Australian Government

TAILINGS MANAGEMENT

Leading Practice Sustainable Development Program for the Mining Industry

September 2016

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Support for the LPSDP was provided by the Australian aid program administered by the Department of Foreign Affairs and Trade due to the reports' value in providing practical guidance and case studies for use and application in developing countries.

Cover image: Maximising water re-use through the Coal Handling and Preparation Plant at Anglo American's Moranbah North mine in Queensland. Water is collected and stored in several dams for reuse.

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CASE STUDIES:

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The Leading Practice Sustainable Development Program is managed by a steering committee chaired by the Australian Government Department of Industry, Innovation and Science. The original 17 themes in the program were developed by working groups of government, industry, research, academic and community representatives. The leading practice handbooks could not have been completed without the cooperation and active participation of all working group members. We acknowledge the following people who participated in the revision of the leading practice *Tailings management* handbook and their employers who agreed to make the participants' time and expertise available to the program:

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FOREWORD

The *Leading Practice Sustainable Development Program for the Mining Industry* series of handbooks has been produced to share Australia's world-leading experience and expertise in mine management and planning. The handbooks provide practical guidance on environmental, economic and social aspects through all phases of mineral extraction, from exploration to mine construction, operation and closure.

Australia is a world leader in mining, and our national expertise has been used to ensure that these handbooks provide contemporary and useful guidance on leading practice.

Australia's Department of Industry, Innovation and Science has provided technical management and coordination for the handbooks in cooperation with private industry and state government partners. Australia's overseas aid program, managed by the Department of Foreign Affairs and Trade, has co-funded the updating of the handbooks in recognition of the central role of the mining sector in driving economic growth and reducing poverty.

Mining is a global industry, and Australian companies are active investors and explorers in nearly all mining provinces around the world. The Australian Government recognises that a better mining industry means more growth, jobs, investment and trade, and that these benefits should flow through to higher living standards for all.

A strong commitment to leading practice in sustainable development is critical for mining excellence. Applying leading practice enables companies to deliver enduring value, maintain their reputation for quality in a competitive investment climate, and ensure the strong support of host communities and governments. Understanding leading practice is also essential to manage risks and ensure that the mining industry delivers its full potential.

These handbooks are designed to provide mine operators, communities and regulators with essential information. They contain case studies to assist all sectors of the mining industry, within and beyond the requirements set by legislation.

We recommend these *leading practice* handbooks to you and hope that you will find them of practical use.

Senator the Hon Matt Canavan

Minister for Resources and Northern Australia

The Hon Julie Bishop MP

Minister for Foreign Affairs

1.0 INTRODUCTION

This handbook is a revised and updated version of *Tailings management*, published by the Australian Government Department of Industry, Tourism and Resources in 2007.

1.1 Context

This handbook addresses the theme of tailings management in the Leading Practice Sustainable Development Program. The aims of the program are to identify the key issues affecting sustainable development in the mining industry and to generate information and case studies that illustrate a more sustainable basis for mining operations.

Surface tailings storage facilities (TSFs) are among the most visible legacies of a mining operation, which after closure and rehabilitation are required to remain stable and produce no detrimental effects to the environment in perpetuity. Poorly designed or managed TSFs lead to increased costs of closure and ongoing impacts on the environment, and are a perpetual risk to public health and safety.

TSFs need to be designed, constructed and operated to the highest standards, taking into account the eventual need for closure and rehabilitation. Closure and rehabilitation plans are increasingly influencing the location of TSFs and the selection of tailings disposal methods, so as to minimise the costs of closure, the future risks to the environment and the legacy for future generations. As described in Section 3, the design of the TSF should be integrated with the life-of-mine (LoM) plan so that the most cost-effective and acceptable risk solution for closure can be developed.

Optimal strategies for tailings management are very much site specific. For these reasons, a range of tailings management approaches is presented. In particular, key technical aspects of siting, design, construction, operation and closure are highlighted and discussed.

The TSF location, disposal method, approach to water management and long-term closure objectives need to be clearly defined. Financial and technical analysis of options must accommodate social and community concerns about environmental, aesthetic and cultural issues. As well as initial siting and disposal design decisions, the proposed tailings management, storage and closure strategies must be communicated to regulatory authorities and the community.

A number of historical mine sites in Australia carry a negative legacy of environmental and social impacts from TSFs that were not designed and operated to achieve successful closure; for example, Mt Lyell, Mt Morgan and Rum Jungle. The impacts relate to inappropriate disposal practices, contaminated seepage and associated impacts to surface water and groundwater, and the erosion of tailings and outer batters. These historical legacy sites do not reflect current leading practice tailings management as outlined in this handbook, although their operators may well have complied with leading practice tailings management at the time.

1.2 What are tailings and tailings storage facilities?

Tailings are a combination of the fine-grained (typically silt-sized, in the range from 0.001 to 0.6 mm) solid materials remaining after the recoverable metals and minerals have been extracted from mined ore, together with the water used in the recovery process. The physical and chemical characteristics of the tailings vary with the nature of the ore and the processing method. Tailings management is a minerals processing waste management issue.

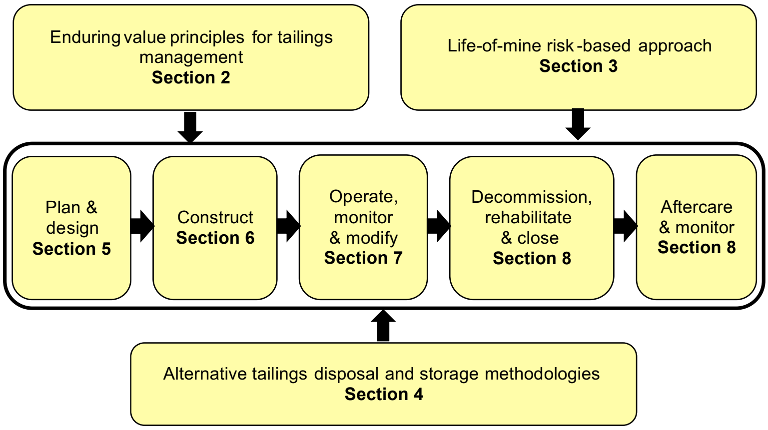
Tailings may be stored in a variety of ways, depending on their physical and chemical nature, the site topography, climatic conditions, regulations and environmental constraints, and the socioeconomic context in which the mine operations and processing plant are located. They are most commonly transported in slurry form to surface storage facilities, which can occupy up to half the area of disturbance at a mining operation, and are the main focus of the handbook. Tailings can also be stored in pits and integrated waste landforms (WA Department of Mines and Petroleum 2013). The basic requirement of a TSF is to provide safe, stable, non-polluting and economical storage of tailings, presenting negligible public health and safety risks, and acceptably low social and environmental impacts during its operation and after mine closure.

This handbook discusses a systematic, risk-based approach to tailings management. It provides examples of tailings containment, disposal and rehabilitation, and points to future trends in tailings management. It does not provide specific consideration of riverine, shallow submarine or deep submarine tailings placement methods. Such methods are not supported by the Australian regulatory environment or bathymetric conditions.

1.3 Audience

The primary audience for this handbook is onsite mine management, the pivotal level for implementing leading practice at mining operations. The handbook is also relevant to people with an interest in leading practice in the mining industry, including environmental officers, mining consultants, governments and regulators, non-government organisations, mine communities and students. All readers are encouraged to take up the challenge to continually improve the mining industry's performance in the area of tailings management by applying the principles outlined in this handbook.

1.4 Handbook structure



The handbook encompasses the key principles of achieving enduring value[1] through risk-based TSF design and management through all phases of the tailings life cycle, including planning and design, construction, operation (incorporating monitoring and any required modification), decommissioning (incorporating rehabilitation and closure or completion), and aftercare. It is important to cover all aspects of the LoM tailings storage, which may involve a number of TSFs, each developed in stages, as dictated by the ore reserves and changing commodity prices.

Section 2 highlights the importance of applying a broad sustainable development framework to tailings management and includes discussion on business drivers, lessons learned, community values and the regulatory context. Section 3 examines the need for an LoM risk-based approach to tailings management to achieve sustainable outcomes, covering risk and risk analysis, risk analysis methods, appropriate guidelines, managing change, and cost- and risk-effectiveness. Section 4 covers tailings dewatering, alternative disposal and storage methodologies, and tailings minimisation, recycling and re-use.

Sections 5 to 8 present TSF design, construction, operation, and closure. Section 5 deals with tailings storage planning and design aspects, including background and baseline conditions, planning and design risks, LoM plan and design criteria, and design aspects. Section 6 covers TSF construction aspects, including construction risks and construction records. Section 7 examines TSF operational aspects, including leading practice tailings management, operational risks, operational controls, and reporting. Section 8 covers TSF closure and rehabilitation, including closure risks, closure objectives, completion criteria, community engagement, closure tailings water balance, closure landforms and post-closure maintenance requirements.

Section 9 is a brief conclusion and future directions.

The fundamental principle underlying responsible and effective leading practice tailings management is to design and operate to achieve effective closure and completion.[2] This is an important objective because it addresses the longer term liability aspects of TSFs. If those aspects are not adequately considered early, they can add significant ongoing clean-up and maintenance costs to a project after revenue from mineral production has ceased.

1 As defined in *Enduring value: the Australian minerals industry framework for sustainable development* (MCA 2004).

2 See the *Mine closure* handbook in this series (DIIS 2016a).

2.0 SUSTAINABLE DEVELOPMENT AND TAILINGS

Key messages

- *Enduring value,* encompassing sustainable development principles and design for closure, underlies the mining industry's social licence to operate.
- The failure or poor performance of a TSF can have substantial negative impacts on surrounding communities and the environment, and a profound impact on the corporate bottom line and ability to develop future projects.
- The main reported causes of tailings incidents are a lack of control of the water balance, inadequate adherence to design, poor construction control, and a general lack of understanding of the key features that control safe operations.
- Early and ongoing consultations, information sharing and dialogue with stakeholders are required during the design, operation and closure phases.
- Leading practice tailings storage methods seek to eliminate the potentially catastrophic risks associated with the release of tailings slurry from TSFs by dewatering the tailings before deposition and by minimising the containment of water in the TSF.
- Compliance with industry-recognised guidelines such as those issued by the Australian National Council on Large Dams (ANCOLD 2012a) and with applicable government regulations establishes a minimum performance platform for sustainable tailings management.
- From the earliest planning stages, sustainable closure of TSFs requires the incorporation of closure landform design that will achieve agreed completion criteria and ensure a sustainable post-mining land use, ecological function, or both.
- Dry tailings transport and storage may be preferred over conventional slurried tailings transport and storage, if practical and sustainable.

To provide a framework for articulating and implementing the mining industry's commitment to sustainable development, the Minerals Council of Australia (MCA) developed *Enduring value: the Australian minerals industry framework for sustainable development* (MCA 2004). *Enduring value* supports the take-up of policies to ensure that current activities in the minerals sector do not compromise the ability of future generations to meet their own needs. It is specifically aimed at supporting companies to go beyond regulatory compliance and to enhance their social licence to operate. This handbook reflects the *Enduring value* framework's risk-based continual improvement approach.

Enduring value: principles for tailings management

- Implement an environmental management system focused on continual improvement to review, prevent, mitigate or ameliorate adverse environmental impacts.
- Provide for the safe storage and disposal of tailings by integrating tailings storage and facility closure planning into life-of-asset planning.
- Rehabilitate land disturbed or occupied by operations in accordance with appropriate post-mining land uses.
- Consult with interested and affected parties in the identification, assessment and management of all significant social, health, safety, environmental and economic impacts.
- Inform potentially affected parties of significant risks from mining, minerals and metals operations and of the measures that will be taken to manage the potential risks effectively.

Source: Based on the MCA's Enduring value framework (MCA 2004).

2.1 Business drivers

The business case for applying leading practice in tailings management is compelling. The failure or poor performance of a TSF can have a profound impact on the corporate bottom line. In extreme cases, TSF failures have severely eroded share value as the market anticipates the cost of clean-up and class actions, suspension of operations and possibly mine closure. This is in addition to the loss of company reputation and the loss of the social licence to operate. The cost of leading practice tailings management systems is more than offset by the reduced risk of a major incident.

Reported significant TSF incidents worldwide continue at a rate of about two per year, and a similar number of incidents may go unreported. Evidence from well-known TSF failures,[3] such as Aberfan in 1966, Merriespruit in 1994, Los Frailes in 1998, Kolontár in 2010 and Mount Polley in 2014, shows that a major TSF failure can not only cause deaths, but can result in (typically) a one-third loss of market capitalisation, clean-up costs and direct losses exceeding US$100 million (in 2014 dollars) and potential class action costs of up to twice that (Vick 2014), with an average 60% chance of permanent shutdown of the mine.

Conventional economic analysis can lead to minimising initial capital expenditure and deferring rehabilitation costs. Net present value analysis discounts the current cost of future expenditures on closure, rehabilitation and post-closure management. Therefore, if this short-term economic perspective is taken, without taking into account the longer term social and environmental costs, there is little motivation to invest more substantially at the development phase to avoid or reduce expenditures at the closure phase. There are a number of reasons, however, for applying leading practice at the earliest stage of development and for designing and operating the TSF to achieve optimal closure outcomes.

Designing and operating to achieve successful TSF closure can avoid significant earthworks expenditures to re-establish stable landforms and drainage systems. Progressive rehabilitation, where possible during

3 See WISE Uranium Project, *Chronology of major tailings dam failures,* March 2016, http://www.wise-uranium.org/mdaf.html.

operations, enables rehabilitation costs to be reduced by eliminating double-handling, allowing the work to be completed while there is an operational cash flow and management and resources are available. Progressive rehabilitation of a TSF enables various rehabilitation options to be trialled and evaluated against completion criteria before its closure, potentially reducing ongoing regulatory financial costs. By demonstrating the successful achievement of completion criteria, leading practice tailings management also minimises the time required for post-closure monitoring and maintenance. The following case study describes two business approaches to TSF planning.

Case study: Two business approaches

Minimum effort and minimum initial capital cost approach
The TSF may unintentionally be undersized and thus unable to handle an increased mine throughput, resulting in an underconsolidated, low-density, low-strength tailings deposit. A larger storage volume will ultimately be required for the tailings. The tailings will continue to consolidate for a long period, resulting in the possible need for groundwater recovery wells to capture contaminated seepage for a lengthy time after closure. Access to the tailings surface for rehabilitation purposes will be delayed until the tailings gain sufficient strength for trafficking, and ongoing settlement will delay the placement of cover systems. Major earthworks may be required to control surface run-off, and drainage systems may be affected by differential settlement as the tailings consolidate. As a result, the mining company will be regarded with suspicion by regulators and other stakeholders and its reputation and capacity to gain future mining approvals will be damaged.

Leading practice approach
Consideration of the final TSF landform influences the siting, size, geometry, seepage control requirements, and tailings deposition strategy. Operators will be well trained in managing the facility as intended by the design engineer. Any significant variations in or changes to ore throughput, reagent use, water balance or tailings parameters are assessed to identify their risk implications and to inform decisions. At closure, the TSF would be shaped, and armoured if necessary, for natural surface drainage and to achieve erosion rates similar to those of natural landforms in the area. Leading tailings management practices, including dewatering, tailings disposal in thin layers to facilitate consolidation and drying, good surface water management, and underdrainage and seepage management, where appropriate, result in adequately consolidated, stable tailings. This allows access to the surface for rehabilitation purposes with the minimum delay. Adequate design and operational seepage control remove the need for long-term groundwater collection. The TSF is a showcase for responsible tailings management, building credibility for the mine owners with stakeholders and a reputation for sustainable mining practices, assisting future proposed mining developments.

2.2 Causes of historical TSF failures

Leading practice tailings management in Australia has been developed drawing from the lessons learned from international TSF failures and incidents. The International Commission on Large Dams (ICOLD) *Bulletin 121* (2001) provided a comprehensive report of the main causes of TSF failures and identified incidents, which included:

- lack of control of the water balance
- inadequate adherence to design
- poor construction control
- a general lack of understanding of the features that control safe operations.

Tailings containment wall failures were (in order of prevalence) due to:

- slope instability
- earthquake loading
- overtopping
- inadequate foundations
- seepage.

Tailings incidents appeared to be more common where upstream construction was employed, compared with downstream construction (see Section 5.3), particularly in seismically active regions. Tailings containment walls constructed using the downstream method performed similarly to water-retaining embankments.

ICOLD *Bulletin 12*1 (2001) also concluded that successful planning and management of TSFs could benefit greatly from:

- the involvement of stakeholders
- thorough investigations and risk assessments
- comprehensive documentation
- tailings management integrated into mine planning, operations and closure.

The leading tailings management practices described in this handbook reflect the Australian minerals industry's progression towards the risk-based design and management of TSFs, which has so far been successful in minimising serious tailings incidents in this country.

2.3 Community values

A key challenge for mining companies is to earn the trust of the communities in which they operate and to gain the support and approval of stakeholders to carry out the business of mining. A 'social licence to operate' can only be earned and preserved if mining projects are planned, implemented and operated by incorporating meaningful consultation with stakeholders, in particular with the host communities. The decision-making process, including where possible the technical design process, should involve relevant interest groups, from the initial stages of project conceptualisation right through the mine's life and beyond.

Stakeholder consultation, information sharing and dialogue should occur throughout the TSF design, operation and closure phases, so viewpoints, concerns and expectations can be considered for all aspects of planning and execution. Regular, meaningful engagement between the company and affected communities is particularly important for developing trust and preventing conflict.

The 'precautionary principle' should be drawn on when considering the impacts of mine operations, particularly TSFs. The principle states that where there is a clearly identified threat of serious or irreversible harm to people or the environment, the lack of full scientific certainty should not be used as a reason for postponing measures to prevent harm to people or environmental degradation. A proactive approach to risk mitigation through the development and implementation of appropriate engineering controls must be taken where there is significant uncertainty in relation to the likelihood or consequence of significant environmental impacts. [5]

2.4 Regulatory context

The primary responsibility for tailings and TSF regulation in Australia rests with state and territory governments. While the regulatory requirements vary between jurisdictions, common principles apply, including the following:

- The responsibility for tailings deposition and management regulation (including rehabilitation and closure) rests with the mining department or environmental protection agency.
- The responsibility for pollution control and TSF water discharge regulation rests with the environmental protection agency.
- The focus of the regulation is on ensuring that tailings management methods and TSFs are safe, stable and non-polluting during operations, and that TSFs remain safe, stable and non-polluting after closure (this requires continuous consideration of closure design, construction and aftercare throughout the TSF life cycle).

Regulators nowadays expect all TSF design submissions to demonstrate beyond reasonable doubt that sustainable outcomes will be achieved during operations and after closure by the application of leading practice risk-based design that:

- fully assesses the risks associated with tailings storage at a particular site
- compares the suitability of all available tailings storage methods, in particular those that involve tailings dewatering and/or eliminate the requirement for the damming of surplus water within the TSF
- demonstrates that the tailings storage method selected will manage all risks to within acceptable levels and as low as reasonably practicable (ICOLD 2013).

In some states, the regulation of TSF design, construction and ongoing management may be covered by specific legislation. Some jurisdictions issue their own tailings management guidelines.[6] For example, in New South Wales, the Dams Safety Committee oversees tailings containment regulation under the *Dams Safety Act 1978*. In Western Australia, the Department of Mines and Petroleum has developed a code of practice (DMP 2013) for TSFs with the aims of:

- meeting the approval requirements under mining and mining-related legislation
- demonstrating that a TSF is safe, stable, erosion-resistant and non-polluting
- ensuring the involvement of competent practitioners
- meeting the broader occupational health and safety requirements for operating TSFs.

Where tailings management actions are likely to have a significant impact on a matter of national environmental significance, they are subject to a rigorous assessment and approval process under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Matters covered by the EPBC Act include natural national heritage, threatened species and wetlands of international importance.

Compliance with government regulations establishes a minimum performance platform for the mining industry in relation to tailings management.

5 Principles and leading practices for stakeholder engagement are addressed in the *Community engagement and development* (DIIS 2016b) and *Working with Indigenous communities* (DIIS 2016c) leading practice handbooks.

6 See the references sections at the end of this handbook.

3.0 LIFE-OF-MINE RISK-BASED APPROACH

Key messages

- Tailings storage facilities must be designed, operated, closed and rehabilitated to ensure negligible operator and public health and safety risks, and acceptably low community and environmental impacts.
- A risk-based design approach provides a framework for managing the uncertainty and change associated with TSFs.
- Stakeholders, including the community and regulators, expect TSF design engineers to identify all risks associated with tailings storage at a particular site and to demonstrate that the selected tailings storage method will manage them to within acceptable levels and as low as reasonably practicable.
- Alternative tailings management strategies, in particular those that eliminate the need for low-permeability dams and minimise excess stored water through dewatering of the tailings or good surface water management, need to be thoroughly evaluated for cost and risk-effectiveness over the full TSF life cycle, including after closure.
- Risk-based operational tailings management requires continuous performance observation and monitoring and rapid response to any leading indicators of failure or potential impacts, thereby ensuring that all risks are effectively managed even under changing circumstances.

The principles of leading practice tailings management are underpinned by a risk-based approach to the planning, design, construction, operation, closure and rehabilitation of TSFs. In this approach, plans need to be tailored to manage the TSF effectively over its full life cycle, with sufficient detail to manage the potential risks within acceptable limits. TSFs with a high consequence category require more rigour at the design phase, greater quality control during construction, and closer attention to risk management, emergency action planning systems and documentation during the operational and closure phases.

3.1 Risk and risk analysis

There are many definitions of risk. *Best practice environmental management in mining* (Environment Australia 1999) defines hazard as a potential cause of harm; describes risk as having two dimensions—likelihood and consequence; and defines risk as the likelihood of harm.

Risk analysis allows quantification of the options and of the likelihood, consequences and costs of failure. A 'risk ranking' is obtained by the product of the likelihood and the consequence.

AS/NZS ISO 31000:2009 (which supersedes AS/NZS 4360:2004) recommends the following general risk assessment process:

- Establish the context—geographically, socially and environmentally—and decide on the design criteria.
- Identify the hazards—what can happen, where and when, and how and why?
- Analyse the risks—identify existing controls and determine the likelihoods and consequences, and hence the level of risk.
- Evaluate the risks—compare them against the design criteria, carry out sensitivity analyses to highlight both the key and unimportant risks, set priorities, and decide whether the risks need to be addressed.
- Address the selected risks—identify and assess options, prepare and implement treatment plans, and analyse and evaluate the residual risk.

Overarching this process is the need to communicate and consult with stakeholders, and to monitor and review the TSF. ISO 31000 *Risk management* provides the principles, framework and process for managing risk. It can be used by any organisation regardless of its size, activity or sector. Using ISO 31000 can help organisations increase the likelihood of achieving objectives, improve the identification of opportunities and threats, and effectively allocate and use resources for risk treatment. ISO 31000 cannot be used for certification purposes, but does provide guidance for internal or external audit programs. Organisations using it can compare their risk management practices with an internationally recognised benchmark, providing sound principles for effective management and corporate governance.

3.2 Risk analysis methods

Various risk analysis methods are used by different design consultants and mining companies, depending on the scale and complexity of the tailings risks being evaluated or assessed. The main types of risk analysis methods are:

- Qualitative risk evaluations—including hazard identification, likelihood, consequence, risk ranking and remedial action. Qualitative risk evaluations are commonly used for less complex design and operational issues.
- Semi-quantitative and quantitative methods—which lend themselves to well-defined and quantifiable hazards. These methods (refer to ANCOLD 2012a) are used for higher failure consequence dams in more complex settings, and sometimes require large amounts of data to be collected to support complicated probabilistic interrelationships that may lead to the catastrophic failure of a dam.

The semi-quantitative and quantitative methods rely on assigning numerical values to likelihoods and consequences. The most commonly used quantitative method is the probabilistically based fault/event tree method (summarised, for example, by Williams 1997, Bowden et al. 2001 and Williams 2001, which also provides case studies), which is set up as a series of connected faults and events, typically in a spreadsheet. In applying the method, the key event or outcome must first be identified, such as failure of the TSF with the potential for loss of life and/or property damage. This forms the top of the event tree. The causes or failure modes that might lead to this key event are then identified. They form the tops of the branches of the fault tree. Each of these causes has a variety of contributing sub-causes, some of which contribute to more than one cause.

3.3 Risk-based guidelines

Leading practice tailings management requires that a TSF be designed, constructed, operated, closed and rehabilitated to manage all risks within acceptable levels and as low as reasonably practicable to ensure performance that meets or exceeds regulatory requirements and the criteria agreed to through consultation with key stakeholders.

Guidelines on tailings dams: planning, design, construction, operation and closure (ANCOLD 2012a) provides a sound foundation for the risk-based design of tailings management systems. With collaborative inputs from expert TSF design consultants, mining company representatives and regulators, the ANCOLD guidelines provide a framework of management principles, management policies and checklists for implementing the framework throughout the life cycle of a TSF.

3.4 Managing change

Risk-based tailings management systems must ensure that changing circumstances can be effectively managed. The changes could involve routine and anticipated TSF raises, unforeseen expansions or the bringing on line of completely new facilities, new disposal methodologies or ore types. Managing such change should be a core consideration in the planning, design, construction, closure and rehabilitation of TSFs. Independent expert geotechnical and dam peer review, including by a team of experts for more complex dams, is a critical component in effective risk management.

Changing circumstances that may lead to increased environmental impact and risk of failure, and possible responses, are as follows:

- Increases in processing plant throughput and/or the mine life—requiring raising and/or expansion of existing TSFs and/or the construction of new facilities. Increased tailings generation rates will require the permitting and construction of storage facilities to be brought forward to provide adequate tailings and stormwater capacity in time to prevent issues arising.
- Changes in the nature or source of the ore and/or a change in cut-off grade—possibly involving a finer grind, which would be likely to increase the tailings storage requirement and result in a wetter, softer tailings deposit. Loss of a fines processing circuit will have a similar effect. A change to closure cover designs and water management measures may be required where more geochemically hostile ore is introduced into the TSF.
- Changes to the process—potentially changing the tailings generation rate, their solids concentration and/or their physical and chemical nature.
- The depletion of water resources—possibly requiring increased dewatering of the tailings before disposal to recover more water for re-use before it is lost to evaporation and seepage.
- Higher or lower than normal rainfall—requiring the water management system to be changed significantly. Lower than normal rainfall could require the sourcing of additional supplies of process water. Higher than normal rainfall could require wall raising to create additional water storage capacity, constructing separate water storage facilities, or mine water treatment to allow discharge to the environment.
- Changing regulatory requirements and community expectations—subject to change over time.
- Early or sudden closure of the mine and TSF—possibly resulting in a thin deposit of tailings over a large footprint, requiring costly management and rehabilitation. The possibility and implications of premature closure must be considered throughout the operational phase.

3.5 Cost- and risk-effectiveness

Alternative tailings management, storage and closure strategies can usually be accurately costed for inclusion into a financial analysis (see, for example, Bentel 2009) that allows a weighed comparison of the cost- and risk-effectiveness of the alternatives. TSF designs and strategies included in such financial and risk comparisons include appropriate consideration of stakeholders' opinions and concerns.

The attractiveness of reducing the costs of tailings management in the short term must be carefully weighed against the possibility of increasing environmental and social costs and risks at closure and beyond. The decision-making process requires a robust and flexible evaluation of the costs and risks of tailings storage, operation and TSF closure throughout the TSF life cycle.

Public health and safety risks and the broad social and environmental impacts of the TSF need to be considered, including situations where contaminants could be released to the environment over the long term. There must also be a high degree of confidence that the proposed design will enable the successful closure of the facility. If this is not done thoroughly and objectively, and if steps are not taken throughout the mine life cycle to reduce potential post-closure liabilities, the costs of mitigating those liabilities can exceed the profits and other benefits accrued over the operational life of the mine (Bentel 2009).

3.6 Closure liabilities and completion criteria

The closure of surface TSFs presents significant complexities, including post-closure design criteria that are at least an order of magnitude greater than operational design criteria (ANCOLD 2012a), making completion criteria much more difficult to meet. Hence, it is important to consider closure design risks and design criteria from the earliest stages of the project so that successful closure can be facilitated through leading practice design, operation and maintenance.

4.0 TAILINGS DISPOSAL AND STORAGE

Key messages

- Tailings disposal and storage methods are a function of the extent of pre-disposal dewatering applied to the tailings (whether in the processing plant or at the TSF just before disposal), and include slurry disposal, thickened and paste disposal, dry stacking and co-disposal with coarse wastes.
- The common disposal and storage of slurried tailings in a surface TSF can result in greater infiltration to the underlying foundation than occurs naturally due to rainfall alone.
- Decant systems for the collection of supernatant tailings water from conventional slurry and thickened tailings disposal, as well as rainfall run-off from the TSF catchment, include central, perimeter, and floating decants.
- Tailings may be stored in surface facilities, stored in-pit or used as backfill in underground mining voids.
- The topography of a surface TSF location dictates whether a valley storage or ring dyke storage is required.
- Tailings transport by pumping in a pipeline remains the most commonly used method, generally involving optimising the thickening of the tailings so that they are still pumpable using centrifugal pumps and low-pressure pipelines, while still being sufficiently flowable on discharge to ensure effective distribution of tailings across the TSF without excessive movement of the pipe discharge.
- Surface TSF containment walls or dams may be constructed, usually in a series of stages, by the downstream, centreline or upstream methods, using borrow materials, mine wastes or harvested tailings.

4.1 Tailings dewatering and thickening

An increasing number of mining operations employ dewatering to produce thickened and paste tailings (Figure 1) and this is likely to become more widespread in the future. The past limitations to successful thickened tailings transport and disposal were either cost or the lack of suitable flocculant and thickener technology. Today, thickener technology has developed well beyond the conventional thickener to produce high underflow densities, and thickening costs have reduced considerably. These thickeners range from deep bed thickeners (typically used for red muds) through to paste or deep tank thickeners developed for the production of cemented paste tailings backfill for underground application (Potvin et al. 2005).

Figure 1: Paste tailings: (left) cemented underground backfill; (right) surface disposal

The solids concentrations achieved on dewatering vary for different tailings, since particle size distributions, clay mineral content, particle shape, mineralogy, electrostatic forces and flocculant dosing vary considerably. Table 1 gives some typical slurry and paste solids concentrations (ratio of mass of solids to mass of solids plus water) for a range of tailings types.

Table 1: Typical slurry and paste solids concentrations

TAILINGS TYPE	SLURRY % SOLIDS	PASTE % SOLIDS
Bauxite red mud	25	45
Base metal tailings	40	75
Coal tailings	25-30	-
Gold tailings	45	72
Mineral sands slimes	15	24
Nickel tailings	35	45 to 55

Source: Williams & Williams (2004).

Due to the highly variable solids concentrations of slurried, thickened and paste tailings from different ore sources, the consistency of tailings of different solids concentration is better measured in terms of their physical behaviour. The slump cone test is sometimes used to illustrate the consistency of thickened or paste tailings at increasing solids concentrations (Figure 2). Physical characteristics of tailings can be described quantitatively by their yield stress, as described in Jewell & Fourie (2006).

Figure 2: Consistency of tailings: (left) high density slurry; (centre) high slump paste; (right) low slump paste

On discharge, tailings slurry segregates, with coarser and higher specific gravity particles being deposited on the upper beach, and produces substantial supernatant water that carries finer and lower specific gravity particles to the decant pond. The segregation and settling of particles results in significant curvature of the beach profile (becoming flatter further down the beach). Thickened tailings show some segregation, settling and bleed on placement, accompanied by some curvature of the beach profile. Paste tailings have a non-segregating, non-settling consistency that releases only small quantities of water after placement.

The advantages of using thickened or paste tailings include:

- improved water and process chemical recovery at the processing plant
- potentially reduced tailings storage volume, although the volume of slurried tailings can be reduced dramatically by desiccation
- reduced seepage
- a more stable landform.

These are key considerations for sustainable development and reflect community expectations. Jewell & Fourie (2006) provided a comprehensive and definitive reference on these technologies.

Tailings can be brought to a ‘solid-like’ state by centrifuging or filtration (Figure 3), producing a consistency that is potentially transportable by truck or conveyor. For given tailings, either of these techniques can produce a cake of similar moisture content or percentage of solids, but the greater pressures applied in the filtration process will create a ‘structure’ that makes the filtration cake more transportable and manageable (Figure 3).

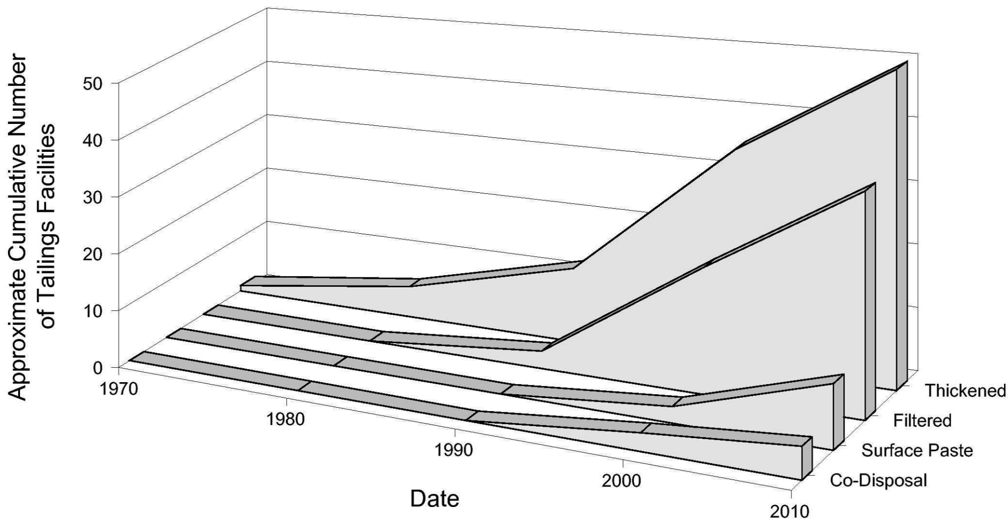
Figure 3: Consistency of tailings: (left) centrifuged; (right) filtered

4.2 Tailings disposal methods

Tailings disposal methods include slurry disposal, thickened and paste disposal, dry stacking and co-disposal with coarse wastes, including coalmine coarse reject, metalliferous smelter scats or slag, and waste rock or spoil.

The selection of the appropriate and optimal tailings disposal method for a particular project is a function of the extent of pre-disposal dewatering applied to the tailings, which in turn is a function of the rheology and transportability of the tailings, the chemical and biological reactivity of the tailings, the return water requirements, the process water quality and its suitability for recycling to the processing plant, and the availability of raw water for processing. The selection is also influenced by the site climatic conditions, the topography, the distance to and elevation of the selected TSF site relative to the plant, and the conditions imposed by the regulator. There is an increasing worldwide trend towards pre-disposal thickening and filtering of tailings, with some increase in surface paste tailings disposal and the co-disposal of tailings and coarse-grained waste, as demonstrated by Figure 4.

Figure 4: Trends in tailings thickening, filtering and disposal



Source: after Davies (2011).

4.2.1 Slurry disposal

Tailings are commonly pumped as a slurry in a pipeline and discharged sub-aerially into a surface TSF (Figure 5). The consistency of the slurry (% solids by mass) depends on the type of tailings, the particle size distribution and specific gravity, and the extent of thickening at the processing plant. Tailings slurries are typically pumped at 25% solids (for low specific gravity coal tailings) to over 50% (for hard rock metalliferous tailings), as indicated in Table 1. At low solids concentrations, the annual tailings water volume can be many times annual rainfall in dry climates such as Australia's. Hence, slurried tailings disposal into a surface TSF has the potential, if not well controlled and managed, to produce incrementally greater water losses through evaporation and seepage. Seepage to the underlying foundation and through the TSF wall can potentially be much greater than occurs naturally due to rainfall alone, particularly in a dry climate.

Slurry disposal may be from a single discharge or, preferably, from multiple spigots. Multiple spigotting has advantages over single point discharge, including:

- production of a more even tailings beach
- achievement of greater control over the direction of the tailings beach and hence over the direction of supernatant water and surface run-off towards the decant
- deposition of thin and controllable lifts of tailings, and the cycling of tailings deposition to facilitate consolidation and drying throughout the depth of the stored tailings
- facilitation of upstream raising, along with the potential to use desiccated, coarse-grained tailings deposited near the wall for wall raises.

Decant systems for the collection of supernatant water from conventional slurry and thickened tailings disposal, as well as rainfall run-off from the TSF catchment, include central, perimeter and floating decants.

4.2.2 Thickened and paste disposal

Thickening of tailings in the processing plant before disposal enables process water to be recycled directly back to the plant, reducing water losses and reducing plant raw water demand. A range of thickening technologies is available; the most commonly applied are outlined in Table 2.

Table 2: Commonly applied thickening technologies

TAILINGS CONSISTENCY	THICKENING EQUIPMENT REQUIREMENTS
Slurry	Conventional or high-rate thickener
Thickened	High-compression thickener
High-slump paste	Deep bed thickener
Low-slump paste or filter cake	Filters

Source: Williams & Williams (2004).

Thickening tailings reduces the quantity of water delivered to the TSF. This in turn reduces the risks of overtopping and reduces seepage and evaporation losses. Further, it reduces the risk of failure of the TSF embankment by lowering the pond level and reducing the phreatic surface within the embankment. Thicker tailings discharge also enables better control of the decant pond and return water system. Where tailings are discharged into surface storage facilities, depositional beach angles steepen as the tailings are discharged at a thicker consistency, and the reducing moisture content, in turn, reduces the containment risks. Typical relationships between placement consistency and average beach angle for pumped tailings are shown in Table 3.

Table 3: Typical relationships between placement consistency and average beach angle

PLACEMENT CONSISTENCY	BEACH ANGLE (%)
Slurry	Up to 1
Thickened	1 to 3
High-slump paste	3 to 6
Low-slump paste[a]	6 to 10

[a]Note that even high-slump tailings paste is rarely produced for surface disposal, and there is known discharge of low-slump paste to a surface TSF.

Source: Williams & Williams (2004).

Figure 5 shows a conventional tailings slurry disposal.

Figure 5: Conventional tailings slurry disposal

4.2.3 Dry stacking

True dry stacking requires that the flocculated tailings be filtered, usually under pressure or possibly under vacuum (Davies 2011), to produce a product that is transportable and stackable using 'dry' material transportation and disposal techniques. The term 'dry stacking' is sometimes misused when referring to thickened and/or paste disposal techniques that do not move the tailings in a dry state.

Drums, horizontally or vertically stacked plates and horizontal belts are the most common pressure filtration methods. Both the gradation of the tailings and their mineralogy are important determinants in filtration design. In particular, high proportions of clay minerals tend to limit effective filtration, as do some residual minerals, such as bitumen in oil sands tailings. It is important to anticipate mineralogical and grind changes that could occur over the life of the mine as the mining operation moves through a variable ore body.

Filtered tailings are transportable by truck or conveyor and may then be placed, spread and compacted to form an unsaturated, dense and stable tailings 'dry stack', in some cases, such as geochemically benign tailings, requiring no dam for retention and no associated tailings pond (Figure 6).

Figure 6: Dry-stacked, filtered tailings transported by conveyor and compacted by dozer

Filtration and stacking of tailings are typically considered in very arid regions where water conservation is crucial, most notably in the desert regions of Chile and Peru but also in Western Australia, the south-west United States, arid parts of South America, parts of Africa, and the Arctic regions of Canada and Russia, where the handling of tailings is very difficult in the frozen winter. Filtration enhances the recovery of process reagents, and dry stacking provides enhanced seismic stability over wet tailings deposition methods. Dry stacking may also overcome difficult site topography and foundation conditions, or very constrained sites, which make conventional tailings dams very difficult to construct. Dry stacking also facilitates rehabilitation, including progressive rehabilitation, thereby reducing closure risks and liabilities. The two key drivers of filtration and dry stacking of tailings have to date been the recovery of scarce process water and difficult topography and foundation conditions.

4.2.4 Co-disposal of coarse wastes and tailings

The co-disposal of the coarse wastes and tailings from a mine provides a means of reducing the volume or footprint required to store the separate waste streams by means of the tailings filling the void space between the coarse wastes. A more stable deposit is also formed, with obvious economic, social and environmental benefits. A key challenge with co-disposal is finding a safe, practical and economic method of mixing the two waste streams. Logistically, it can be difficult to mix the two operations of large haul trucks dumping waste rock and slurry pipeline discharge, particularly as the dump face is moving continuously. One successful co-disposal operation involved the filling of a completed open pit by the end-dumping of benign waste rock from the crest at one end and the deposition of thickened benign tailings from the other (Williams 2002; Figure 7).

Figure 7: Co-disposed waste rock and thickened tailings in a completed open pit

In coalmining, it is possible to combine the coal washery coarse and fine rejects and pump and co-dispose this stream (Figure 8). The co-disposal mixture provides a coarse-grained upper beach, which is trafficable and forms a stable outer perimeter containment wall for the balance of the segregating fines. While pumped co-disposal requires a large volume of transport water, the system does not lose any more water than slurry tailings disposal alone.

Figure 8: Co-disposed coal washery wastes

4.2.5 Integrated disposal of coarse waste and tailings

An integrated mixture of waste rock and paste tailings (Figure 9) can potentially be used as a sealing material in covers over potentially contaminating mine wastes. For this application, the tailings and waste rock selected must be geochemically benign. The waste rock is typically limited to 100 mm top size by crushing and screening. This size restriction facilitates mixing and ensures a good mixture consistency. The waste rock can be combined with tailings slurry, with dried tailings (and mixed mechanically) or with paste tailings.

Integrated coarse and fine wastes achieve a high density and low hydraulic conductivity, making the mix well suited for use as a sealing material. It has particular application at mine sites where supplies of natural clays for sealing purposes are limited or absent, and achieves a hydraulic conductivity at least comparable with, and often lower than, that achieved by compacted natural clay.

Figure 9: Integrated coarse and fine wastes in the laboratory

Waste rock is often used as a TSF embankment construction material. The integrated disposal of coarse waste and tailings, in which the waste rock dump and TSF are combined in a single landform, is an extension of this. The waste rock is used to form a wide encapsulation into which the tailings are disposed. The tailings may be dewatered to limit the loss of water to the coarse-grained waste rock encapsulation, and the waste rock may be pushed progressively into the tailings to facilitate capping. It may be advantageous to submerge potentially acid-forming waste rock beneath slurried tailings to limit oxidation.

4.3 Tailings transport

Tailings transport by pumping in a pipeline remains the most commonly used method. The thicker the tailings produced in the processing plant, the more difficult and expensive they are to transport by pumping, and discharge management may also increase because thickened tailings beach at a steeper angle, requiring more frequent movement of the pipe discharge.

Tailings transport by pumping generally involves optimising the thickening of the tailings so that they are pumpable using centrifugal pumps and low-pressure pipelines, while still being sufficiently flowable on discharge to ensure effective and ready distribution of tailings across the TSF. This is because the capital cost of positive displacement pumps for transporting thickened or paste tailings can be an order of magnitude higher than for the equivalent capacity centrifugal pump system for less thickened tailings.

Figure 10 illustrates the full range of options for pumpable tailings thickening and non-pumpable tailings filtration. Depending on the pumping distance and head, thickened tailings can usually be pumped using centrifugal pumps. Recent developments make it possible to pump tailings with a yield stress in excess of 100 Pa using centrifugal pumps, and further improvements are likely. However, paste tailings are likely to require the increased power of positive displacement pumps and high-pressure piping for delivery to a surface TSF. Gravity flow may be used to deliver cemented paste tailings for underground backfill, and could be used to deliver paste tailings to surface storages, by locating the thickeners at elevated locations.

Figure 10: Tailings continuum

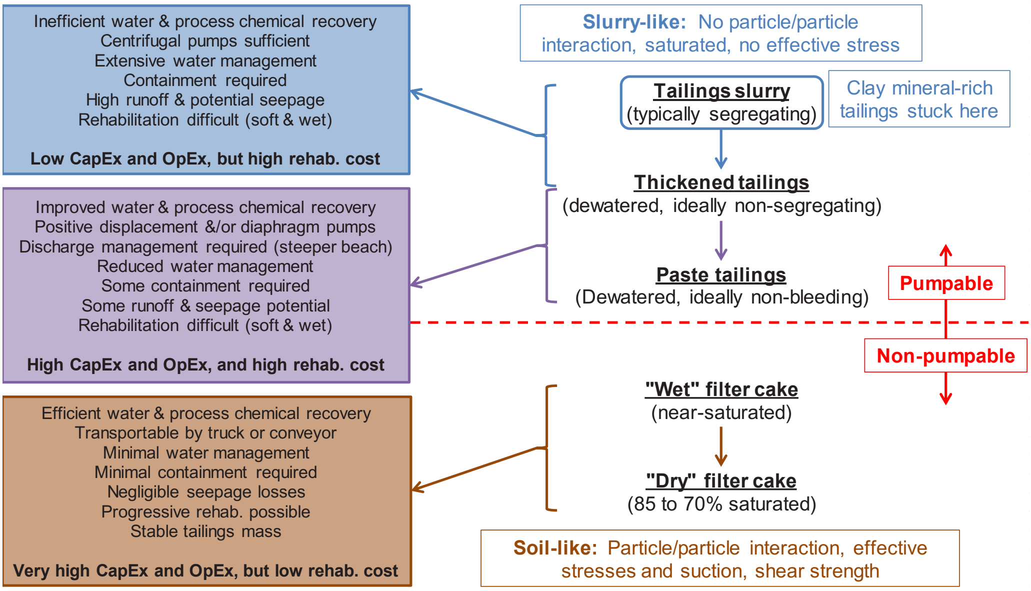


Figure 10
Source: adapted from Davies and Rice (2004).

While the capital cost of positive displacement pumps can be much higher than that of an equivalent capacity centrifugal pump system, the paste system may provide life-of-system cost benefits, including a reduced make-up water requirement, ease of rehabilitation and reduced post-closure seepage.

Where it is cost-effective to dewater tailings to a wet or dry filter cake, the tailings may be transported by truck or conveyor to the TSF, where they can be 'stacked' or combined with coarse-grained waste disposal.

4.4 Types of surface tailings storage facilities

Surface TSFs include:

- valley storage involving tailings discharge downstream towards a water-retaining containment wall where the decant to collect the supernatant water is located, or upstream away from the containment wall with a decant facility located at the upstream end (significant diversion structures are generally required to divert upstream fresh water around the storage)
- disposal from a perimeter or 'ring' containment wall on relatively flat ground, usually with a centrally located decant facility
- disposal to a series of cells or 'paddocks', with tailings deposition cycled between the cells to facilitate consolidation and drying

- central thickened discharge (CTD) on relatively flat ground, with supernatant water collected behind a water-retaining perimeter containment wall or in a watertight perimeter channel or dedicated storage facility (Williams 2000; see first case study below)
- disposal to cells in combination with mechanically enhanced evaporative drying, such as 'farming' of red muds in the alumina industry (see second case study below and Section 7.3.4).

Case study: Central thickened discharge at Sunrise Dam, Western Australia

Sunrise Dam Gold Mine, owned and operated by Anglo Gold Ashanti and located 55 km south of Laverton in Western Australia, commenced operation in 1997. A paddock-style TSF for conventional medium-density tailings slurry was commissioned for the design throughput of 1.5 million tonnes per annum (Mtpa). One downstream raise was carried out in 1998 before decommissioning of the TSF in 1999. Design throughput was scheduled to increase from 2 Mtpa in 2000 to 3 Mtpa in 2003, and a decision was made to thicken the tailings to a higher solids concentration and change to the central thickened discharge (CTD) method of tailings disposal in a new location.

The CTD TSF site is located in a regional drainage line with a catchment area of 60 km^2. Groundwater is unconfined and typically within 5 m of the surface. Run-off diversion channels were required to manage the substantial flows from cyclonic rainfall. The site slopes gently at a gradient of about 0.2%. The design area of the CTD TSF was 300 ha in 1999 and by 2005 it had increased to 330 ha.

The CTD TSF comprises a tailings storage area and a storm storage pond. Other features include an earth-fill ramp from the perimeter to the centre of the TSF, where multiple tailings discharge points are located, and a small lined pond located within the storm storage pond for collecting tailings bleed water. Water is pumped from the lined pond back to the processing plant.

The shape of the CTD TSF is a low-profile cone. In 2005, the height at the crest was about 15 m. For an annual tailings dry mass of 3.6 Mtpa, the original design was to provide storage capacity until 2009, with the expansion of the CTD TSF providing storage capacity to the end of mine life.

The processing plant uses gravity separation and carbon-in-leach technology to extract gold from the ore. The tailings are thickened to about 64% solids using two high-rate thickeners (24 m in diameter), and two pairs of centrifugal pumps transport the tailings a distance of 3 km. A seepage collection drain had been constructed around the southern half of the TSF for the purposes of intercepting and lowering the watertable adjacent to the facility.

The parameters of the tailings are:

Specific gravity:	2.85	Liquid limit:	23%
Shrinkage limit density:	1.47 t/m^3	Segregation threshold:	39% solids
Initial settled density:	1.2 t/m^3	D_{80}:	0.075 mm
Soil classification:	Sandy silt (ML)	Salinity bleed water:	>200,000 µS/cm

Plan view of CTD TSF (left); view along ramp from CTD TSF perimeter (right)

The tailings are deposited as very thin layers and evaporative drying is significant, although it is somewhat inhibited due to the hypersaline nature of the tailings water. As a result, the phreatic surface remains at or slightly above the original ground surface. Seepage is most prevalent around the perimeter of the CTD cone where tailings bleed water and storm run-off can accumulate, which has necessitated additional internal drainage measures.

The tailings beach slope is close to the original design value of 1.5%. However, operational variations have led to a concave beach development; the upper third being 2%, the middle third 1.5%, and the lower third 1%.

In 2005, multiple discharge points were placed around the crest of the CTD cone. The purpose of this was to reduce the discharge flow rate and thereby increase the beach slope and improve the efficiency of storage.

No CTD facilities in Australia have yet been closed and rehabilitated. Central thickened discharge results in a relatively low-elevation tailings deposit covering a very large footprint. If a cover is required for rehabilitation purposes, financial closure provisioning for a very large volume of suitable cover material would be required.

Case Study: Thickened residue disposal and farming at Alcoa alumina refineries in Western Australia

Alcoa has three refineries in Western Australia, at Kwinana, Pinjarra and Wagerup, with a combined capacity of approximately 9 Mtpa of alumina. During the refining process, a caustic soda solution is added to bauxite to dissolve alumina, allowing separation of the alumina (in solution) from the un-reactive residue. Although the residue is washed to recover and recycle caustic, it retains a residual level of caustic, and has an alkaline pH of approximately 13.5.

Since the mid-1970s, Alcoa has extensively and collaboratively developed improved residue disposal and storage practices. The company's commitment has seen a transition from traditional wet disposal to the farming of thickened residue, a method developed and implemented at Alcoa's three Western Australian refineries through the late 1980s. This method requires a large active drying area and sufficient time to farm, drain and desiccate residue to a dry density and shear strength that will allow continued raising of the deposit.

Farming of thickened residue to aid drainage and desiccation.

Alcoa is currently assessing pressure filtration as an alternative method of achieving the desired residue dry density. The proposed concept involves filtering and stacking residue so that maintaining a minimum drying area is no longer a critical factor.

While the active residue drying areas are not generally visible outside of the operations, Alcoa is committed to rehabilitating the outer embankments of the storage areas to as natural an appearance as possible. Embankment rehabilitation aims to generate self-sustaining ecosystems, which can take years to establish. As the external embankments are lifted to comprise coarse-grained residue, new embankment sections are progressively rehabilitated, facilitating rehabilitation during residue drying.

Field trials and research to optimise revegetation performance are undertaken at the residue storage areas of all three Western Australian refineries. This work varies from large-scale field trials, such as demonstration areas at Pinjarra, to bench-scale laboratory experiments by local, interstate and international universities. This research aims to better understand water-nutrient-plant-residue-sand dynamics to improve rehabilitation and revegetation strategies and performance.

Revegetation on the outer embankment slopes of a residue storage.

The current closure strategy at Alcoa's three refinery residue areas has three main objectives. Decommissioned residue areas should have the capability to be used for productive community benefit, be safe and self-sustaining structures in the long term and allow future access to the residue for alternative uses.

Alcoa has also supported extensive research into potential beneficial uses for bauxite residue. The most promising bauxite residue by-products are Red Sand™ and Alkaloam®. Alcoa has developed a carbonation and washing system to process residue sand to produce a red crushed rock called Red Sand™. Testing shows that Red Sand™ can be used as general fill, construction backfill and road base. Not only does Red Sand™ have the potential to be a cost-effective alternative to general purpose sand, it also has excellent drainage and strength characteristics. Sand from residue has commercial potential to provide a viable substitute for increasingly scarce supplies of quarry sand in the local region, thereby reducing the clearing of natural bushland for sand quarries while also reducing the volume of residue to be stored.

Road construction by Main Roads Western Australia, using Red Sand.™

Alkaloam® is another Alcoa produced soil amendment. In 1993, a proposal to trial Alkaloam® in Peel–Harvey coastal plain catchment projects was submitted to the Environmental Protection Authority Western Australia by the then Department of Agriculture and approved (following a public environmental review). Since then, trials have consistently demonstrated that adding Alkaloam® to the sandy soils that are common in coastal regions of Western Australia is beneficial. Alkaloam® has proved successful as a soil amendment for nutrient-deficient, acid sulphate soils, and can increase the productivity of farmland. Alkaloam® increases soil pH in the same way as agricultural lime. While traditional lime can take a number of years to effectively reduce the pH of soil, Alkaloam® can achieve this result almost straight away.

While Alcoa continues to improve the way alumina refinery residue is stored and the ways storage areas can be closed and rehabilitated, it is also putting considerable effort into addressing technical and regulatory barriers to the production and sale of residue-based products, so that bauxite residue can be a valuable resource into the future.

4.5 In-pit tailings storage

Open-pit mining creates voids, and it would seem that the most environmentally responsible place to store tailings would be in the voids that were the source of the wastes,[7] although tailings disposal in completed open pits may sterilise resources and a single open pit might not be available for tailings disposal during active mining operations.

Tailings can be placed in completed open pits as a slurry, thickened or filtered, or in combination with waste rock. In-pit placement often facilitates rehabilitation (Figure 11).

In Western Australia (see the first case study below) and the Northern Territory (see the second case study below), it has been shown that it can be economical for a mine to remove its TSF and place its tailings in the completed open pit, especially where the tailings pose a future risk to the environment (such as from acid and metalliferous drainage).[8] Typically, in these cases the tailings would be remined, conditioned to a paste consistency and then pumped or gravity-fed into the pit. Shovel or excavator and truck rehandling can be used for tailings that have undergone sufficient dewatering and consolidation.

Figure 11: In-pit tailings disposal: (left) in operation; (right) rehabilitated

7 A review of leading practice in in-pit tailings disposal is in Potvin et al. (2005).

8 See also the Woodcutters Mine case study in the *Preventing acid and metalliferous drainage* leading practice handbook (DIIS 2016d).

CASE STUDY: Paste tailings backfill at Tanami, Northern Territory

In 2011, Newmont Australia's Tanami operation commissioned a paste tailings backfill plant at its Dead Bullock Soak operation. The basic process of backfilling the underground stopes with cemented paste tailings involves the harvesting of tailings from the paddock-style TSFs located at the Granites mineral lease, drying the tailings, and transporting them 40 km to the paste backfill plant on the Dead Bullock Soak mineral lease.

Historically, cemented aggregate fill (CAF) was used for backfilling the underground stopes following initial filling with waste rock. During 2008, the use of CAF ceased due to reduced productivity and rising costs associated with the increasing depth of the underground mine.

From 2011, the harvested tailings have been deposited in a prepared drying area at the Granites and dried to a total moisture content of 7%–9% by layering the tailings into mounds using excavators and scrapers. The drying areas were specifically designed to meet Newmont standards and the requirements of the International Cyanide Management Code (UNEP–ICME 2009), which includes a low-permeability, 300 mm thick compacted clay liner, overlain by a 200 mm thick rock fill protection layer, with high density polyethylene-lined ponds for run-off storage, and surface water management structures.

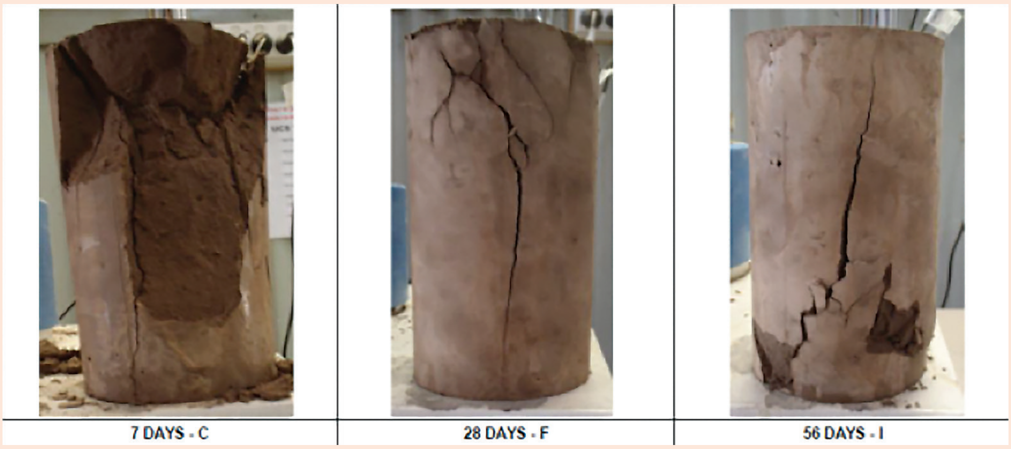
Once the tailings have dried sufficiently they are loaded onto ore haulage road trains and back-loaded to the Dead Bullock Soak, where they are side-dumped into mounds for reclaiming by a loader and loaded into a hopper. They are then screened and water and binder added, before pumping underground through one of two available boreholes. Barricade systems, usually comprising waste rock, rock mesh and shotcrete, are used to block off openings to facilitate backfilling. The paste begins to set about six hours after placement. Upon setting, the paste becomes plastic and no longer applies hydraulic pressure to the stope walls.

The major environmental benefits associated with using paste tailings backfill at Newmont's Tanami operations are:

- a reduction in the surface tailings storage volume and footprint
- a reduction in the risks and liabilities associated with the existing TSFs, by reducing their size through harvesting tailings
- the cessation of sand mining, which was required as part of the previous CAF backfilling operation but not required for the paste tailings backfill.

Backfill plant.

Slump of paste tailings backfill.



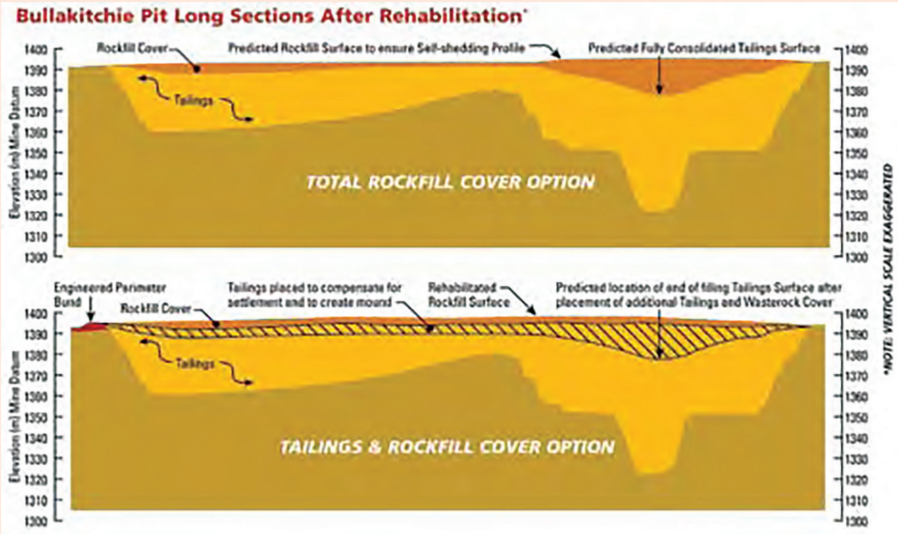
Paste tailings strength.

Case study: In-pit tailings storage at Granites Gold Mine, Northern Territory

Granites Gold Mine, operated by Newmont Australia Ltd, has a number of worked-out pits that are being progressively filled with tailings. Bullakitchie Pit was the first pit to be filled. The traditional landowners and the Central Land Council require pits to be backfilled where possible. The closure strategy is to rehabilitate pits to a water-shedding landform. A number of consultations were held on site with the key stakeholders to gain agreement on closure strategies before their implementation. The quantity of waste rock required to form a suitable cover, allowing for future settlement, was estimated at 350,000 m^3. To improve tailings consolidation and reduce costs and waste rock requirements, the pit was periodically topped up with tailings discharged from a series of central standpipes, compensating for ongoing settlement and forming a flat or convex rainfall-shedding final tailings surface. Tailings were discharged intermittently from 2000 to 2002, and the final tailings surface desiccated to form a trafficable crust. Seepage from the deposited tailings has been closely monitored via perimeter monitoring bores. Impacts from in-pit tailings placement, while measurable, have been confined to a limited halo around the pit.

Creating a convex rainfall-shedding profile by central discharge of thickened tailings into Bullakitchie Pit.

The tailings were discharged at a slow rate, and a low perimeter containment bund was created at low points around the perimeter to minimise the risk of stormwater discharge during rainfall. The use of tailings reduced the amount of waste rock needed by about 150,000 m^3 and saved about $350,000. Future pits will be rehabilitated using similar principles. The final landform, a gentle mound over the original open pit, blends with the surrounding unmined landscape. At final mine closure, the four pits at the Granites will all have been closed and filled to the natural ground surface, with no voids remaining. This has been a positive outcome for the traditional owners, who expressed a preference for the pits to be backfilled.



Bullakitchie Pit longitudinal sections for rock only and tailings and rock options (note that the vertical scale is exaggerated).

4.6 Underground tailings backfill

In general, for safety reasons (the potential for the flooding of workings), slurried tailings are not used in underground fill. Tailings can be used to backfill mined-out underground stopes as a component of cemented hydraulic fill (usually restricted to the coarse-grained fraction of the tailings) or as cemented paste whole tailings backfill. Landriault (1995) pioneered the use of cemented paste whole tailings backfill in Canadian underground metal mines. In paste backfill, the particle size distribution of the tailings can affect every aspect of the material characteristics, from how it dewaters to how it will travel in a pipeline, and hence is an important parameter in the design of a paste backfill plant and the delivery of the paste underground.

The finer grained the tailings, particularly if the fines comprise clay minerals, the more difficult it is to dewater in the processing plant and the lower the final shear strength achieved in the backfill. A high proportion of fine-grained tailings requires larger dewatering capacity and the addition of more cement, adding substantially to the cost. Hence, fine-grained particles may selectively be removed from such tailings using de-sliming cyclones to enhance the tailings' performance as paste backfill. A certain proportion of fines is needed to produce a stable paste and to allow its transport by pipeline without the coarser particles settling out.

A review of leading practice in the use of tailings for underground backfill is provided in Potvin et al. (2005).

4.7 Comparison of tailings disposal and storage methods

Some advantages and disadvantages of the different tailings disposal and storage methods are summarised in Table 4. (Note that an appropriately qualified geotechnical engineer experienced in tailings management should be engaged when considering tailings disposal and storage.)

Table 4: Advantages and disadvantages of different tailings disposal and storage methods

DISPOSAL	STORAGE	ADVANTAGES	DISADVANTAGES
Slurry—discharge towards wall	Valley	Makes use of natural topography to provide storage volume at low cost Maximises storage volume for a given wall height Water return system can be fixed	Natural valley flows will be disrupted Foundation may be soft A water-retaining containment wall is required to limit seepage Deposition of tailings fines against wall could affect its stability Evaporation losses may be high unless decant pond is kept small Potential for overtopping by water and/or tailings (including under seismic action) Requires a final spillway May need treatment of contaminated water before discharge to environment
Slurry—discharge away from wall	Valley	A water-retaining containment wall may not be required, provided water is never stored against the wall With proper management and appropriate freeboard allowances, overtopping should not occur during operations	Natural valley flows will be disrupted Evaporation losses may be high unless decant pond is kept small Water return system will have to move upstream ahead of tailings beach
Slurry	Ring	With a central decant, a water-retaining containment wall is not required, provided water is never stored against the wall Footprint is minimised by continued raising of ring containment wall	Natural drainage channels will be disrupted Evaporation losses are high unless shallow decant pond is kept small Proper closure of central decant is needed to stop ongoing seepage where pipes pass beneath the external containment wall
Slurry	Cells	With central decants, a water-retaining containment wall is not required, provided water is never stored against the wall Cycling between cells allows consolidation and drying of tailings and may reduce seepage Total footprint can be minimised by raising cell containment walls	Natural drainage channels will be disrupted Proper closure of central decants is needed to stop ongoing seepage where pipes pass beneath external containment wall

DISPOSAL	STORAGE	ADVANTAGES	DISADVANTAGES
Slurry	On–off cells	Utilises evaporation and desiccation, and possibly underdrainage and seepage through permeable walls, to dewater deposited tailings No residual tailings deposits, and hence readily rehabilitated to a high level of post-closure land function and/or use	Harvesting and rehandling dried tailings and reconstruction of cell walls add to operating costs Loss of tailings water to evaporation
Thickened	Central thickened discharge (CTD), down-valley discharge or cells	Thickening will reduce water and process chemical losses, supernatant water volume and seepage Thickening allows accelerated access for rehabilitation CTD creates a low-profile, self-shedding landform, often in keeping with surrounding natural landforms	Thickening and pumping incur additional capital and operating costs over slurry disposal Due to the low-beaching angle of thickened tailings, the CTD footprint area will be large, with implications for surface water management and rehabilitation CTD may require a water-retaining perimeter embankment or channel Mechanically working surface of cells requires some desiccation for trafficability, which may be expensive
Paste	Cone	Paste production will further reduce water and process chemical losses, supernatant water volume and seepage Paste allows more rapid access for rehabilitation Cone is relatively low-profile and water-shedding, often in keeping with surrounding natural landforms	Paste production and pumping incur additional costs over slurry disposal Cone footprint will be large, with implications for rehabilitation Cone surface will require some desiccation for trafficability
Centrifuged	Cone	Centrifuging will reduce water and process chemical losses similarly to paste production, reduce supernatant water volume, and reduce seepage Usually transportable by conveyor Allows more rapid access for rehabilitation Cone is low-profile and water-shedding, often in keeping with surrounding natural landforms	Centrifuging and pumping or conveyoring incur additional costs over slurry disposal Cone footprint will be large, with implications for rehabilitation Cone surface will require some desiccation for trafficability

DISPOSAL	STORAGE	ADVANTAGES	DISADVANTAGES
Filtered	Stack	Filtration will further reduce water and process chemical losses, and almost eliminate supernatant water seepage Usually transportable by haul truck or conveyor Trafficable and compactable, facilitating landform construction and progressive rehabilitation	Filtration incurs additional costs over thickening
Slurry	In-pit	Eliminates need for additional surface tailings storage Can be delivered under gravity Supernatant water recovery is possible by pumping	Tailings consolidation rate may be reduced, and surface desiccation is reduced or eliminated (if underwater) Failure to recover supernatant water and process reagents leads to high losses Supernatant water recovery requires that in-pit pumps be maintained, and pumping head must be overcome
Thickened	In-pit	Eliminates need for additional surface tailings storage Can be delivered under gravity Reduced supernatant water may not require recovery	Thickening incurs an additional cost Tailings consolidation rate is reduced, and surface desiccation is reduced or eliminated (if underwater)
Cemented paste	Underground	Can be delivered under gravity Little supernatant water is produced, allowing rapid backfilling Provides stability for subsequent mining of adjacent stopes	Paste production and cement addition incur high costs

4.8 Tailings minimisation, reprocessing and re-use

In order to minimise the potential risks associated with tailings storage, ideally the production of tailings should be minimised, any potential to reprocess the tailings should be exploited, and alternative uses of the tailings should be found wherever possible. Tailings volumes are a function of the run-of-mine (ROM) ore throughput, which is a result of the mine plan. Ways to improve the ore grade and hence minimise the production of tailings include reducing ore dilution through improved grade control and improved mining techniques. In many instances, tailings have inherent value through reprocessing or via other industrial uses. Historical gold tailings are the prime example of changing technology providing a means to make reprocessing viable. This is also the case for a range of other types of mine tailings. The disposal of tailings in a way that will make tailings recovery and reprocessing unviable or uneconomic, or that potentially sterilises ore that may become economically viable to mine and process in the future, should be discouraged. However, this should not be used to justify no or minimal tailings rehabilitation.

There are opportunities to use some tailings for industrial or environmental purposes, thus reducing the storage requirement, including:

- the finer portions of fly-ash used as a pozzolan in the manufacture of cements
- power station bottom ash used as inert building fill
- red mud from the alumina industry used as a soil conditioner and to clean polluted water streams
- power station ash used to fill coalmining voids
- coal tailings used as a low-grade fuel
- some tailings used as a construction material (for example, for upstream raises of TSFs).

Where mineral processing, refining or smelting operations are located within industrial regions, synergistic opportunities may exist where waste streams from one industrial process may become a valued input to other industrial process. This 'industrial ecology' approach (also termed 'regional synergies') is being taken at the Gladstone (Queensland) and Kwinana (Western Australia) industrial areas.[9]

9 See *CSRP Projects,* Sustainable Engineering Group, Curtin University, http://seg.curtin.edu.au/research/csrp/.

5.0 PLANNING AND DESIGN

Plan & design Section 5 → Construct → Operate, monitor & modify → Decommission, rehabilitate & close → Aftercare & monitor

Key messages

- Background and baseline conditions need to be established well before the commencement of operations for environmental impact and risk assessments and to inform closure criteria.
- As part of the TSF planning and design process, formal environmental impact and risk assessments are required to identify and, where appropriate, quantify the risks that need to be prevented, mitigated and managed, including change management and closure.
- Environmental and risk assessments should consider different TSF locations and configurations, which may have different long-term risks.
- Risk assessment is also used during TSF option evaluation to assist in the selection of the optimal TSF location and design.
- Key planning and design constraints on surface TSFs are the site climate, topography and drainage patterns; competing water and land users; and reducing ore grades and finer grinding, producing ever greater amounts of finer grained, lower strength tailings.
- Surface water management must take into account not only the removal of the large volume of water that is discharged annually with slurried tailings, but also extreme rainfall that rapidly increases the volume of ponded water on the tailings surface.
- Investigations are required of tailings geochemistry, rheology and geotechnical parameters and behaviour and of the capacity of the site to support revegetation.
- Leading practice design criteria, regulatory requirements, guidelines and community values must be considered.
- TSF dam-break and risk evaluations should be used to establish the TSF failure consequence category (ANCOLD 2012b) and, using this, TSF design criteria should be established using the risk-based processes and/or minimum requirements outlined in ANCOLD (2012a).
- Tailings containment and delivery, tailings water management and recovery and tailings design to achieve successful closure must also be considered in the planning and design phase.
- The integration of TSF design and planning into the whole-of-site LoM planning is necessary to ensure that operational and public health and safety, community and environmental objectives are met over the entire life of the operation, including after closure.

5.1 Planning, investigation and design phases

The TSF planning, investigation and design phases cover baseline conditions (for the environmental impact assessment), design criteria, pre-feasibility (options identification, evaluation and selection of the preferred option), bankable feasibility (seeking finance to move the project to the construction phase), design information and data, and detailed design.

At the environmental impact assessment stage, it is important to measure the nature, quality, level or quantity of any environmental feature that may be affected by the presence of a TSF before it is constructed. Background conditions that need to be defined normally include:

- land tenure and use, including heritage areas
- any beneficial water use
- the climatic setting, including rainfall, evaporation, temperature, humidity and wind
- the TSF's proximity to sensitive receptors, such as inhabited areas, agricultural activities, and surface water or groundwater-dependent fauna, flora or ecosystems
- the TSF's proximity to habitats for endangered or rare species
- surface topography, drainage patterns and hydrology
- hydrogeology, including groundwater levels and quality
- the moisture content and geochemistry of the foundation soils and rocks
- air quality
- natural and background radiation levels, where radioactive tailings are to be stored
- social, recreational, commercial and heritage values that may be affected by the TSF.

It is important to identify the background data required as part of the planning and design process through a public health and safety, community and environmental risk-based process well before the commencement of operations.

In addition, baseline parameters need to be defined, including for:

- the tailings or ore mineralogy and geochemistry
- the expected tailings particle size distribution and composition
- the approaches to deposition and associated solids concentrations
- the tailings beaching, settling and consolidation parameters at various solids concentrations
- the expected tailings liquor, stored water and seepage water quality.

These background and baseline conditions are important—it is the difference between the background and the tailings and water parameters that assist in defining the lead indicators to be used to detect contaminants that could damage soils or groundwater. This process is also required to enable the regulator to draft operating licence conditions for the facility.

Should the expected tailings parameters change during the TSF's operating life due to changes in the ore type or grade or processing changes, the changes should be noted alongside the original data, together with their expected timing. The changes may result in modifications to the design and the management plan for the TSF.

5.2 Planning and design considerations

The key planning and design constraints on surface TSFs are the influence of the site climate, the topography and drainage patterns; foundation conditions, competing water and land uses; and reducing ore grades and finer grinding, producing ever greater amounts of finer grained tailings. The first step in planning and design is in siting the TSF. If all options are not carefully considered, a suboptimal TSF location may be selected, which limits development options, increases costs or ensures long-term management and aftercare consequences.

The main aspect of the climate that needs to be considered is high rainfall, which is managed through the provision of adequate and timely freeboard or spillways (if discharge to the environment is allowed). Water has become critically important due to the decreasing availability of raw water for mineral processing and post-process water quality, which can be affected by acid and metalliferous drainage (AMD), salinity, residual process reagents and other potential contaminants. The volume of water entrained within the tailings, post-process water quality and the availability of raw water dictate the extent of recycling to the processing plant and the dirty-water storage requirements.

The more finely ground ores and clay mineral-rich ores increasingly being processed affect the extent to which and the rate at which the resulting tailings settle and release supernatant water. They also dictate the final settled dry density of the tailings, the extent to which and the rate at which they desiccate on exposure to evaporation, and hence the shear strength they develop. The salinity of tailings and tailings water also greatly reduces evaporation and desiccation rates from the tailings decant pond and wet tailings. The settled dry density achieved dictates the rate of wall raising required to contain the tailings generated, particularly if the raising relies on the strength of previously deposited tailings. The shear strength achieved in the tailings dictates whether or not upstream wall raising is possible, and the ease with which the tailings may be capped for rehabilitation purposes on closure. The design of tailings cover systems and the source of capping materials must be developed, along with provisions for seepage collection and treatment, if necessary. The shear strength of the underlying tailings also dictates the potential post-mining land use or function of the TSF after closure.

The design conditions and constraints under which a given TSF must operate are summarised in Williams (2014):

- the climatic and topographic setting of the TSF, affecting the rainfall run-off that must be accommodated by the TSF, the TSF site selection and type, and associated drainage works
- suitable foundation conditions to support the required TSF embankment
- processing plant tailings generation rates that must be accommodated within the TSF
- the need to manage and store supernatant tailings water and to recycle it when possible
- the need to meet discharge water quality licence requirements, which may necessitate the need to control TSF seepage, and to store poor-quality supernatant tailings water on the TSF or in a separate evaporation or water storage pond
- the need to maximise tailings' settled dry density, and hence minimise the requirement for wall raising and the tailings storage volume requirement
- the possible current or future need to facilitate upstream wall raising, possibly using tailings, and increase the tailings' dry density and shear strength to facilitate this
- the need to rehabilitate the TSF on closure to minimise environmental impacts and achieve the planned post-closure land use or function.

5.3 Planning and design risk considerations

TSFs require a thorough risk evaluation to identify and, where appropriate, quantify the risks that need to be managed during the planning and design process and later during the subsequent construction, operation and closure phases. The potential dam failure consequence category of a TSF can range from 'very low' to 'high A' (ANCOLD 2012a, 2012b), depending on the population at risk and the potential severity level of damage or loss. The assigned dam failure consequence category is used to determine the design criteria; the construction management and supervision requirements; and the risk management, inspections and reporting requirements and frequencies.

The higher the dam failure consequence category, the more stringent the design, construction supervision, risk management and emergency action and response planning requirements. High-risk TSFs are often auditable by regulatory agencies.

State and territory guidelines provide additional methods of ranking risks for the planning and design of TSFs,[10] although most regulatory agencies now defer to ANCOLD (2012a) for the setting of minimum extreme flood and earthquake design criteria.

It is important to integrate TSF planning into the broader whole-of-site LoM planning to ensure that operational, public health and safety, community, and environmental objectives are met over the entire life of the operation, including after closure.

Where a TSF is developed in stages to satisfy production requirements and to spread capital expenditure, a detailed schedule needs to be prepared. The schedule should include:

- the timing of new stages or modifications
- the sequence and timing for designs, investigations and approvals
- the estimated capital and operating costs, annually and for each stage
- the designs and schedules for progressive rehabilitation at each stage, where opportunities present themselves.

Such planning ensures an adequate budget for the work, that the investigations and design are performed on time, and that there is adequate time for construction (including a contingency for extreme climatic events and storage capacity for tailings, process water and mine-affected rainfall run-off) to complete and commission each new stage or modification.

The risk-based approach applied to the integrated planning and design of tailings management ensures that sufficient flexibility to deal with changing parameters and constraints is incorporated into planning and design. It includes due consideration and allowances for ever-changing climatic conditions, changing demands for tailings storage volume, changes in the nature of the ore and hence the nature of the tailings, changing demands for water, changing regulatory requirements and community expectations, and the potential for premature mine closure.

The conceptual stage identification and evaluation of options in the planning and design of TSFs is outlined and illustrated in the following scenario.

10 See the references sections of this handbook.

Identification and evaluation of options—conceptual stage

Options for tailings management are all too often predetermined due to:

- engineers and operators relying too heavily on their previous experiences—disregarding new technologies and the particularities of the project
- limited advice being sought from a limited number of internal and external experts
- constraints on capital expenditure, often driven by net present value (NPV) accounting in which a high 'discount factor' favours delaying expenditure.

The most important step in developing a conceptual tailings management system for a project is to assemble a multidisciplinary design team capable of assessing the LoM implications of the site's tailings management. The design team should take the following steps.

1. Define operating parameters

The conceptual study must be based on data. The data should include the LoM plan; site topography; hydrological catchment areas; hydrogeology; historical rainfall and evaporation data; the projected volume and rate of production of tailings, and their physical, chemical and rheological characteristics; the availability, quality and price of water; the geotechnical parameters of available construction materials and the foundation; and seismic data.

The design team also needs to:

- collate all previous tailings studies
- identify and quantify the key performance drivers (for example, fresh water demand, minimising AMD or salinity generation, or reducing the noise and visual impact experienced by a nearby community)
- identify all regulatory requirements and laws governing the design, operation and closure of a TSF in the project jurisdiction
- identify the inventory of resources that will be available through mining or borrowing to close and rehabilitate the TSF, including armouring material, various cover materials, drainage material and topsoils
- identify community concerns, including run-off and seepage water quantity and quality, dust, and post-closure land use or function.

In some cases, water can be the overriding operating consideration, while in other cases closure can be the determining consideration.

2. Identify possible tailings storage sites

Possible tailings storage sites may include greenfield sites, existing TSFs, current and future mine voids, underground paste backfill, and waste rock storage areas. When reviewing the tailings storage options, the design team should consider:

- options to maximise water recovery and tailings consolidation
- tailings discharge rotation between multiple storage cells to reduce the rate of rise and maximise the consolidated density
- ore body sterilisation

- potential AMD drainage or salinity and visual, noise and dust issues
- the impact of a tailings containment or pipeline failure
- catchment run-on to the TSF, or clean water diversions
- direct disturbance or proximity impacts (potential seepage, drainage shadow or sediment discharge) on environmental, heritage, commercial or public amenity or aesthetic values
- whether the TSF can successfully and cost-effectively be closed and rehabilitated, including the suitability and proximity of closure materials, and post-closure water management.

This step will produce a comparative risk evaluation, a storage capacity versus time graph to assess whether the possible storage volumes are adequate, a minimum tailings density specification, and a short list of recommended tailings storage sites and disposal methods.

3. Carry out a life-of-mine water balance

While many mines in Australia periodically experience water shortages, some need to deal with excess water. A site water balance is required to evaluate the impact of different tailings disposal and storage options as a function of various water supply and rainfall scenarios. This step recommends a conceptual TSF design and provides a risk evaluation of the various tailings dewatering and storage options.

4. Dewatering options

The dewatering options are driven by the risk evaluation carried out at the conceptual stage in order to manage the environmental risks and water balance. A range of mechanical and in situ tailings dewatering options can be applied at a particular tailings operation. They include conventional, high-rate and paste thickeners, vacuum and pressure filters, centrifuges and cyclones. There is no single rule of thumb for selecting the appropriate tailings dewatering method. At the conceptual stage, it is recommended that the design team review:

- current and future tailings requirements—after several years of mining, for example, voids may become available for tailings storage that would require a dewatering method different from that used in a constructed tailings facility (more than one tailings dewatering method may therefore be required over the LoM and the TSF's location may need to be a compromise)
- technologies employed at similar mining operations
- new technologies
- novel technologies.

The various dewatering options can be initially screened using the site water balance and tailings density targets established in the previous steps. Typical dewatering equipment performance data can be collated from other operating sites, experts employed by equipment vendors and/or benchtop laboratory tests. This step produces an assessment of the various dewatering options and a recommended short-list that meets the water and tailings density design specifications and addresses the previously identified risks.

5. Net present cost and value assessment

The various tailings dewatering, storage and closure options can then be ranked from a financial and risk viewpoint. To enable options to be compared, it is necessary to calculate the net present cost (NPC) and value (NPV) of each. At this stage, the costs associated with the location of the dewatering equipment and storage site, tailings transportation options (pumping, hauling and conveying) and price sensitivity of consumables (reagents and water) can be assessed. The application of NPV accounting significantly diminishes the consideration of longer term costs discounted over long periods. Therefore, it is important to base TSF choices and decisions not on NPV/NPC values alone, but also on the potential risks and costs, including closure costs for reprofiling, armouring and cover strategies, construction of drainage measures and long-term water management, including seepage interception. Discounting over very long periods has frequently led to the selection of TSF designs that have long-term closure cost implications.

6. Final assessment

Combining all of the above steps, the project team can rank the options and recommend the optimal tailings dewatering, transportation, storage and closure options. The team's recommendations also provide guidance in the selection of appropriate external vendors and consultants for more detailed studies.

Note that this assessment may be strongly influenced by non-numerical parameters, such as community concerns. The project team should therefore engage the community, address its concerns, and carefully document and communicate the team's findings to the mining company and to the community.

5.4 Tailings storage facility design considerations

The following sections cover siting, design parameters and criteria, geochemistry, rheology, geotechnical characterisation and parameters, regulatory requirements, and community values.

5.4.1 Siting

A siting study aims to identify and evaluate locations and disposal methods for the safe and cost-effective storage of tailings. The study should consider a broad range of options, including using tailings for underground or pit backfilling, and methods for developing integrated tailings and waste rock disposal facilities, as well as the more conventional surface storage options. A siting study should consider:

- the site setting—climate, topography and (local and regional) hydrology, geology and hydrogeology; foundation conditions; mine site layout; the potential for ore body sterilisation; storage volume requirements; public health and safety risks; and potential social and environmental impacts
- a fatal flaw evaluation—for example, not locating the TSF directly upgradient of populated areas, and avoiding areas of significance such as wetlands, areas underlain by karst terrain, heritage sites and floodways
- the type of tailings—particle size distribution, rheology and potential to contaminate
- the proximity and elevation of the proposed site in relation to the processing plant, affecting the tailings delivery method
- the appropriate disposal method and storage type for the proposed site and tailings
- the available storage volume and potential for expansion
- the extent of the footprint (area of disturbance)
- surface drainage and groundwater impacts
- closure issues—long-term (in perpetuity) tailings containment; outer batter and surface stability; seepage and water quality; the suitability and proximity of closure materials; public health and safety risks; and potential social and environmental impacts.

5.4.2 Design parameters and criteria

It is important for the key design parameters and criteria for the TSF to be defined by the mine project team, and to be clearly documented in the basis for design provided to the facility design engineer. Key design parameters and criteria include:

- minimum, maximum and average tailings generation rates at which the delivery system will operate (dry tonnes/hour or m^3/hour)
- geochemical characteristics that may influence the selection of the most appropriate design for operation and closure
- the range of solids concentrations and the average solids concentration (% by mass) over which the production rates are applicable
- the range of rheological characteristics of the tailings slurry
- annual and life-of-operation tailings tonnages for which the TSF must be designed
- capacity to handle extreme climatic conditions, including high rainfall and droughts
- the rated maximum capacity of the return water system (m^3/hour)
- the availability of suitable and sufficient TSF containment wall borrow materials, including their shear strength and hydraulic conductivity parameters
- the suitability of beached tailings for use in upstream wall raises, including their compaction, shear strength and hydraulic conductivity parameters
- construction specifications and quality assurance/quality control (QA/QC)

- the need for and specifications of a TSF liner, if required
- the availability of suitable and sufficient materials for the rehabilitation of the TSF on closure, including their shear strength, hydraulic conductivity and erodibility parameters
- public health and safety, community and environmental compliance targets, as defined in consultation with stakeholders, including seepage, groundwater quality, air quality and radioactivity compliance levels
- operating and maintenance requirements
- decommissioning, rehabilitation, closure and aftercare monitoring requirements, including consideration of final TSF landforms and slope profiles, armouring, covers and the construction of drainage measures to accommodate design floods.

ANCOLD (2012a) provides a flow sheet for the design of TSFs covering:

- assignment of the design life for the facility
- assignment of a dam failure consequence category
- determination of the dam failure flood requirement
- checking of the dam spill consequence category covering water and tailings spills, leading to the required water storage requirement and freeboard and spillway design
- determination of the tailings storage requirement.

ANCOLD (2012a) provides recommendations on the minimum wet season water storage allowance for TSFs; for example, in Queensland this is the design storage allowance. It also provides recommendations on the minimum extreme storage allowance, contingency freeboard requirements, design floods for spillway design and wave-freeboard allowance, and design earthquake loadings including the assessment of the potential for the tailings to liquefy, as a function of the assigned dam failure consequence category. Minimum allowable factors of safety for the stability of TSF embankments are also suggested, noting that for high and extreme dam failure consequence category facilities, consideration should be given to increasing the acceptable factors of safety above the suggested ANCOLD minimum values.

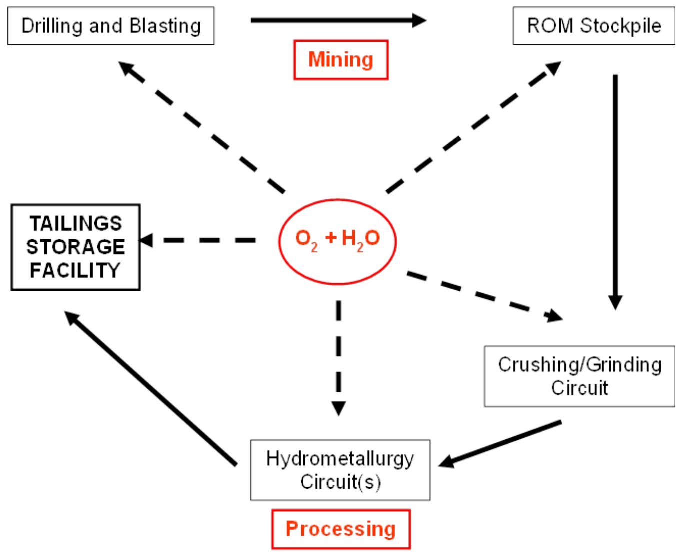
5.4.3 Tailings geochemistry

The mineralogical and geochemical characterisation of the ore body will, to a large extent, characterise the geochemical nature of the resulting tailings, which may be further affected by the process reagents used. The presence of clay minerals can have a substantial influence on the dewatering, settling and consolidation of the tailings. The expected geochemistry of the tailings (in particular, the potential for AMD, salinity and other contaminants to be generated by the tailings[11]) influences how they need to be contained and subsequently rehabilitated. Ideally, potentially acid-forming (PAF) sulphidic tailings should be maintained underwater or saturated before their lag time for acid generation has been exceeded. Alkaline process reagents and/or process water extend the lag period by providing buffering. The design report should contain reference to all geochemical investigations conducted during the design of the TSF.

The cycle of weathering, which in soils and weak rocks leads to their degradation and softening, begins with the exposure of the ore and host rocks to air and water through drilling and blasting, followed by mining and stockpiling of the ROM ore, then processing, and finally conventional storage of the tailings in a relatively free-draining surface facility open to atmospheric conditions (Figure 12).

11 Refer to the *Preventing acid and metalliferous drainage* leading practice handbook (DIIS 2016d).

Figure 12: Cycle of soil and weak rock weathering on mining, processing and tailings storage



Tailings that contain sulphides and insufficient acid neutralising/buffering minerals are particularly susceptible to oxidation and acid generation and sulphate and metal release on exposure to the atmosphere. This is because the finely ground tailings have a large available reactive surface area. Such tailings are also susceptible to acid base reactions leading to neutral to alkaline drainage with elevated dissolved sulphates and metals.

Where residual process reagents add alkalinity, and due to the near-saturated state, tailings may experience a lag of up to several years before acid drainage commences, and oxidation may occur slowly, since it is driven by the slow diffusion of oxygen from the desiccating tailings surface. AMD from oxidising tailings can occur through surface run-off or seepage. Contaminated run-off can leave the facility via the spillway, if provided, or seepage can emerge at the toe of the embankment and/or into the foundation beneath the TSF, possibly re-emerging at the surface.

Clearly, the potential for and likely magnitude of AMD from tailings need to be carefully evaluated in the siting, planning, design, operation and closure of the TSF to avoid or minimise the impact on the receiving surface water or groundwater. The effective assessment of the potential for AMD from tailings must include:

- assessment of the tailings geochemistry, including acid base accounting, metals analysis, leachate testing and reaction kinetics under oxidising conditions, and the presence of process reagents
- assessment of potential attenuation characteristics of the tailings, the TSF embankment and foundation and the groundwater geochemistry.

While little can be done to alter the hydrological regime of a mine site, much depends on the water management practices implemented at the site. Metals released from tailings may be attenuated through a range of geochemical processes, including:

- ion exchange
- adsorption onto oxy-hydroxides of iron, magnesium, carbon complexes or clays

- neutralisation reactions (driven, for example, by carbonate in the tailings and foundation or bicarbonate groundwater)
- precipitation reactions (such as the formation of gypsum, iron oxy-hydroxides, aluminium hydroxides and silicates and amorphous silica)
- redox reactions creating reduced conditions that remove sulphates from solution (for example, in wetland reactions).

The conventional sub-aerial deposition of sulphide tailings in a surface TSF facilitates the oxidation of the sulphide minerals on surface desiccation that may generate run-off and seepage enriched in sulphate, metals and possibly acidity in the absence of excess acid-neutralising minerals. Options to consider for managing sulphide tailings include maintaining them under water to limit oxygen ingress, controlling the tailings physically to reduce oxygen ingress, adding alkalinity, and desulphurisation. Where it is possible, sulphide tailings can be deposited and maintained below a water cover, although this generally requires a wet climate and favourable topography to recharge the cover through rainfall run-off. A water cover is more likely to be possible during operations than after closure, even in a dry climate. After closure, a permanent water cover requires sufficient natural recharge to maintain the water cover behind a water-retaining dam. It may be possible after closure to maintain a wetland cover to limit oxygen ingress and also passively treat any AMD, or a saturated soil cover overlain by a recharge and protective layer. In all cases, the sulphidic tailings should not be allowed to oxidise, or else alkaline material will need to be added to the tailings to neutralise the oxidation products that have formed. For both wetlands and saturated soil covers, it is critical that oxygen is depleted and reducing conditions are maintained at the base of the cover to protect the underlying unoxidised sulphidic tailings from oxidation and to reduce any sulphates that are formed.

The susceptibility of tailings to oxidation may be controlled by methods including increasing the rate of rise so that the tailings on the beach always remain saturated (the beach tailings are covered by wet tailings before they can desiccate), thickening to produce a non-segregating slurry or paste more able to remain saturated on deposition, filtration to produce a cake that can be compacted to limit oxygen entry, and blending with coarse-grained wastes to enable compaction to limit oxygen entry. Oxygen diffusion rapidly decreases by three to four orders of magnitude as the degree of saturation is increased above 85%, which can be facilitated by dewatering and/or compaction. For geotechnical reasons, TSF containment walls are generally designed to be well drained and unsaturated, providing ready ingress of oxygen to the adjacent tailings. The construction of a TSF containment wall with sulphide-bearing tailings may pose significant AMD risks compared to construction with non-acid forming borrow materials or tailings.

Alkaline materials, such as limestone ($CaCO_3$) and lime (CaO or $Ca(OH)_2$), can be added as a surface cover over sulphide tailings to generate and infiltrate alkalinity, mixed in with the sulphide tailings before deposition to offset the acidity reactions, or used to treat AMD from the tailings.

The desulphurisation (or depyritisation) of tailings, where possible, involves the separation of the non-economic sulphide minerals into a low-volume stream, leaving most of the tailings with a low sulphur content that will be less reactive and preferably non-acid-generating. The two tailings streams can be managed separately and differently. The high-sulphur material can be selectively deposited beneath the tailings pond to remain submerged during operations, and possibly after closure, or be covered by low-sulphur tailings after closure to maintain saturation of the underlying high-sulphur tailings. Desulphurised tailings with non-acid-generating or acid-consuming characteristics may be co-disposed with waste rock in dumps or used as a cover material. The cost of tailings desulphurisation may be offset by the production of a low-sulphur tailings stream that can potentially be used to provide a final cover material, rather than having to mine cover material or import it from elsewhere.

5.4.4 Tailings rheology

The tailings' rheology is a function of their expected solids concentration, particle size distribution, specific gravity, and mineralogy and geochemistry, and is the key determinant in assessing tailings slurry and thickened tailings pumpability. The design report should contain reference to the rheological investigations conducted, including the rheological parameters selected for the purposes of tailings transport design.

Slurried tailings of low solids concentration exhibit Newtonian behaviour (Boger et al. 2002), in which the shear stress of the tailings is a linear function of the shear rate applied. Once tailings are thickened above a certain consistency, they exhibit non-Newtonian behaviour in which the tailings possess a yield stress beyond which the shear stress increases with increasing shear rate in some fashion, with the possibility of time-dependent behaviour. The design of the appropriate tailings disposal system and operation requires an understanding of the rheological characteristics of the tailings, both in shear and in compression. The implementation and optimisation of a tailings disposal system involves rheological studies to determine:

- the feasibility of dewatering of the tailings to the required solids concentration before their transport and disposal
- the optimal conditions for tailings pumping and pipeline transport
- the solids concentration required to achieve the optimal management of the tailings on disposal (Boger et al. 2002).

Boger et al. (2002) described a planning, design and testing flow sheet to take into account the tailings rheology in the design of an appropriate disposal system. Under 'planning', they highlighted the rheological parameters required for the selected disposal method, the transportation of the tailings and its cost and risk-effectiveness, and the optimal degree of tailings thickening. Under 'design considerations', they highlighted thickener design, pumpability, and the prediction of the tailings beach slope and settling. The relevant rheological tests include yield stress versus solids concentration, viscosity versus shear rate, and the effect of flocculants.

5.4.5 Geotechnical characterisation and parameters

Geotechnical investigations are required of the hydrological and hydrogeological conditions of the TSF site, the foundation conditions underlying the TSF containment walls, wall construction materials, and the tailings, including geotechnical characterisation and parameter determination. These investigations should be tailored to the complexity of the project and the consequence category of the TSF, and are required to provide information for detailed design and project decision-making. Often, tailings samples are not available for geotechnical testing during the planning and design phase, necessitating the assessment of their likely geotechnical nature, parameters and behaviour based on a limited number of tests carried out on simulated tailings or on the testing of similar tailings. The design report should contain reference to the investigations conducted during the design of the TSF and specify the confirmatory studies that must occur when representative tailings samples are available, comprising (but not limited to):

- a geotechnical investigation for each proposed TSF and footprint and associated components, including foundation conditions, and the availability and suitability of borrow materials
- a flood assessment of the site
- a seismic assessment of the site
- physical characteristics and geotechnical engineering parameters of the tailings, including their particle size distribution, plasticity and specific gravity

- a hydrogeological investigation—a conceptual groundwater model including background water quality within the projected zone of influence of the TSF.

5.4.6 Regulatory requirements

Different state jurisdictions may prescribe a range of requirements for the design of TSFs, including, for example, the wet season water storage allowance, freeboard requirements, design floods to be catered for, design earthquake loadings, required factors of safety for the stability of TSF embankments and, in some cases such as uranium tailings, minimum closure cover requirements. Most states, however, defer to ANCOLD (2012a) for TSF design criteria.

5.4.7 Community values

Community values such as health, heritage, surrounding land uses, aesthetics and the environment must be included throughout the decision-making process for a TSF from planning to closure. This involves meaningful, ongoing, regular consultation with the relevant interest groups, including information sharing and dialogue with stakeholders. This consultation is normally carried out as part of the stakeholder engagement during the mine approval process and throughout operations to ensure that the community is fully informed of any possible impacts and how they are being managed. Further consultation will be required as TSF closure approaches to ensure that the community is fully informed and able to contribute to closure objectives and plans.

5.5 Design aspects

Leading practice TSF design requires all aspects of the TSF to be designed to meet or exceed minimum design criteria and standards that reflect an appreciation of the potential dam failure consequence category and the potential health, safety, environmental and community impacts associated with the construction, operation and closure of the TSF. The performance of the TSF must meet the minimum criteria established in the design throughout the life of the facility, extending to after closure. Because the post-closure design life (tens of thousands of years) is so much longer than the operational life (tens of years), the closure design criteria for floods and earthquakes are more stringent than the operating design criteria (ANCOLD 2012a).

A risk-based design approach provides a framework for managing the uncertainty and change associated with TSFs and has a number of benefits (Williams 1997), including:

- improved quantification of the magnitude and costs of exposure to hazard
- provision of a defensible argument for the adoption of the optimal strategies
- identification and elimination of low-risk hazards
- highlighting of significant risks that need to be reduced by appropriate engineering treatment measures
- facilitation of cost-effective solutions that achieve an acceptably low risk.

Leading practice TSF management also requires alignment between the TSF planning and the mine plan. TSF planning must be reviewed in response to any changes to the mine plan, and revised, if necessary, to ensure that any staging or sequential raising requirements are adequately financed and scheduled. Operation and management activities must strive to achieve closure objectives throughout the project life.

Consideration should be given to:

- the integration of the TSF plan into the mine plan and schedule in developing the tailings disposal methodology (for example, using or stockpiling topsoil and waste rock for the construction of containment wall raises and/or caps and covers)
- the location of the TSF to avoid sterilising mineral resources or contaminating water resources
- stockpiling suitable embankment construction materials and surface capping materials
- the potential to surround the TSF in waste rock to form an integrated waste landform
- the geochemical characterisation of tailings to assess their potential for AMD during operation and after closure[12]
- change management—increases in processing plant have impacts on storage requirements for tailings and water and the rate of rise of the tailings, which can, in turn, have implications for tailings strength and stability
- reprocessing of tailings—some tailings may contain valuable minerals, so a management objective may be to provide interim storage until economic recovery becomes feasible; however, this should not be used as a justification for leaving tailings in a geochemically unstable or reactive state for prolonged periods, and a contingency plan for closure in situ should still be prepared.

5.5.1 Tailings containment

Tailings containment structures must be designed and constructed in accordance with sound geotechnical engineering principles, such as those provided by ANCOLD (1998, 2000a, 2000b, 2003, 2012a). The principal considerations for the design of a tailings containment structure are:

- suitable foundation conditions
- the zoning of the containment wall and geotechnical parameters of the construction materials
- geotechnical slope stability, including consideration of the potential for liquefaction and/or loss of strength (particularly of the tailings) during and/or after seismic loading
- seepage and the need for filters, internal drainage or clay cores and cut-offs in the foundation beneath the containment wall
- staged construction, by progressive wall raising, the addition of containment cells or the construction of new facilities over time
- the selection of construction materials, including excavated tailings or ROM waste rock, where appropriate
- the selection of construction techniques and equipment requirements
- QA/QC of the construction process, including control of borrow material quality, its moisture content and degree of compaction, and survey.

12 Refer to the *Preventing acid and metalliferous drainage* leading practice handbook (DIIS 2016d). The selection of tailings placement methods, possible liner requirements and the type of embankment construction can be influenced by the level of geochemical risk. Samples for characterisation can be obtained from the metallurgical test work typically carried out as part of the pre-feasibility phase of a new mining project.

5.5.2 Tailings delivery

Tailings are normally pumped as a slurry along a pipeline, although in some situations it may be possible to convey tailings under gravity to the storage facility (for example, in a concrete channel). The pumpability of tailings slurry is a function of its rheology and the capabilities of the pumping systems. The higher the solids concentration of the tailings slurry, the higher its yield stress and the more difficult it is to pump, for a given pump type.

Typical tailings pumping equipment requirements for different tailings consistencies are given in Table 5. The increasing power and line pressure requirements with increasing tailings solids concentration (and, in some cases, with increasing pumping distance and head) correspond to a significant increase in pumping costs. The increased costs of tailings thickening may be offset by improved process water recovery, a smaller tailings pipeline diameter, increased tailings density, a reduced requirement for TSF embankment raising, a reduced risk of overtopping and reduced seepage.

The separation of coarse- and fine-grained tailings in the processing plant to create two tailings streams may allow more effective tailings delivery and storage. For example, sand tailings can easily be dewatered and pumped, trucked or conveyed. The remaining fine-grained tailings may be able to be more effectively thickened, thus improving process water recovery.

Table 5: Typical pumping equipment requirements for different tailings consistencies

TAILINGS CONSISTENCY	PUMPING EQUIPMENT REQUIREMENTS
Slurry	Centrifugal pump (with low line pressure)
Thickened	Centrifugal or piston/diaphragm pump (with high line pressure)
High slump paste	Pumpable by centrifugal pumps up to a yield stress of about 150 Pa, otherwise requiring a piston/diaphragm pump (with higher line pressure)
Low slump paste	Dual piston positive displacement pump (with high line pressure)

Source: Williams & Williams (2004).

Along the tailings pipeline corridor, there is a need to protect the environment against tailings spills due to possible pipeline leaks and breaks and the clearing of pipeline blockages. Methods for controlling the discharge of tailings if such incidents occur include:

- the construction of containment bunds, drains or sumps along the pipeline corridor
- sleeving the pipeline with a larger diameter pipe for situations where the tailings pipeline is traversing sensitive environments (such as a river crossing) or crossing transport routes
- regular inspection of the pipeline route for corrosion and leaks
- the use of differential pressure sensor or flow measurement instrumentation and an alarm system to alert operators in case of pipeline failure
- the measurement of pipeline wall thickness for abrasive tailings to assist the planning of maintenance for pipelines and fittings.

5.5.3 Tailings water management and recovery

The effective management of water quantity and quality is a key driver for responsible tailings management. Key water-related considerations in the design, operation and closure of a TSF are:

- the availability and cost of water of acceptable quality for processing and other uses
- competing water users and the value the community places on water
- the need for supernatant, rainfall run-off and reagent recovery
- setting the target for settled and consolidated tailings dry density (achieved by appropriate design); that is, managing TSF sizing and tailings discharge to achieve the target supernatant water recovery
- pumping flow rates and distances
- reducing evaporative losses (where the water balance is in deficit) or encouraging evaporation (if water is in surplus)
- minimising the generation of AMD and salinity
- dewatering the tailings to reduce the discharge of processing reagents with the tailings
- managing water treatment (if required) and discharge to the environment (of surplus water)
- reducing the risks of overtopping (a common cause of TSF failure)
- reducing seepage to groundwater, including by providing underdrainage
- reducing the risks associated with the storage of water on TSFs, which could involve perimeter fencing, minimising the area of ponded water, netting or intermittent noise to distract birds
- providing sufficient storage and/or spillway capacity to accommodate seasonal rainfall as well as extreme storms.

Mines often compete for water resources with other users, such as agriculture, domestic and industrial water supply, other mines and the environment. It is important that the mining industry be seen as a responsible user of water and committed to the preservation of water values to ensure its continued access to a limited and valuable resource.

At many mine sites across Australia, water is scarce or of poor quality. The recovery of additional water from tailings can augment the mining project's water resource, reduce water drawn from natural water resources and recover valuable reagents (such as cyanide, in the case of gold processing).

As the surface dries through evaporation, tailings containing sulphides have the potential to oxidise and produce acid and metalliferous run-off and seepage. Rainfall infiltration may leach the oxidation products, releasing contaminants to the groundwater. Tailings and/or tailings water may contain high salinity levels due to the saline nature of the tailings and/or the processing water used. Tailings water will contain any residual processing chemicals, such as cyanide, and may be rendered alkaline or acidic for processing purposes. Contaminants may be transported in run-off and seepage emanating from the TSF. These risks to the environment are controlled by effective design, operating, closure and rehabilitation strategies.[13]

It is important that the true cost of water be used in the economic evaluation of water recovery options. Water costs include:

- the capital and operating costs of developing, operating and maintaining water supply systems

13 Refer to the *Preventing acid and metalliferous drainage* (DIIS 2016d) and Mine closure (DIIS 2016a) leading practice handbooks.

- environmental costs, taking into account the value of receiving natural wetlands, streams, lakes and dependent ecosystems
- the cost to displaced users
- the cost of seepage interception, offset by the volume of water this may return to the processing plant
- the cost of production disruptions due to supply shortfalls.

Water recovery from the TSF is generally limited to the recovery of supernatant water and rainfall run-off, although seepage from an underdrainage system or through the wall may also be collectable. Other tailings water is lost to entrainment within the tailings, evaporation from the decant pond and wet tailings, and seepage into the foundation. In order to maximise the recovery of surface water from the TSF, good design, construction and management of the decant system is required. This should include the planning and implementation of perimeter tailings disposal to direct surface water to the decant pond, minimising the size of the decant pond, the rapid return of surface water to minimise evaporation losses, and maintaining the decant pumps and water return pipelines.

5.5.4 Seepage control

The volume of water that is discharged annually with slurried tailings can be several times the average annual rainfall in a dry climate, although the discharge rate is normally reasonably constant, unlike the discharge from isolated heavy rainfall events. This will increase the potential for seepage, although the supernatant tailings water alone could readily be handled by pumping. Heavy rainfall, on the other hand, rapidly adds large volumes of ponded water on the tailings surface, which would take a considerable time to pump down.

For tailings slurry deposition, there is a high likelihood that seepage will occur into the foundation. Some of the foundation seepage will go into storage within the foundation, increasing its hydraulic conductivity, and some will infiltrate to ground causing the watertable to mound. Consideration could be given to providing underdrainage where there is a high likelihood of contaminated seepage into a permeable foundation, although underdrains will tend to become blinded by an adjacent cake of consolidated tailings. There is also a high likelihood that potentially contaminated seepage will occur through the containment wall, emerging at the toe.

There is a risk that seepage from stored tailings may cause groundwater contamination that could threaten public health, render the groundwater unsuitable for other users (for example, for livestock or irrigation), cause environmental impact, exceed regulatory conditions or commitments (which may be decoupled from impacts), or contribute to a reduction in geotechnical stability. The following aspects need to be considered in the design to adequately control seepage:

- the geochemical and hydraulic characteristics of the foundation beneath the TSF, including the underlying hydrogeology and the possible need for a TSF liner
- the hydraulic characteristics of the containment wall, including the possible need for a clay core, a cut-off into the foundation beneath the containment wall and internal drains to prevent piping
- the prevention of high-permeability layers forming between TSF embankment raises, which could cause future seepage or stability concerns
- underdrainage to help prevent gravity drainage from the deposited tailings
- decant systems designed and operated to limit the storage of supernatant tailings water and incident rainfall on the surface of the tailings, and hence limit seepage.

Liners are not used beneath TSFs where there is no risk of impact from seepage into the foundation. However, TSFs must be lined to limit the migration of potential contaminants where there is a risk of contamination of an underlying groundwater resource or impact to a groundwater-dependent ecosystem. New mining projects may be asked to justify why a liner is not required (that is, to prove that seepage will not cause a measurable detrimental impact to the groundwater quality or to a groundwater-dependent ecosystem). Such justifications may be that the tailings seepage is geochemically benign, that the foundation has an acceptably low hydraulic conductivity (a saturated value of, say, $<10^{-9}$ m/s), or that the groundwater has no beneficial use (for example, it is hypersaline). All liners leak to a degree, and the more effective they are the less the tailings will drain and consolidate. Further, liners have a finite life, and will fail following the closure of the TSF, when the resources available to remediate the failure will be limited.

Where a liner is required to control contaminated seepage, in the absence of a foundation of very low hydraulic conductivity, a compacted clay, geomembrane or composite liner may be considered. A compacted clay liner would normally be expected to achieve a saturated hydraulic conductivity of $< 10^{-8}$ m/s, requiring suitable clay soil, appropriate compaction equipment and good compaction control. A geomembrane, placed using good-quality control, would be expected to achieve an equivalent hydraulic conductivity of about 10^{-10} to 10^{-11} m/s (although installation damage often results in higher flow rates). Also, the life of a geomembrane may be limited to 50–100 years. Further, a geomembrane is typically only 1–2 mm thick, so that the high head imposed by saturated tailings would result in a very high hydraulic gradient, effectively nullifying the effectiveness of the geomembrane as a liner (Williams & Williams 2004). A geomembrane would therefore normally be used in combination with an underlying compacted clay layer (commonly known as a composite liner).

In some cases, a liner over part of the TSF footprint may be considered to limit seepage, such as against the upstream face of the containment wall or beneath areas of high head or a fixed decant pond. The installation of a liner can lead to the long-term build-up of excess stored water on the TSF, which can render closure and rehabilitation of the TSF difficult.

5.5.5 Planning and designing for closure

In the early stages of TSF planning and design, consideration must be given to setting the environmental and closure criteria and to the proposed final TSF landform, including the treatment of exposed surfaces. After closure, the TSF is required to remain safe, stable and non-polluting, requiring a sustainable landform and cover system. The slopes of the TSF containment walls will need to have a stable profile, preferably mimicking analogous, usually concave, natural profiles, be covered with suitable erosion protection and, where possible, be revegetated to further minimise erosion and prevent exposure of the contained tailings.

A closure spillway may be needed to shed heavy rainfall and minimise the ponding of rainfall run-off on the TSF that would drive infiltration into and seepage from the tailings. The spillway should ideally be excavated through natural rock, where possible, to increase its stability. Associated with the spillway will be the need to capture sediments generated from the surface of the TSF, requiring a sediment pond, which could be located on the TSF upstream of the spillway overflow crest.

The tailings surface will require a stable cover system that minimises erosion and prevents exposure of the underlying tailings, particularly if they are geochemically reactive. Benign tailings may support direct revegetation, provided that dust generation is not an issue. In a net positive water balance climate, and where the surrounding topography recharges the TSF, geochemically reactive tailings could have a permanent water cover, a wetland or saturated soil cover. To limit net percolation into reactive tailings, a rainfall-shedding cover (appropriate for wet climates) or store-and-release cover (appropriate for dry climates) could be provided.[14]

If contaminant plumes develop beneath existing or closed TSFs, remedial measures include interception trenches and/or seepage recovery bores installed around the TSF perimeter, or downstream if the facility is a valley fill type. Where these measures have been installed during operations (that is, they were installed as soon as the contaminant plume was observed), they may require continuous pumping and recirculation to the TSF or water treatment before discharge.

After deposition, the entrained water within the tailings can lead to ongoing seepage, usually at a diminishing rate as the perched watertable within the tailings disappears. Rainfall run-off can recharge the tailings, leading to further seepage over time. Where ongoing seepage after closure may pose a risk to public health or the environment, a key closure consideration is to limit infiltration into the surface of tailings (such as by using a suitable cover system) and to control the flow of seepage from the TSF.

In extremely dry climates, such as in the Western Australian goldfields region, closed TSFs desiccate strongly, reducing the likelihood of seepage after closure, even after prolonged heavy rainfall (Chapman & Williams 2014). In addition, much of that region's groundwater is hypersaline and of little economic value other than as mineral processing water.

The use of hypersaline groundwater for mineral processing and the processing of saline ores lead to hypersaline tailings. The tailings form a hard surface crust that can limit infiltration and dusting but also restrict evaporative drying. Interception trenches or recovery bores may be required around the perimeter of those facilities during operation and for a period after closure to control the drain-down of hypersaline water. Once the groundwater table mound has subsided, the risk of seepage to and impact on the surrounding environment is usually low as long as suitable post-closure water management systems are in place.

5.5.6 Design report and records

TSFs and all associated components must be designed by suitably qualified and experienced geotechnical engineers.

The design report describes the basis of the design, including all design parameters and criteria, and the key performance and environmental compliance criteria. It is critically important to determine the safety controls, operating procedures and maintenance programs that are necessary to manage the key risks and ensure the safe operation of the TSF. The design report provides easy and quick reference when evaluating a proposal to modify the operation or design. It also provides details in the event of an emergency. A comprehensive design report contains details of:

- background and baseline conditions
- design constraints and risk evaluation of the TSF
- minimum design standards (ANCOLD 2012a)
- geochemical, rheological and geotechnical investigations
- regulatory requirements and community values
- tailings containment and delivery

14 Further details on TSF closure and rehabilitation are in Section 8.5 and the *Mine closure* (DIIS 2016a) and *Mine rehabilitation* (DIIS 2016e) leading practice handbooks.

- tailings water management and recovery and seepage control
- dam-break analysis; geotechnical slope stability and tailings consolidation analyses; stage capacity curves and TSF sizing; deposition design; foundation and containment wall design; and liner and underdrainage system design, if required
- TSF water balance, tailings pump and pipeline system design, and decant and return water system design
- design for closure.

The design report should fully describe the design standard, process and methodology adopted. This includes minimum design standards prescribed by state and territory regulators and ANCOLD (2012a), supported by applicable ICOLD design guides and standards.[15]

Once key decisions have been made and the detailed TSF design has been finalised, key documents need to be compiled and maintained for future reference, as outlined in the following description of the components of a tailings management system.

Components of a tailings management system

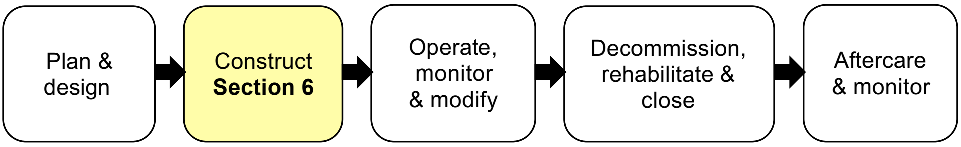
Leading practice tailings management should ensure that the following plans and documents, which together make up the tailings management system, are up to date and available to all personnel associated with TSF management:

- life-of-mine TSF plan—how and where tailings will be stored over the life of the operation, the estimated budget (and schedule), and how construction will be staged
- design criteria—production, geotechnical, geochemical, operational and closure public health and safety, community and environmental performance objectives that the TSF (and each stage) is expected to achieve, at each stage in the mine life
- design report(s)—detailed designs for each structure or stage of the TSF, including drawings, to achieve the specified design criteria (this will include geotechnical and other investigations and laboratory testing carried out in support of the design)
- construction report(s)—detailed reports on the construction of the TSF as measured against the drawings and construction quality plans (this should contain as-constructed drawings and photographs to assist in the identification of future risks and in the back-analysis of issues that arise)
- operating manual—operating principles, methodology and associated resources and training
    - safety (or risk) management plan—surveillance and monitoring plans, including inspections, monitoring, water balance and performance reviews
    - emergency action and response plan—the steps to be taken in case of an emergency to minimise public health, safety, community and environmental risks and the responses to be taken to minimise impacts if an incident occurs
- closure plan—the closure strategy that forms the ultimate objective of the tailings management plan.

The operating manual, safety management plan, emergency action and response plan and closure plan may be substantial and detailed for a high-risk TSF, and brief (a single document incorporating all aspects) for a simple, low-risk facility.

15 See the references lists at the end of this handbook.

6.0 CONSTRUCTION



Key messages

- Successful TSF operation depends heavily on the construction quality of all aspects of the TSF.
- Key TSF project management roles include the design engineer, responsible engineer (for the construction project), owner's representative and quality assurance technician.
- Key risks associated with TSF construction include the construction not following the design, construction materials not conforming to specifications, poor or inadequate construction quality and the failure of QA/QC (Quality Assurance/Quality Control) to identify construction inadequacies.
- It is important that TSF construction management, technical supervision and QA/QC are all undertaken by competent practitioners who understand the dependence of the successful operation of the TSF on good construction practices and who are capable of ensuring that the construction is carried out in accordance with the specifications and the design intent.
- The contractor must be carefully selected and adequately managed, and the construction must be appropriately and adequately supervised.
- The design engineer must have appropriate input during TSF construction in order to be able to confirm in the construction report that all aspects of the construction have been completed in accordance with the specifications and the design intent.
- The construction report, approved by the facility owner, must provide an accurate record of the construction works, including as-constructed drawings, photographic records of construction details, and clear documentation of any design changes made in response to changes in expected foundation or other conditions.

6.1 Construction risks

According to ANCOLD (2012a), the integrity of a tailings embankment is as critical as the integrity of any water dam. Assuming a sound design, the success or failure of a tailings embankment or wall raise depends heavily on the manner in which it is constructed. Hence, TSF construction management, technical supervision and QA/QC are essential for the initial starter embankment and for subsequent wall raises and must be undertaken by competent practitioners.

The key risks presented by the construction of TSFs include:

- construction not following the design
- inappropriate or insufficient construction materials

- inadequate construction quality, including lack of or inadequate compaction
- failure of QA/QC to detect and rectify poor or inadequate construction quality
- wall raises not following the design and/or not being compatible with the existing TSF embankment
- subsequent poor operational practices, such as tailings deposition and decant pond management not being compatible with the intent of the design, which can increase construction complexity and risk and contribute to a reduction in construction quality by making construction conditions so difficult that it is not possible to achieve the stated specifications.

6.2 Construction management

In order to minimise the above risks, it is essential that the contractor be carefully selected and adequately managed and that the construction be appropriately and adequately supervised to maintain the required construction quality through appropriate QA/QC.

Construction management should cover:

- comprehensive design drawings, specifications and project scheduling to enable cost estimation and contractor tendering and selection
- the selection of appropriate construction equipment capable of meeting the design specifications for the TSF starter embankment or wall raise earthworks
- the definition of key project management roles, including the design engineer, responsible engineer (for the construction project), owner's representative and quality assurance technician, and the appointment of competent practitioners to those roles
- the engagement of experienced construction supervisors to ensure adherence to the design and to recognise the need for consultation with the design engineer for clarification of the design and discussion about any required changes to the design
- the involvement of the design engineer during construction, including periodic inspections of the works by the design engineer and to ensure that any design changes made during construction are approved by the design engineer and are clearly documented
- the maintenance of construction records, photographs and logs of significant milestones, including design changes
- the preparation of as-constructed drawings.

Where the owner employs mine operations equipment and personnel to construct the TSF embankment or wall raise, caution should be exercised to ensure that construction quality is not compromised, and that appropriate QA/QC is carried out and the design engineer is appropriately involved, particularly if the mine operators do not have experience in civil earthworks requiring specialised construction techniques and compaction equipment.

6.3 Construction records

It is important that the construction report be an accurate record of the construction works in order to:

- ensure that the TSF was constructed by a competent contractor, with an appropriate level of supervision and quality control of construction materials and techniques to show they were in accordance with the design drawings and specifications

- provide a detailed record and description of geotechnically critical aspects, such as the preparation of foundations, the treatment of cracks in key and cut-off trenches or the compaction of backfill around outlet works (this record assists in the design and construction of remedial works if any post-construction problems occur)
- provide as-constructed drawings that
  - give an accurate representation of the detailed construction works, particularly where design changes may have occurred during construction
  - assist in improved designs for later stages
  - provide details and dimensions for remedial works so that those works do not affect the integrity of existing structures
  - provide details for back-analyses should they be required.

6.4 Tailings storage facility embankment construction

For the storage of tailings slurry in surface facilities, a starter embankment is first constructed. The embankment is normally raised in a series of lifts or wall raises using the downstream, centreline or upstream methods, which are so called because they involve the crest advancing either downstream, vertically upwards or upstream, respectively requiring progressively less containment wall earthworks. Figures 13, 16 and 14 show schematic diagrams of downstream and upstream raising. Figure 15 highlights the much greater volume of borrow material required for downstream raising compared to that required for upstream raising. The diagrams do not include details about internal drainage or clay cores within the containment walls, which may be required to ensure geotechnical stability and/or to control seepage.

Centreline raising is midway between the two extremes of downstream and upstream raising and is not commonly used in Australia. In all cases, the initial starter containment wall is generally constructed using borrow material, which is often benign (non-acid-forming) waste rock. Downstream wall raises are also generally constructed using borrow material, while centreline and upstream wall raises may be constructed using a combination of the coarse fraction of the tailings and waste rock or borrow material. Downstream raising can be extended to form an integrated waste rock and tailings landform (see Section 4.2.5).

Figure 13: Downstream construction using borrow

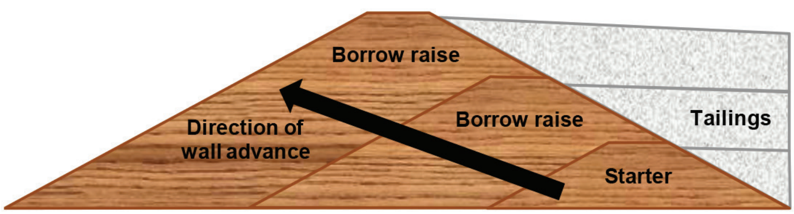


Figure 14: Upstream construction using tailings

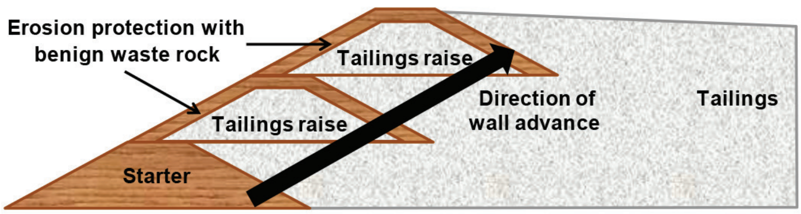
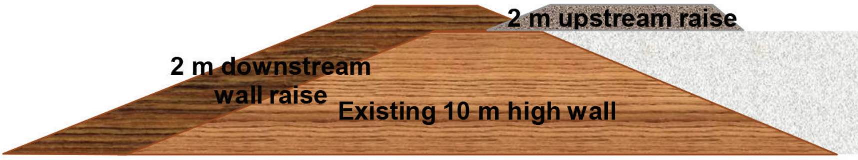


Figure 15: Downstream versus upstream raising



For upstream raising using tailings, desiccated tailings are usually excavated from the tailings beach and used to construct an upstream lift largely over desiccated tailings (Figure 16(right)). It is often necessary to place benign waste rock on the slopes and crest of the raise to protect those surfaces against erosion by rainfall run-off, wind or wave action. Upstream lifts can also be constructed by placing waste rock or borrow material largely on top of desiccated tailings, provided that the tailings have sufficient strength.

For centreline raising, tailings may be separated into coarse and fine fractions using hydro-cyclones, with the coarse fraction directed downstream to form the wall and the fine fraction directed upstream. In this case, no erosion protection is applied to the downstream face during operation. The downstream face may be dozed to reduce the slope angle, increase density and improve the geotechnical stability of the wall. Centreline lifts can also be constructed in a manner similar to upstream lifts using waste rock or borrow material placed partially on desiccated tailings.

Figure 16: TSF embankment construction: (left) downstream using waste rock; (right) upstream using tailings

There is a need to consider the long-term stability of a TSF containment wall and to construct the downstream slope profile and surface texture to facilitate this. To reduce closure risks and costs, the downstream profile should be constructed to a slope profile that will achieve a sustainable final landform. Final slope contouring is often completed at closure, but costs can be minimised by constructing the slope profile close to the final landform requirements. For upstream construction, this approach may enable progressive slope rehabilitation and reduce earthworks requirements at closure. Where tailings are used for upstream wall raising, a sufficient thickness of erosion-resistant cover material must be placed on the surface to ensure that the underlying tailings will not become exposed over time.

Some advantages and disadvantages of using the downstream and upstream methods of progressive tailings containment wall raising are highlighted in tables 6 and 7. Consideration of the issues in tables 6 and 7 does not substitute for the engagement of an appropriately qualified geotechnical engineer experienced in tailings management and dam design to consider all relevant issues.

Table 6: Advantages and disadvantages of downstream construction

ISSUE	ADVANTAGES	DISADVANTAGES
Borrow material	A wide benign encapsulation is provided	Large borrow volumes are required
Construction cost	Starter embankment section is no larger than that required for upstream construction	Subsequent wall raises are increasingly costly, unless waste rock is available and the haul is short
Footprint	Starter embankment footprint may be much smaller than that required for an upstream starter embankment	Subsequent wall raises increase footprint Increasing footprint of containment wall reduces volume available for tailings storage
Geotechnical stability	Will be likely to be enhanced by use of coarse-grained borrow material	Use of fine-grained borrow material may result in a high phreatic surface on further tailings deposition, which may reduce geotechnical stability
Seepage	Seepage control measures can readily be incorporated within successive wall raises	Coarse-grained waste rock borrow may increase wall seepage, but drains or a seepage barrier or filter can mitigate this
Contaminants	Encapsulation limits exposure of tailings to oxidation	Encapsulation maintains tailings moisture content and potential for transport of contaminants
Erosional stability	A wide encapsulation will be likely to prevent exposure and erosion of tailings	Fine-grained borrow material or weathered rock on surface may be prone to erosion
Rehabilitation	A wide encapsulation should allow reshaping of outer batter	Any additional reshaping for rehabilitation purposes may increase footprint

Table 7: Advantages and disadvantages of upstream construction

ISSUE	ADVANTAGES	DISADVANTAGES
Borrow material	After construction of starter embankment, only small volumes of borrow are required for raises	Above starter embankment, only limited cover over wall raises constructed using tailings is provided, although imported fill material may be used
Construction cost	Subsequent wall raises with tailings involve little borrow material, negligible hauling of tailings, and haulage only of facing material	Subsequent wall raises require tailings to be sufficiently desiccated to be trafficable and suitable for wall building if they are used
Footprint	Subsequent wall raises do not increase footprint A larger starter embankment may be required than that required for downstream construction, but the final footprint will be smaller	Excavated tailings have greater exposure to oxidation
Geotechnical stability	Will be likely to be reduced by the use of tailings for wall raises	A high phreatic surface within an upstream raise constructed using tailings will reduce geotechnical stability An upstream raise constructed using tailings may be more susceptible to liquefaction under significant seismic loading
Seepage	Tailings used for wall raising will have a relatively low permeability, limiting seepage	Seepage control measures are more difficult to incorporate within successive wall raises
Contaminants	Drying tailings and their elevation in raises reduces water available to transport contaminants	Excavation of tailings and their use in raises exposes potentially acid-forming tailings to oxidation
Erosional stability	Cover over tailings wall raises is specifically intended to provide erosion protection	Limited cover or cover material that is not well-graded over tailings wall raises may be prone to erosion loss in the longer term
Rehabilitation	Relatively flat outer batter slopes of tailings wall raises lend themselves to rehabilitation by placement of additional borrow material at the same slope angle	Limited cover over tailings raises places limitations on future reshaping options Additional borrow material is likely to be needed to achieve optimal cover depth, final profile and surface treatment Reshaping for rehabilitation purposes will be likely to increase the footprint

6.5 Construction for closure, rehabilitation and aftercare

The construction requirements and methods employed for closure, rehabilitation and aftercare may differ markedly from those employed for TSF operations. Closure and rehabilitation works require that the final TSF landform be made safe, stable and non-polluting, with a sustainable landform and cover system where applicable. TSF embankment raises should be configured in a fashion that anticipates and accommodates the final TSF landform. Final outer TSF embankment slope profiles should be based on consideration of the erodibility of the face material, catchment size and design rainfall intensity.

Specialist and small-scale construction equipment may be needed to achieve subtle landform and cover features. Suitable slope cover materials need to be selected and placed, and the surface shallow contour ripped to create the specified mixture of surface material textures required to provide erosion resistance and water-holding capacity to establish and sustain revegetation in the longer term.

The construction of the closure spillway, ideally through natural rock, as dictated by the hydrology, requires specialised construction equipment and methods. The associated sediment pond may require the construction of a liner.

The design, construction and maintenance of cover systems over geochemically reactive tailings are particularly specialised, whether they involve wet covers or soil covers, and whether or not the soil covers are rainfall-shedding or store-and-release cover systems. The cover systems need to minimise erosion and prevent exposure of the underlying reactive tailings, in addition to minimising oxygen ingress and the net percolation of rainfall into the reactive tailings.

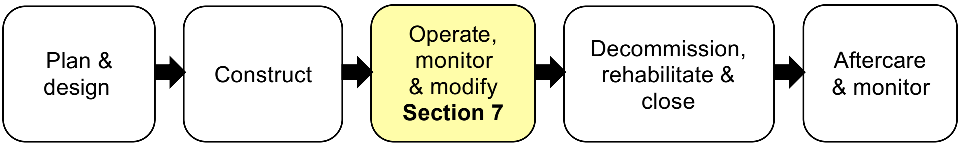
Aftercare involves the construction of boreholes for monitoring groundwater quality (where they have not previously been installed for operational monitoring purposes) and the installation of instrumentation for monitoring cover performance and seepage rates and quality. Monitoring boreholes need to be carefully constructed, cased and sealed to isolate the depth intervals of interest for monitoring. Boreholes can be monitored and sampled manually, although automatic, semi-continuous monitoring and downloading are preferred.

Depending on the complexity of the cover system and the resulting closure completion criteria, the monitoring of cover performance may include the installation of a full and automated climate station, the construction of lysimeters for the collection of net percolation, and strings of water and matric suction sensors installed through the cover thickness and into the underlying tailings to monitor the water balance of the cover system and tailings over time. Lysimeters should preferably drain under gravity to tipping buckets that automatically record net percolation rates. The climate station, lysimeters and water and suction sensors can be automatically and semi-continuously downloaded via telemetry.

Monitoring programs for groundwater and surface water down-gradient of the TSF should include in the list of analytes calcium, magnesium, pH, EC, sulphate, acidity, alkalinity, metals (applicable to the geochemistry of the ore) and process reagents, including sodium for sodium-based process reagents such as sodium cyanide for gold ore tailings.[16]

16 Further details on TSF closure and rehabilitation are in Section 8.5 and in the *Mine closure* (DIIS 2016a) and *Mine rehabilitation* (DIIS 2016e) leading practice handbooks

7.0 OPERATION



Key messages

- Tailings storage facilities should be operated to ensure that their performance meets or exceeds regulatory requirements and design criteria.
- Good tailings management generally includes diverting clean rainfall run-off; discharging the tailings as thick as can effectively be managed; spigotting the tailings in thin layers and cycling deposition between a number of cells; maintaining a small decant pond; and having separate evaporation or tailings water storage ponds.
- The principal objective of a TSF is for tailings solids and any stored water to remain contained in such a way as to cause no measurable health and safety or environmental impacts or operational interruptions.
- Leading practice tailings management can demonstrate clear operational accountability at a senior mine management level at all times, with a thorough understanding of the design, operating and closure objectives.
- All TSFs and associated pumping and pipeline systems should be inspected on a daily basis as a minimum.
- The pre-disposal recovery of tailings water is an effective means of maximising the recovery of water and residual process reagents for recycling to the processing plant.
- To ensure optimal performance, the TSF should be reviewed throughout the year, using a risk-based approach, by an appropriately qualified geotechnical engineer experienced in tailings management and dam design.
- All TSFs should have an emergency action plan that ensures prompt and effective responses to any leading indicators of potential impacts or dam failure.

7.1 Leading practice tailings management

Leading practice tailings management generally includes diverting clean rainfall run-off around the TSF; discharging the tailings as thick as can effectively be managed; spigotting the tailings in thin layers and cycling deposition between a number of cells (Figure 17(left)); maintaining a small decant pond to maximise dewatering (Figure 17(right)), desiccation, densification and strengthening of the tailings; and having separate evaporation or tailings water storage ponds (Williams 2014). However, PAF and otherwise potentially contaminating tailings may benefit from being kept under water, which restricts desiccation.

Figure 17: Leading tailings management: (left) spigotting tailings in thin lifts; (right) maintaining a small decant pond

Given that tailings are conventionally deposited as an aqueous slurry and will drain down during operations and after closure, their successful rehabilitation requires that the potential for tailings seepage to contaminate the environment be minimised. Where there is a high potential for environmental impacts from particular stored tailings, it may be necessary to consider chemical treatment and/or the eventual physical containment of the tailings, perhaps in-pit below the groundwater table. Examples of the chemical treatment of potentially contaminating tailings include:

- desulphurisation of sulphidic tailings to reduce their acid-generation potential
- lowering of the pH of red muds by seawater addition or by carbonation using CO^2 sourced from the alumina refinery stacks to reduce aluminium and trace metal concentrations, to reduce the crusting of the tailings and to enhance drying
- neutralisation by combining waste streams of opposing pH (for example, combining PAF tailings with alkaline power station fly-ash or red muds).

7.2 Operational risks

The principal objective of a TSF is for tailings solids and any stored water to remain contained. Failure modes and risks to public health and safety, the community and the environment during operation of a TSF could include:

- rupture of the tailings slurry delivery pipeline or decant water return pipeline
- rainfall-induced erosion or piping of the outer tailings face

- geotechnical failure or excessive deformation of the containment wall

- overfilling of the TSF with tailings, leading to overtopping of the containment wall by water
- seepage through the containment wall, potentially leading to tree deaths

- contaminated seepage into the foundation, with impacts on the groundwater
- particulate (dust) or gaseous emissions (such as radon, hydrogen cyanide,[17] sulphur dioxide and hydrogen sulphide

17 Environment Australia (1998) and the *Cyanide management* leading practice handbook (DRET 2008).

- exposure of birds, wildlife or livestock to potentially contaminated decant water that ponds on the surface of the TSF
- exposure of wildlife or livestock to soft tailings in which they may become trapped.

7.2.1 Managing change

The risk-based approach must be applied to the operational phase of tailings management to ensure appropriate and adequate responses to deal with changing constraints, conditions and/or parameters. The changes may include ever-changing climatic conditions, changing demands for tailings storage volume, changes in the nature of the ore and hence the nature of the tailings, changing demand for water, changing regulatory requirements and community expectations, and the potential for the prolonged suspension or premature closure of the operation.

7.3 Operational controls

Leading practice tailings management demonstrates clear operational accountability at a senior mine management level, with a thorough understanding of the design, operating and closure objectives. The implications of not operating in accordance with the design intent and design criteria must be clearly understood.

A tailings operating manual is required for each TSF. The manual must be aligned with the design objectives of the facility and the key engineering and operational risk controls. It is intended to guide and assist the TSF operators with daily operation, as well as with forward planning of the facility's operation and maintenance. Using suitable reference drawings and sketches to illustrate important operating features, principles and limitations, the operating manual should describe the following aspects, and the operators should receive training in those that contribute to leading practice:

- principles of good tailings deposition and beach development—thin layers with maximum drying to maximise strength and minimise seepage
- correct management of the decant pond and efficient water recovery to maximise stability (Figure 18)
- examples of poor tailings management practices and their negative impacts
- the facility's daily operation and the frequency and correct method of changeovers
- operational procedures that require specific precautionary measures, such as the correct order of valve opening/closing to avoid blockages of tailings pipelines
- procedures for changing and flushing tailings pipelines
- the key leading indicators used to monitor the facility's successful operation, and each operator's role and responsibilities in support of the tailings management plan
- scheduled and preventive maintenance to keep critical equipment operational
- the importance of recording and storing monitoring and performance data
- the intended closure strategy and how the TSF can be effectively managed for its ultimate closure
- the need to report any exceptional, untoward or unexpected observations, particularly TSF embankment seeps, cracking and erosion, to a supervisor
- the need to follow through with early responses to prevent the escalation of minor issues
- ultimately, if and where necessary, emergency and risk management actions that are required to ensure that all people who may be affected are safely evacuated before the anticipated failure of a TSF.

Figure 18: Minimising decant pond

7.3.1 Safety management and emergency preparedness

A safety management plan should exist for any dam where there is a potential for loss of life in the event of a dam failure (ANCOLD 2003).

The TSF safety management plan relates to:

- risks identified for the facility
- public health and safety, community and environmental risks and necessary controls to ensure the integrity of the operation
- the surveillance and maintenance program to ensure the ongoing integrity of the various structural components.

The emergency action plan (UNEP 2001):

- identifies conditions that could result in an emergency, such as a severe storm
- describes procedures to isolate people from hazards, including the warning and evacuation of downstream communities
- identifies response plans to mitigate impacts, such as clean-up plans
- identifies the resources needed to implement the emergency action and response plans
- identifies emergency response training requirements for key people
- documents the location of emergency warning alarms and their maintenance requirements to ensure serviceability at all times
- through the effective implementation of the safety management plan in the event of a failure, ensures that appropriate actions are taken to minimise the safety risk to people on and off the site, and that impacts are minimised by an organised and systematic response to the incident.

7.3.2 Containment wall inspections and monitoring

All TSFs and associated pumping and pipeline systems should be inspected daily, as a minimum (ANCOLD 2003). Observations should be recorded. Any extraordinary observations or maintenance requirements must be documented and appropriate action taken, including reporting to regulators and the community. The inspections should include assessments of:

- the position and size of the decant pond and observations relating to freeboard requirements (the water level compared to the dam crest height)
- lead indicators, such as damp patches, seepage and erosion, by visual and operating checks
- the status of leak detection systems

- the status of secondary containment systems
- the status of automatic flow measurement and fault alarms
- the condition of pump and pipeline systems
- impacts on birds, wildlife or livestock, particularly birds that may be affected by tailings water consumption.

The monitoring of TSFs should include:

- piezometers in TSF embankments to monitor the phreatic surface against agreed trigger levels to maintain embankment stability
- piezometers and bores to monitor groundwater mounding and outward movement beneath and surrounding the facility
- surface water and groundwater quality sampling both upstream and downstream of the facility to check against agreed trigger levels
- rehabilitation trials and monitoring of closure strategies, including slope treatments and covers, and revegetation performance.

Monitoring reports should be prepared annually and reporting should be accessible, easily understood and transparent to stakeholders. Provisions need to be made for the containment of tailings along delivery pipelines and within the TSF at all times, supported by timely and appropriate maintenance in response to inspections.

7.3.3 Tailings water management and recovery

The net water flux from tailings, whether it be net infiltration during tailings deposition or net evaporation during drying (Figure 19), needs to be determined so that the potential for seepage and/or spillway flow and the requirement for extreme storm freeboard capacity can be established. Monitoring the phreatic surface within the tailings alone will not inform the direction of flow, particularly once the phreatic surface drops below the tailings deposit after closure. Importantly, the suction profile should be monitored (either directly or via measurements of the moisture content profile) to determine the direction of flow, which might not be downwards or outwards.

Inputs to an operational TSF water balance are tailings water, of which a proportion remains entrained, rainfall, run-off and any storage of mine-affected water on the TSF (although leading practice is for this to be minimised). Water losses from an operational TSF include evaporation from ponded water, supernatant water flowing over beached tailings, and wet and drying tailings; and seepage into the TSF foundation and through the TSF embankment. The operational tailings water balance is given by:

$$\boldsymbol{TW + RR + WW = RW + EW + SE + SF + SW} \qquad [1]$$

where ***TW*** is the tailings input water, ***RR*** is the TSF catchment rainfall and runoff, ***WW*** is the net (added - removed) waste water stored on the TSF, ***RW*** is the water recycled to the processing plant, ***EW*** is the entrained water, ***SE*** is the surface evaporation, ***SF*** is the seepage into the foundation, and ***SW*** is the seepage through the wall.

A schematic of an operational TSF water balance is illustrated in Figure 20 for a TSF with a central decant, together with an operational water balance flow chart in Figure 21. A phreatic surface will develop within the tailings during deposition, which is likely to remain perched within the tailings. Infiltration into the foundation will be likely to cause the original groundwater table to mound. Seepage from the tailings is also likely to emerge from the toe of the wall, and a seepage recovery well may be needed to direct it back onto the TSF.

Figure 19: Evaporative, no-flow and infiltrative fluxes within tailings

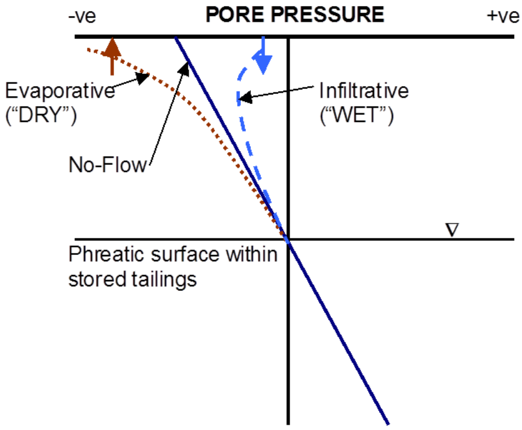


Figure 20: Schematic of operational tailings storage facility water balance

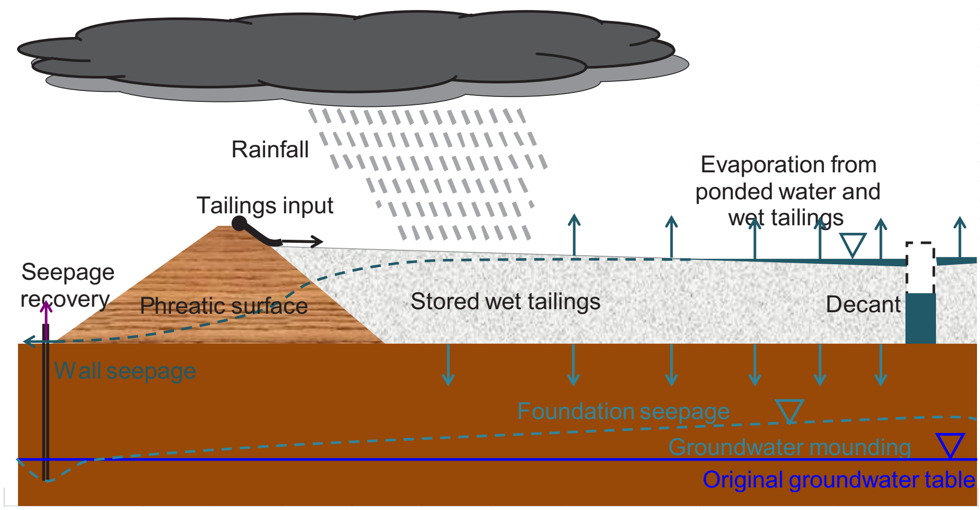
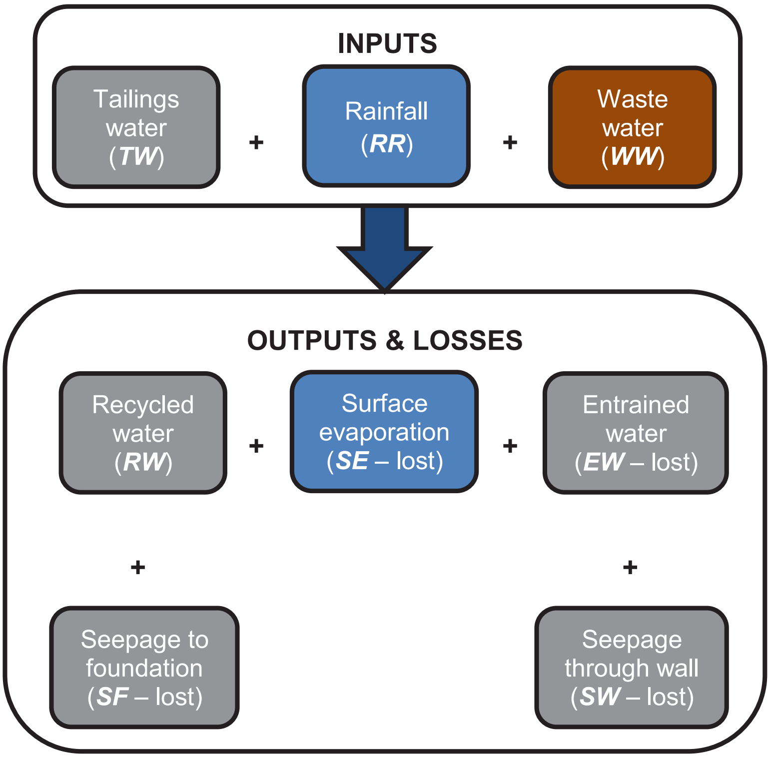


Figure 21: Flow chart of operational tailings storage facility water balance



Typically, the best known water volumes are the initial solids concentration of the tailings, rainfall, and possibly the evaporation from ponded water, depending on the accuracy of mapping of its extent and the reduction in evaporation due to possible salinity of the tailings water. Water volumes that can be determined with some difficulty include water entrained within the tailings; rainfall run-off; any net input and storage of waste water; and evaporation from ponded water, supernatant water flowing over beached tailings, and wet and drying tailings. Water volumes that are least well known are seepage into the TSF foundation and through the TSF embankment.

The operational tailings water balance is influenced by water quality, which dictates whether the tailings supernatant water can be recycled to the processing plant and governs the potential for environmental impacts via bird deaths and through seepage, and entrainment and evaporation losses.

For an arid climate, evaporation dominates the operational tailings water balance, accounting for around 50% of total losses, while in a semi-arid climate evaporation may account for around 20%, and even less in a wet climate. Depending on the hydraulic conductivity of the tailings and the water losses, up to 50% of the water discharged with the tailings could be available for recycling to the processing plant if the water quality is suitable. TSF embankments constructed by the downstream method in dry (limited pond) and wet climatic conditions (permanent pond) are shown in figures 22 and 23.

Figure 22: Tailings storage facility embankment in a dry climatic setting

Figure 23: Tailings storage facility embankment in a wet climatic setting

The pre-disposal recovery of tailings water is an effective means of maximising the recovery of water and residual process reagents for recycling to the processing plant. The cost of the recovery of process water can be balanced against the cost of additional raw water for processing. The percentage of water recovery from a TSF depends on the tailings placement methodology and consistency, the tailings and water practices implemented, and the extent of resulting losses from the TSF. Table 8 gives an indication of the total water recoveries possible, depending on the level of thickening of the tailings before discharge, expressed as a percentage of the water discharged with the tailings.

Table 8: Total water recoveries possible in relation to tailings thickening level

TAILINGS CONSISTENCY	POTENTIAL TOTAL WATER RECOVERY (% OF WATER DISCHARGED WITH TAILINGS)
Slurry	50 to 60
Thickened	60 to 70
High slump paste	~ 80
Low slump paste	85 to 90

7.3.4 Mechanical dewatering of deposited tailings

Soft and wet tailings deposits, particularly clay mineral-rich tailings or process residues such as red mud formed during the refining of bauxite to form alumina, may achieve enhanced dewatering, densification and strengthening on farming by an amphirol and/or later by a D6 Swamp Dozer. An amphibious excavator can also be used to facilitate the drainage of supernatant water to the decant pond. An amphirol (Figure 24(left)) exerts a very low bearing pressure of 3–5 kPa and would be used first. The principles of tailings or residue farming by amphirol are as follows:

- Some drying and strengthening of the tailings or residue surface is required to allow safe and efficient amphirol operation.
- Too heavy a bearing pressure from the amphirol and/or too soft a tailings or residue surface leads to bogging of the amphirol (an amphirol will only achieve minimal consolidation or compaction of the tailings or residue since its bearing pressure is low).
- An amphirol should:
  - essentially 'float' over the tailings or residue surface
  - create trenches down the tailings or residue beach to facilitate the drainage of surface water
  - maximise the tailings or residue surface area exposed to evaporation and strengthening
  - expose undesiccated tailings or residue on further farming.
- An amphirol should not over-shear the tailings or residue by excessive or repeated farming (about four amphirol passes are optimal).

A D6 Swamp Dozer (Figure 24(right)) exerts a bearing pressure of about 35 kPa and can be used once the tailings or residue has gained sufficient shear strength and bearing capacity to safely support it. A dozer could be used after amphirolling or simply after the tailings or residue has desiccated naturally on exposure. Dozing improves the already desiccated tailings by compaction and by breaking up any cementation of the desiccated tailings, leading to a further increase in dry density and shear strength.

Figure 24: Farming red mud: (left) by amphirol; (right) later by D6 Swamp Dozer

The upper bound tailings dry density achieved due to self-weight is given by their specific gravity, typically about 2 (for coalmine tailings) to about 3 (for metalliferous tailings); that is, solids only with no voids. If the tailings are maintained underwater and the rate of rise is high (due to flooding and the footprint being too small for the tailings generation rate), the tailings may remain underconsolidated with a settled dry density as low as 0.5 t/m^3 or lower. If the rate of rise of the tailings is slow enough to allow self-weight consolidation, an average dry density of about 0.70 t/m^3 or higher is achievable under water.

To allow farming of the tailings, the surface must be free of water. Figure 25 shows schematics of the profiles of effective stress and shear strength with depth for self-weight only for a watertable at the surface, and self-weight and desiccation for a watertable at the surface and at 2 m depth, respectively. If the deposited tailings are always maintained below water, their effective stress and shear strength profiles will increase linearly with depth from zero at the surface of the settled tailings, at a rate dependent on their specific gravity and how long they are allowed to consolidate. A lowering of the watertable increases the wet unit weight and induces matric suction, in turn increasing the effective stress and the shear strength. Figure 25 clearly demonstrates that desiccation is far more effective than self-weight consolidation alone in dramatically increasing the effective stress and hence shear strength of the tailings. However, the desiccation effect diminishes exponentially with depth, and hence requires that thin layers of tailings be deposited and desiccated before the next layer is placed.

Figure 25: Schematics of profiles of effective stress and shear strength with depth

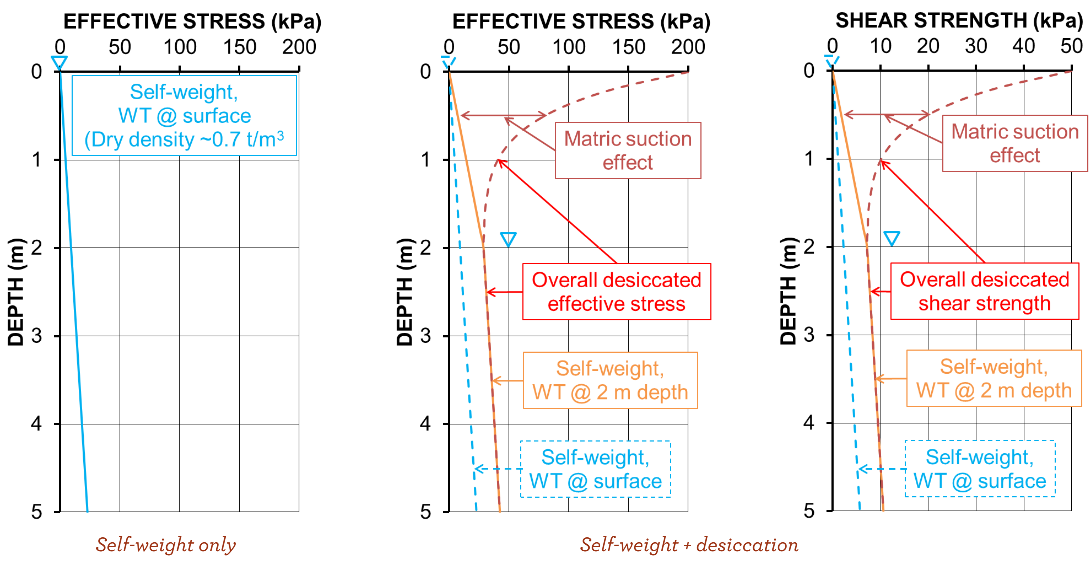


Figure 26 shows schematics of the effect on the tailings shear strength profile with depth of self-weight only, amphirolling wet residue, desiccation, and the placement of 2 m of fill, representing an upstream raise on farmed and desiccated residue once the excess pore water pressures generated by the loading have dissipated.

The height of a strip of fill (representing an upstream wall raise or capping layer) that can safely be placed by a D6 Swamp Dozer on desiccated tailings is given by conventional bearing capacity analysis as:

$$\boldsymbol{H = (N_c\, s_v) / (F\, \gamma_{fill} - H_e)} \qquad [2]$$

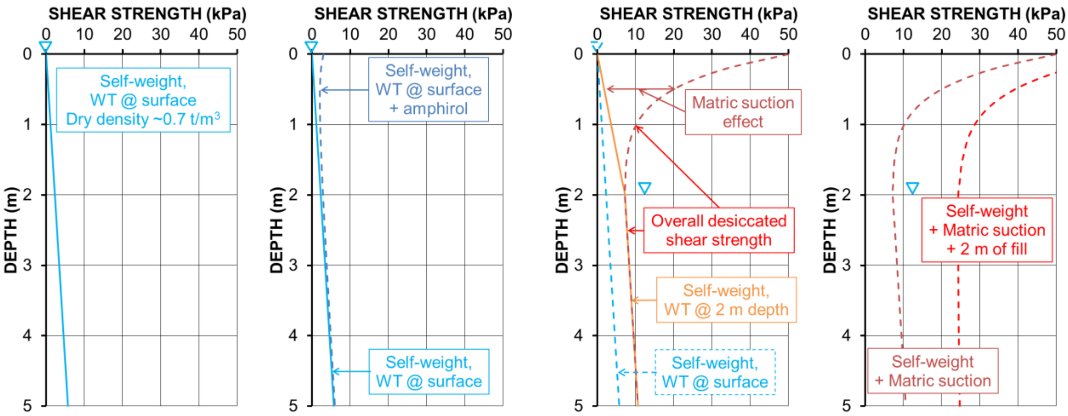
where $\boldsymbol{H}$ = safe fill height in m, $\boldsymbol{N_c}$ = bearing capacity factor (5.14 for a strip loading), $\boldsymbol{s_v}$ = appropriate vane shear strength in kPa, $\boldsymbol{F}$ = appropriate factor safety (perhaps 2), $\boldsymbol{\gamma_{fill}}$ = unit weight of fill (about 18 kN/m^3), and $\boldsymbol{H_e}$ = equivalent height of fill represented by a D6 Swamp Dozer (about 1 m).

The rate of dissipation of the excess pore water pressures generated by the applied loading is a function of the hydraulic conductivity of the tailings, which will decrease on settling and will decrease particularly dramatically on desiccation. It is likely that pore water pressure dissipation will take from days for settled tailings to weeks for desiccated tailings. The maximum increase in shear strength on the dissipation of the excess pore water pressures is given by:

$$\Delta\tau_{max} = \Delta\sigma' \tan \phi' \qquad [3]$$

where $\boldsymbol{\Delta\tau_{max}}$ = maximum increase in shear strength, $\boldsymbol{\Delta\sigma_v'}$ = increase in vertical effective stress due to the applied loading, and ϕ' = drained friction angle of the tailings (about 30°).

Figure 26: Schematics of profiles of shear strength with depth



(a) S-W *(b) S-W + A* *(c) S-W + D* *(d) S-W + D + F*

Figure 26(a) is for self-weight only for a watertable at surface; Figure 26(b) is for self-weight plus amphirol for a watertable at surface; Figure 26(c) is for self-weight plus desiccation for a watertable at 2 m depth; and Figure 26(d) is for self-weight plus desiccation plus 2 m of fill.

For placed fill of height $\boldsymbol{H}$ and unit weight $\boldsymbol{\gamma_{fill}}$ of 18 kN/m^3:

$$\Delta\tau max \sim 18\ H \tan 30° = 10\ H \qquad [4]$$

Desiccation and the placement of fill are the most effective means of achieving consolidation and strengthening of tailings.

7.3.5 Dust control

Dust generated from the surface of TSFs may be a public health risk and cause environmental impacts from airborne particulates and contaminants. It may be a key concern of neighbouring communities, which could include mine workers and their families. Unbound silty or sandy tailings are likely to cause dust problems during periods of high wind.

Tailings dust can be controlled by:

- spraying the surface with chemical dust-suppressants
- using pop-up sprinkler systems (as at Alcoa Kwinana)

- covering the tailings with a thin veneer of gravel (as at Mt Isa)
- using silt trap fences, although they need to be closely spaced and maintained to be at all effective
- discharging tailings to maximise the wetted surface (although this increases evaporative water loss)
- providing some degree of surface compaction using a dozer.

Tailings that form a hardpan due to accumulation of a high salt content may not create dust problems, unless disturbed by traffic. However, the potential for the salt crust to break down in the long term should be considered, as that may require a cover of benign material.

7.4 Annual reviews and reporting

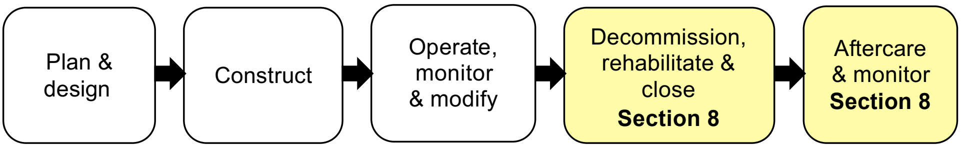
The performance of the TSF should be reviewed annually, using a risk-based approach, by a geotechnical engineer experienced in tailings management and dam design. The review should critically assess the actual performance against the design and make recommendations for improvements and risk mitigation actions. Such reviews are mandated by some regulatory authorities.

The review should consider:

- the stage construction performance against design—crest and beach levels, tailings tonnage stored and volume occupied
- confirmation of assumptions used in design—the assessment of stability under normal and seismic loading and design meteorological events, in situ tailings parameters (density, strength and permeability) and position of phreatic surface
- the performance of control measures such as underdrains (for seepage control), or internal filters (which control internal erosion or piping)
- liner condition, where a liner is used
- the performance of surveillance and monitoring systems—the status and condition of the monitoring systems, their performance in detecting changes in lead indicators (environmental and/or structural) and the analysis and evaluation of monitoring data against predicted trends
- groundwater monitoring results—comparison of the groundwater levels and quality against baseline data and against design and closure criteria, considering
    - near-surface lateral seepage, which may stress vegetation or destabilise a containment wall
    - vertical seepage, which may cause localised mounding beneath the storage
- operational performance—tailings deposition practices (thin layer deposition) and surface water control (minimum stored water and maintenance of required freeboard)
- assessments of operational incidents and recommendations for improvements or modifications to rectify and to carry lessons learned into future design and operation
- reviews of construction progress and processes against the existing closure plan to ensure that they continue to be aligned and are complementary.

Reporting should include operational, monitoring and incident reports, which are kept up to date and complete, in addition to the independent annual geotechnical engineering review. It is important that collected data and reports be securely stored and backed up, and that the electronic records be tamper proof and retrievable. This is particularly important to preserve corporate knowledge, given the high turnover rate of mine site personnel. In addition, data should be continuously plotted, with time to highlight sudden changes for checking against trigger levels.

8.0 REHABILITATION AND AFTERCARE



Key messages

- Tailings storage facilities represent a high risk to public health and safety and to the environment, both during operations and after closure.
- Exposed sediments on the tailings surface may be remobilised by wind and rainfall run-off, and AMD, salinity and any other contaminants may be transported by rainfall run-off or by seepage through the foundation and/or walls of the TSF.
- Once a 'platform' has been established on the surface of the tailings for safe construction activities, possibly constituting a future capillary break layer, a cover system may be constructed, whether it is a simple vegetative cover over benign tailings or a rainfall-shedding or store-and-release cover over potentially contaminating tailings.
- Ideally, surface tailings landforms should mimic surrounding natural landform analogues in their geometry, surface cover, surface texture and stability, to the extent possible.
- The minimum regulatory requirements and principal objective of TSF closure are that the TSF be decommissioned and rehabilitated to achieve a safe, stable, non-polluting structure with little need for ongoing maintenance.
- Community engagement is particularly important in the decommissioning and closure of TSFs.
- TSF closure and rehabilitation should achieve the agreed post-closure land use or functional ecosystem, with sustainable revegetation and biodiversity outcomes.
- A site-specific monitoring and maintenance plan should be followed to confirm that TSF closure has achieved the agreed TSF closure objectives and completion criteria.

8.1 Closure risks

The dominant mine-related risks to public health or the environment are from TSFs (Envec 2005). This is reflected in the high level of community concern about their operation, closure, decommissioning, rehabilitation and aftercare. Contaminants can be mobilised from these facilities through a number of mechanisms, including airborne transport (tailings dust can contain heavy metals and toxic compounds), mass movements of tailings in liquid or semi-liquid form, and waterborne transport as suspended solids and dissolved materials (Lacy 2005).

Failure modes and risks after closure of a TSF could include most of the operational failure modes and risks, apart from failure of the tailings delivery or return water pipelines. Additional post-closure failure modes and risks could include:

- rainfall-induced erosion of the outer face of the containment wall, which may expose and mobilise tailings
- failure of the spillway (if provided)
- overtopping by rainfall run-off, causing erosion of the containment wall
- failure of the cover system placed over the tailings surface, including failure to limit infiltration to the degree intended and failure to establish target levels of revegetation.

Exposed sediments on the tailings surface may be remobilised by wind and rainfall run-off; and AMD (see the following two case studies), salinity and other contaminants may be transported by rainfall run-off or by seepage through the foundation and/or walls of the TSF. Hence, the rehabilitation of the tailings surface generally requires some form of capping and cover system. However, the tailings may continue to settle, often differentially, at an exponentially diminishing rate long after deposition ceases. This will be driven by the ongoing self-weight consolidation of underconsolidated tailings, the ongoing desiccation and densification of exposed tailings, and the loading imposed by capping placed on the tailings surface. Further, the tailings surface may remain soft and inaccessible for construction equipment, particularly towards the decant pond where the finer grained tailings slimes will accumulate and beneath ponded water where desiccation cannot occur.

The closure of the TSF should be carefully considered as part of the mine closure plan to ensure that appropriate public health and safety, community and environmental criteria can be established for the design.[18]

Case study: Rehabilitation of TSF at Benambra Mine, Victoria

The Benambra Mine site in eastern Victoria operated as an underground base metal mine from 1992 to 1996. During operations, 927,000 tonnes of ore was processed on site, and nearly 700,000 tonnes of sulphidic tailings was transferred to a nearby TSF, which was engineered as a competent water-retaining structure. Following liquidation of the mining company in 1996, the site has been managed by the Victorian Government. Site rehabilitation works were conducted in 2006, with a key focus on the risk of AMD generation from the tailings (Earth Systems 2003).

18 Refer to the *Mine closure* (DIIS 2016a), *Mine rehabilitation* (DIIS 2016e) and *Community engagement and development* (DIIS 2016b) leading practice handbooks.

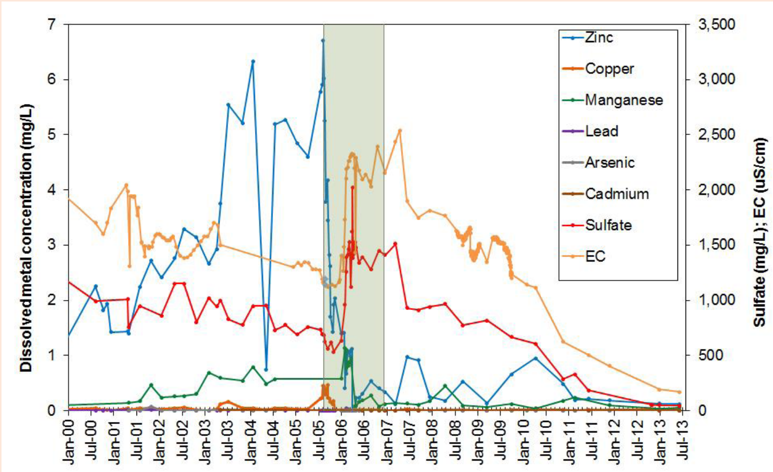
Before rehabilitation, the TSF contained about 160 ML of contaminated supernatant water and rainfall run-off, to depths varying from 0 to 8 m due to the irregular bathymetry of the tailings. The ponded water was near-neutral, with elevated metal concentrations and sulphate. Seepage from the TSF, flowing at around 1 L/s, was strongly influenced by the pond water quality, but with slightly acidic pH and a relatively high concentration of manganese.

Rehabilitation of the TSF involved creating a permanent water cover over the tailings with a minimum depth of 2 m to prevent AMD generation. The rehabilitation works included:

- reinstatement of the original creek alignments to direct water from the upstream catchment back into the TSF
- spillway construction to maintain a 2 m water cover, allow controlled overflow and ensure the long-term stability of the TSF embankment
- redistributing tailings to reduce variations in bathymetric depths and ensure a minimum 2 m water cover across the tailings surface
- covering the levelled tailings with a layer of limestone sand to minimise wave-based resuspension and oxidation of the tailings in the water column
- placing organic matter above the limestone sand to promote metal sulphide precipitation and contribute alkalinity to the water cover, to promote sulphate-reducing bacterial activity, and to further minimise the potential for oxidation by inhibiting dissolved oxygen migration into the tailings
- revegetating the TSF embankment to provide a constant supply of organic inputs to the tailings, promote sulphate-reducing bacterial activity and improve water quality
- constructing a 4:1 (H:V) slope on the downstream face embankment to ensure geotechnical stability in the event of extreme earthquakes
- adding alkalinity to the creek upstream of the TSF to raise its naturally acidic pH to near-neutral levels
- constructing an anaerobic vertical upflow wetland to passively treat seepage from the downstream toe of the TSF containment wall, with a design life of 20–30 years.

Key findings from tailings water monitoring since the completion of rehabilitation works in 2008 are as follows:

- The pH has effectively stabilised at near-neutral to slightly alkaline values, despite inflows of slightly acidic creek water.
- Dissolved metal concentrations (see figure below) have decreased by at least 90%—copper from 2.4 to 0.01 mg/L, lead from 0.44 to less than 0.001 mg/L, manganese from 1.3 to 0.05 mg/L, zinc from greater than 1 to 0.1 mg/L, arsenic from 0.068 to less than 0.001 mg/L, and cadmium from 0.014 to 0.0003 mg/L.
- The sulphate concentration has dramatically decreased, from approximately 2,000 mg/L in 2006 to less than 50 mg/L by 2013, with a corresponding reduction in sulphate load (mass) in the water body, from greater than 200 tpa in 2006 to around 15 tpa in 2013, indicating no evidence of AMD generation.



Trends in quality of water cover demonstrating success of rehabilitation (duration of works shown in green; after Earth Systems 2013).

The seepage from the downstream toe of the TSF embankment is now near-neutral, with dissolved metal concentrations generally below detection limits. This is attributed to the improved quality of the water cover, combined with effective operation of the downstream anaerobic wetland.

Decreasing copper concentrations have gradually permitted algal growth, encouraging frogs and waterbirds to return. Vegetation growth around the embankment will add carbon, and droppings from waterbirds are introducing new organic matter and phosphorus, which is expected to further improve water quality.

Aquatic ecosystem gradually developing in water cover, with subaqueous vegetation evident alongside the water's edge.

Anaerobic vertical upflow wetland downstream of TSF embankment.

Case study: Rehabilitation of Pond B at Henty Gold Mine, Tasmania

The Henty Gold Mine is located at 550 m above sea level in the mountains of Tasmania's rugged west coast—a sensitive alpine region receiving average annual precipitation of 3,600 mm. The mine's location resulted in stringent operating conditions and government regulations being set for the mining and processing operations.

The underground mine commenced production in 1996, originally operated by Placer Dome, which became Barrick Ltd in 2006. Unity Mining Ltd took ownership in 2009. Initially, the operation planned for a five-year mine life, but the discovery of additional ore resources extended the mine life to late 2015.

Tailings from the mine were initially stored in the Pond B leach residue storage facility, which consisted of a 'turkeys nest' downstream, zoned earth and rock fill embankment constructed using material sourced from underground development and onsite borrow areas. Pond B operated from 1997 to 2001 before reaching its capacity of 700,000 tonnes of tailings produced from the cyanide leach process. The potential for acid generation in the leach residue was identified as low.

GHD was involved in investigation, design and construction of Pond B during the operational phase and was subsequently engaged in 2002 to provide closure designs and construction services that developed a unique partial soil/water cover system over the tailings (named 'mushy closure' by the mine operators). The brief for the closure required a final landform that would meet the following strict criteria and objectives:

- safe, stable, non-eroding
- natural, visually pleasing lines

- partial vegetative cover conforming with the surrounding landscape, allowing re-establishment of the original ecosystem
- low maintenance, progressing to zero maintenance in the medium to long term.

The cover was constructed from January to April 2002. Borrow materials were obtained from stockpiled peat from the construction of Pond B and from the clearing for a new leach residue storage facility. The non-organic borrow materials were used to profile the downstream slopes of the Pond B embankment to form a 'tarn-like' (mountain lake) landform in keeping with the surrounding topography. Peat borrow material was used to form the soil cover, and waste rock access fingers were pushed out into the area to have a permanent water cover. The mushy closure took the conservative approach of assuming that the leach residue was acid-generating, and maintains the leach residue either below the permanent water cover or below the saturated soil cover.

Henty Gold Mine Pond B after rehabilitation.

Monitoring of Pond B water quality since operations commenced in 1996 has shown that the supernatant water is low in sulphate and dissolved metals. The seepage from Pond B also has low dissolved metal concentrations, but higher sulphate concentrations. Sulphate concentrations in the water cover have shown a rapid decline since the completion of cover construction, from about 800 mg/L to less than 50 mg/L.

Closure criteria for the TSF should be reviewed in consultation with the community during the operating phase, and the tailings management plan (including design modifications) revised accordingly.

The leading practice approach to TSF closure planning clearly defines, at the earliest possible stage in the design, the post-closure land use and the final closure landform and then demonstrates the commitment to achieve these goals through regular transparent reporting against lead indicator criteria and community consultation (Bentel 2009). Leading practice also demonstrates a commitment to achieving stable and self-sustaining landforms by testing closure engineering and revegetation concepts well before closure occurs so that the closure design can be confidently and cost-effectively engineered.

Critical closure-related design considerations relate to geotechnical and landform surface stability and pollution control through the design and construction of effective surface covers and treatments.

Careful consideration must be given to:

- post-closure land use and final landform—consideration must start in the design phase and continue throughout the life cycle through to stakeholder consultation during closure planning
- characterisation and inventory of the materials required to complete the closure—considering materials available, their physical and geochemical characteristics and an understanding of their attributes with regard to infiltration control, armouring potential and suitability as a revegetation substrate
- financial provisioning—which may be an appropriate probabilistic financial model to fully consider possible ranges of closure costs, footprint size and cover thickness (including sourcing acceptable and sufficient cover materials), events (such as storms and earthquakes), scheduling (design, construction and post-closure monitoring and maintenance), on and off facility drainage measures, project risks (for example, more stringent criteria than those assumed) and the costs of trials to avoid significant underestimation of the required financial provision (Bentel 2009);
- aftercare monitoring and maintenance plan—listing all post-closure criteria and scheduling tasks and activities required to measure key post-closure impact and sustainability indicators.

The aftercare monitoring and maintenance plan may include quantities and rates of release of solutes and vegetation regrowth (species, density and weed management). The post-closure monitoring period is site dependent, but is determined by the period required to confirm that no unacceptable detrimental impacts are occurring or could occur after completion. The plan must also detail post-closure accountabilities, responsibilities, schedules and financial provisioning for monitoring activities, reporting, consultation and maintenance, if required.

8.2 Closure objectives

The principal objectives of TSF closure, decommissioning and rehabilitation are to leave the facility safe, stable and non-contaminating, with little need for ongoing maintenance. In some cases it will be possible to enhance the value of mined land to create a modified landscape that offers recreational, commercial or natural value that can be enjoyed in the future. TSF closure and rehabilitation should always aim to establish sustainable ecosystems, with sustainable revegetation and biodiversity outcomes analogous with the original land values. To achieve such outcomes, it is essential that post-mining land use and ecological function objectives are developed and agreed with regulators, the local community and stakeholders.

The *Strategic framework for tailings management* (MCMPR–MCA 2003) considers the following objectives when planning the final TSF landform:

- containing/encapsulating the tailings to prevent their escape to the environment
- minimising seepage of contaminated water from the TSF to surface waters and ground waters
- providing a stabilised surface cover to prevent erosion from the TSF
- creating a substrate conducive to the establishment of appropriate revegetation
- designing the final landform to minimise post-closure maintenance.

Factors to be considered when planning the closure, decommissioning and rehabilitation of a TSF include:

- ore type and geochemistry, which will dictate the potential for the tailings to contaminate, taking into account the variable nature of the ore

- the crushing and grinding approaches and process reagents used for ore extraction, which dictate the particle size distribution of the tailings and the pore and seepage water quality
- the quality of the water after processing
- tailings disposal technique
- operating the TSF in preparation for closure (for example, depositing benign tailings or discharging centrally to create a water-shedding surface)
- the environment and climate in which the TSF is located
- post-closure land use
- closure cost estimation
- long-term landform stability, including geotechnical and erosional stability
- managing surface run-off and ponding on the tailings, which will affect seepage, and the need for a closure spillway
- off-facility drainage and clean water diversion measures
- suitability and proximity of closure materials
- long-term seepage to the environment of potentially contaminated tailings water
- potential for dust generation before, during and after rehabilitation
- the need for, and the desired function and selection of, cover systems for the tailings
- surface treatment and vegetation of the tailings
- profiling, surface treatment and vegetation of outer batter slopes
- perimeter requirements, including drainage requirements, long-term seepage interception and access ways, which may be affected by reprofiling.

Each site will have specific commitments relating to the closure of a TSF, based on the outcomes of technical studies and agreements with landowners and regulatory agencies. These commitments should be reviewed before finalising the closure design. Active stakeholder engagement is an important part of the process, enabling the mining company to present closure plans, listen to feedback from key stakeholders and refine plans to a point where community acceptance and government endorsement are achieved.

Technical closure issues generally relate to geotechnical, geochemical, hydrological and environmental aspects, requiring a multidisciplinary team approach.[19] TSF closure, decommissioning and rehabilitation require a staged approach, involving:

- stakeholder engagement (discussions, site visits and document review)
- sampling, investigations and research to define tailings and rehabilitation materials (this knowledge is then used to resolve closure issues)
- preparation of a draft decommissioning plan for submission to regulators and other to other stakeholders
- preparation of a final decommissioning plan, which includes stakeholder feedback and the most recent technical data and studies
- decommissioning and rehabilitation of the TSF and preparation of a final decommissioning report
- monitoring, aftercare and sign-off.

19 Examples of common issues encountered and possible closure options are in Appendix 2 of the *Mine closure* leading practice handbook (DIIS 2016a).

8.3 Community engagement

Community engagement is particularly important in the decommissioning and closure of TSFs, at which time stakeholder consultation, information sharing and dialogue should intensify, although it should be initiated during the planning phase of the project and continued thereafter. This will enable stakeholder viewpoints, concerns and expectations to be identified and considered in the planning and execution of TSF decommissioning and closure. The greater the uncertainty, the more proactive the approach that is required.[20]

8.4 Post-closure tailings water balance

Inputs to a post-closure TSF water balance are normally limited to rainfall and run-off (unless the facility is used as a periodic or emergency water storage facility). Hence, water losses from a TSF after closure normally include spillway overflows, evaporation from ponded water, wet tailings and desiccating tailings, plus seepage into the TSF foundation and through the TSF embankment. The post-closure tailings water balance is given by:

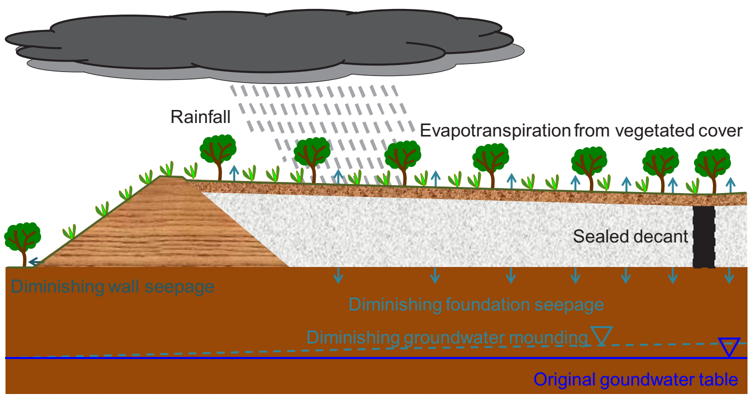
$$\boldsymbol{RR = SO + EW + SF + SW + SE} \qquad [5]$$

where ***SO*** is the spillway overflows, and ***EW*** is the residual entrained water. (other terms are defined on page 69).

A schematic of a post-closure TSF water balance is illustrated in Figure 27, showing a sealed central decant and a vegetated cover over the tailings and wall. The phreatic surface within the tailings will be likely to drain down after closure, and the foundation and wall seepage flows will be likely to diminish exponentially with time, with some recovery following periods of heavy and prolonged rainfall. The mounding of the groundwater table will also tend to diminish with time.

Post-closure TSF water balance issues include water quality, dictating whether or not spillway overflows can be discharged directly to the environment or require treatment, and ongoing seepage, which would be expected to diminish as the tailings drain down, but would be recharged by rainfall run-off that is not spilled. Drain-down of the tailings would expose them to oxidation and potentially contaminate run-off and seepage.

Figure 27: Schematic of post-closure tailings storage facility water balance



20 Principles and practices for stakeholder engagement are covered in the *Community engagement and development* (DIIS 2016b) and *Working with Indigenous communities* (DIIS 2016c) leading practice handbooks.

8.5 Post-closure landforms

Ideally, surface tailings landforms should mimic surrounding natural landform analogues in their geometry, surface cover, surface texture and stability. TSFs on flat terrain, such as the geologically old, arid to semi-arid inland of Australia, are relatively shallow and cover a relatively large area (Figure 28). Even in a naturally flat topography there is some vertical relief. This typically involves relatively low mounds extending over large areas—a product of the long periods of weathering and erosion that sculpt the flat landform.

Figure 28: Shallow, extensive tailings and natural elevated tailings landforms

In a dry climate, where vegetation cover is naturally limited, the sustainability and erosion-resistance of slopes is dependent on a rocky surface texture that is vegetated, at best, by sparse shrubs. For semi-arid conditions, the tops of tailings landforms may be revegetated, either directly or after the placement of a suitable cover (Figure 29(left)). In such cases, the ability to retain water on the TSF landform following extreme rainfall should be considered to avoid erosion of the outer slopes on overtopping. In arid conditions, the dished tops of tailings landforms resemble elevated saltpans, analogous to natural saltpan depressions that are covered by fine-textured soils and vegetated only by sparse salt-tolerant species (Figure 29(right)). However, consideration must be given to the possibility of dust entraining metals emanating from uncovered or poorly vegetated tailings surfaces.

In an arid climate, closed TSFs will desaturate and are likely to maintain a net upward flux of water, driven by evaporation. Any downward water flux following high rainfall is likely to be limited (unless significant ponding occurs), with evaporation driving a return to upward water flux before any significant percolation through the tailings occurs. This is analogous to the water flux of natural saltpans, which give rise to very limited and slow recharge to the ground.

In a wetter climate, to avoid the percolation of potentially contaminated tailings water to the toe of the TSF or to the ground, it may be necessary to provide a permanent spillway to remove run-off from heavy rainfall. The spillway should, where possible, be excavated through natural rock or be concrete-lined. The run-off will need to have sufficient residence in a sediment pond to allow any suspended solids to be collected and may need treatment to ensure acceptable water quality before release. The potential for erosion and degradation of a spillway and the need for water quality management imply the probable need for ongoing maintenance.

Figure 29: Direct revegetation on tailings: (left) revegetation in a semi-arid climate; (right) salt-tolerant revegetation in an arid climate

All landforms erode over time, and TSFs are no different. The objective is to create final TSF landforms that erode at a very slow rate, which the receiving environment can assimilate. As a consequence, stored tailings should be encapsulated by a thick surround of benign material and covered by rock and vegetation that limit erosion loss. Further, run-off from the top of the tailings landform should not be directed over the outer slopes, but be evaporated or transpired by vegetation or directed to a purpose-built spillway, recognising that post-closure maintenance of the spillway is likely to be required.

Most TSFs are constructed on the surface and therefore form an elevated landform, making them highly visible and also providing the potential for erosion. TSFs should therefore be planned, designed, constructed and rehabilitated with aesthetics and erosion potential in mind. The likelihood that the TSFs will expand during the operation of the mine and processing plant should also be carefully considered. The final tailings landform should be aesthetically acceptable, present negligible public health and safety risks, and present an acceptably low risk of future harm to the environment.

There is increasing regulator, community and minerals industry pressure for TSF final landforms to be less visible and for progressive rehabilitation and underground or in-pit disposal to occur, where possible. In cases where mining is advanced as a series of pits, the progressive filling of mined-out pits with mining wastes, including tailings, should be integrated into the mine plan.

8.5.1 Integrated landform construction

On most mine sites it is necessary (for safety, functionality and other reasons) to separate the various operational elements involved—open pits, underground workings, waste rock piles, TSFs, the processing plant and the office complex. However, it may be neither necessary nor desirable to completely separate waste rock piles and TSFs, and completed open pits and underground workings can safely and economically be used to store mining and processing wastes.

Waste rock dumps and TSFs may well be able to share a common wall and the two final landforms may be integrated, in some cases to the extent that a TSF is entirely encircled by the waste rock dump. Waste rock can be cost-effectively pushed into wet or desiccated tailings during dumping operations, creating a stable platform over the tailings on which the final cover may be constructed (Figure 30). This outcome will ensure that community and environmental interests and concerns can be met.

Figure 30: Waste rock pushed into desiccated tailings

8.5.2 Tailings capping and cover options

Uncovered potentially contaminating tailings present human health risks and social and environmental impacts, particularly if the tailings are prone to dust generation, rainfall run-off is allowed to pond directly over the tailings or the tailings surface remains soft. Possible tailings cover systems, in approximate order of increasing technical complexity and cost, are:

- direct revegetation of the tailings (see the following case study on the direct revegetation of the TSF at Kidston Gold Mine in Queensland)
- a thin layer of gravel placed directly over the tailings surface for dust mitigation
- a permanent water cover, wetland or saturated soil cover over reactive tailings in wet climates
- a vegetated cover aimed at shedding rainfall run-off in a humid climate
- a vegetated, non-shedding store-and-release cover, best suited to a dry or seasonally dry climate, aimed at minimising percolation by the release of stored wet season rainfall by evapotranspiration during the dry season
- a capillary break layer, overlain by a non-shedding, vegetated growth medium, aimed at controlling the uptake of salts into the growth medium to sustain vegetation, for application in a dry climate
- combinations of the above (Williams 2005; DIIS 2016e).

Any direct revegetation of the tailings or cover placed on the tailings will affect the net percolation into the tailings. The hydraulic conductivity of the tailings at depth, the hydraulic gradient and the entrained water in the tailings that is available to seep will dictate the potential for seepage into the foundation or through the TSF embankment. The hydraulic conductivity of the TSF foundation and wall will then dictate the pathways for any tailings water seepage and the relative seepage proportions that report to the foundation and the downstream toe of the wall. The higher the elevation of the TSF, the greater the potential hydraulic gradient that may be available for driving seepage into the foundation or through the wall. Any wall seepage will emerge at topographic low points around the perimeter of the TSF, coinciding with original drainage lines. With reduced water input to the TSF on the cessation of tailings disposal, the tailings will drain down at a rate that will diminish exponentially over time, and seepage rates will diminish accordingly, apart from when they are recharged by heavy rainfall or permanent ponding on the covered surface.

Case study: Direct revegetation of the tailings storage facility at Kidston Gold Mine, Queensland

Kidston Gold Mine, 260 km south-west of Cairns in north Queensland, was operated until 2001 by Placer Pacific. The climate is characterised by pronounced wet and dry seasons. On average, over 80% of annual rainfall (averaging 719 mm) falls between November and April in high-intensity storms and monsoonal rain. Mean daily temperatures are 18°C in winter and 33°C in summer.

Closure objectives for the Kidston Gold Mine included a self-sustaining savannah woodland vegetation of native trees and introduced and native ground cover species. The 310 ha TSF contained around 68 Mt of tailings deposited between 1985 and 1996. Early revegetation trials conducted in the early to mid-1990s demonstrated the capacity of the relatively benign tailings to support vegetation growth directly, without the requirement for a capping layer of soil or other cover material.

The TSF was decommissioned at the end of 1997 and, as the accessible area on the surface of the facility became progressively available (from March 1998 through to December 2001), planting and seeding of over 50 native tree and shrub species and eight introduced and native pasture species was undertaken. With the support of drip irrigation over the first few months and initial fertilisation, the alkaline tailings were proven to be a substrate conducive to the establishment of vegetation.

Early studies demonstrated that the use of tube stock was likely to be a successful means of initially establishing the middle- and upper-storey components of the vegetation community on the tailings. Broadcast seeding trials of native species on tailings in March 1998 proved to be successful, indicating that it was possible to establish woody species, particularly local ironbark species, from direct seeding on tailings. Numerous other research trials and monitoring campaigns were conducted to build confidence in the robustness of the strategy to directly revegetate the tailings, providing a cover that could support the presence of cattle.

Kidston Gold Mine tailings storage facility before the direct revegetation program (left) and a few years after (right).

Older section of revegetated Kidston Gold Mine tailings storage facility, seven years after planting and seeding.

The vegetation communities established on the Kidston tailings initially developed positively, contributing to a reduction in deep drainage and seepage from the downstream toe of the TSF embankment. However, over time the condition of the revegetation cover on the tailings has deteriorated due to a combination of overgrazing, mainly by cattle and brumbies, prolonged dry years, the free-draining nature of the sandy tailings, and the loss of nutrients from the upper tailings profile. Also, the seepage from the downstream toe of the TSF embankment has increased following heavy rainfall, and its quality has remained poor, with depressed pH and elevated dissolved metals and sulphate.

Some of the advantages and disadvantages of a range of alternative cover systems are summarised in Table 9.

Table 9: Advantages and disadvantages of alternative cover systems

COVER SYSTEM	ADVANTAGES	DISADVANTAGES
Direct vegetation	Low cost, if (benign) tailings support it and sufficient time for development of self-sustaining organic cover	May not be sustainable due to lack of nutrients and/or fresh water, or if net percolation needs to be limited
Thin gravel	Low cost, if dust suppression is the key aim	May not vegetate Will not limit rainfall infiltration and resulting seepage Reduces evaporation
Permanent water cover, wetland, or saturated soil cover over reactive tailings	Will limit oxygen ingress into tailings, limiting oxidation and AMD	Requires a net positive water balance climate or an adequate catchment and topography recharging TSF footprint to maintain sufficient water cover/saturation Already oxidised tailings will require lime addition to neutralise AMD May require a base liner
Rainfall-shedding	May limit net percolation by encouraging run-off Provides a vegetated cover in a humid climate	May deform due to differential consolidation of underlying tailings or desiccate in a dry climate, resulting in ponding and seepage of rainfall infiltration Likely to erode if revegetation is insufficient or seasonal and/or surface texture is erodible May require concentration of rainfall run-off in drains and spillways that will probably require maintenance
Store-and-release	Harvests rainfall to support a vegetated cover May limit net percolation to underlying tailings	Requires a significant thickness of growth medium over a base sealing layer Base sealing layer may be susceptible to differential consolidation of underlying tailings, which may also result in localised ponding of rainfall infiltration May fail if inappropriate or unsustainable vegetation is selected, or fauna traffic and grazing affects the integrity of the cover
Capillary break	May limit uptake of salinity into the overlying growth medium, allowing revegetation	An inappropriate or too thin a capillary break will allow salt uptake into overlying growth medium in an evaporative climate Too thin or too coarse-grained a growth medium will not hold water to sustain vegetation Quality control is vital, and angular material is often unsuitable as it allows ingress of overlying fines

The rehabilitation of soft tailings may require the initial hydraulic placement of capping material (Figure 31(left)) to establish a construction platform for completing the rehabilitation. Depositing the tailings at an appropriately low rate of rise and in thin lifts that allow desiccation between lifts (Figure 31(right)), or using paste or filter cake tailings, will allow earlier safe access for capping for rehabilitation purposes and higher value post-mining land use and ecological function.

The safe capping of tailings commences from the exposed upper part of the beach, generally using small-scale, low bearing pressure equipment, and proceeds onto softer tailings slowly and on a broad front (Figure 32), to avoid uncontrolled bow wave failures (Figure 33). Once a construction platform has been established on the surface of the tailings, a cover system may be constructed.

Figure 31: Examples of: (left) capping tailings hydraulically; (right) increasing the bearing capacity of tailings by depositing in thin lifts and desiccating

Figure 32: Capping tailings gradually using small-scale equipment: (left) surcharging tailings using small trucks; (right) pushing surcharge in thin lifts using a D6 Swamp Dozer

Figure 33: Capping tailings: (left) causing bow wave failure due to use of large mine-scale equipment; (right) loss of an excavator on too thin a cover over soft tailings

Most tailings covers follow the gentle slope (about 1%) of the tailings beach and hence are conventionally rainfall-shedding, generally towards a spillway constructed through natural high ground. If the tailings are potentially contaminating, the construction platform on soft tailings should be coarse grained and have no fines to form a capillary break and limit the potential for the uptake of any oxidation products and salts into the cover. Such a layer needs to be at least 300 mm thick to prevent surface evaporation induced capillary rise, and is generally made thicker than that to facilitate its placement and to provide a factor of safety against long-term infiltration of fines that would render it less effective. Depending on the hydraulic conductivity of the tailings, a compacted seal above the capillary break layer may or may not be required. If a compacted seal is provided, allowance must be made in the selection of the sealing material for the long-term differential settlement of the tailings, which may threaten the integrity of the seal. A surface growth medium would be provided, sloping in the direction of the underlying tailings beach slope.

A store-and-release cover (Williams 1997, 2005) may also be appropriate for a PAF or saline tailings beach. Given the greater thickness of a store-and-release cover compared with that of a rainfall-shedding cover, evaporative effects are unlikely to reach the depth of the tailings and a capillary break layer is unlikely to be required. However, soft tailings may require the placement of a construction platform and, depending on the hydraulic conductivity of the tailings, a compacted seal above the construction platform may or may not be required. A loose, rocky soil mulch layer with a mounded surface to capture rainfall and prevent run-off would be provided. Schematics of typical rainfall-shedding and store-and-release cover systems suitable for use on a potentially contaminating tailings beach are shown in Figure 34.

Figure 34: Schematics of typical soil cover systems suitable for use on potentially contaminating tailings beaches: (left) rainfall-shedding; (right) store-and-release

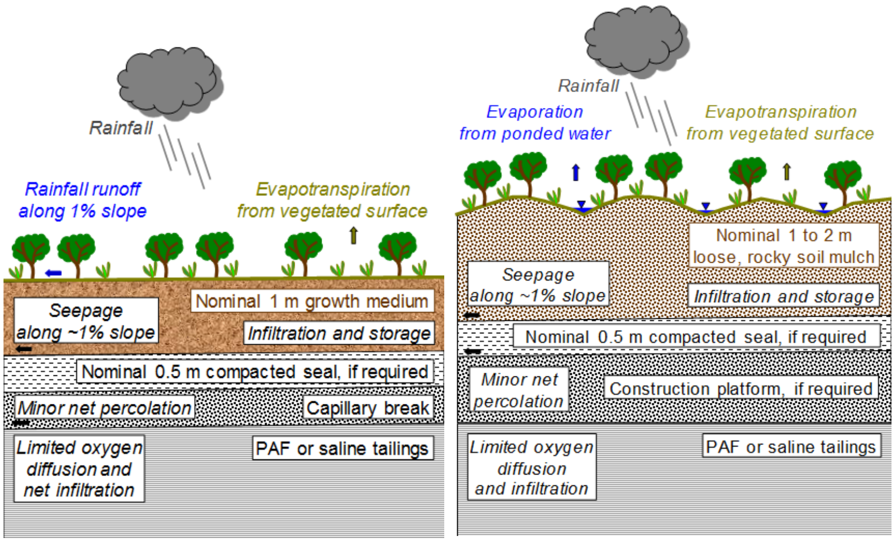


Figure 34a

34b

Note changed Figure 36a

Note changed Figures 37a and 37b

8.5.3 Treatment of containment walls

Most TSF containment wall outer slopes are now constructed at overall closure landform slope angles from 4(H):1(V) to 3:1. However, some outer slopes of older TSF containment walls, as well as containment walls constructed using waste rock dumped at its angle of repose, may still be at relatively steep slope angles from 2.5(H):1(V) to 1.5:1 at closure, which serves to minimise the TSF footprint and outer slope catchment size. Materials best suited to low-permeability containment wall construction often have high fines/clay contents, which may be erodible. Steep and/or erodible slopes may require reprofiling to provide a suitable closure profile.

Slope reprofiling and formal drainage measures may be required, together with armouring and revegetation of faces. Covers may be required on outer TSF slopes to limit net percolation (as described in Section 8.5.2), but they are difficult to sustain on slopes.

In dry climates that do not support an adequate or sustainable vegetative cover, the surface is often covered with benign rocky material for erosion protection (Figure 35). In wet climates, the outer slopes are generally topsoiled and revegetated.

Figure 35: Rock armouring and vegetation of outer face of a tailings storage facility

8.5.4 Water and sediment management

At the post-closure stage, deposited tailings will continue to drain down, potentially generating contaminated seepage into the foundation and through the wall. Drain-down seepage will continue regardless of whether a low net percolation cover is in place. However, rainfall run-off will pick up any transportable surface sediment and contaminants, which will be delivered towards the final spillway, or towards the centre of the facility if it has an internally draining concave design. In the discharging scenario, sediment may be captured in a sediment pond located on the tailings upstream of the spillway to avoid it spilling to the environment (Figure 36). Spillways are a very frequent failure point in closed TSFs, as they are often not designed and/or constructed to specifications that can withstand the high flows and velocities of periodic high-intensity rainfall.

Figure 36: Views of: (left) sediment pond located upstream of spillway; (right) spillway constructed through natural high ground

8.6 Aftercare monitoring and maintenance

A post-closure aftercare monitoring and maintenance plan must be prepared (see the following case study). The purpose of the plan is to ensure that the agreed post-closure objectives and completion criteria are being achieved. The aftercare period can demand greater resources and attention than is sometimes expected, but good-quality monitoring, maintenance, repair and refinements to improve the plan can increase the likelihood of the agreed post-closure objectives being met. This also enables progressive engagement with stakeholders where completion criteria require review and adjustment based on actual performance. The extent and duration of the aftercare period depend on the conditions at the particular site and therefore on the complexity of the closed site and its completion objectives and criteria, and in the case of closed TSFs is likely to last for at least 10 years.

Case study: Planning for TSF closure at Mt McClure, Western Australia

Mt McClure Mine is in the arid climate northern goldfields, 80 km north-east of Leinster in Western Australia. The Mt McClure gold operation commenced in 1991. The site was owned and operated by four different mining companies before coming under the control of Newmont Australia Ltd in 2002. The mine was bought by View Resources in 2005 after decommissioning works were completed by Newmont.

A carbon-in-leach plant processed ore at a rate of 1.2 Mtpa. The oxide and fresh rock ore (with some pyritic shales) was sourced from multiple pits, and tailings were placed in two storage facilities.

TSF 4, the subject of this case study, is circular with a radius of around 325 m and a surface area of 33 ha. It is surrounded by ROM waste 70–300 m thick. Discharge of tailings ceased in March 1999.

Aerial view of Mt McClure integrated TSF 4.

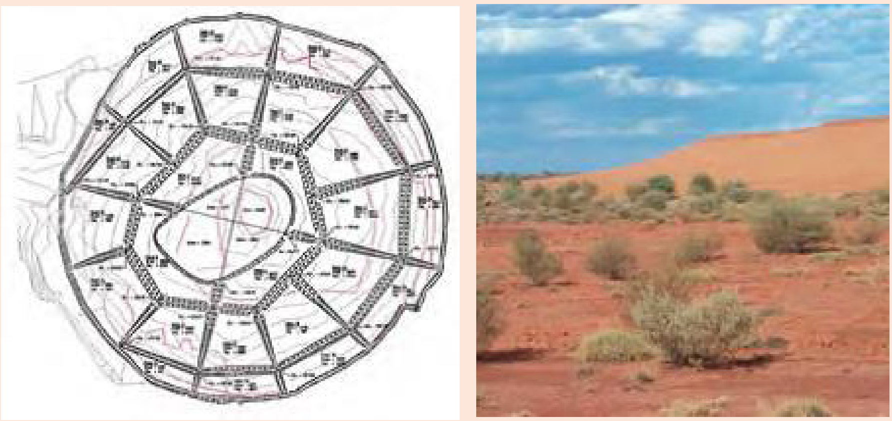
The decommissioning program for TSF 4 involved a staged program that identified future closure issues early in the mine life and management options to overcome those issues. Considerable attention was given to investigating and understanding the facility before decommissioning, and that led to an appropriate final closure design that included engineered covers and concave profiled embankment slopes. The five-step decommissioning approach described above was implemented.

A principal component of effective decommissioning is to identify present and potentially long-term risk issues. This information provides essential reference material and can guide the TSF decommissioning process towards an appropriate closure strategy. It requires a multidisciplinary approach to ensure that all significant risk areas are investigated. Four primary technical disciplines were identified: geotechnical, hydrological, geochemical and environmental.

The geochemical parameters of the tailings were found to be a key factor for closure of TSF 4. The tailings were found to be acid-producing, a situation which could lead to long-term impacts to the surrounding environment and groundwater system. The following risk mitigation strategies were developed in response:

- A 2 m oxide/saprolite tailings cover overlain by 0.5 m of laterite/cap-rock/topsoil was built. Field test work and column testing predicted that the water-holding capacity of this cover would be sufficient to restrict most rainfall from deep infiltration.
- The upper surface was designed with numerous individual smaller cells to contain rainfall within each cell. Much of the water that infiltrates into the cover is later released via evaporation and evapotranspiration.
- The angle of repose slopes were battered to a 20°/14°/8° concave slope, engineered to reduce run-off and minimise embankment erosion. A 0.5 m thick laterite/caprock cover was placed as an armour, followed by a thin topsoil layer, cross-ripped on the contour and seeded.

The earthworks were completed in 2004, and the TSF is now in the monitoring stage. During 2006, View Resources applied to the Department of Industry, Tourism and Resources for a performance bond reduction, which was granted. The application was submitted on the basis of demonstrated stability and continuing success in vegetation establishment and growth.



Plan showing surface cells to capture rainfall and minimise erosion on slopes (left); concave slope after topsoil had been applied in 2006 (right).

Monitoring requirements might include seepage quantity and quality, surface water discharge quality, air quality, net percolation performance, settlement, erosion and revegetation. This information can be used to identify areas where performance is inadequate to meet the completion criteria. Maintenance may involve erosion repair, reseeding, access management, and the reconstruction of drainage measures where grades have changed or drains have failed.

9.0 CONCLUSIONS AND FUTURE DIRECTIONS

Plan & design **Section 5** → Construct **Section 6** → Operate, monitor & modify **Section 7** → Decommission, rehabilitate & close **Section 8** → Aftercare & monitor **Section 8**

Key messages

- Enduring value, encompassing sustainable development principles and design to achieve successful closure, underlies the mining industry's social licence to operate.
- The failure or poor performance of a TSF can have a dramatically negative impact on surrounding communities and the environment, and can have a profound impact on the corporate bottom line and reputation and the social licence to operate.
- The main causes of reported tailings incidents are a lack of control of the water balance leading to overtopping, inadequate adherence to design, poor construction control, and a general lack of understanding of the features and good practices that control safe operations.
- Early and ongoing consultation, information sharing and dialogue with stakeholders are required during the design, operation and closure phases.
- Background and baseline conditions need to be established well before the commencement of operations for environmental impact and risk assessments.
- A risk-based design approach provides a framework for managing the uncertainty and change associated with TSFs and the potential environmental impacts.
- Key planning and design constraints on surface TSFs are the influence of the site climate, topography and drainage patterns; competing water and land users; and decreasing ore grades and finer grinding producing ever greater amounts of finer grained, low-strength tailings.
- Key risks presented by the construction of TSFs include the construction not following the design, inappropriate or insufficient construction materials, poor QA/QC, and tailings deposition and decant pond management not being compatible with the intent of the design.
- Good tailings management generally includes diverting clean rainfall run-off, discharging the tailings as thick as can effectively be managed, spigotting the tailings in thin layers and cycling deposition between a number of cells, maintaining a small decant pond, and having separate evaporation or tailings water storage ponds.
- To ensure optimal TSF performance, the TSF should be reviewed throughout the year, using a risk-based approach, by an appropriately qualified geotechnical engineer experienced in tailings management and dam design.

- Regulators now expect all TSF design submissions to demonstrate beyond reasonable doubt that sustainable outcomes will be achieved by the application of leading practice risk-based design that:
  - fully assesses the risks associated with tailings storage at the particular site
  - compares the suitability of all available storage methods, in particular those that dewater tailings before disposal and/or eliminate the requirement for the damming of surplus water within the TSF
  - demonstrates that the selected tailings storage method will manage all risks to within acceptable levels and as low as reasonably practicable.
- The pre-disposal recovery of tailings water is an effective means of maximising the recovery of water and residual process reagents for recycling to the processing plant.
- The minimum regulatory TSF closure objectives are a safe, stable, non-polluting structure.
- Agreed completion criteria for an agreed post-closure land use or ecological function require the establishment of a sustainable ecosystem, with sustainable revegetation and biodiversity outcomes.
- Ideally, closed surface tailings landforms should mimic surrounding natural landform analogues in geometry, surface cover, surface texture and stability, to the extent possible.
- A site-specific closure monitoring and maintenance plan should be followed to demonstrate that the agreed TSF closure objectives and completion criteria have been achieved.

9.1 Conclusions

A broad sustainable development framework must be applied to the initial design of TSFs, tailings management and TSF closure. Management systems incorporating an integrated LoM risk-based approach are needed to ensure that operating and closure objectives are met. There are many examples of leading practice available to assist mining companies to achieve a responsible outcome, some of which are documented in this handbook.

TSFs must provide safe, stable and economical storage of tailings so that the risks to public health and safety are negligible, and the social and environmental impacts during operation and after closure are acceptably low. A systematic approach to effective tailings management is advocated. Such an approach should include risk-based management strategies that take into account the viewpoints and expectations of the communities in which companies operate. Short-term cost savings aimed at minimising the costs of tailings management, storage and closure must be weighed against the potentially high social and environmental risks and associated high costs of long-term management of remediation if failure occurs or if successful closure cannot be achieved.

Many challenges must be overcome to achieve a leading practice tailings management outcome. Tailings disposal methods can create environmental problems, because they can:

- take up large surface areas (Figure 37)
- be highly visible (Figure 37).

Figure 37: Large (up to 6 km across), highly visible TSFs

- entrain and possibly store large volumes of water
- cause seepage of contaminated water into the foundation and through the containment wall, which peaks during the operation of the TSF and declines after closure when tailings water is no longer being added to the facility
- release contaminated run-off into surface streams
- be susceptible to erosion, thereby potentially releasing tailings solids to the environment
- become areas of low biodiversity and weed infestation
- cause dust problems.

Avoiding these issues and the associated risks requires a commitment to rigorous planning and the application of leading practices over the full mine life cycle, including after closure. Such outcomes also require foresight and recognition that TSFs can incur environmental and social costs in the long term if leading practice principles are not followed.

More efficient and economical tailings dewatering, treatment and disposal techniques are being introduced at Australian mine sites. Some of these systems achieve greater efficiency and economy by removing excess water from the tailings before their transport and deposition. This maximises the recovery of water and process reagents for re-use and minimises the discharge of water and contaminants to the TSF, thereby reducing the risk of seepage and release to surface waters.

Leading practice TSF design, operation and closure are to leave a safe, stable landform that does not require ongoing management post-closure and blends in with the surrounding landscape. It provides a mining company with the opportunity to showcase social and environmental management commitments—and, when the company proposes future developments, positions it as one that is committed to sustainable development.

9.2 Future directions

Since the failure or poor performance of a TSF facility can have a dramatically negative impact on surrounding communities and the environment, and can have a profound impact on the corporate bottom line and reputation, responsible mining companies are putting in place tailings management principles and practices that minimise the risk of failure. They include implementing daily inspections of TSFs, monitoring against agreed trigger levels, reporting incidents, managing the construction of wall raises, managing change, commissioning independent annual geotechnical engineering reviews of TSFs, and commissioning independent expert geotechnical peer reviews at a frequency related directly to the hazard potential and/or the dam failure consequence category.

Good design and management of surface TSFs generally includes providing an adequate storage area to ensure a rate of rise slow enough to enable thin layer deposition, consolidation and drying; diverting clean rainfall run-off; discharging the tailings as thick as can effectively be managed; spigotting the tailings in thin layers and cycling deposition between a number of cells; maintaining a small decant pond; and having separate evaporation or tailings water storage ponds.

Increasingly, the community, regulators and the minerals industry are striving for a reduction in slurried tailings transport and storage in surface TSFs in order to reduce the associated operational risks and the future potential closure risks and liabilities. The recovery of water before transport and deposition maximises the recovery of water for recycling and the retention of any residual process reagents.

Pre-disposal dewatering can involve thickening, up to a paste consistency, centrifuging or filtration, and the costs and effectiveness increase in that order. However, paste tailings are more expensive to transport to a surface TSF, requiring a dual piston positive displacement pump and frequent movement of the discharge point due to the steep beach that forms. Centrifuged tailings may be just pumpable with a dual piston positive displacement pump, and may not be transportable by truck or conveyor. Filtration of tailings is the most expensive dewatering technique, but is one that allows transportation by truck or conveyor and ready stacking and compaction if necessary.

The increased costs involved in thickening or centrifuging of tailings may be offset by improved process water recovery, a smaller tailings pipeline diameter (where the dewatered tailings are still pumpable), increased tailings density, a reduced requirement for TSF embankment raising, a reduced risk of overtopping, and reduced seepage. Where coarse reject is also produced on processing, thickened or centrifuged tailings may be mixed with this waste stream to facilitate transport by truck or conveyor and possible dry stacking.

The further increased costs involved in filtration of tailings may be offset by further improved process water recovery, the ability to transport the filtered tailings by truck or conveyor, the ability to dry stack the filtered tailings without the need for containment walls, greatly increased tailings density (particularly if the tailings are compacted), greatly increased mass stability of the stored tailings and greatly reduced seepage. The two key drivers of filtration and dry stacking of tailings have to date been the recovery of scarce process water, and the disposal of tailings in difficult topography or foundation conditions. In future, the filtration and dry stacking of tailings may become the preferred means of tailings disposal and storage in surface TSFs and in-pit.

Where appropriate, the rehabilitation of TSFs has moved beyond the minimum regulatory closure objectives of a safe, stable, non-polluting structure towards rehabilitation to an agreed post-closure land use or ecological function, with a focus on sustainable revegetation and biodiversity. Sustainable closure of TSFs must incorporate final landform design and surface textures that mimic surrounding natural landform analogues in their geometry, surface cover, surface texture and stability, to the extent possible. The successful closure and rehabilitation of TSFs requires that a comprehensive, site-specific monitoring and maintenance plan be developed and followed to ensure that the TSF meets its closure objectives and completion criteria over the long term.

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GLOSSARY

Acid and metalliferous drainage (AMD)

Acid and metalliferous drainage, traditionally referred to as acid mine drainage or acid rock drainage, includes both acidic, metalliferous drainage, and near-neutral but metalliferous drainage

Adaptive management

A systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. The ICMM *Good practice guidance on mining and biodiversity*, 2006, refers to adaptive management as 'do–monitor–evaluate–revise'.

Air permeability

The ability of unsaturated porous material, including tailings, to pass air.

As low as reasonably practicable (ALARP)

Management of all tailings and TSF risks to within acceptable levels, within practical reason.

Annual exceedence probability (AEP)

The probability that a particular storm or event will be exceeded in any year; for example, a 1 in 1,000 AEP storm (or 1 in 100 AEP or 1 in 10,000 AEP) is a storm that produces a rainfall that is statistically likely to occur once in 1,000 years (or 100 or 10,000 years) at the site under study (ANCOLD 2012).

Bulk density

The overall density of a material, being the mass of solids and water per unit volume of the solids plus liquids plus air voids. See also 'dry density' and 'particle specific gravity' (ANCOLD 2012).

Bund

An earthen retaining wall.

Capillary break

A coarse-grained material with a limited capillary rise, intended to limit the uptake of contaminants by evaporative forces.

Cemented paste tailings

Tailings with the consistency of a paste, to which cement is added to enhance strength for underground stope backfilling.

Central thickened discharge

The discharge of thickened tailings from one or more towers or discharges located within the body of the facility, with only a nominal perimeter wall where any supernatant water is recovered.

Centreline method, construction or raising

Construction of the tailings containment walls above a fixed crest alignment, using waste rock, borrow materials or tailings.

Centrifuge

A device that dewaters a slurry through the application of centrifugal force against a drainage surface.

Coarse (coal) reject

The coarse fraction of the mineral matter removed from ROM coal by washing.

Co-disposal

The combined disposal of coarse and fine-grained mine wastes, such as the pumped co-disposal of coal washery wastes.

Community

In mining industry terms, generally applied to the inhabitants of immediate and surrounding areas who are affected by a company's activities. 'Local community' usually indicates a community in which operations are located and may include indigenous and non-indigenous people.

Community impact

Detrimental harm to the neighbouring community.

Compaction

The expulsion of air from unsaturated (desiccated) tailings on trafficking.

Completion criteria

The agreed stability, environmental and land-use or ecological function criteria for the TSF after closure.

Consequence category

The ranking of the severity of the consequences of dam failure as defined in *Guideline on consequence categories of dams,* ANCOLD, 2012. This term supersedes the term 'hazard rating' used in earlier guidelines.

Consolidation

The expulsion of water from settled, saturated tailings slurry on loading.

Consultation

The act of providing information or advice on, and seeking responses to, an actual or proposed event, activity or process.

Containment wall

A structure providing outer encapsulation for tailings (see also 'embankment').

Cost-and risk-effectiveness

The effectiveness of the selected tailings management strategy in minimising both cost and risk.

Decant or supernatant water

Process water that has separated from the tailings solids (supernatant water) within the TSF on the settling and consolidation of the tailings, plus any rainfall run-off collected within the TSF catchment.

Decant pond

A pond within a TSF where tailings supernatant water collects and clarifies, plus any rainfall run-off collected within the TSF catchment.

Decommissioning

A process undertaken between the operating phase and the possible reopening of the operation, when the TSF is put under care and maintenance, but not necessarily rehabilitated.

Deep bed thickener

A thickener relying on a lifting action to minimise the likelihood of bogging and allowing a deep bed of slurry to be thickened and delivered on demand.

Desiccation

Drying, shrinkage and cracking of tailings from an exposed surface by solar and/or wind-induced evaporation.

Design storage allowance (DSA)

The remaining safe storage capacity that needs to be provided in a non-release TSF to accommodate tailings (solids and water), rainfall and wave action, with a sufficient factor of safety against overtopping and spillage of contaminated water. The DSA must also consider the post-wet-season time that it may take to return the pond level to its normal operating level, or the time required (considering weather delays) to construct an incremental increase in storage capacity (a new dam or raise of existing embankment) (ANCOLD 2012a).

Dewatering

Removal of water from a slurry by thickening, filtration or centrifuging.

Dewatering in situ

Drain-down of deposited wet tailings as they undergo sedimentation, consolidation and desiccation.

Dow-valley discharge

Discharge of thickened tailings down a valley towards a containment wall, located at the head of a catchment.

Downstream method, construction or raising

Construction of the tailings containment walls in a downstream direction, generally using waste rock or borrow materials.

Downstream or outer face

External perimeter of a TSF exposed to the environment..

Dry density

Mass of dry solids per total volume (of solids, plus water, plus air) (see also bulk density and particle specific gravity).

Embankment or wall

A tailings or water containment wall (see also ‘containment wall’).

Encapsulation

Surrounding a reactive waste by benign materials that isolate the reactive waste material from oxygen ingress and/or water flow.

Environmental impact

Detrimental harm to the environment.

Factor of safety

The factor by which the resisting actions exceed the disturbing actions.

Failure

The occurrence of an event outside the expectation of the design or facility licence conditions, which could range from the uncontrolled release of water, including seepage, to a major instability of an embankment leading to loss of tailings and/or water (ANCOLD 2012).

Failure modes

The mechanisms by which a TSF may fail.

Filter cake

The semi-solid structure formed on the application of pressure during filtration of a slurry.

Filter press

A device that dewaters a slurry to the consistency of a filter cake through the application of pressure across two drainage surfaces between which the slurry is passed.

Fine (coal) reject

The fine fraction of the mineral matter removed from ROM coal by washing.

Flocculants

Chemical additives that facilitate the agglomeration of tailings particles to aid and speed up their sedimentation and consolidation.

Freeboard

The vertical distance between a water level within a dam and a critical design level. For tailings dams, various freeboards are required for different purposes, including total freeboard, tailings storage allowance, minimum decant storage allowance, wet season storage allowance (or DSA), extreme storm storage allowance, contingency storage allowance, operational freeboard, maximum operating level, flood spill depth, wave freeboard, beach freeboard, and maximum operating level (see ANCOLD 2012a for details).

Geomembrane

A manufactured low-permeability sheet, such as high-density polyethylene (HDPE) (see also ‘liner’).

Geosynthetic clay liner (GCL)

A low-permeability clay sandwiched between geotextile layers.

Geotechnical

The engineering of the ground and/or earthen structures.

Gravimetric moisture content

Mass of water/mass of solids, expressed as a percentage. See also 'total moisture content', 'volumetric water content' and 'solids content'.

Hazard

A potential to cause harm.

High compression thickener

A high-rate thickener, with added compression derived from the configuration of the rakes to increase the density achievable.

High rate thickener

A thickener through which a slurry is passed at a high rate, with limited residence time, allowing a high flocculant dose.

Hydraulic backfill

Fill, usually including coarse-grained tailings, that is placed as a fluid to backfill an underground mine stope.

Hydraulic conductivity

Otherwise known as (water) permeability; a measure of the ability of a porous material, including tailings, to pass water, whether saturated or unsaturated.

Hydraulic sorting

Segregation of tailings down a tailings beach according to their particle size and/or specific gravity.

Industrial ecology

Synergies between industrial processes.

Infiltration

The ingress of water into a porous material.

Leading practice

Best available current practice promoting sustainable development.

Life cycle

The full life of the TSF from planning, through design, construction, operation, closure, rehabilitation, and after closure.

Life-of-mine (LoM)

Planning and design for the duration of mining, including after closure.

Liner

A low-permeability base comprising compacted clay, and/or a geomembrane or geosynthetic (clay in a geotextile ‘sandwich’), or a composite, used beneath tailings and/or ponded water.

Long term

Typically a nominal period of 1,000 years; applies to the consideration of the potential design life of the post-closure landform (ANCOLD 2012a).

Maximum credible earthquake (MCE)

The largest hypothetical earthquake that may be reasonably expected to occur along a given fault or other seismic source. It is a believable event which can be supported by all known geologic and seismologic data. A hypothetical earthquake is deterministic if its fault or source area is spatially definable and can be located a particular distance from the dam under consideration. A hypothetical earthquake is probabilistic if it is considered to be a random event, and its epicentral distance is determined mathematically by relationships of recurrence and magnitude for some given area. The MCE can be associated with specific surface geologic structures and can also be associated with random or floating earthquakes (movements that occur at depths that do not cause surface displacements) (ANCOLD 2012).

Maximum design earthquake (MDE)

The earthquake selected for design or evaluation of the structure. This earthquake would generate the most critical ground motions for evaluation of the seismic performance of the structure. The dam could be expected to be damaged by this earthquake but would retain its functionality (ANCOLD 2012).

Natural analogue

An unmined landform to which a mined landform may be compared to develop sustainable post-mining landforms.

Net percolation

The seepage of rainfall infiltration through a cover system into the underlying tailings.

Operational basis earthquake (OBE)

That earthquake which, considering the regional and local geology and seismology and specific characteristics of local subsurface material, could reasonably be expected to affect the dam site during the operating life of the processing plant; it is that earthquake which produces the vibratory ground motion for which those features of the dam necessary for continued operation without undue risk to the health and safety of the public are designed to remain functional (ANCOLD 2012).

Particle specific gravity (or ‘soil particle density’)

Mass of dry solids per unit volume of dry solids, relative to the specific gravity of water (unity for pure water), best determined using a pycnometer with helium.

Paste tailings

Tailings slurry thickened to a paste consistency, with a high yield stress and reduced slump and bleed water. Cement is added to produce cemented paste tailings backfill for underground mine stopes.

Percolation

The seepage of infiltration to the receiving environment

Personal safety

Preserving the safety of mine site personnel and the general public in the face of mine site risks of injury.

Piezometers

Sensors used to monitor groundwater mounding beneath and surrounding a TSF.

Piping

The formation of an erosion tunnel through an earthen structure due to the induced flow of water through it.

Post-closure

The period after mine closure when the TSF is expected to perform safely into the long term.

Post-closure ecological function

An agreed ecological function where a post-mining land use for the TSF footprint is not possible or desirable,.

Post-closure land use

Agreed post-closure land use for the TSF footprint.

Potentially acid-forming (PAF) tailings

Sulphidic tailings with a potential to oxidise on exposure and combine with water to generate acidity.

Power station ash

A by-product of the production of electricity from coal-fired power stations.

Probable maximum flood (PMF)

The largest flood hydrograph resulting from the PMP and, where applicable, snowmelt, coupled with the worst flood-producing catchment conditions that can be realistically expected in the prevailing meteorological conditions (ANCOLD 2012a).

Probable maximum precipitation (PMP)

The theoretical greatest depth of precipitation for a given duration that is physically possible over a particular catchment, governed by the theoretical maximum volume of moisture that the atmosphere can hold (ANCOLD 2012a).

Processing plant

A facility designed to concentrate the economic mineral or metal from the run-of-mine ore.

Public health risk

The likelihood of harm to public health.

Quality assurance

Ensuring the quality of a process, such as construction, including the documentation and reporting of test work.

Reagent recovery

The capture of processing chemicals from the tailings stream.

Red mud residue

A by-product of the production of alumina from bauxite.

Rehabilitation

The rendering of a safe, stable and non-polluting TSF in the long term, taking into account beneficial uses of the site and surrounding land.

Return water pumping and pipeline system

System designed to return supernatant process water back to the mineral processing plant (recycling).

Rheology

The study of the deformation and flow of tailings slurry under the influence of an applied stress.

Risk

The likelihood of actual harm.

Risk management process

The systematic application of management policies, procedures and practices to the activities of communicating, consulting, establishing the context, and identifying, analysing, evaluating, treating, monitoring and reviewing risk (AS/NZS and ISO 31000).

Run-of-mine (ROM)

Ore or waste rock produced directly from an open-pit or underground mine.

Scats or Slag

Coarse-grained wastes from the smelting of metalliferous ores.

Sedimentation

The separation of solids from an aqueous slurry.

Seepage control system

System that may include a low-permeability or compacted foundation or liner (compacted clay and/or geomembrane or GCL), and an underdrainage collection system.

Shear strength

The ability of a porous material, including tailings, to support load; typically measured using a shear vane in situ in saturated tailings.

Slimes

Silt and/or clay-sized component of tailings that deposit at the tail end of the tailings beach, usually having a high moisture content and soft consistency.

Slurry density (or pulp density)

Total mass of slurry per total volume (of solids, plus process water).

Solids content (or ‘concentration’)

Dry mass of tailings solids per total mass (of dry solids plus process water) in a tailings slurry, expressed as a percentage.

Storage capacity

The potential capacity of a TSF to store tailings, usually referred to in units of dry tonnes. This requires knowledge of the in situ dry density of the tailings likely to be achieved on deposition.

Slope

The angle of the tailings containment walls and of the tailings beach.

Social impact

Detrimental harm to society

Social licence to operate

The recognition and acceptance of a company’s contribution to the community in which it operates, moving beyond meeting basic legal requirements towards developing and maintaining the constructive stakeholder relationships necessary for business to be sustainable. Overall, it comes from striving for relationships based on honesty and mutual respect.

Spigot

A branch off the main tailings delivery pipeline from which tailings are discharged from the containment wall of a TSF.

Spillway

A structure constructed at the perimeter of a TSF, designed to pass excessive rainfall run-off.

Stakeholder

A person, group or organisation with the potential to affect or be affected by the process of, or outcome of, mine closure.

Starter embankment

The initial containment wall of a TSF.

Store-and-release cover

A vegetated, non-shedding soil cover, aimed at minimising percolation through it by the release of stored seasonal rainfall by evapotranspiration during the dry season.

Supernatant water

The water ponded on a tailings surface following the sedimentation of the deposited tailings slurry.

Tailings

The fine-grained waste or residue produced by a mineral processing plant, generally in an aqueous environment. Can be a ground rock flour from the processing of metalliferous ores; fine-grained wastes produced on the beneficiation of coal, bauxite, or mineral sands; residue from the processing of alumina or nickel laterite; fly-ash from coal-fired power production; gypsum produced on phosphate processing; etc.

Tailings beach

The delta that forms on discharge of a flowable, aqueous tailings slurry.

Tailings containment

Facility usually constructed initially as an earthen starter embankment, with wall raises constructed using borrow material and/or tailings. Construction may be downstream using borrow material, or centreline or upstream using borrow material or predominantly tailings.

Tailings dam

A containment wall or embankment built to retain tailings and/or to manage water associated with the storage of tailings.

Tailings engineer

A qualified geotechnical engineer experienced in the investigation, planning, design, construction or management of tailings dams and storage facilities.

Tailings management

The management of tailings over their full life cycle, including their production, transport, placement, and storage, the closure and rehabilitation of the TSF, and post-closure management.

Tailings pumping and pipeline system

System designed to deliver tailings slurry from the mineral processing plant to the TSF.

Tailings slurry

Tailings solids embedded in process water that are produced in the processing plant at a low density, which beach at a flat slope, segregate down the beach, and produce considerable supernatant water.

Tailings storage facility (TSF)

Usually a surface storage area used to contain generally slurried tailings, in which the tailings solids will sediment, consolidate and desiccate, and supernatant water will be recovered and recycled to the processing plant or stored without affecting the environment. Refers to the overall facility, and may include one or more tailings storages and associated features.

Thickened tailings

Tailings thickened to a high density, which beach at a steeper slope and segregate less than tailings slurry, producing far less supernatant water.

Thickener

A device for increasing the density of a slurry.

Total moisture content

Mass of water/mass of solids plus water, expressed as a percentage. See also ‘gravimetric moisture content’, ‘volumetric water content’ and ‘solids content’.

TSF closure

A process undertaken between the operating phase and the completion of decommissioning (followed by a period of care and maintenance and possible reopening) or rehabilitation.

TSF completion

The goal of closure whereby the mining lease is relinquished and responsibility is accepted by the Crown or the next land user.

Underdrainage

Drains beneath a tailings deposit to facilitate drain-down.

Upstream method, construction or raising

Construction of the tailings containment walls in an upstream direction on top of consolidated and desiccated tailings, using waste rock or tailings.

Volumetric water content

Volume of water/total volume (of solids, plus water, plus air), expressed as a decimal. See also ‘gravimetric moisture content’, ‘total moisture content’ and ‘solids content’.

Water balance

The sum of the water inputs, including process water and rainfall run-off, and outputs, including evaporation, return water, water entrained in the tailings and seepage, in a TSF.

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