CHAPTER VIII
CLOSURE AND RECLAMATION

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1. INTRODUCTION

Tailings landforms are an enduring legacy of many mining landscapes – the design and construction of these facilities to perform well for the next millennium is just as great a challenge and effort as is maintaining operational dam safety. This chapter provides an overview of leading practices for design, construction, deposition, stabilisation, decommissioning, capping, reclamation, and aftercare for tailings facilities. It builds on the work detailed in *Sustainable design and post-closure performance of tailings dams* (ICOLD 2013).

An important advance in mine closure design is the framework of landform design — a new concept that is breaking out internationally under different names by various groups and practitioners. Landform design entails a paradigm shift away from the practice of separating construction and operations from closure and reclamation. Instead, it calls for a fully integrated approach that provides design, support, and stewardship throughout the life of the mine and beyond.

A new Landform Design Institute (LDI 2020) was recently formed, which provides ‘how-to' advice on designing, constructing, and reclaiming mining landforms and landscapes that are easy to reliably reclaim. The Institute helps mines meet their commitment to be temporary users of the land. Effective reclamation of tailings facilities requires sound design and planning before construction of the mining landform even begins. Globally, there are tens of thousands of mining landforms that are partially constructed and in need of improved reclamation practices. Sections 5 and 6 of this chapter provides a more complete discussion of the landform design approach to overall mine (and specifically tailings) closure for both existing and new mining landforms.

2. OVERVIEW OF CURRENT PRACTICE

Worldwide, many mines have one or more active or inactive tailings facilities. Each tailings facility is a mining landform that is already part of the permanent landscape, and which will require reclamation as part of mining's commitment to be a temporary use of the land and to enable individual mines to leave a positive mining legacy. Each of these tailings landforms must be sited, designed, constructed/filled, decommissioned, stabilised, reclaimed, and deregulated as dams, relinquished and then maintained over the long-term by landowners or regulatory agencies. Where the relinquishment cannot be accomplished, ongoing maintenance will be responsibility of the mine owner.

Tailings facilities typically occupy 10 to 40 per cent of the area of a reclaimed mining landscape, with pits and waste rock dumps responsible for most of the rest. Typically, regulators require reclaimed facilities to meet agreed-upon land uses and performance standards that sustain landscapes for the benefits of local communities (e.g. Brazilian Mining Association [IBRAM] 2014). After mining, the sites are commonly used as natural areas or wildlife habitat (especially for remote mines). Near cities, they may be used for agricultural, recreational, or industrial activities (Pearman 2009).

Most tailings facilities are difficult to stabilise and reclaim to the point where they meet societal expectations of only an extremely low risk of catastrophic failure, acceptable residual impacts on the environment, and access for agreed-upon land uses. Many dams cannot be deregulated (i.e. where they are no longer regulated as a dam but as a mine waste storage facility). In particular, it is very unlikely that a dam will be deregulated if it contains ponded water or potentially mobile materials, due to concerns

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regarding catastrophic dam failure even after closure. In practice, most tailings landforms need regular monitoring and maintenance, perhaps in perpetuity.

Historically, tailings dam design has focussed on safely containing hydraulically placed tailings during mine operations. More recently, designing these tailings landforms to be safe, stable, and useful after filling and reclamation has become a parallel but not necessarily integrated focus (ICOLD 2013). But improvements are needed. Most tailings facilities owners and users still face one or more significant geotechnical, safety, geo-environmental, or financial risks related to operational reclamation activities and long-term landscape performance (McKenna 2002).

Reclamation practices vary widely according to climate, commodity, and regulatory environment. Most mines employ conventional reclamation techniques, including regrading of slopes, placement of cover materials (usually a growth medium), and planting with site-appropriate, ideally native, vegetation. Reclamation is often conducted progressively, whereby mine areas, especially mine waste landforms such as tailings facilities and waste rock dumps, are reclaimed soon after bulk material placement is completed. At some mines, each lower bench of dams and dumps is reclaimed as the next bench above is placed. This approach cannot be used for most downstream and centerline constructed facilities which can generally only be reclaimed once all lifts have been added.

Though it is an increasingly rare practice, some mines still carry out little in the way of reclamation until after mining and milling cease. Small mines often have just one tailings facility, one pit, and one or two waste rock dumps, and at these sites the opportunities for progressive reclamation are limited. On the other hand, many active underground and open-pit mines have about 10 to 30 per cent of their area reclaimed. These mines benefit from a 'learn-as-you-go' approach to mine reclamation, allowing operators, regulators, and local communities to see first-hand how the landscape performance of reclaimed land is faring. Operators are also able to reduce liability for future reclamation. In some jurisdictions, mines vie for reclamation awards given by the regulator for exemplary achievements in progressive reclamation. It should be noted though that, progressive reclamation of tailings dams is not always practical. This is most notably the case for dams constructed by the downstream method, which receive regular depositions. For some dams with active pouring above reclaimed areas, line spills and deposition of windblown sand from beaches or benches, can damage the reclamation below.

Currently, most mines have a 'conceptual closure plan' that details what needs to be done for the mine site (landscape scale) and for each mining landform (such as waste rock dumps, tailings facilities, open pits, and plant sites). The plan applies to decommissioning, regrading / stabilisation, mine reclamation, and water management and water treatment. Excellent guidance for development of modern closure plans is provided by IBRAM (2014), Government of Western Australia (2015), Asia Pacific Economic Cooperation (APEC, 2018) and ICMM (2019). However, at most mines, the design and operation of tailings facilities is conducted separately from closure and reclamation.

Mines are required to post financial assurances to cover the costs of reclamation and long-term care in most jurisdictions, but depending on the regulatory framework, the assurances can end up being a small fraction of the eventual requirements. In some jurisdictions the land may be abandoned while only partially reclaimed, and must be managed by the state, with little or no funding available for the remaining work.

3. TAILINGS CLOSURE: WHAT IS GOOD PRACTICE?

Good practice tailings closure development and design starts during the initial stages of the mine development programme, when decisions are made about site selection and tailings management. The initial closure plan forms the basis for ongoing plan refinement and confirmation as the operations proceed. Pilot studies can be used to refine cover design and placement, vegetation plans, surface drainage plans, etc. The closure plan is never stagnant.

Similarly, there should be ongoing engagement of communities to get their perspectives and advice on the closure of the site. The communities are to be the long-term neighbours of the site and will often become the owner of the closure facility. It is therefore important that they not only understand the closure concepts and approaches but also contribute to and accept the designs and resulting landforms.

A good-practice approach to closure therefore includes the following aspects.

3.1 DEVELOP CLOSURE CRITERIA

Site specific closure criteria are ideally developed at the outset of the project by drawing on:

- regulatory requirements
- mining company corporate closure criteria
- commitments made by the company to regulatory agencies and communities during the mine life cycle
- leading international practices for projects in similar climates, with similar physical and chemical conditions and environmental settings, and in similar socio-economic settings.

These criteria are captured and addressed in the design basis memorandum (DBM) as described below, and then reviewed periodically. For existing tailings facilities that have no or too simplistic closure criteria, a DBM should be developed as a high priority.

3.2 IDENTIFY ALTERNATIVE TECHNOLOGIES

The next step is to identify the alternative tailings and closure technologies and practices that will satisfy the closure criteria. An options analysis is undertaken using mine plans that incorporate each of the leading tailings technologies. (See Consortium of Tailings Management Consultants [CTMC] 2012, for a list of nearly 100 tailings technologies). This requires considering the climatic and topographical location of the tailings facility and the feasibility (technical and economical) and constructability of different options.[1]

Technology developments during the facility mine life may also generate new technologies that can then be considered for adoption during regular closure updates, as part of the mine lifecycle refinements of the closure plan.

3.3 COMMUNITY ENGAGEMENT

Meaningful community engagement is undertaken as an ongoing process throughout the mine lifecycle, with the aim of ensuring that the concerns of local communities are heard and addressed. True collaboration, rather than just consultation, is key to closure reclamation success. (See Joyce and Kemp, this volume.)

4. SPECIFIC TAILINGS CLOSURE AND LANDSCAPE PERFORMANCE ISSUES

Tailings facilities typically have several components, with some attributes easier to reclaim than others. Dams constructed of clean rockfill or borrow are often straightforward to reclaim and perform well, as do tailings sand beaches. However, tailings facilities typically present several challenges for closure and reclamation:

Sand dams, comprised of fine sand and silt tailings, are highly erodible. Even when capped and revegetated, gullies can penetrate the cover, leading to erosion of mine waste, fan deposition, and elevated suspended sediments in downstream watercourses, necessitating ongoing maintenance.

Tailings and the tailings pore-water (the water that fills the porosity between the grains of tailings) may contain elevated levels of metals and may be prone to acid rock drainage. Both can affect groundwater and surface water, creating unacceptable water quality and toxicity to plants, animals, and aquatic life.

- Tailings dam internal drainage systems (underdrains, gravel drains within the dam, and socked-slotted drainage pipe) can be prone to clogging, fouling, or collapse, affecting the long-term groundwater table and the geotechnical and erosional stability of dams.
- Potentially mobile materials (soft tailings, liquefiable tailings, or water) stored behind dams may pose elevated risks of sudden catastrophic dam failures and outflows that threaten lives, the environment, and property downstream.
- Soft tailings are difficult to drive equipment on, expensive to stabilise, cap, and reclaim, and may be prone to many metres of post-reclamation settlement over decades or centuries. At most tailings landforms, just a small percentage of the beach / plateau area is underlain by soft tailings); in some cases (including most oil sands tailings facilities), the majority of the beach area (the tailings plateau) is comprised of soft tailings.
- The outlet spillway structure for tailings dams, if not anchored in bedrock, is a fragile element for closure, especially when retrofitted to a sand dam.
- Few tailings facilities have a DBM that addresses long-term reclamation performance. Lack of clear agreement on design objectives and future performance creates a gap between what is planned by the mine and what is expected by regulators and local stakeholders.
- 'Conceptual closure plans' for many or most tailings facilities are not detailed enough for informed decision-making, and many have undetected fatal flaws.

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[1] In practice, most of the decisions regarding closure and reclamation of tailings are made before tailings deposition even begins – especially the tailings technology and the location and form of the tailings landform.

In many cases, mine operators have expected to be able to 'walk away' from reclaimed landscapes, including the associated tailings facilities once reclamation has been completed. This strategy implies that the dams can all be deregulated, and that no human inputs are needed to continue to meet the agreed-upon uses, goals, and objectives. The new owner (usually the state) presumably cares for the landscape and protects the past miners' liability. However, experience has shown that only the smallest and most basic mines can realistically implement walk-away solutions; almost all mines need to have some level of effective, permanent aftercare to continue to meet their commitments, especially those with large tailings facilities (Bocking and Fitzgerald 2012). The level of care and maintenance must be factored into the design basis and should be considered when determining the financial assurance posted.

These and other risks, and associated costs, can be reduced by recognising them early in the mine lifecycle and by using a more systematic life-cycle approach to tailings technology selection, production, containment, deposition, stabilisation, capping and reclamation. The growing acknowledgment of the shortcomings in closure and reclamation performance has attracted considerable attention and given rise to several new guidelines from governments and other organisations. Some solutions to these issues are highlighted below.

5. LANDFORM DESIGN

Landform design is the multidisciplinary process that builds mining landforms, landscapes, and regions to meet agreed-upon land use goals and objectives. This section considers four useful terms related to scale: the region, the landscape (mine site), the landform, and the element scale (see Figure 1 and Table 1).

Table 1. Landform design scales

Design scale		Representative dimension, m	Description and examples
Regional		100,000	A grouping of mines in a valley or region Regional plan, cumulative effects assessment
Lease/landscape		10,000	A single mine lease/property. More generally: everywhere you can see from a point on the land (the Renaissance definition) Life-of-mine-plan, mine closure plan, landscape ecology
Landform		1,000	A single mine facility: dump, mined out pit, stockpile, tailings facility Dump design, dam design, landform design
Landform elements	Macro-topography	100	A single designed feature on a landform: toe berm, bench, shoreline, wetland Landform design (as above)
	Meso-topography	10	Fine tuning of topography: swales and ridges Field fit
	Micro-topography	1	Roughening: mounds and pits, individual boulders Field fit

Source: Adapted from Pollard and McKenna 2018

Source: Illustration by Derill Shuttleworth, dshuttleworth.com

Figure 1. Four scales of landform design

The *region* typically hosts several mine sites. Designers and regulators consider the cumulative effects of neighbouring mines and other extractive industries (McGreevy *et al.* 2013). There is also an opportunity for sharing resources and know-how between the mines in a region.

Each mine site can be considered a landscape. Renaissance artists considered the landscape as comprising everywhere that can be seen from a point. Today we think of a mine site as at the landscape scale. Life-of-mine plans are done at this scale. The site-wide surface water drainage and groundwater management are a major focus of working at this landscape scale. The discipline of landscape ecology also comes to bear as the design for wildlife habitat land uses consider the needs of wildlife to move through and use the reclaimed land.

It is useful to divide the mine site into distinct *landforms*, which are distinct topographic features created by natural or artificial processes (McKenna *et al.* 2013). Taken together, natural and artificial landforms make up the surface of the earth. Mining landforms include tailings facilities, waste rock dumps, pits and pit lakes, landfills, borrow sites, and similar facilities (Pollard and McKenna 2018). It can also be useful to consider site-wide drainage, the plant site, and perhaps the access roads and infrastructure as individual mining landforms for management and design purposes. Using this landform terminology allows mines to tap into hundreds of years of geomorphic and ecological experience and literature for use in design and assessment, as well as to learn from the performance of natural and other mining landforms in the region.

Most mine sites have 10 to 20 mining landforms planned, in construction, or reclaimed. Recent literature suggests that tailings facilities should be turned into landforms 'at closure.' The alternative view, as argued in this chapter, is that the tailings facilities are each their own landform even during the planning phase, and certainly with the initial construction of the starter dam. One can argue that at any point in time, every square metre of the earth's surface belongs to a landform. As mentioned above, this framework allows the design to focus on the long-term issues.

The smallest scale of interest, the *element* scale, refers to features on a landform such as mounds, trails, or wetlands). These elements are chosen and built to satisfy the requirements in the DBM.

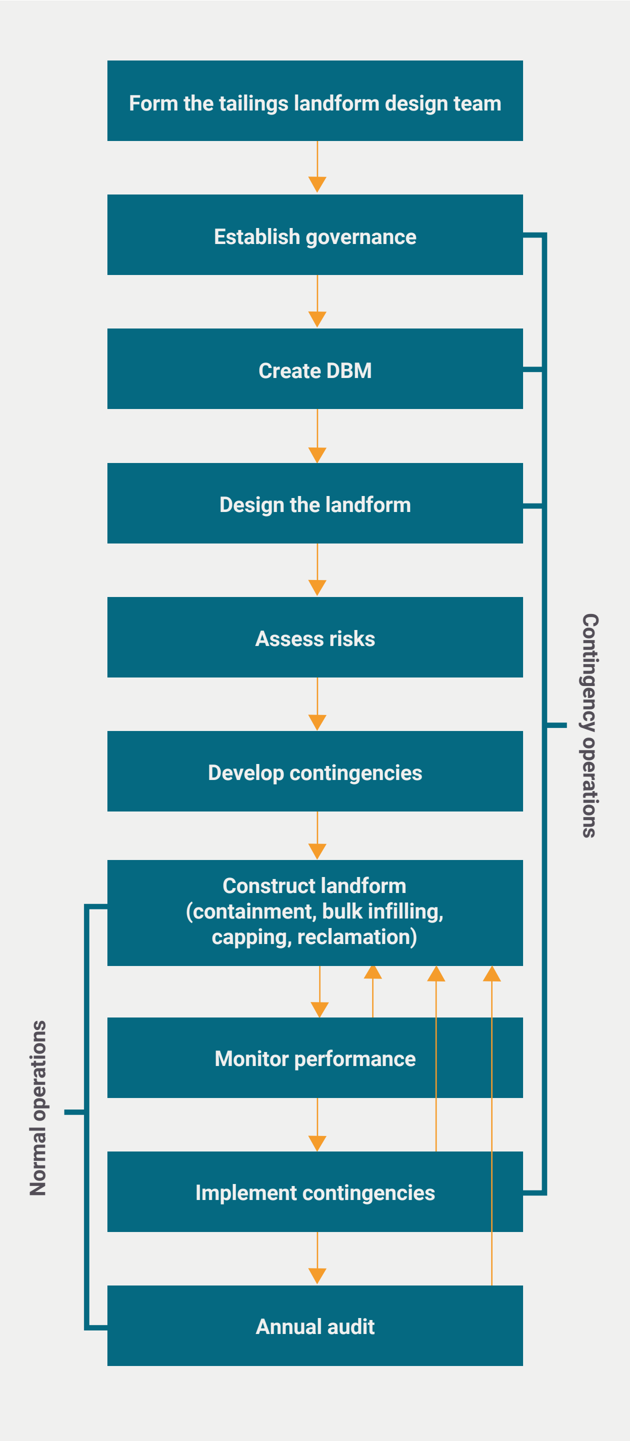


Figure 2. Steps in landform design for tailings facilities

6. LANDFORM DESIGN FOR TAILINGS FACILITIES

This section provides a step-by-step basis for landform design of tailings facilities. The major steps are shown in Figure 2 and described in the subsections below.

At most tailings facilities, the level of uncertainty in the foundation geology, dam construction, and tailings deposition usually precludes a fully deterministic landform design. Instead, design teams can follow Peck's (1969) geotechnical observational method which involves designing for the most likely conditions, developing a full suite of contingencies that can be enacted if field conditions are worse than expected, and a monitoring programme that allows timely adoption of contingency measures where needed. This method is used widely in dam design and is suited to landform design, mainly because it embraces the full development of contingencies. In the same way that a pre-designed toe berm may be a contingency for dam safety on dams with poor foundation conditions, shallow wetlands may be a contingency for reclamation for pockets of beaches that have undergone differential settlement.

The first two steps involve defining the landform boundary and forming the tailings landform design team. The team works at the various scales (region, landscape, landform, element) with a focus on the specific tailings landform. At successful mines, the landform design team works around a single plan – the life-of-mine-plan – rather than with separate mine, tailings, closure, and reclamation plans. The team works to support the life-of-mine plan by providing landform designs at each scale: the landscape scale for the life-of-mine plan, the landform design for an individual tailings landform (which embraces and influences the dam design), and design of various elements as needed.

The team provides various levels of design, ensuring that each design has enough detail to allow for sound financial, operational, regulatory, and stakeholder decisions. The notion of 'conceptual designs' is no longer entertained as these have been consistently shown to be insufficient for good decision-making and often contain fatal flaws. Instead, designs are completed to a pre-feasibility, feasibility, detailed, and issued-for-construction level. As built / construction and annual performance reports are also produced as a matter of routine.

6.1 DEFINING THE LANDFORM BOUNDARIES

Defining the tailings landform boundary is essential to successful reclamation. This is often done at the landscape scale. Usually the entire tailings facility is selected as a single landform. This includes the dam, the pond/plateau/beach depositional area, and the disturbed area around the periphery of the tailings facility (including roads, pipelines, powerlines, and other related infrastructure). In the past, some operators have chosen to treat the dam and its beaches/ pond contents as different landforms. While sometimes practical, this separation often leads to a lack of cross-disciplinary coordination, whereby the operational geotechnical stability of the dam can become the sole focus, with the contents simple considered 'dense fluids,' which overlooks the need to integrate the two elements of the deposit. Mines are diligent with dam safety but then are surprised by the cost of soft tailings stabilisation (see below).

6.2 FORMING THE TAILINGS LANDFORM DESIGN TEAM

The landform design team usually includes mine and tailings planners, a geotechnical engineer, a surface water hydrologist, a groundwater hydrologist, a geochemist, and specialists in covers/soils, vegetation, and reclamation, along with other specialists as required (McKenna 2002). One member of the team, sometimes the geotechnical Engineer of Record, takes overall responsibility for the design.

Teams typically comprise a 40/40/20 mix of engineers, biologists, and other specialists. Large mines often have all the engineers and specialists on staff, while smaller mines often use consultants. All members are part of all phases of design, construction, in-filling, stabilisation, capping, reclamation, and aftercare, though their level of activity varies over the decades. These teams often take a few years to learn to work as a highly functioning team, one in which each member understands the different approaches and priorities of their colleagues.

6.3 ESTABLISHING GOVERNANCE

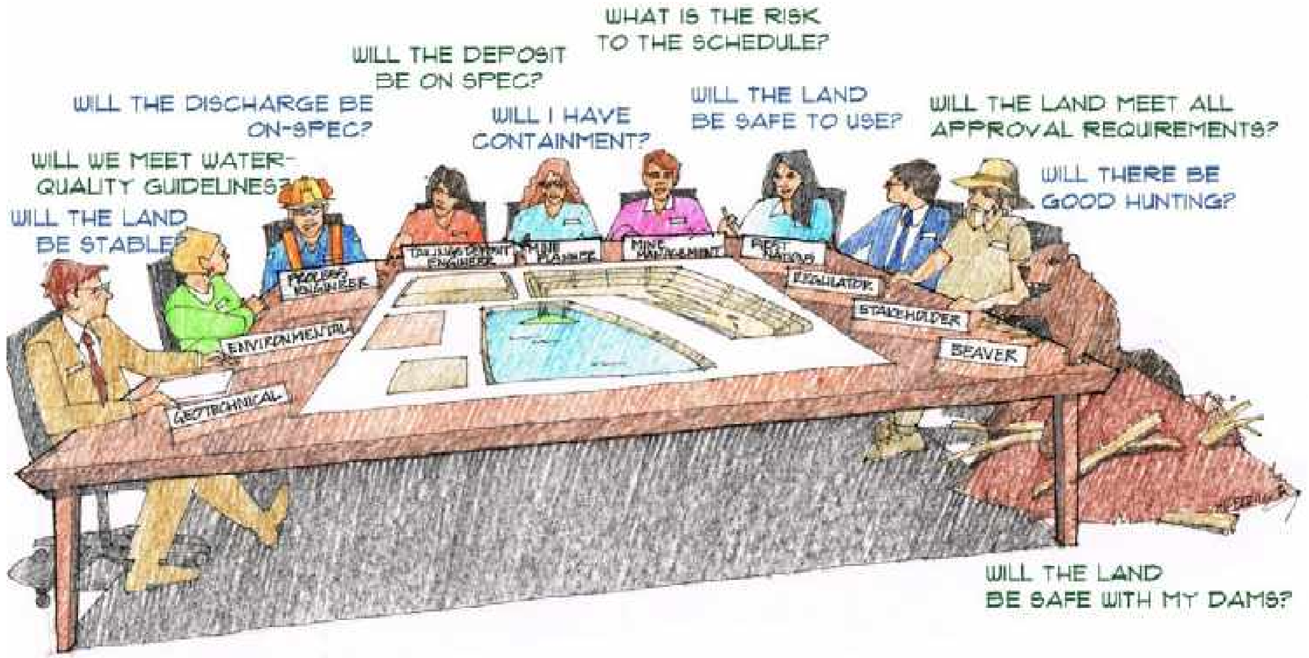
Just as there can be an accountable executive for tailings management and/or dam safety there should be an accountable executive for closure landform integrity including design and construction of the tailings landform – the two activities are one and the same. Often the costs of closure and reclamation of a tailings facility are similar to the cost of tailings containment and deposition, which is one more reason for close management. The accountable executive defines the project, provides adequate resourcing, delegates the activities to qualified personnel, and ensures the landform is designed and constructed to meet the agreed-upon goals and objectives in the design basis.

6.4 CREATING THE DESIGN BASIS MEMORANDUM

The landform design team creates a 10-20 page design basis memorandum (DBM) at the landscape level (to support the life-of-mine plan) and a separate, slightly more detailed, DBM for each mining landform (Ansah-Sam *et al.* 2016). Producing a DBM is a critical step often missing in the current state of practice. This oversight can lead to higher risks, costly rework, and ultimately to non-acceptance of the completed landform by regulators and local communities, even if the project is otherwise well constructed and reclaimed.

The vision is set out by working with regulators and local communities to determine target post-mining land uses. The report requires a lengthy table that describes the goals, supporting design objectives, and design criteria. The design objectives are measurable, and criteria may include items such as geotechnical factors of safety, allowable settlement, the service life, and magnitude and return periods for design events such as precipitation and seismic events. Each of the disciplines on the design team will contribute design objectives and criteria.

Ideally, a DBM is written jointly by the mine operator, its regulators and local stakeholders (Figure 4). In practice, the DBM is usually advanced in consultation (or sometimes even collaboration) with these groups. Periodic reviews of the DBM and the design and performance of the tailings landform, in conjunction with all affected groups, is key.



Source: Illustration by Derrill Shuttleworth , dshuttleworth.com

Figure 3. Different perspectives on tailings landform design

6.5 DESIGNING THE LANDFORM

The landform team designs the tailings landform to meet the requirements of the DBM and to align with the overall mining landscape during and after operations. The designs are supported by site investigations, which entail not just an examination of the pre-existing conditions prior to dam construction and infilling, but also of the dam construction and annual investigations of the pond and infilling. A large investigation is required just before capping and reclamation and is usually dominated by cone penetration testing, along with sampling of tailings materials and installation of piezometers and settlement monuments.

One of the major components of landform design is the selection of tailings technology, as described above. This decision, which is typically based on results of laboratory analysis of samples from a pilot milling process, has a profound effect on all remaining decisions for a tailings facility. There is a trend toward the use of 'dry-stack' tailings to minimise many of the concerns about dam safety and long-term stability. However, such tailings facilities still need landform design, and care must still be exercised to ensure that dry-stack tailings present an extremely low risk of post-closure static or dynamic liquefaction.

6.6 ASSESSING RISKS

The design is assessed using engineering risk assessment tools. A fatal-flaw analysis may be used to uncover any design aspects that are technically impossible or economically unfeasible. A failure modes assessment (FERC 2019) has proven useful for screening long lists of failure modes, with the highlighted failure modes then subjected to a more detailed failure modes and effects analysis (FMEA) (see MEND 2012). A list of residual risks is used to develop the contingencies and monitoring programme. Risk assessment is an ongoing activity throughout design and construction of tailings landforms. It is done formally every three to five years, or when there is a significant design change.

6.7 DEVELOPING CONTINGENCIES

Contingency measures for the residual risks are developed in some detail. They are part of the design. The monitoring programme aims to identify when performance deviates from what is expected and when these pre-planned contingencies are enacted. Where there are deficiencies, construction practices can be changed, or design contingencies implemented. In some cases, the DBM will need to be revisited.

6.8 CONSTRUCTING THE LANDFORM

Tailings dam construction is a mature technology, as is tailings deposition methods. The other components, which include stabilisation of the tailings plateau (especially in the case of soft tailings), capping, placement of reclamation material, and revegetation may or may not be common at commercial scales in the region where the tailings landform is located. Ideally, tailings would be easy to stabilise, cap, and reclaim. To this end, production of fluid tailings and soft tailings should be minimised (McKenna *et al.*, 2016).

6.9 MONITORING AND AUDITING PERFORMANCE

Throughout all phases of construction, performance is monitored and compared against design assumptions, by applying first-class construction practices and the observational method. This is routine for geotechnical dam construction and can be applied to tailings management and reclamation. An annual third-party independent audit can help to improve the effectiveness of the observational method. This should ensure that all aspects of the tailings landform are designed, constructed and monitored according to the design basis and the operating and maintenance manual.

Source: Illustration by Derrill Shuttleworth , dshuttleworth.com

Figure 4. Good practices for design of tailings landforms

7. PRACTICAL ADVICE FOR DESIGNING FOR DEREGULATING AND CLOSURE

This section contains useful advice for the landform design team. It provides some hard-won lessons and outlines techniques to improve the design and construction of tailings dams and tailings facilities. Much of the advice is unique to certain climates, which is the main filter of landform design. The objective is for facilities to be easily decommissioned, easily reclaimed, and easily deregulated. In time, these sites transition to agreed-upon post-mining land uses with acceptable performance, cost, and risk. Figure 4 highlights some of the elements important to building a sustainable tailings landform.

7.1 LANDFORM LONGEVITY

The service life of a tailings landform is the subject of considerable debate, and declaration of a service life is a key aspect of the DBM. In the absence of an agreed-upon service life, some will assume that this life is 'forever' or 'until the glaciers return,' while others give it little thought. Service life is important for long-term geomorphic and ecologic processes (Holden *et al.* 2019) and will affect predictions and designs for dozens of evolutional mechanisms, such as: dam slope erosion, failure of internal drainage elements and liners, geochemical evolution and geochemical weathering, impacts on water balance and flows due to climate change, and ecological and land use changes. There may be a convergence of consideration of service life of 1000 years for tailings facilities (ICOLD 2013; Slingerland 2019). Some components, such as some internal drains, may require ongoing monitoring and maintenance over the service life unless they can be demonstrated to be robust or unimportant to future performance.

Designing for climate change is part of the state of practice for design and construction of tailings landforms. Changes in vegetation in response to climate change can have a significant effort on landscape performance. Design methods for including climate change are evolving rapidly (e.g. Slingerland 2019).

7.2 FREEBOARD, BEACH LENGTHS, AND GEOTECHNICAL CRITICAL AND BUFFER ZONES

In the effort to arrive at successful reclamation of tailings facilities, one of the main considerations is the potential for ponded water to gather behind a tailings dam. It is often difficult to decide upon an acceptable area, volume, or location of water in the final landform. Clearly, there needs to be a generous stable outlet, suitable freeboard, and a required offset from the ponded water to the inside dam crest. If a wet cover is employed (typically to mitigate acid rock drainage), the water pond will be large and managed, and will have a freeboard and minimum beach lengths similar to those of the active pond.

Even for tailings facilities with very small ponds, the freeboard requirement for closure is typically greater than that of an actively managed pond, especially if inspections are infrequent or have been discontinued. For large, active, oil sands ring-dam tailings facilities in northern Canada, a typical operating freeboard is 3 m, with long sand beaches to control seepage and wave runup. For closure, when no human intervention is anticipated, 6 m of freeboard or more may be required in order to manage up to 1 m of long-term dam settlement, a 3 m high beaver dam at the outlet, a probable maximum precipitation event of 0.6 to 1.0 m, wave setup and runup, while allowing some residual freeboard.

Ponded water near the dam crest may trigger overtopping, slope instability, piping (internal erosion), or loss of crest due to wind-wave or current erosion. But how far should any ponded water be kept away?

A useful design requirement is to allow no water to pond in the geotechnical critical zone. This area is built-up and sloped upstream to avoid the potential for any ponded water. Upstream is a geotechnical buffer zone that allows water to pond only during extreme events, such as in a 1-in 500-year precipitation event, for a period of weeks or months. This area is also sloped toward the pond with enough gradient to ensure the static water level does not encroach. Designs are complicated by slow consolidation settlement of soft tailings and by the desire, in some jurisdictions, for wetlands and other aquatic habitat in tailings areas. Where long-term management is assured, the numerical values of these criteria will be less than in cases where no, or infrequent, monitoring or maintenance is planned. Poor communication of these criteria during operations means that many (or even most) tailings ponds are 'overfilled' with tailings by the time of closure.

7.3 OUTLET DESIGN AND MAINTENANCE

For the reclaimed tailings facility, the final outlet location and elevation (to the nearest 0.1 m) is one of the main design considerations. The design of the topography of the tailings plateau is governed by this requirement, and all the plateau water (and the upstream watershed) must flow to this point. The outlet location should be determined before the tailings facility is constructed. Many tailings facilities, especially ring dams, have no outlet during operations, with the result that the outlet location is often overlooked until closure.

Ideally, the outlet and spillway are sized to pass the design flood, which for closure is typically the probable maximum flood. Loss of a spillway can lead to a loss of the dam or a major erosion event for the landform. Ideally, the outlet and spillway are founded in competent *in situ* bedrock. Where this is impractical, the spillway should be located on compacted, stable dam fill with low permeability and low erodibility. Retrofitting sand dams that contain soft tailings near an outlet is especially expensive and challenging and highlights the need for up-front design. Often what would otherwise be an ideal location for an outlet requires earthworks on soft tailings (that usually accumulate at the low point in the beach next to the dyke). This is clearly a less than optimal outcome.

Spillways in non-bedrock locations are typically armoured with durable, angular riprap. Smaller spillways with low risk may be armoured with vegetation. Almost all spillways will require periodic monitoring and maintenance. Limiting the gradient of the spillway improves its robustness.

7.4 SOFT TAILINGS

Soft tailings are those that are difficult to traffic with normal mining equipment, due to extremely low shear strengths (Jakubick *et al.* 2003). The strengths of soft tailings are often compared to various foods such as porridge, yogurt, pie filling, and even chocolate milk (McKenna *et al.* 2017).

Soft tailings are typically generated by the partial segregation of fines from the coarse tailings stream; the sand drops out on the beach, and the fines are carried with the water to the distal toe of the deposit (the fines content increases down the beach). In some cases, it is the rock-flour-like gradation that causes the tailings to settle slowly and form loose liquefiable deposits with fluid-like strengths (peak undrained strengths < 2 kPa). Often 5 to 10 per cent of the deposit will exhibit peak undrained strengths that are very soft (< 12 kPa), requiring amphibious equipment for access.

Tailings that have naturally occurring clay minerals can cause the majority of the tailings plateau to be soft or even fluid. These are common in oil sands, some kimberlite operations, some coal mines (Williams 2017), and a few metal mines (Montana DEQ and BLM 2008). The cost to stabilise and reclaim soft tailings can be ten times the cost of normal dump or dam reclamation, approaching the combined cost of dyke construction and tailings operations.

Common techniques for stabilising soft tailings include: allowing time for consolidation, re-handling, and reprocessing; crust management techniques; use of wick drains to speed consolidation; reprocessing; or deep soil mixing with cement-like amendments. Five common techniques for capping soft tailings are: water capping, floating covers, raining-in of sand, beaching with sand, and soft ground techniques (Figure 5). McKenna and Cullen (2010) provide an overview of the design process for capping and reclaiming soft tailings for existing deposits.

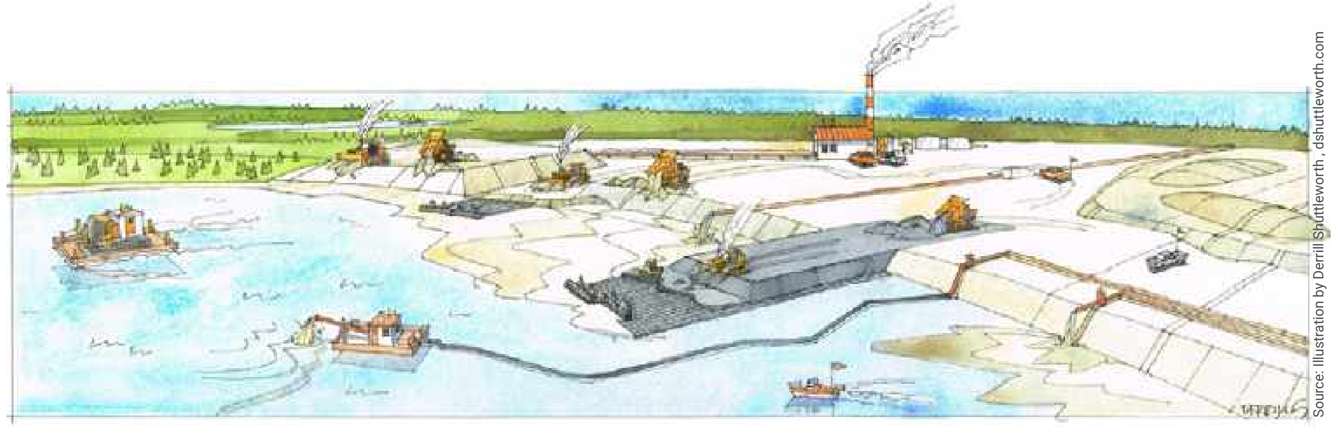

Source: Illustration by Derrill Shuttleworth , dshuttleworth.com

Figure 5. Common methods for capping soft tailings (McKenna et al 2018)

7.5 SAND DAM EROSION

Tailings sand, which is typically angular, cohesionless fine sand or coarse silt, has a high friction strength when compacted, but is vulnerable to erosion by wind and water. Many tailings dams are constructed from hydraulically placed and compacted tailings sand (sand dams) without regard to long-term erosional stability of the downstream face. Erosion is typically controlled by regrading the downstream face of dams to avoid concentrating or ponding of runoff water, and by using a soil cover and vegetation to limit erosion. In some cases, a rock erosion cover is employed. The slopes are maintained in the operational phase and are likely to require some maintenance during after-care.

Several methods can be employed to predict erosion of reclaimed slopes (Slingerland *et al.* 2019). Various empirical agricultural erosion models, such as RUSLE have been adapted to predict erosion rates on mining landforms but provide little design guidance. Complex numerical models such as SIBERIA and CEASAR are rapidly evolving models that are becoming more useful for the design of tailings dam slopes, especially with respect to cover systems and surface water drainage schemes. Such models, and hard-won experience, indicate the need for consideration of erosion control measures as part of the initial tailings landform (dam) design.

7.6 CONTROL OF TAILINGS SEEPAGE WATER

Tailings pore waters contain process-affected water, which is often elevated in salts and metals, especially where there are elevated sulphide contents which can lead to acid rock drainage. Control of dyke seepage is key to limiting the need for expensive, long-term, water collection and treatment. Several methods can be applied to limit these impacts. These include: the selection of tailings technologies that do not produce acid rock drainage (e.g., desulphurising tailings); avoiding (or sealing against) aquifers in the tailings foundation; lining the facility with a low-permeability liner (although the longevity of such liners may be less than the service life); installing seepage cut-off facilities downstream of the facility; and using low-net-infiltration covers on the tailings plateau and downstream facilities. Control of groundwater entering the facility may also be required. (See MEND 2012; INAP 2017; INAP 2018 for useful guidance). It is often practical to control tailings geochemistry by limiting the oxygen and water ingress into the tailings by constructing an engineered cover system after tailings deposition is complete.

7.7 DECOMMISSIONING

Decommissioning involves the removal of unneeded infrastructure (pipelines and pumphouses, powerlines, roads, instruments, derelict equipment, etc.) and trash from the tailings landform footprint. Ideally, housekeeping has been exemplary so that there is little trash and debris, and the rest of the equipment – once no longer needed – has already been removed.

7.8 DEREGULATING AND RECLAMATION SIGNOFF

Many mines are intent on eliminating the need to monitor and maintain reclaimed tailings facilities as dams. Under this scenario, there would be no requirement for daily inspections of the pond and beaches, no annual dam safety inspections, and no dam safety reports.[2]

To achieve this objective, the mine operator must convince corporate management and the regulator that the reclaimed tailings facility no longer meets the criteria of a dam, and that it no longer needs to be regulated as a dam (although it would still be regulated as a mine waste structure like a waste rock dump, until final completion / signoff). This requires the operator to demonstrate that the failure modes important to dam safety no longer apply or are extremely unlikely to occur. The main failure modes are overtopping, downstream slope failure, upstream slope failure, piping failure / internal erosion, failure of the outlet or spillway, settlement leading to ponding behind the dam, liquefaction, and excessive slope erosion.

Regulatory agencies that do not wish to inherit responsibility for dams may require the deregulation of tailings facilities prior to signoff. Prospects for signoff are improved if the mine, the regulator, and local communities have been involved with crafting and updating the DBM and have jointly monitored performance of the landform throughout its life.

7.9 AFTERCARE

Most jurisdictions, and most operators, recognise the need for managing long-term liability for the majority of reclaimed tailings facilities, as part of the reclaimed mining landscapes. This management will require ongoing operation, monitoring and maintenance. Large international mining companies each have up to several dozen closed sites and have institutionalised such activities. Common activities include maintaining access and access controls, periodic visual monitoring, monitoring of geotechnical and groundwater instrumentation, repairing gullies, collecting and treating contaminated water, maintaining the surface water drainage system, and annual reporting. Ideally, the facilities will have been designed and constructed to minimise or streamline these activities. Financial assurance for long-term maintenance can be costly, especially if active water treatment is required. The intensity of aftercare is best managed through the DBM and landform design process before landform construction begins.

8. CASE STUDY: SUNCOR POND 1 / WAPISIW LOOKOUT LANDFORM DESIGN

Suncor Energy's Pond 1 is a case history that demonstrates the application of landform design to the stabilisation and reclamation of a 2.2 square kilometer tailings plateau (see Anderson and Wells 2010; Russel *et al.* 2010). Figure 6 below shows the progression from end of operations, through design, capping, and revegetation.

Pond 1 and Tar Island Dyke represent the first tailings facility in the oil sands region. Construction of Tar Island Dyke's initial sand dam began in 1967 and reached its final height of 92 m in 1985. Afterward, settling pond operation and tailings infilling continued at a slower rate, with sand infilling of the pond to create an internal underwater buttress beginning in 2003.

Suncor, working with the regulator and local communities, decided in 2007 that this oil sands tailings pond surface would be stabilised and reclaimed by the end of 2010. The goals listed in the design basis were to create a trafficable landscape that could be rapidly reclaimed to boreal forest wildlife habitat, and to direct all surface water away from the dam crest and toward a future pit lake that would be developed from the existing tailings pond (visible in the upper left corner of each photo in Figure 6). A key aspect of the design involved using topography and 8.9 km of vegetated swales to manage seepage and surface water.

Capping soft tailings in this way was new in the oil sands and, following the observational method, contingency measures were put in place. A monitoring programme was used to track performance during construction. This was done by mostly visual, means, supplemented by standpipes and vibrating wire piezometers and frequent bathymetric soundings

Figure 6. Suncor Pond 1 tailings landform case history

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[2] The Oil Sands Tailings Dam Committee for the Oil Sands Research and Information Network (OSTDC 2014) provides a model for deregulating oil sands tailings dams. More general guidance is available from The Canadian Dam Association (CDA 2019).

An initial design basis and whiteboard-level design was crafted in early 2008. Sand capping and displacement of the soft tailings using cycloned tailings sand was implemented immediately. Site investigations, detailed design, and stabilisation and reclamation operations continued in parallel over the next three years. The displaced fluid tailings were reprocessed and deposited in a nearby tailings facility, the water was recycled to the extraction plant, the newly formed tailings sand beach was landform-graded into a ridge-and-swale topography, a small wetland was constructed, and the site was revegetated, first with native grasses, then with 600,000 native shrub and tree seedlings. Various wildlife habitat enhancements were added as part of this reclamation.

Construction and reclamation were completed successfully. Landscape performance monitoring continues as the vegetated cover matures. through a reclamation observation, monitoring and maintenance plan (see Crossley et al. 2011). This plan is referenced for closure and reclamation work in Suncor's Operations, Maintenance, and Surveillance Manual, which is employed for the overall facility and dam. As expected, the main challenge during construction was excavation of the deep channels in the saturated tailings sand cap. To deal with this, construction practices and designs were adjusted to accommodate changes in local conditions on a daily basis. A celebration with management, staff, contractors and consultants, regulators and politicians and the local First Nations communities capped the 50 years of landform construction. During the celebration, the landform's name was changed from Pond 1 to Wapisiw Lookout, with the local First Nation intending to use the area again for community gatherings as they had been doing traditionally for thousands of years.

9. CONCLUSION

Designing and constructing tailings landforms so that they can be safely and efficiently decommissioned and reclaimed requires as much attention as operational dam safety. To be successful, both activities need to commence well before mining begins, and be factored into planning and design of the mine and associated infrastructure. Planning and design for closing tailings facilities reduces costs, reduces risks, and allows mines to meet the agreed upon goals and objectives. Landform design, done well – and underpinned by good governance and collaboration between the mine, the regulator, and local communities – will result in a positive mining legacy for generations to come.

KEY MESSAGES

1. Current practice at most mining operations largely divorces the long-term closure and reclamation of tailings facilities from the operational dam construction, tailings deposition, and geotechnical dam safety considerations. This artificial division leads to higher life-cycle costs, reduced performance and increased risk.

2. Closing and reclaiming tailings facilities presents numerous challenges, especially if these challenges are overlooked during the initial design and construction of these mining landforms.

3. Landform design provides a framework for inclusion of all aspects of the life cycle of a tailings facility. This is a multidisciplinary process for building mining landforms, landscapes, and regions to meet agreed-upon land use goals and objectives. The process ideally begins with the initial designs of tailings landforms (or in the case of most existing sites, are adopted midstream) and continues long after operations have ceased.

4. Tailings landforms are important features in the mine's closure landscape that will last for millennia and will serve as a major component of a mine's enduring legacy. Mines, by working with their regulators and local communities, can help establish a positive mining legacy by returning lands for use by local communities in a timely manner.

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