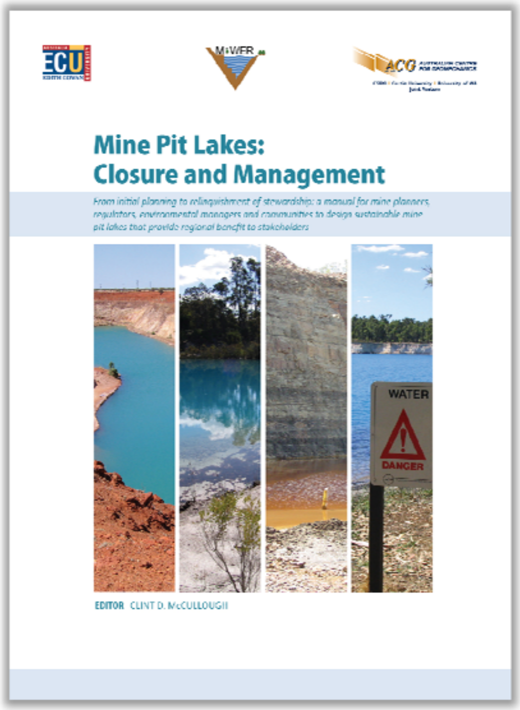
Mine Pit Lakes:
Closure and Management
WATER
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Management of mine wastes using pit void backfilling methods – current issues and approaches

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Abstract

Mined voids are increasingly viewed by industry as a resource for the storage of wastes such as tailings, heap leach residues, acid/solute generating waste rock and salts derived from mine water treatment and as a means to reduce post-closure risks to receiving environments. Mine closure guidelines and regulator feedback of mine closure plans are also showing a greater recognition of backfilling in the context of achieving agreed post-closure land use.

A key driver for mines, where multiple voids are developed, is that existing voids provide a cost-effective opportunity to store tailings in an existing 'engineered structure' rather than build and operate a new tailings or waste rock storage facility. Key issues for consideration include resource sterilisation which may preclude future open pit mining, long-term rates of tailings consolidation and the fate/impact of expressed tailings porewaters on water quality and the stability of the final landforms in the case of open cut mines with in-pit tailings storage and agreed end point or closure criteria for the void, e.g. need for full or partial pit backfilling.

In mine closure planning, placement of mine wastes in voids is often seen as 'best practise', particularly in environments where sensitive ecosystems exist downstream of the mine site. Generally, risks to the environment can be greatest where mine wastes are located closest to the ground surface, due to relatively high groundwater movement in near-surface aquifers and/or risks of failure of engineered structures due to extreme rainfall events or erosion. Placement of problematic mine wastes at significant depths in-pits or underground voids, as part of partial backfilling approaches, can address these risks by increasing the path length from contaminant source to receptor and enhancing encapsulation. In some instances, backfilling is used as an approach to avoid pit lakes altogether, in circumstances where the results of assessments indicate that pit lake water quality may deteriorate in the long-term and affect downstream water quality and ecosystems.

1 Introduction

Mined voids have long been viewed as an inevitable consequence of the economic benefits of mining. Historically, in open cut operations, pits have often been left in an open condition post-closure, although pit design or operational aspects have at times warranted partial backfilling to support further, safe excavation of ore, e.g. provide support due to wall instability, facilitate underground mining (Castendyk, 2011).

Increasingly, mined voids are being looked at more holistically, as an asset that can reduce costs and post-closure land disturbance and minimise both operational and closure risks. Operating mines create wastes and can expose materials that pose risks to the environment. Backfilling provides an opportunity to cover or encapsulate these materials cost-effectively, provided that assessment of this opportunity is carried out at an early stage of mine planning.

Backfilling can also prevent the development of pit lakes with poor water quality, often due to the accumulation of solutes in the water column via groundwater ingress and/or leaching of exposed waste materials.

Backfilling can significantly reduce the areas of land left in a disturbed state (post-closure), related closure-rehabilitation costs, e.g. ongoing water management, and the safety issues associated with leaving an open pit. In addition, backfilling makes efficient use of the excavated storage space with improved containment or encapsulation by geological materials adjacent to the void rather than constructing above ground facilities such as tailings dams with specifically engineered liners and waste rock dumps with covers. In addition, regulatory agencies and indigenous organisations are increasingly seeing backfilling as a way of returning land to a form that supports pre-mining land use.

2 Key drivers of mine void backfilling

2.1 Operational imperatives for mine void backfilling

While void backfilling may be costly or not economically feasible in many instances, in some circumstances it can significantly reduce operational and/or closure costs. Backfilling is most feasible where multiple pits or underground voids have been or are being developed, permitting mine or other wastes to be deposited in the voids. There are four key issues requiring consideration in any decision-making process:

1. Operational costs, schedules and engineering considerations.
2. Resource sterilisation.
3. Water management and environmental risks.
4. Land disturbance.

The relative costs of managing wastes using an above-ground facility versus in-pit deposition are a key issue. For example, the operational and capital costs of constructing a new tailings storage facility or waste rock dump/stockpile may be high relative to deposition in a mined out pit. However, this may be offset by greater distances of pumping tailings or trucking waste rock materials. Mine scheduling, pit availability and the time required to prepare the pit for backfilling are all important considerations.

The primary engineering issues related to lining (if required), backfilling and operating a void for containment of wastes relate to the installation and long-term behaviour of an in-pit liner versus an above ground liner, geotechnical stability pit walls, geotechnical risks related to the in-pit materials and the ability to achieve construction and long-term stability of a pit lake or constructed landform. An in-pit liner becomes more practical and cost-effective if included early in the mine's operating plans, e.g. stockpile and placement of clay and other waste materials close to the pit.

In the case of open cut mining, resource sterilisation may result from pit backfilling, since it may preclude continuation, or re-commencement of future mining. However, pit backfilling may only have a slight, negative impact if economic assessments indicate that underground mining of the resource should be progressed. A 'crown pillar' between the pit and the underground mine may need to be established if the pit is backfilled with tailings and the risk of geotechnical failure, i.e. flow of tailings from the pit to the underground workings.

Comparison needs to be made of the relative operational risks to the environment between managing wastes using pit backfilling and an above-ground facility. An above-ground facility will often comprise complex liner and monitoring systems, ensuring that downstream surface water resources and near-surface groundwater resources remain protected. Depending on the hydrogeological context, and the connectivity between in-pit wastes and downstream receptors of importance, and their beneficial use attributes, backfilled pits may in themselves provide significant encapsulation of wastes. This might reduce water management effort and costs and preclude the need for the installation of extensive lining and monitoring systems.

Minimising land disturbance is increasingly being viewed by regulators, and the community, as an important objective for proposed mining operations (Heikkinen, 2008; ICMM, 2006). Pit backfilling provides the opportunity to reduce the footprint of mining operations, e.g. precluding the need to construct additional tailings or waste rock storage facilities.

In reality, a decision to proceed with pit backfilling will often require consideration of the aforementioned technical issues as well as the outcomes arising from community engagement and regulatory feedback. As an example, Newmont Australia has incorporated both economic and technical considerations, as well as community feedback, at its Granites Gold Mine in Northern Territory, Australia (DITR, 2007). Use has been made of multiple pits to deposit tailings and waste backfill, permitting re-instatement of pre-mining landforms (Figure 1).

Figure 1 In-pit tailings deposition, Granites Gold Mine, Northern Territory, Australia (DITR, 2007)

In underground mining operations, tailings backfill has been common since the 1980s, for economic, safety or mine closure reasons. The economic reasons relate to the costs of building new, above ground tailings storage dams and providing support to underground workings to maximise ore recovery.

2.2 Managing post-closure environmental risks

Studies have shown that wastes, particularly those that are sulfidic and/or acid-generating, often require minimised interaction with the hydrosphere, in order to minimise oxidation processes and generation of acid or solutes and mitigate impacts to downstream environmental receptors. Various authors (Thienenkamp and Lottermoser, 2003; Szymanski et al., 2003; Hoepfner, 2007) have determined that wastes placed above the water table and remaining uncovered within the unsaturated zone, particularly those that are highly sulfidic or potential acid forming (PAF), are exposed to atmospheric oxygen and prone to significant leaching.

Covers have often been used to limit oxygen and infiltration into wastes, and comprise either soil or synthetic liner 'barrier' covers, e.g. compacted soil layer or synthetic liner, or 'store-and-release' covers. In a comparison of the performance of covers, Paul et al. (2003) report that barrier covers have been 'borrowed' from landfill liner technology. They often comprise compacted clay overlain by a growth medium, are usually elevated to promote runoff and minimise infiltration and are best suited to humid climates. Barrier covers that comprise a soil layer can be problematic because they are prone to cracking due to wet/dry or freeze/thaw cycling.

According to Paul et al. (2003), store-and-release covers are more robust and sustainable than barrier covers because they are relatively easy to construct, using mine site equipment. These covers comprise a loose soil ('growth media') layer that provides a thick protective layer over an underlying compacted clay 'sealing' layer, helping to maintain moisture conditions. These covers address erosion risks by promoting infiltration, but ultimately, the long-term behaviour of soils and re-established vegetation will determine the long-term success of covers, e.g. development of macro pores and establishment of preferred infiltration pathways. Store-and-release covers are generally designed for seasonal, semi-arid climates, where pan evaporation is well in excess of rainfall and aim to capture rather than shed rainfall, to minimise clay cracking/desiccation, vegetation die-back and erosion. Depending on site conditions, a store-and-release cover might typically comprise a sealing layer about 0.5 m thick, overlain by growth media of about 1.5 m thick, to store wet season rainfall and release it during the dry season through evapotranspiration.

In the soil barrier and store-and-release cover scenarios, quality assurance/quality control of construction, geotechnical properties of soils, climate, geomorphological conditions and ecosystem behaviour all play critical roles in determining whether these covers will maintain their initial performance in the future. While sealing layers may initially provide the desired hydraulic conductivity ($<10^{-8}$ m/s), clays are prone to deterioration over time, e.g. cracking or desiccation and deterioration due to ecosystem variables. This can result in significant increases in hydraulic conductivity by one or more orders of magnitude, no longer providing a ‘seal’.

A number of mine operations have addressed these risks by constructing synthetic liners such as geosynthetic clay liners over acid generating mine wastes (DITR, 2007), although some uncertainty exists in relation to the effective life of such liners. An example of covers that have deteriorated due primarily to ecosystem variables are those constructed at the former Rum Jungle Uranium Mine in the Northern Territory, Australia in the 1980s (Figure 2) (Taylor et al., 2003). Long-term monitoring data indicate that the permeability of the covers has steadily increased over time, primarily due to cracking of the clays, penetration of deeper roots through the covers and into the underlying waste materials and termite activity. These processes have created permeable, preferential pathways for water and oxygen movement.

Partial or full backfilling of mine voids provides the opportunity to remove the connections between problematic mine wastes and the hydrosphere by placing materials in contact with deeper geological environments that are naturally stable, comprise low permeability and are less connected to the hydrosphere and local ecosystems.

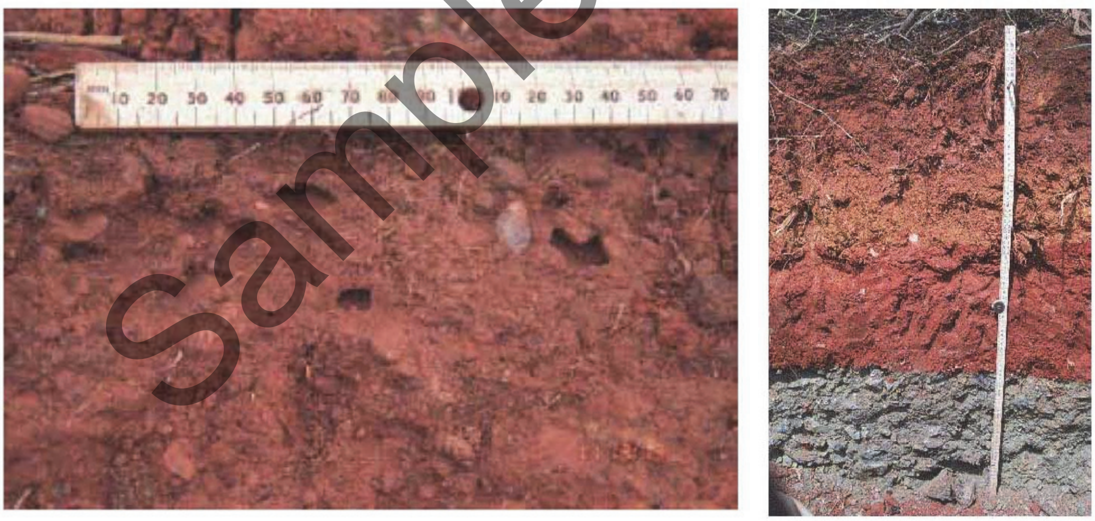

Figure 2 Deterioration of covers due to termite activity and root penetration into wastes, former Rum Jungle Uranium Mine, Northern Territory, Australia (Taylor et al., 2003)

2.3 Post-mining land uses and emerging community and regulatory expectations

Stakeholder expectations are increasingly focussed on mining company’s approaches to designing and constructing post-mining landforms that provide a positive, beneficial use for the future. Numerous examples exist of mining operations, particularly large-scale coal mines, which have successfully established or re-established productive lands or ecosystems, e.g. various coal mines in the Hunter Valley, New South Wales, Australia (Hunter Valley No.1, Warkworth Mine, etc.). A key consideration of the feasibility of void backfilling is the 'swell factor' of the excavated materials and the availability of wastes to be returned to voids and the ability to concurrently mine an advancing pit face or other pits, thus allowing progressive backfilling activities.

The geotechnical properties and behaviour of wastes to be disposed of in voids is a critical issue. Waste rock returned to pits will generally not consolidate significantly relative to processed ore/wastes, such as tailings, which will often have a much finer grained composition and will show much greater magnitudes of consolidation but at slower rates.

When depositing tailings in a pit, the upper surface of the tailings rises rapidly especially in the early stages of deposition when the pit has a large pit volume:area ratio, i.e. at the time the area of the upper surface of tailings is small. The result of this is that drying and desiccation of the tailings mass is low, the tailings are low in strength and have relatively poor consolidation characteristics. Poor consolidation behaviour can cause settlement of the final landform over extended periods after a pit has been filled. This is often a result of the low solids content of the tailings and the depth of the stored material. This leads to difficulties for mining operations to expedite the pit backfilling process, as tailings need to be deposited slowly. Once consolidation rates have declined, either under quiescent consolidation or surcharged with rock to expedite the process, a cover can be constructed to allow landform shaping and revegetation.

Notwithstanding the above challenges, pit backfilling does permit mine operations to construct pre-mining landforms, and ideally, a landscape that permits re-establishment of land access for local communities or development of productive landscapes for community use.

Regulatory expectations have also evolved over time with a greater emphasis on mining operations to more critically examine and manage long-term environmental risks and return land to a condition that does not negatively impact on legacies for future generations. Establishing healthy ecosystems in-pit lakes or void backfilling are seen as very positive approaches in this context. The following comments are pertinent to pit backfilling and/or establishing pit lakes internationally.

ANZMEC-MCA (2000) state that ... "Mine closure should not be an 'end of mine life process' but should be integral to 'whole of mine life' if it is to be successful. Planning for closure should commence at the feasibility phase of an operation. In this way, future constraints on, and costs of, mine closure can be minimised, post-mining land use options can be maximised and innovative strategies have the greatest chance of being realised."

WA Govt. (2010) state that ... "Proponents are encouraged to consider applying resources to achieve improved land management and ecological outcomes on a wider landscape scale, and to take into account the following hierarchy in the consultation process to determine agreed post-mining land use options: 1. Reinstate natural ecosystems as similar as possible to the original ecosystem. 2. Develop an alternative land use with higher beneficial uses than the pre-mining land use. 3. Reinstate the pre-mining land use. 4. Develop an alternative land use with other beneficial uses than the pre-mining land use."

Similar statements can be found in other international papers describing emerging changes in community and regulatory expectations (Heikkinen, 2008; ICMM, 2006; MEND, 1995).

3 Backfilling methods

3.1 Placement of waste rock

Void backfilling with waste rock commonly utilises mining equipment such as front-end loaders, haul trucks, dozers and support equipment to maintain trafficability and safe working conditions, i.e. graders, water trucks and other miscellaneous equipment. Smaller, specialised earthmoving equipment may be used if backfilling needs to be undertaken in a specific manner, if liners or in-pit drains need to be constructed to minimise seepage from the pit or enhance tailings consolidation (respectively) or if backfill materials are to be blended with other materials such as lime to meet requirements relating to environment protection, i.e. lime can be used to neutralise seepage and reduce the solubility of metals.

Waste rock is typically excavated from stockpiles, hauled and dumped at the base of the void and spread using dozers or end dumped from benches located higher in the pit profile. Key issues for consideration in planning include understanding haulage distances and schedules, geotechnical, geochemical and moisture properties of the wastes, preparation of wastes prior to placement (if required), preparation of covers or drains and final landform design assumptions. In circumstances where pit backfilling is considered early in the mine planning process, and forms a key element of closure-rehabilitation activities, wastes may be hauled directly from the active mine face to parts of the pit being prepared for closure and rehabilitation (Figures 3 and 4).

Figure 3 Progressive mining and pit backfilling, Warkworth Coal Mine, New South Wales, Australia (Photo courtesy of Panoramio, Google)

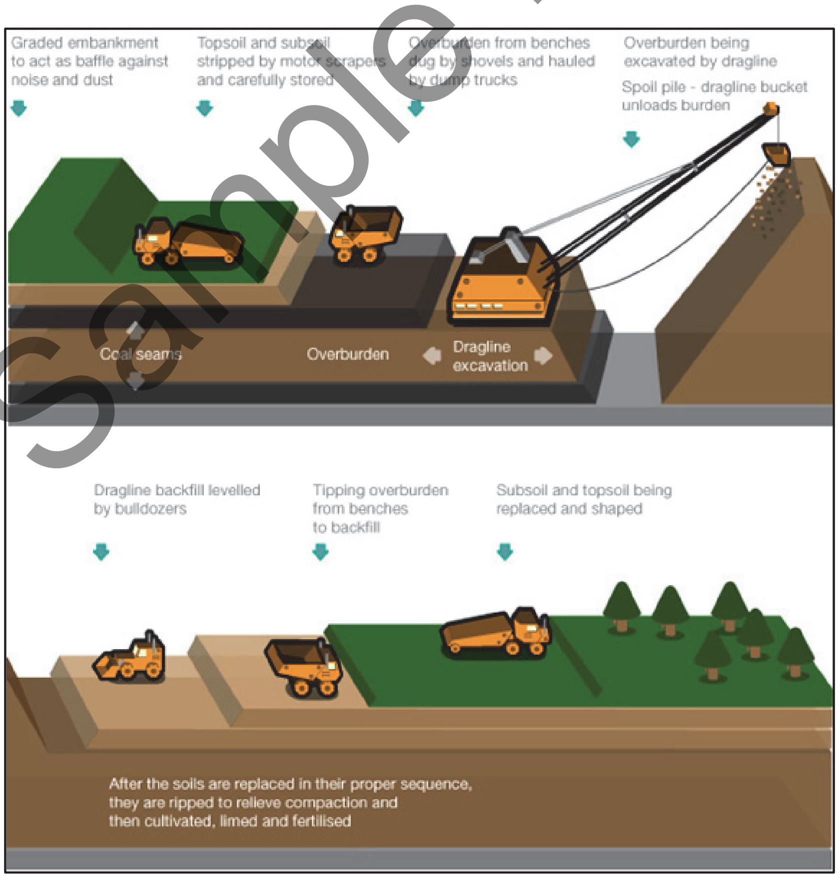

Figure 4 Typical coal mining, void backfilling and restoration activities (Photo courtesy of ERCE Trading London)

3.2 Placement of tailings

The mill (or refinery) tailings solids concentration is typically raised using conventional thickeners to conserve water and reagents and then pumped as a solids–water slurry to a storage facility. The tailings slurry is discharged into the pit via a single or multiple points (spigots) located on the haulage ramp, the pit benches, or along the pit's crest. Upon completion of tailings deposition the pit is then backfilled with waste rock to encapsulate the tailings and produce the final landform.

The deposition strategy should minimise tailings segregation, maximise tailings consolidation and water (or reagent) recovery. The tailings deposition design needs to control the tailings beach to ensure the decant pond location is maintained against the haul ramp or the pump location, and to ensure safe pit access. For example, it is possible to deposit the tailings slurry from the haulage ramp into a flooded pit without significantly diluting or segregating the discharge.

The tailings deposition can be either sub-aqueous (below water) or sub-aerial (above water). Both methods can result in the segregation, or separation of tailings particles according to their size and density. The degree of segregation is a function of the particle size distribution (PSD), slurry rheology and momentum, the beach topography, the depth of the overlying water or intersection with the decant pond (Vick, 1990). Normally the coarse fractions will settle close to the discharge point with the finer fractions distributed further afield. The segregated fines tend to exhibit higher compressive yield stresses and thus hinders the tailings consolidation producing long-term settlement issues.

Co-disposal, or co-placement, of coarse waste with the tailings slurry can reduce the site's storage footprint and produce a more stable deposit. Partial co-placement can be achieved by dumping the coarse waste from a pit bench or the pit crest. Co-disposal of the tailings and coarse waste has several advantages. For example, the tailings can be used to encapsulate coarse sulfate mineral waste. But co-disposing fine and coarse material as a single stream into the pit is problematic because the coarser material will tend to segregate and settle at the discharge point. This segregation can be reduced by thickening the tailings to a paste consistency and transferring the mixture under gravity or by positive displacement pumps.

The pit deposition strategy, particularly during the initial stage, will also determine the post-closure landform stability and the quality and quantity of water expressed. Mine pits narrow as they get deeper to maintain wall stability. When tailings are deposited into the base of the pit its shape tends to produce a high rate of rise. This rate can exceed the tailings consolidation rate and constrain the tailings densification. When surcharge with additional tailings and/or waste rock this low density tailings will continue to consolidate expressing water causing long-term water management and settlement issues.

Thus, it is advantageous to discharge the tailings slurry at high concentrations (examples are shown in Figure 5). Hence, the interest in high compression and paste thickeners, which have been proposed for the mining industry as the answer to its water and tailings storage management issues. While this may be true, the implementation of paste thickeners at brownfield operations other than alumina refineries has been slow due to a number of technical and cost issues.

Poor tailings consolidation can be partially corrected by installing geotextile wicks to encourage vertical drainage of the entrained pore waters (Figure 6). But this technique is currently limited to the maximum wick installation depth of approximately 40 m.

The pit deposition and post-closure issues can be virtually eliminated by vacuum or pressure filtering the tailings to produce an unsaturated filter cake. But the costs associated with filtering tend to make this option less favourable unless there are significant environmental and topography drivers. Examples of above ground filter tailings storage operations are the Greens Creek Mine in Alaska, USA (Davies et al., 2002) which filters its tailings to meet strict environmental requirements while the La Coipa Mine in Chile (Davies and Rice, 2001) filters its tailings to conserve water.

Ultimately, cost-effective mining and processing methods, together with water management and closure requirements, will dictate whether in-pit tailings disposal is the appropriate method.

Figure 5 Cemented paste underground backfill (left), surface paste tailings disposal (right)

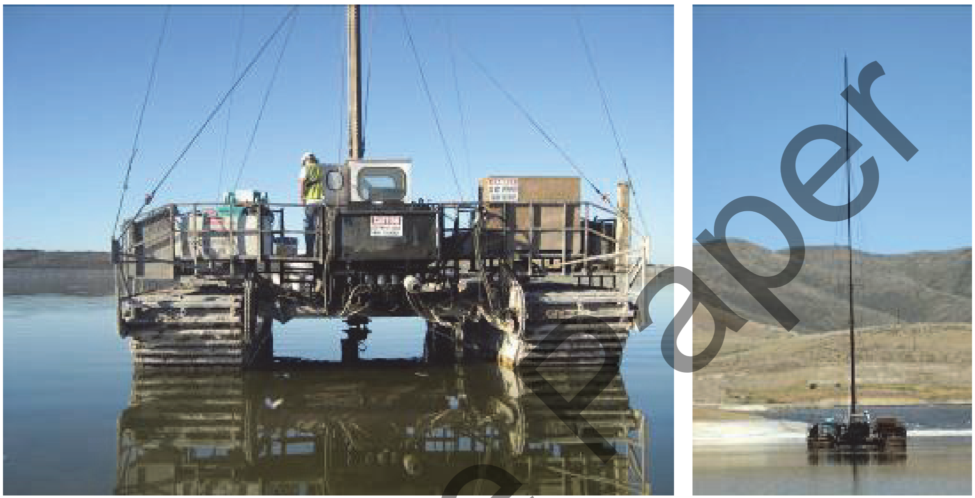

Figure 6 Investigations of in-pit tailings geochemistry, Ranger Uranium Mine, Northern Territory, Australia (Photo courtesy of HB Wick Drains)

3.3 Neutralisation of backfilled wastes

Tailings backfilled in underground voids are often thickened or strengthened with cement so that support is provided to previously mined ore stopes. Addition of cement, in this instance, can result in neutralisation of acidity in the tailings wastes and reduce risks of acid mine drainage to downstream environments. Waste rock that is backfilled in open pits is sometimes neutralised with lime to reduce acidity and/or solute generation, in circumstances where the materials are unable to be sufficiently encapsulated by low permeability geological materials located in the pit walls (Ayres et al., 2007; Parshley et al., 2006; Paul et al., 2003).

4 Implications of backfilling methods

4.1 Material consolidation and landform stability

Tailings consolidation is substantially greater than consolidation of waste rock backfill. This, together with the often complex geometry of pits, is a major issue that needs to be considered and accounted for when designing final landforms. Figure 7 presents an example of how the tailings mass may need to be apportioned in columns to enable predictions to be made of three-dimensional, post-consolidation elevations of the upper surface of the final landform. Figure 8 presents an example of how, utilising consolidation modelling approaches, tailings consolidation and dry density varies spatially across the pit over a given time. The conclusions here are that tailings consolidation is a complex geotechnical process and the implications to implementing mine closure and, ultimately, a stable final landform can be challenging.

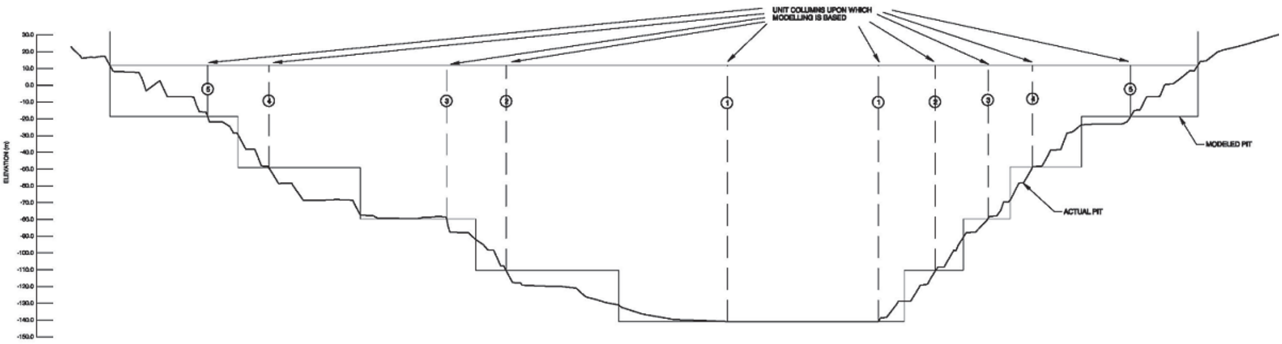

Figure 7 **Assumed model 'columns' used to predict tailings consolidation, Ranger Uranium Mine, Northern Territory, Australia (Photo courtesy of Energy Resources of Australia Ltd)**

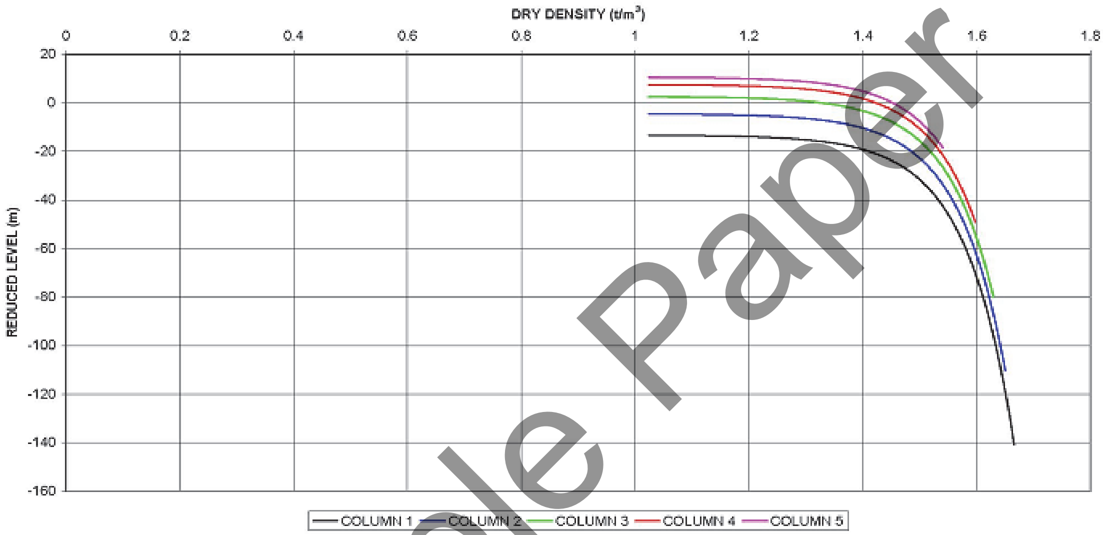

Figure 8 **Prediction of changes to the dry density of in-pit tailings, Ranger Uranium Mine, Northern Territory, Australia (Photo courtesy of Energy Resources of Australia Ltd)**

4.2 Solute release and impacts to receiving environments including pit lakes

Backfilling will typically see leachable wastes, such as waste rock, tailings or salts (derived from water treatment), deposited from the base of the pit and covered with waste rock to the natural surface or covered with water, i.e. pit lake. Wastes will usually be placed below the lowest, seasonal water table to ensure that oxygen ingress to the wastes, and generation of acid and/or solutes, is minimised. A key objective of this strategy is to limit solute mobilisation/acid generation, place wastes in contact with low permeability geological materials (in the pit), increase the pathway distance between the wastes and downstream receptors and reduce overall solute migration from the wastes to downstream environments.

Studies are required to support the development of an in-pit wastes deposition plan, including site geological and hydrogeological investigations, geotechnical and geochemical characterisation of wastes, characterisation of the attenuation and flow pathways for solutes, in-pit water and solute balance modelling, fate and transport modelling, and importantly, derivation and agreement of closure criteria for the pit (and site) with stakeholders including regulatory agencies. An important consideration is the change in the hydrological status of the pit as it evolves from a groundwater 'sink' to groundwater 'source'. Hydrological equilibrium between the pit and downstream groundwater systems may take decades and so groundwater monitoring programmes need to be established in a way that will provide useful information to support the results of predictive modelling.

The wastes geotechnical behaviour is an important consideration and particularly important to the release of solutes in the case of consolidating tailings. As tailings consolidate, porewaters are released and will express into the overlying waste rock. The fate, transport and impact of these porewater solutes needs to be incorporated in-pit water and solute balance modelling.

In circumstances where local groundwater systems do not have an environmental or beneficial use for humans, the manner in which wastes are placed in the pit may not be constrained by the geotechnical or geochemical properties of the wastes. In other words, the leaching of solutes from the pit does not pose any specific risk to downstream environments. If on the other hand, protection of downstream environments or beneficial uses is threatened by seepage from the pit, then wastes may need to be placed in parts of the pit that have much lower inherent permeability. This approach results in minimisation of seepage rates from the pit. Alternatively, in-pit liners or barriers such as that installed at the Ranger Uranium Mine and other mines, may need to be installed or neutralisation of backfill wastes may need to be implemented.

Figure 9 Investigations of in-pit tailings geochemistry, Ranger Uranium Mine, Northern Territory, Australia (Photo courtesy of Energy Resources of Australia Ltd)

5 The future of backfilling

Backfilling of mine voids will increasingly be seen in the future as an opportunity to be considered as part of the mine planning process. This will be for two reasons:

1. Changes in regulatory regimes and community expectations are dictating that land disturbance is minimised, with affected lands returned to a condition that more closely reflects pre-mining land uses.
2. Mining companies are increasingly viewing mine planning in a holistic manner, with consideration given to risks, liabilities and costs over both the operational and post-closure life of the project. To minimise long-term environmental risks, and hence long-term costs and liabilities, whole-of-life mine plans will increasingly look at integrating the options for operational and post-closure management of mine wastes, e.g. some wastes stored in above-ground facilities, others in underground repositories.

In the future, voids will be seen as containment cells for mine and non-mine wastes. Mine wastes will be characterised during the life of the mine and assessments of the most appropriate, final containment location will be made earlier in the life of the mine. Decisions will emphasise the long-term survival of covers over geomorphological timeframes and placement of ‘problematic’ wastes in underground repositories wherever possible.

In circumstances where it is not economic or practicable to return mined voids to pre-mining land uses or viable pit lakes, placement of non-mine wastes such as domestic wastes/putrescibles will increasingly be in mine voids. An example of this exists at Bristol, United Kingdom, where a former open quarry has been converted to a landfill facility (Figure 10). In this instance, a conventional composite compacted clay and geomembrane liner was installed across the valley floor with wastes placed in containment cells.

Figure 10 Landfill liner installation as part of landfill construction in a former quarry, Bristol, United Kingdom (Breitenbach, 2008)

6 Summary

While high costs and the lack availability of wastes may preclude the backfilling of voids, there are nonetheless many drivers for backfilling. In underground mines, mine wastes are often returned to underground voids on the basis of economic and engineering considerations. In open pit operations, backfilling is often only cost-effective and feasible where it is considered during the operational (or earlier) phase of the mine and is driven by cost-savings (e.g. removing the requirement to construct a new tailings storage facility), regulatory requirements, managing long-term environmental risks, e.g. predicted potential poor quality water within a pit lake, and/or closure objectives which aim to achieve an agreed post-mining land use.

There are many different approaches to backfilling of mine voids. The method and nature of waste deposited will determine the geotechnical and geochemical properties of wastes and their long-term behaviour. This behaviour will in turn influence the manner in which solutes are released, the geotechnical stability of in-pit materials and settlement of final landforms. Understanding these behaviours is critical in predicting the long-term impacts to downstream water and ecosystem receptors, changes in water quality in-pit lakes and stability and erosion of final landforms.

Backfilling is increasingly seen as 'best practise' for mine closure rehabilitation and an important aspect to whole-of-mine planning. This is because long-term management of environmental risks and return of land to an acceptable post-mining land use can in some circumstances only be achieved by pit backfilling.

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