Mine Waste Cover Systems: An International Perspective and Applications for Mine Closure in New Zealand

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Abstract

Defining design objectives is the first step in developing an appropriate cover system design for closure of a mine waste storage facility. These vary from site to site but generally include objectives related to physical and chemical stabilisation, as well as meeting land-use objectives and other societal values. Two key processes are fundamental to both defining and meeting these objectives; namely, the surface water balance and surface energy balance. Controlling oxygen ingress into above-grade waste storage facilities is certainly more challenging than controlling water ingress, based on the authors’ experience.

Cover system design alternatives most applicable to closure of mine waste storage facilities include erosion protection cover systems, store-and-release cover systems, enhanced store-and-release cover systems, barrier-type cover systems, and cover systems with engineered layers. Selection of an appropriate cover system design requires completion of a receiving environment impacts analysis. The goal is to select a closure scenario that will attenuate peak concentrations of contaminants of concern in the receiving environment to levels that can be assimilated without adverse affects over the long term.

Three additional elements reviewed in this paper include landform design and surface water management, cover system construction, and performance monitoring. Developing an appropriate closure landform design and surface water management system are critical to ensure that the performance of the cover system will be sustainable over the long term. It is imperative that cover systems be constructed with a high level of quality control to ensure the as-constructed cover systems are representative of the designs. Finally, direct measurement of field performance is the preferred methodology for measuring performance of a closure cover system for mine waste storage facilities.

Keywords: Reclamation, performance monitoring, landform design, construction, surface water management.

Introduction

Earthen or “dry” cover systems are typically required for closure of mine waste storage facilities (MWSFs) including tailings impoundments, waste rock stockpiles, and spent heap leach piles. The primary purpose of a cover system is restoration of the surface to a stable, natural condition while minimising degradation of the surrounding environment following closure. Cover systems can have numerous design functions, including but not limited to isolation of waste, limiting the influx of atmospheric water and/or oxygen, controlling the upward movement of process-water constituents / oxidation products, and providing a medium for establishing sustainable vegetation (MEND, 2004; 2012; INAP, 2011).

Cover systems can be simple or complex, ranging from a single layer of earthen material to several layers of different material types, including native soils, suitable overburden, non-reactive waste materials, geosynthetic materials, and oxygen-consuming materials (MEND, 2004). The complexity of any given cover system design depends on several factors, including the climate regime at the site, reactivity and texture of the waste material, hydrogeologic setting of the facility, and both physical and chemical properties of locally available cover materials.
Design objectives of cover system designs applicable to closure of MWSFs are reviewed first, followed by key characteristics of generic cover system designs, and finally, key aspects related to cover system design, landform design and surface water management, construction, and performance monitoring.

**Background**

A key design function of most cover systems placed over mine waste material is to protect the downstream receiving environment following closure of the facility (O’Kane and Wels, 2003). This is achieved by reducing “net percolation of meteoric water” (defined below) into the MWSF, which reduces effluent seepage volumes. This reduction in seepage volumes ideally limits peak concentrations of contaminants in receiving waters to levels that can be assimilated without adverse effects on the aquatic ecosystem.

Net percolation is the net result of meteoric water infiltrating into the cover profile (see Fig. 1). Meteoric water will either be intercepted by vegetation, runoff the cover, or will infiltrate into the surface. Water that infiltrates will be stored in the “active zone” and a large majority will then subsequently exfiltrate back to the surface and evaporate, or be removed by transpiration. The infiltration can also move laterally downslope within and below the active zone. In addition, a percentage of the infiltrating meteoric water will migrate beyond the active zone due to gravity overcoming the influence of evapotranspiration and moisture retention, and result in net percolation to the underlying waste.

![Figure 1. Schematic of hydrologic processes that influence performance of sloping mine waste cover systems (from MEND, 2012).](image-url)
Developing cover system design objectives

A cover system is often an integral component of a closure plan for any given MWSF. The objectives of a cover system may vary from site to site but generally include (from MEND, 2012):

1. **Physical stabilisation:**
   - Provide dust and erosion control, particularly wind and water erosion of mine waste materials; and
   - Act as a barrier to prevent direct contact of the mine waste material by flora and fauna;

2. **Chemical stabilisation:**
   - Chemical stabilisation of mine waste through control of oxygen or water ingress; and
   - Contaminant release control through control of infiltration;

3. **Meeting land-use objectives and other societal values:**
   - Provide a growth medium for establishment of sustainable vegetation; and
   - Reclaim the area for desired post-closure land uses.

Two key processes are fundamental to both defining and meeting these objectives; namely, the surface water balance and surface energy balance (MEND, 2012). The surface water balance is a function of many factors such as climate, soil type, and hydrogeologic setting. Of these factors, the hydrogeologic setting of a MWSF exerts a predominant control on the cover system requirements. For example, the location of the final water table has a large influence on predicted amount of net infiltration, leaching processes, and oxygen ingress into a MWSF. In a setting where the water table interacts with stored waste, leaching (by water and any remnant acidity) will take place regardless of the ability of the cover system to control water infiltration. Therefore, the design of a cover system is highly dependent on the conceptual and detailed understanding of hydrogeologic conditions at the site, leading to an understanding of the surface water balance of the cover system.

Controlling oxygen ingress into MWSFs is certainly more challenging compared to controlling water ingress based on the authors’ experience. For tailings impoundments, one can arguably achieve oxygen ingress control by maintaining high saturation, or ideally, flooded conditions thereby reducing the issue of oxygen ingress to one of diffusion, as opposed to advection. However, for waste rock stockpiles, in the absence of flooded conditions it is challenging to maintain sufficient saturation levels within the pile such that diffusion will be the dominant mechanism influencing gas transport. In this case, one must rely on high saturation conditions in a cover layer over the stockpile. Furthermore, given the elevation differences, there is the potential for temperature differences within the mine waste stockpile compared to ambient conditions. Temperature differences may induce convective gas transport deep within the stockpile. Other convective transport phenomena, such as barometric pumping, wind action, and pressure differentials can also induce convective flow (Wels et al., 2003). Therefore, it is clear that limiting oxygen availability to stockpiled mine waste material is challenging. Finally, a cover system designed to limit oxygen ingress would need to adhere to a high level of construction quality control, seek to minimise the potential for differential settlement and cracking following construction, and would require a commitment to maintenance of these conditions.
Cover system design alternatives

MEND (2004; 2012) and INAP (2011) provide good overviews of cover system design alternatives applicable to closure of MWSFs. Table 1 summarises five types of cover systems that are most applicable to closure of MWSFs.

Table 1. Cover system design alternatives for closure of MWSFs.

<table>
<thead>
<tr>
<th>Category</th>
<th>Best suited for:</th>
<th>Key attributes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion protection cover system</td>
<td>• Non-reactive, low-metals, and/or low-salt mine waste</td>
<td>• ~0.3 m of topsoil seeded with native grasses, OR</td>
<td>• Landform grading may be required to shed runoff waters</td>
</tr>
<tr>
<td></td>
<td>• Control of water and oxygen ingress not required</td>
<td>• ~0.3 m of coarse gravel or riprap (for sites where vegetation is undesirable)</td>
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<tr>
<td>Store-and-release cover system (also referred to as ET cover system)</td>
<td>• Arid and semi-arid climates</td>
<td>• ~1−2 m of well-graded soil or inert run-of-mine (ROM) waste material</td>
<td>• Sustainable vegetation cover is critical</td>
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<tr>
<td></td>
<td>• Higher net percolation rates (10−40% of MAP)</td>
<td></td>
<td>• Landform grading may be required to shed runoff waters</td>
</tr>
<tr>
<td></td>
<td>• Control of gas ingress/egress not required</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enhanced store-and-release cover system</td>
<td>• Arid and semi-arid climates</td>
<td>• ~1−2 m of well-graded soil or inert ROM waste material overlying a reduced permeability layer (RPL)</td>
<td>• Longevity of RPL must be addressed during design stage</td>
</tr>
<tr>
<td></td>
<td>• Moderate net percolation rates (10−15% of MAP)</td>
<td>• RPL can be compacted</td>
<td>• More robust landform design required to prevent erosion</td>
</tr>
<tr>
<td></td>
<td>• Control of gas ingress/egress not required</td>
<td>• Sites where higher soil water needed for revegetation efforts</td>
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<td>• Sites where higher soil water needed for</td>
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<tr>
<td>Barrier-type cover system</td>
<td>• Semi-humid and humid climates</td>
<td>• ~1 m growth medium/protective layer overlying a low permeability layer (LPL)</td>
<td>• Longevity of LPL must be addressed during design stage</td>
</tr>
<tr>
<td></td>
<td>• Low net percolation rates (5−10% of MAP)</td>
<td>• LPL can be compacted</td>
<td>• More robust landform design required to prevent erosion</td>
</tr>
<tr>
<td></td>
<td>• Control of gas ingress/egress desired</td>
<td>• permanently frozen layer</td>
<td></td>
</tr>
<tr>
<td>Cover system with engineered layers</td>
<td>• Semi-humid and humid climates</td>
<td>• ~1 m growth medium/protective layer overlying a geo-membrane liner (e.g. LLDPE, GCL, BGM2)</td>
<td>• Costly</td>
</tr>
<tr>
<td></td>
<td>• Very low net percolation rates (&lt;5% of MAP)</td>
<td>• Bedding and drainage layers usually required</td>
<td>• Longevity of geomembrane liner must be considered</td>
</tr>
<tr>
<td></td>
<td>• Control of gas ingress /egress desired</td>
<td></td>
<td>• Require robust landform design</td>
</tr>
</tbody>
</table>

1 MAP: mean annual precipitation.
2 LLDPE: linear low-density polyethylene; GCL: geosynthetic clay liner; BGM: bituminous geomembrane liner.

The mining industry has generally labelled cover systems for mine waste stockpiles as per the cover system’s primary function (O’Kane and Ayres, 2012). Examples include:

(1) “store-and-release” type cover systems;
(2) “water-shedding” type cover systems; or
(3) “capillary break” type cover systems.
However, this approach has led to a significant misunderstanding in regards to cover system performance expectations. For example, a “water-shedding” cover system will typically include a barrier or low permeability layer within the cover system and then an overlying growth medium layer. In reality, the growth medium layer is simply another label for a store-and-release cover layer because the functionality of the two is the same (i.e., store surface infiltration within the material, then evapotranspirate moisture to release it back into the atmosphere). The underlying barrier layer is required to promote “water-shedding” for conditions when storage is overwhelmed in the growth medium layer (e.g., periods of high precipitation).

Cover system design methodology

A key component in developing a defensible cover system design for a MWSF is a receiving environment impacts analysis. The specific environmental impacts to be evaluated depend on the objective(s) of the proposed cover system design in conjunction with the site closure plan as well as local, state, and federal government commitments. Environmental impacts most commonly evaluated during a cover system design include:

- impacts on surface water quality;
- impacts on groundwater quality;
- impacts on air quality;
- impacts on vegetation; and
- impacts on wildlife.

The goal is to select a closure scenario that will attenuate peak concentrations for contaminants of concern in the receiving environment to levels that can be assimilated without adverse affects over the long term. Once the required criteria have been determined for closure of a MWSF, feasible cover system design alternatives can be developed and carried forward into a soil-plant-atmosphere (S-P-A) numerical modelling program. In addition, closure criteria, developed on a site-specific basis, provide the basis for measuring field performance of a cover system and ultimately, determination of whether the cover system is working (O’Kane and Ayres, 2012).

The design of a closure cover system and in particular, determination of predicted rates of net percolation over the long term, should involve S-P-A numeric simulations using a long-term climatic database. This database should be comprised of at least 50 to 100 years of daily records from local and regional meteorological stations. Each year of the long-term climate database should be run continuously for each cover design alternative, thereby taking into account antecedent moisture conditions. This allows curves, as shown in Fig. 2, to be developed for each cover alternative, providing mining companies with a means of understanding “risk” or the “probability of exceeding” a certain net percolation rate for a given MWSF.

A key factor to consider during the design process is the anticipated climax vegetation species that will develop on the cover system. A vegetation cover is important not only for minimising soil erosion, aesthetics and creating wildlife habitat, but lower net percolation rates can be realised with a mature vegetation canopy due to higher rates of interception and evapotranspiration.
The authors suggest that for general context, cover systems that achieve:

1. “very low” net percolation rates are those that have a high probability for the net percolation rate for any given year to be between 1% to 5% of precipitation;
2. “low” net percolation rates are those that have a high probability for the net percolation rate for any given year to be between 5% to 15% of precipitation; and
3. “moderate” net percolation rates are those that have a high probability for the net percolation rate for any given year to be between 10% to 40% of precipitation.

Figure 2. Example illustration of net percolation probability of exceedence curves generated from the results of continuous 100-year S-P-A simulations for a “no cover” scenario, and three different cover system design alternatives.

Landform design and surface water management

Historically, rehabilitated mine landforms possess uniform slopes conforming to neat lines and grades. This lends itself to uniformity of design and construction, but does not necessarily achieve the mine closure objectives of minimum erosion and long-term sustainability. Uniform landforms represent immature topography, and are poised to evolve to lower energy states by shallow slope failures or accelerated erosion. In contrast, the development of a sustainable landscape for mine closure involves the development of landforms that replicate natural landscapes. The replication of mature and relatively stable natural systems reduces the rate and risk of accelerated erosion.

Following a tour of 57 abandoned and partially reclaimed operating mines, McKenna and Dawson (1997) created an inventory of mine closure practices, physical performance of
reclaimed areas, and environmental impacts of reclaimed and abandoned mines. The inventory shows that the greatest physical risk to the landscapes is associated with gully erosion and re-established surface water drainage courses. Poor surface water management and landform instability are common factors leading to failure of mine waste cover systems around the world (MEND, 2004). These factors are much more prevalent at sites situated in cold regions where processes such as frost heave and snowmelt can substantially diminish the integrity and performance of a reclaimed mine landform (MEND, 2012).

The incorporation of natural slope features into the final landform design for stockpiles not only improves aesthetics, but also emulates slopes that are in equilibrium with local conditions of rainfall, soil type, and vegetation cover (Ayres et al., 2006). The relatively small increase in costs for engineering and construction for creating natural landforms are more than offset by improved visual appeal, decreased slope maintenance costs, and improved long-term stability. In addition, constructing mine landforms that visually blend with the surrounding landscape has considerable public relations value for operators.

Landscape design is dependent on numerous factors, including climate, geology, soils, local hydrogeologic patterns, topography and final land use (MEND, 2007). A major challenge concerning landform design is the objective of long-term sustainability; design timeframes may be in the order of hundreds of years. The changes that will occur during this period are difficult to predict and quantify, yet will affect the system.

Processes that affect the evolution of a system can be grouped into physical, chemical, and biological categories, and each will affect the landform differently over time (see Fig. 3). The appropriate approach is to account for site-specific processes that are anticipated to act on the closure landform, rather than have these processes result in an adverse effect on long-term performance. In general, the simpler the closure design, the less one has to be concerned about the potential effect of processes such as wet-dry cycling, frost action, and vegetation developments on long-term performance.

![Figure 3. Conceptual illustrations of processes affecting long-term performance of closure landforms/cover systems (from INAP, 2003).](image-url)
The authors strongly recommend that a failure modes and effects analysis (FMEA) be completed on the proposed final cover system and landform for closure of a MWSF. A FMEA is a top-down/ expert-system approach to risk identification and quantification, and mitigation-measure identification and prioritisation. Its value and effectiveness depends on having experts with the appropriate knowledge and experience participate in the evaluation during which failure modes are identified, risks estimated, and appropriate mitigation measures proposed. The goal is to provide a useful analysis technique that can be used to assess the potential for, or likelihood of, failure of the proposed design and effects of such failures on human health and the surrounding ecosystem. Robertson and Shaw (2006) describe the FMEA approach in greater detail.

**Key aspects of cover system construction**

Several key issues associated with cover system construction are fundamental to long-term cover performance, many of which are atypical when compared to other types of construction (MEND, 2004). It is fundamental that a cover system be constructed with good quality control to ensure that the completed cover system is representative of the actual design. The effect of improper construction of a cover system, or poor QA/QC during construction, can have a dominant influence on cover system longevity. Based on the authors’ experience, the following key issues are often overlooked or not given appropriate consideration during cover system construction:

- **Experienced, informed personnel for construction supervision:** in addition to having experience in earthworks construction, personnel or firms retained to supervise cover system construction should be informed and knowledgeable of the intended functions of all the design elements.

- **Continuous characterisation of cover materials from borrow sources:** an appropriate geotechnical testing program including, at a minimum, particle size distribution analyses (Atterberg limits and Proctor compaction tests for cohesive materials) should commence as soon as a cover material borrow source is identified, and continue throughout cover system construction. This is critically important for a compacted cover layer comprised of local silt or clays, but is equally important for the growth medium layer to ensure an adequate fines content for moisture retention and plant growth.

- **Field compaction trials prior to full-scale construction:** if the cover system design includes a layer of compacted weathered mine waste material or local silty-clay soil, then field compaction trials should be carried out to ensure the two important elements – density and moisture content – are obtainable throughout construction. The trials are also useful to optimise compaction and test equipment selected for construction and identify unforeseen construction issues.

- **Construction of thicker moisture store-and-release layers using ROM waste materials:** these materials tend to be well-graded to gap-graded, which can lead to segregation during placement and the formation of coarser textured zones (i.e. preferential flow-paths for higher infiltration of atmospheric water and oxygen); INAP (2003) describes the adverse affect of ROM material segregation within a moisture store-and-release cover layer at BHP Billiton Iron Ore’s (BHPBIO’s) Mt. Whaleback operation; thicker profiles of material prone to segregation should be constructed in multiple lifts.
Performance monitoring of cover systems

Historically, one of the most common technologies used for evaluation of closure cover system performance has been water quality analyses of seepage discharged from a MWSF. Water samples are typically collected from collection ditches around the perimeter of the facility or from monitoring wells installed below or down-gradient of the site. While this approach empirically describes a facility through monitoring of its cumulative effect at the base, it may take several decades before seepage water quality improves. This is due to the storage capacity in the stockpiled material and the length of time it takes for the phreatic surface to equilibrate with local hydrogeologic conditions. Direct measurement of field performance is the preferred methodology for measuring performance of a cover system for reclaimed MWSFs (MEND, 2004; 2007; 2012). This is the best method for demonstrating to all stakeholders that the cover system will perform as designed.

A “watershed” approach to monitoring is preferred in order to gain a better understanding of cover system performance under site-specific conditions (O’Kane, 2011). The rationale for utilising a watershed approach is such that it allows for the complexity and challenges of cover system performance monitoring, which are apparent given the scale increase of a cover system from a point-scale (e.g. a test plot) to a macro-scale (e.g. a watershed). Although most monitoring techniques used in point-scale cover system monitoring can be applied for macro-scale cover system monitoring, the extent of performance monitoring for a macro-scale cover system is much broader than that for a point-scale cover system. The performance monitoring and evaluation of a macro-scale cover system considers the temporal and spatial variability of the field measured datasets. The monitoring frequency (scale) for obtaining sufficient data, which is associated with spatial instrumentation and temporal data acquisition, must be understood in order to deploy a cost-effective monitoring system.

Several factors need to be considered when designing a cover system performance monitoring program. Cover system performance will be different in upslope versus downslope areas due to differences in runoff and infiltration across a sloping surface. Heterogeneity in the particle size distribution of cover system material will also result in slight differences in cover system performance. Cover system performance monitoring systems should be automated as much as possible to avoid missing collection of field response data during key times of the year (e.g. during and following storm events). In addition, the use of automated systems (see Fig. 4) for data collection greatly reduces the need for human intervention and in particular, demands placed on mine site personnel.

Conclusions

The recommended design philosophy for a MWSF cover system is one that integrates the mine waste material within its environmental context. This is in contrast to isolating the material from the environment to completely prevent the production of contaminated seepage. A cover system must be designed as an unsaturated system exposed to the atmosphere, the performance of which will be significantly influenced by seasonal, annual, and long-term site climate conditions.

The behaviour of a cover system will change with time as a result of various physical, chemical, and biological processes. The key is to account for site-specific processes that are anticipated to act on the closure landform, rather than have these processes result in an adverse effect on long-term performance.
Figure 4. Automated meteorological and soil monitoring stations installed on a closure cover system for a MWSF.

References


