and monitoring temporary waters, which takes into account high levels of variability and is transferable across environments, is required. The authors outline key factors which need to be considered when developing site specific water quality targets for temporary waters and a potential approach which can be implemented in a range of environments.
ECOSYSTEM RECONSTRUCTION AND VEGETATION
In situ bioremediation of South African coal discard dumps

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Abstract

Current rehabilitation of coal discard dumps remains a challenge due to reliance on topsoil for establishment of vegetation. Fungcoal has been developed as a viable and alternative strategy for rehabilitation of coal discard dumps and opencast spoils. Fungcoal exploits fungi-plant mutualism to achieve biodegradation of weathered coal, which in turn, promotes reinvigoration of soil components, grass growth and re-vegetation. The main objective of the present study was to determine the effect of different co-substrate materials as carbon donor to support Fungcoal-induced humic acid-like substance enrichment of coal discard at commercial scale. This was achieved by monitoring changes in physicochemical properties of the substrate after Fungcoal application over a three-year period. Results show that where Fungcoal was applied with weathered coal as the carbon donor, and in the absence of added topsoil, it suppressed acidification and salinisation of the coal discard substrate and promoted humic acid-like substance enrichment to support growth and establishment of annual and perennial grasses. In the absence of co-substrate or where highly oxidised coal discard was used as co-substrate, no humic acid-like substance enrichment of the substrate was observed, substrate pH declined, cation exchange capacity and electrical conductivity remained elevated, and re-vegetation failed. The potential of an in situ bioremediation strategy like Fungcoal as an alternative to topsoil is discussed.
Tree spacing effects on erosion of soil covered waste rock slopes

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Abstract

The management of mine solid waste remains the most important environmental commitment for mine companies. This research project was carried out on the low sulphur waste rock of the Canadian Malartic mine, with the aim of assessing the erosion control effectiveness of different plantation designs on 33% slopes. Since the mine is located in the boreal forest, the purpose of the project is not only to define the design that provides best soil protection, but also to identify which one best promotes the establishment of trees. Fast-growing poplar may prove to be effective in erosion control on the waste rock slopes because of its fine root development in dry soil and its effect on soil cohesion. The plantation was established in May 2013 and was monitored over two growing seasons with the aim of determining the effect of five treatments (planted trees at three different spacings without hydroseeding; planted trees with hydroseeding; and a control without trees or hydroseeding) on soil loss. Soil loss measurements were related to root morphology, canopy development and understory cover. In the centre of the plantations, soil loss occurred mainly during the spring snowmelt while soil deposition occurred during summer rainfall. During the first two years after planting, the combination of planted trees with hydroseeding showed the best erosion mitigation compared to the control because of its greater herbaceous cover and greater root length density which maximised soil protection. No difference in soil erosion rates was found between the tree spacing treatments. However, the 1 × 1 m tree spacing significantly increased root density and tree canopy cover in the second year after planting. Potentially this should be reflected in lower soil loss compared with the other treatments in the third year after planting.
Soil bioengineering and biomonitoring of vegetation and after-care at Wismut’s backfilled and covered Lichtenberg open pit and its surrounding area, Ronneburg, Germany

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Abstract
Since 1991 the state-owned Wismut GmbH has been remediating the legacies of former uranium mining in Germany. In the Ronneburg area, uranium mining, including underground and open pit mining, lasted from 1951 until 1990. The Lichtenberg open pit was mined out between 1958 and 1977 and partly backfilled by 1990. From 1990 to 2007, the open pit was completely backfilled and re-contoured by relocation of more than 130 million m³ of mine waste dumps located in the surrounding area. A thick cover (at least 1.6 m deep), consisting of loamy soils, was placed on nearly the entire re-contoured backfill area, thus creating a new landscape. Only a small disposal area for radioactively contaminated mine wastes currently still exists on the pit’s surface. Located next to the area of the Federal Horticultural Exhibition 2007 in Gera and Ronneburg, and the nearby town of Ronneburg (today with ca. 5,000 inhabitants), the newly formed hill ‘Schmirchauer Höhe’ competes with the highest natural hills in the surrounding area. The land use of the covered pit and its surrounds after closure includes forestation, grassland allowing for establishment of forest, open grassland and local park areas, barren land, wetlands and ponds. In addition, the re-use of the remediated mining sites in the surrounding area includes urban land use (dwellings), some industrial uses and renewable energy production with two large photovoltaic solar power plants that jointly cover ca. 37 ha. This paper presents the strategy and the steps for remediation including relocation of waste rock dumps for backfilling of the open pit and soil covering forming a new landscape. It puts specific emphasis on soil bioengineering strategies and methods applied for erosion control and establishment of vegetation (sowing strategies) in accordance with the requirements fixed in the accompanying landscape management plans for this and other sites. For about a decade, biomonitoring has been carried out on an annual basis, including biotope mapping and test pit excavations, to monitor the soil profile and root zone development in the soil cover over time. Based on the biomonitoring results, after-care measures have been implemented to allow and improve vegetation establishment and development. Nowadays some endangered species are colonising the newly formed habitats. The end of the remediation phase of the Lichtenberg open pit is a few years off. This allows for a preliminary review and outlook on the landscape development and its after-use in the future.
Function and performance targets in ecological rehabilitation

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Abstract

This paper considers, from the view of a rehabilitation practitioner, approaches to establishing a sustainable ecosystem that may reasonably approximate some target vegetation assemblage. Broadly, the target system needs to be defined not only in terms of species assemblages, but also in terms of key soil attributes; some of which may be relatively constant and able to be established when revegetation works are carried out. However, other soil attributes may rely on plant growth for their development and modification, and the role of vegetation in providing essential services to the developing ecosystem is fundamental to long-term ecosystem sustainability. This paper demonstrates how runoff/erosion and water balance models could be used to provide quantitative short- and longer-term targets for the management and assessment of rehabilitation progress and success.
Alleviating arsenic toxicity to plants in a simulated cover system with phosphate placement in topsoil and subsoil

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Abstract

Revegetation of arsenic-enriched mining wastes is challenging due to arsenic (As) toxicity to plants. Inorganic As is easily taken up by the cells of plant roots where it can disrupt plant metabolism partly due to its similarity to phosphate ions. Arsenic toxicity may be alleviated by phosphorus (P) fertilisation partly due to the analogous chemical characteristics of phosphate and arsenate ions, although this effect may vary in different plant taxa.

Many mining cover systems employ a single layer, or multilayers, of soil or soil-like material directly over potential toxic waste material. We simulated this basic design in a glasshouse study by growing plants in a layered system (notionally topsoil and subsoil) where we tested how As and P interacted by assessing the effects of P fertilisation (in topsoil and subsoil) on alleviating toxicity of As placed in subsoil only (to mimic a cover system).

Two contrasting plant species were used: a ryegrass (Lolium multiflorum) and an Acacia species grown in the mining area (Acacia ancistrocarpa). The growth of both plant species decreased in line with increased As concentrations in subsoil irrespective of high or low P treatments to either topsoil or subsoil. Overall we found that P application in topsoil (with As in the subsoil) was more effective than subsoil P application for sustaining improved growth of plants by alleviating As toxicity.
The effect of cover system depth on native plant water relations in semi-arid Western Australia

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Abstract

Cover systems utilising the store and release concept, i.e. evapotranspiration (ET) covers, are reliant on plant transpiration and evaporation to preclude percolation (deep drainage) into waste rock, thus minimising the risk of releasing potentially contaminated seepage. However, attaining persistent plant communities on ET covers is especially challenging in water limited environments. Soil texture permitting, greater water storage may be achieved through increased cover thickness. This study quantified cover material water dynamics, growth, and water use of native Australian plants over one year to determine if differences in plant performance were associated with species, plant available water, and cover thickness on a 1.5 year old irrigated ET cover in a semi-arid region. Plant height growth varied between species but not with cover thickness. Average transpiration per unit leaf area and stomatal conductance ($g_s$) were 1.2 and 2.3 times higher in winter than in summer, respectively, and tended to be higher on thicker covers for both seasons. Overall, transpiration rates were positively correlated with soil volumetric water content (VWC, average from 0.0–0.3 m), but differed between species. Transpiration tended to increase with VWC, $g_s$, and cover thickness (0.7 > 0.5 > 0.3 m), indicating plant (stomatal) control of transpiration in response to drought stress associated with cover thickness. The analysis suggests that plants on thicker covers transpired at greater rates due to access to stored water at greater depths, resulting in higher overall transpiration. This work demonstrates the importance of quantifying water use differences between species, seasons, and cover thicknesses during cover system modelling and design phases. It also highlights the potential for greater plant available water by increasing cover thickness, aiding the establishment of self-sustaining plant communities on ET covers.
PLANNING
Developing Anglo American’s integrated closure planning system requires people, process and technology working together

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Abstract

Integrating closure planning with other mine-planning processes is not a new idea. While most would agree on the benefits of such an approach, examples where the potential is realised remain the exception. Anglo American commenced the development of an Integrated Closure Planning System (ICPS) with the aim to provide a consistent approach over the lifecycle of projects for the reporting and management of long-term liabilities, to achieve their goal of ensuring that they leave a positive and sustainable legacy for their host communities after their operations have closed. We propose that to achieve this objective requires focus on people, process and technology. The elements of the ICPS are: planning (e.g. life-of-mine (LOM), closure, short/medium term mine, rehabilitation), financials (e.g. premature and LOM closure liability, operational expenditure, guarantees), systems (e.g. closure toolboxes, Geographic Information Systems, Environmental Management Systems) and requirements (e.g. internal/external standards, policy, regulation).

A multi-disciplinary team comprising mine closure, mining engineering/planning, technology and business process experts from Anglo and MWH was formed to develop the ICPS. The process involved identifying the current state of processes and systems, the target state of a fully integrated process, developing a maturity scorecard and identifying potential technology solutions that may assist in realising value at the operational level. In defining the current condition across the operations it became evident that roles and responsibilities were not clear across the organisation, both the LOM and immediate mine planning processes had no clear platform or process to facilitate closure planning interactions, and that over 40 software solutions were being used across Anglo’s business units. This finding reinforced the importance and emphasised the critical nature of the ‘people, process and technology’ elements. Through application of a balanced scorecard, and Anglo’s internal assessment of 53 Anglo operations across the globe, potential pilot mine sites were identified with low, moderate and high levels of ICPS maturity, with associated high closure risk or opportunities. Project implementation plans were developed to increase the ICPS maturity at the pilot sites to the required level that will maximise value realisation or minimise value destruction from a mine closure perspective. The paper presents the finding of the evaluation work conducted, will discuss the challenges and process applied in the development of the implementation plans that advance development of Anglo’s ICPS.
Mine site rehabilitation — are we reinventing the wrong wheel?

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Abstract

Mine site rehabilitation generally aims to produce a safe, stable and non-polluting post-mining landscape that serves some agreed post-mining land use. Historically, the presumed post-mining land use has generally driven the rehabilitation process, often regardless of whether the adopted land use matches the pre-mining land use or is achievable. This dictates the flattening of the mine waste landform and the choice of surface cover applied. In the past, the adopted post-mining land use has often been grazing, which dictates that steep (usually angle of repose) mine waste slopes be flattened substantially, and that the surface be topsoiled and grassed. The tops of surface dumps and tailings surfaces often require reshaping to enhance surface drainage or water management prior to capping, topsoiling and grassing. The outer slopes of waste dumps and tailings storage facilities are generally flattened to allow access for equipment, topsoiling and grassing, possibly with the aim of allowing grazing. Even where grazing is not to be the post-mining land use, slope flattening, topsoiling, and grassing are often adopted. Whether or not grazing is the adopted post-mining land use, it may not be utilised, and a grass cover may be difficult to establish and even more difficult to sustain. Further, the limited extent to which steep mine waste slopes can be flattened generally results in slope angles that are still too steep for grazing use, and are prone to erosion, particularly if covered with topsoil and the grass cover is inadequate. This historical approach to mine site rehabilitation has led to repeated failures of flattened, topsoiled and grassed steep mine waste slopes and of regraded, capped, topsoiled and grassed dump tops and tailings. Increasingly, the establishment and sustainability of ecological functionality is seen as the key to achieving a safe, stable, and non-polluting post-mining landscape. Hence, it is argued that ecological function should be the preferred driver of mine site rehabilitation over the post-mining land use, since it better addresses the accepted rehabilitation aims. The paper presents a history of the conventional approach to mine site rehabilitation governed by slope flattening, topsoiling and grass covers, illustrated with global examples of mine site rehabilitation failures due to the adoption of those practices. These include examples from gold mining in Johannesburg, surface coal mining in Australia, and metalliferous mining in Australia, and focusses on the rehabilitation of steep mine slopes in tailings, spoil or waste rock.
The Challenger gold story — do it once, do it well

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Abstract

The Challenger gold mine (Challenger) is located in remote South Australia. Discovered in 1995, mining commenced in 2002. As a relatively new site with no mining legacies, Challenger provided an ideal site to plan the full lifecycle of mining based on digital mine planning, learnings from successful rehabilitation elsewhere, and the full awareness of industry legacy issues such as acid mine drainage, tailings storage and long-term landform stability.

This paper describes the key aspects that will impact the Challenger site post-mining, including:

- Remote site.
- Minimising the disturbance footprint.
- Integrated management of tailings and waste rock.
- Consideration of waste rock properties for landform construction.

A key success factor for the Challenger site has been the progressive support of management towards sustainable mining. By adopting a life-of-mine approach, environmental considerations were incorporated at the inception of the project and have been actively managed during the life of the mine to the satisfaction of internal and external stakeholders. As a result, the operation has a very clear and concise plan as the operation matures and eventually moves towards closure. Adopting a fit-for-purpose, consistent approach to sustainable mining has resulted in cost-efficient environmental activities and confidence around the cost for mine closure.
Progressive rehabilitation — Martabe Gold Mine as a case study

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Abstract

Progressive rehabilitation has been recognised by the mining industry as a key strategy for minimising mine closure costs and environmental risk, with the rehabilitation of potentially acid-forming waste rock being of particular interest due to the very large liabilities associated with sites where this risk has not been properly addressed. When properly implemented as an engineered solution, progressive rehabilitation of potentially acid-forming waste rock can provide an inherently more robust and lower risk rehabilitation strategy compared with the commonly-implemented alternative of an end-of-life waste dump covers.

A case study is presented herein where progressive rehabilitation of potentially acid-forming waste rock has been successfully integrated with ongoing construction of the embankment of a tailings storage facility (TSF). The mine site in question, the Martabe Gold Mine in Indonesia, is thought to be unique in that construction of the TSF embankment at the site will require utilisation of almost all of the waste rock to be produced life-of-mine. The TSF embankment is therefore a fully integrated and engineered structure addressing both tailings and waste rock disposal requirements for the site. This approach offers a number of key benefits, including minimisation of both waste rock rehabilitation and tailings storage costs, and minimising the risk of long-term acid mine drainage.

The progressive mine waste rehabilitation strategy adopted by G-Resources at the Martabe Gold Mine was designed taking into account the inherent properties of the waste rock materials, the run-of-mine waste rock schedule, and the engineering constraints required in order to construct a TSF embankment to exacting geotechnical standards. The strategy has required systematic implementation of outcomes reflective of industry leading practice, including:

- Detailed waste characterisation studies.
- Development of waste characterisation criteria.
- Production of a life-of-mine waste schedule.
- Selection of a waste sealing specification based on oxidation modelling.
- Progressive implementation of selective waste placement and sealing.
- Performance measurement to validate design and implementation.

All key technical teams at the Martabe Gold Mine, including exploration, mine geology, mine planning, TSF construction and environment, have played an integral role in the implementation of this strategy, which can be described as an integrated waste management solution in which minimisation of mine closure risk is process that is carried out across the life of the mine.
A common-sense approach to mine closure design in the remote Western Australian interior

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Abstract

In recent years Western Australia has seen a far greater focus on mine closure planning, with both the Government and the Mining Industry tackling implementation of rather conceptual mine closure strategies that are set early in the mine life. Both practitioners and Government stakeholders have the best of intentions when setting mine closure objectives, standards and completion criteria, but just how realistic are these when it comes to implementation?

This paper looks at what might be considered both pragmatic (cost-effective and achievable) and responsible with regard to mine closure in the arid WA Goldfields region. It draws on twenty years of keen observation of the successes and failures of mining industry efforts in this region and recent scientific findings by several local consultants. The focus is on closure design of those mine landforms that remain post-closure — mine pits, waste rock dumps, stockpiles, leach pads and tailings storage facilities. It examines the actual set of field conditions under which mines operate, post-closure modelling time frames and research (and predicative modelling) limitations. The paper suggests where closure design efforts should be focused and how best we might interpret the current WA Government mine closure guidelines. It identifies several closure design aspects that remain misunderstood by many stakeholders, resulting in unrealistic expectations and closure criteria.
A risk-based approach using process flow diagrams for operational waste rock classification — case studies

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Abstract

Acid and metalliferous drainage (AMD) management plans are generally developed as part of a site’s closure plan to inhibit or mitigate the generation and release of AMD for sites with problematic materials. They are typically constructed around a body of knowledge involving multiple geoscience and environmental disciplines. However, despite the volume and degree of scientific investigations completed, if the waste rock classification system and therefore AMD management plan developed is not practical and does not take into consideration other site drivers such as production, its successful implementation and adoption is unlikely. A common weakness of AMD plans developed based on industry best practice is that they often fail the practicality test, as the characterisation process produces ambiguous outcomes such as the classification of material as uncertain with respect to acid generating potential.

As part of optimising the characterisation process, a site specific waste rock classification process flow diagram approach is discussed herein. The development and use of a process flow diagram to optimise the testing regime opposed to a traditional matrix-style system can reduce the number of tests required, the cost of testing, and the time required to make informed classification decisions. However, to be confident in the use of a process flow method for waste rock classification requires detailed knowledge of site geology and geochemistry; and the completion of a suitable sampling program, incorporating acid base accounting (ABA) before the development of a process flow method.

A flow process often only requires basic parameters for the classification of a block of waste, arriving at the parameter boundary values that incorporate the results of several detailed second and third geochemical testing phases. The use of acid buffering characteristic curves, kinetic net acid generation tests and large scale site column tests allow the consideration of kinetic factors for a risk-based operational waste rock classification that differentiates between different degrees of potentially acid forming (PAF) materials. This differentiation allows more control over AMD management and subsequently reduces closure risk.

At the Martabe Gold Mine, Sumatra, following a detailed ABA classification program, a process flow methodology and specialised rapid field testing program for geochemical classification of waste rock was developed as a tool for the operational management of overburden. This is used as a quality control or verification phase for confirmation of the geochemical waste rock block model, and ensures that waste rock is correctly identified in the field and handled as per the management plan. Application of this approach is discussed in this paper.

At the Escarpment Coal Mine, West Coast, New Zealand, a new process flow method for geochemical classification is being trialled. Results indicate that classification by a process flow method results in far fewer samples being classified as uncertain compared to the current resource consent matrix-style classification. Results presented in this paper indicate that ABA data and field column leach trials validate this approach.
GEOCHEMISTRY AND MINE WASTE
Acid and metalliferous drainage contaminant load prediction for operational or legacy mines at closure

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Abstract

Predicting the acid and metalliferous drainage (AMD) contribution from waste rock dumps (WRDs) containing potentially acid forming (PAF) material is a key step when planning for closure. For sites already demonstrating impacts from the generation and release of AMD, estimating final water quality and flow rates emanating from WRDs is key to quantifying the level of remediation and/or management required at closure. Predictions of final water quality need to be compared with regulatory limits for closure, stakeholder expectations and any anticipated treatment options (including treatment longevity and costs).

In the absence of WRD sample data collected from intrusive investigations, there are often numerous WRD seeps and impacted streams that can be used to determine typical water quality, solubility constraints, flow rates, contaminant loads and thus source terms for PAF WRD drainage. The preceding step critical to the determination of source terms is the development of a conceptual model that incorporates potential/stored acidity components, flow rates and water quality. The developed conceptual model can then be further refined and strengthened with geochemical modelling.

The potential acidity component, that is primarily associated with acid generating sulphides, is typically estimated from assay databases and materials placement records. Laboratory derived pyrite oxidation rates can be used to estimate the remaining potential acidity component as well as the formed stored acidity component. The mobilisation of stored acidity and other oxidation products is often constrained by solubility controls, particularly in older WRDs. These solubility controls are often associated with the formation and dissolution of melanterite-type soluble acidity, jarosite-type sparingly soluble acidity and other secondary phases such as gypsum. The determination of these mineral and/or the proportion of which they make up the estimated oxidised sulphur content allows for more accurate determination of the stored acidity component for source term derivation.

Geochemical testwork can then confirm the presence of such minerals, which is incorporated into an acid-base accounting modelling process and the determination of three key phases of closure water quality; (1) the draindown water quality phase; (2) the transition water quality phase; and, (3) the long-term water quality phase. During the WRD draindown phase, after cover system installation, the seepage quality can be assumed to be equal to the derived WRD source term with the duration of this phase determined by numerical modelling. Seepage quality for the transition phase is determined from the stored acidity (or metalliferous oxidation products), which also incorporates elemental loading. The long-term water quality can be determined by forward reaction path modelling or by using key mineral dissolution kinetics (first principal approach). Combining these three phases then produces a model for the prediction of long-term water quality after operations, which can be utilised for closure planning.

This paper presents a number of case studies that utilise the above methods for the prediction of site water quality at closure.
Mine waste characterisation — complexities with assessing the physical properties of rock

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Abstract

The aim of mine waste characterisation is to assess the geochemical and physical properties of rock in order to identify deleterious or beneficial materials. Mine waste geochemistry is generally well understood and there are accepted procedures to assess the geochemical properties of rock. Predicting the physical properties of mine waste is more difficult and practitioners are achieving mixed results with varied methods.

Routine soil science techniques are commonly applied to assess the physical properties of rock. Such techniques measure the resultant properties of rock, without considering the geological factors that control those properties. Such testwork results can be unreliable in predicting erosion potential of rock. Furthermore, practitioners may fail to develop a working appreciation of deposit scale geology prior to sample collection and testwork. In many cases such limitations result in incorrect predictions relating to the physical properties of rock.

There are five geological factors that control the physical properties of rock: petrology/lithology, alteration, mineralogy, weathering and structural deformation. The interplay between these factors in determining the as-dumped erosion stability of rock on a mining landform can be complex.

This paper considers the geological factors that control the physical properties of rock, the effectiveness of current assessment methods and opportunities to advance current practice. Field data is used to support observations where applicable.
Waste material placement options during construction and closure risk reduction — quantifying the how, the why and the how much

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Abstract

Technical aspects of waste rock characterisation and assessment have been the focus of considerable research over the past decade, with many guidance documents being published on the subject internationally and within Australia. While these documents provide detailed information on how to characterise waste rock, there is not a great amount of guidance on how the placement of waste rock can be optimised to account for the results of the characterisation studies. In this respect it could be reasonably concluded that the science has progressed to a more advanced stage for waste classification in comparison to how to manage it. This has lead in many cases to site specific waste characterisations being followed up with generic waste management solutions such as widespread adoption of the ubiquitous potential acid forming cell as a management solution. The net result of this mismatch is that although acid and metalliferous drainage (AMD) assessments are undoubtedly being carried out to a higher level of detail than in the past, there is not a definitive correlation with site management practices and, therefore, effective closure risk reduction over this time.

The net effect of this trend has been that site operators are being given better information on AMD risks, but not better solutions on how to manage these risks. That is to say site operators are being told why they should manage risks but not how to achieve this, and by how much risks can effectively be managed (if at all). Questions that site engineers and operators may ask about the relative benefit of one placement solution over another have for the most not been adequately addressed by research. Examples include assessment of the quantitative benefit of paddock dumping vs end tipping, determining the optimal tip head height for waste placement in a storage facility, and how sulphide grade control should be carried out.

A detailed risk-based investigation of the influence of factors common to waste placement is presented herein and has been completed as part of a wider research initiative to investigate the technical aspects of developing a quantitative assessment tool. Applying a numerical modelling approach to assessment of the different waste material placement strategies allows for the graphical presentation and communication of the variation in risk through risk matrices and histograms.
Mine closure experiences — Bolivia, South America

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Abstract

Bolivia is a well-known mining country, mainly because of its rich tin, silver and gold deposits mined since the Jesuit and Spanish times; 17th to 18th centuries. There are three types of mining sectors: private, state and cooperatives.

Within the private sector four closures took place on the highlands: Kori Kollo (Golden Hill) and Kori Chaca (Golden Bridge) projects both located in Oruro, COMCO silver heap leaching Project located in Potosi; and Puquio Norte Gold Project located in the lowlands of Santa Cruz, agitation leaching operation.

Within the state sector, there were many mining operations with mine waste and tailings abandoned but not closed. However, in order to mitigate the pollution the Bolivian Government, together with some international donors such as the Danish International Development Agency, have prioritised and encapsulated some tailings deposits in the Potosí Prefecture.

The cooperative or artisanal mining sector lacks mine closures. Neither the government nor the communities have forced them to comply with the environmental mining regulations, which have been in force since 1997. Therefore, there are many environmental issues on the sites operated by artisanal miners.

This paper reviews the results of the closure efforts of the gold and silver heap leaching operations on the highlands of Oruro and Potosí, where pits, mine waste, evaporation ponds and tailings storage facilities were closed. The paper also addresses another gold agitation leaching operation, in the rainforest which was also closed. In all cases, closure plans and monitoring programmes were executed. Special focus was placed upon the physical and chemical stability of closed facilities so that no further effluents would be released and therefore no major threats would be expected to the environment and nearby communities.