CHAPTER 9.1

Tailings Disposal and Management

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Tailings are the by-products generated from mechanical and chemical processes used to extract a desired product (such as gold and copper) from ore. After the ore is processed, the unrecoverable and uneconomic metals, minerals, chemicals, organics, and process water are discharged, normally as slurry, to a storage area commonly referred to as a tailings management facility, tailings storage facility (TSF), or residue disposal area.

The topics discussed in this chapter make up the basic elements of a tailings management framework. A tailings management framework describes the care and management of the facility through its entire life cycle (concept, design, construction, operation, and closure).

RECENT DEVELOPMENTS

Current trends in the mining industry are focused on minimizing water consumption, reducing risk associated with tailings management and storage, and reducing the tailings storage footprint. These trends include the following:

- An increased consideration of the use of thickened, paste, and filtered tailings to reduce water consumption and surface footprint
- Disposal of paste tailings into underground mines to provide ground support and to reduce the surface footprint
- Co-disposal of tailings within waste rock facilities to reduce surface footprint and to mitigate potential geochemical/drainage issues
- In-pit tailings disposal to reduce surface footprint
- Remote sensing and monitoring using satellite-based interferometric synthetic aperture radar (InSar) and drone technology. (These tools are being to monitor tailings facilities. They are used to inspect and measure deformation and seepage [via infrared] over time.)

As noted by Welch et al. (2012), failures and noncompliance of tailings facilities have serious safety, environmental, social, and economic impacts, and can result in loss of reputation and loss of investor confidence. In response, the mining industry continues to develop innovative methods to dispose of tailings to reduce risk and conserve water.

OBJECTIVES AND LIMITATIONS

It is not the intent of this chapter to fully describe a tailings management framework. Several guides and publications are available (MAC 2017; ANCOLD 2012; Martin and Davies 2000) that can be used to develop site-specific frameworks to manage tailings facilities. The primary objective is to provide an understanding of the tailings management framework and the role it plays overall in a mining project.

This chapter is limited to surface disposal of tailings and is not intended to be a comprehensive nor a step-by-step guide to the design, construction, and operation of tailings facilities. Although the basic function of a tailings facility is similar from operation to operation, the facility design, construction, operation, and closure are unique to each site. The discussions presented herein are intended to provide a general overview. Specific testing, procedures, operational controls, and so forth, must be developed specific to the site conditions, mineral processing method, and environmental and social constraints.

TAILINGS STORAGE FACILITY

The TSF is an engineered and constructed facility to contain tailings. The primary objective of a TSF is to provide a dedicated facility that will safely confine tailings solids and process water to a designated area, where they can be managed through life-of-mine, closure, and postclosure.

A TSF can take many forms and shapes depending on many factors, such as the following:

- Site topography
- Local and regional geotechnical and hydrological conditions
- Type of tailings to be contained
- Processing constraints
- Environmental constraints
- Seismicity
- Climate
- Facility construction constraints
- Country mining regulations

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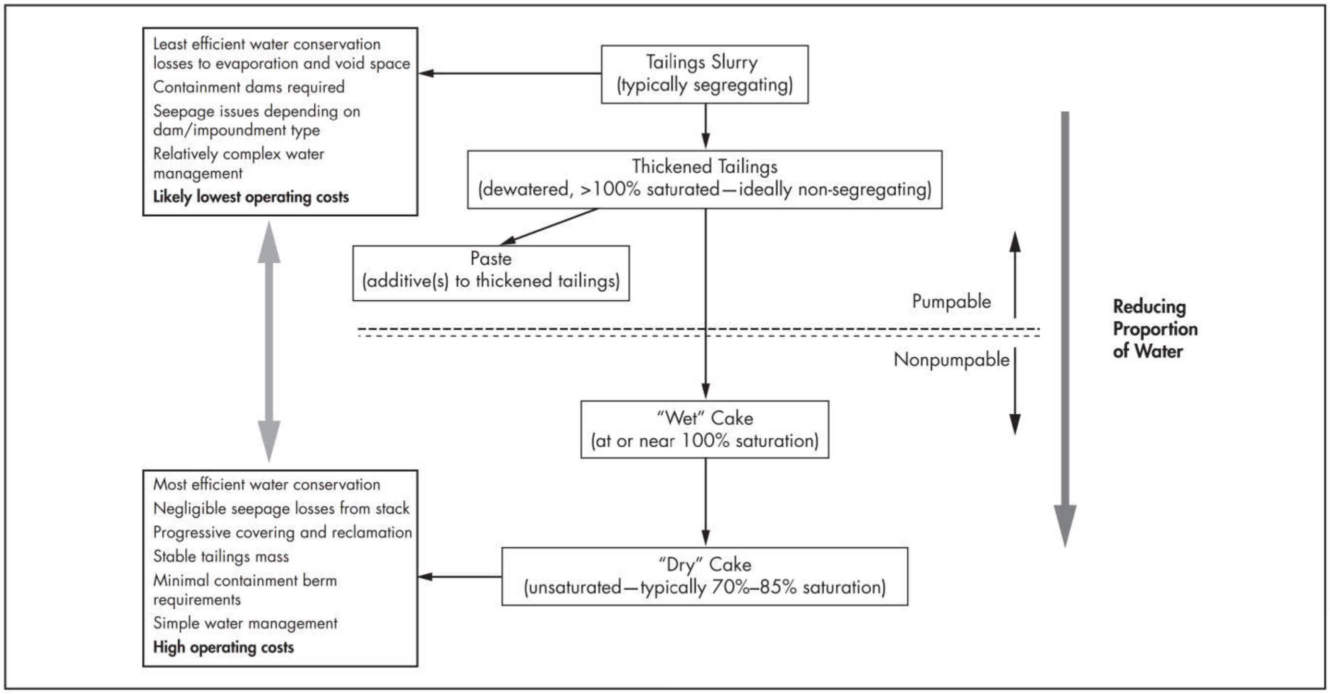


Adapted from Davies and Rice 2001

Figure 1 Tailings continuum

Tailings Continuum

Although a TSF contains tailings, not all tailings behave the same, which can affect the TSF design and management. The tailings continuum refers to the qualitative behavior of tailings at varying degrees of moisture content. Traditionally, tailings are deposited in a slurry form (e.g., a semiliquid mixture). However, as discussed earlier in this chapter, there is a trend to reduce the amount of water deposited with the tailings. As the proportion of water is reduced (by thickening or filtration), the tailings take on different behavior, which affects how tailings are deposited and managed. Additionally, changes in the proportion of water will affect the TSF water balance and water management for the site (discussed later in this chapter).

An illustration of the tailings continuum is shown in Figure 1. On one end of the continuum are slurry tailings, which behave as a semiliquid. On the other end of the continuum are cake or filtered tailings, which behave as a wet soil. In between these end points are thickened and paste tailings. Reducing the proportion of water in the tailings affects how they can be deposited (pumpable or non-pumpable), which can impact both capital and operating costs for tailings disposal. The benefits of reducing the water content of tailings include more effective use of water resources, lower water management costs (less water to handle), reduction in TSF footprint (from reducing water storage in the TSF), and potentially easier closure requirements (Davies et al. 2010).

The selection of the type of tailings to produce at an operation is largely driven by

- Capital and operating costs;
- Ore mineralogy and processing requirements;
- Availability of water for processing;
- Environmental constraints;
- Social acceptance;
- Land availability;
- Risk and risk tolerance; and
- Seismic, climate, geotechnical, and hydrological conditions at the TSF location.

At the start of a project, trade-off studies are recommended to evaluate which type of tailings may be better suited for a given site.

Tailings Storage Facility Configuration

For surface disposal of tailings (slurry, thickened, paste, or filtered), four main TSF storage configurations can be considered.

1. **Cross-valley.** A cross-valley TSF is formed by constructing containment embankments across a natural valley or drainage. The natural topography combined with the containment embankments forms the primary tailings storage basin. An example of a cross-valley TSF is shown in Figure 2.
2. **Paddock.** A paddock TSF (often referred to as a cell TSF, a ring dike TSF, or a turkey's nest TSF) is one where containment embankments are constructed around the entire facility, as shown in Figure 3. A paddock TSF is generally used in areas that are very flat and have little topographical relief.
3. **In-pit disposal.** As the name implies, an in-pit TSF is one where tailings are deposited into an inactive open pit, as illustrated in Figure 4.
4. **Comingling.** Comingling or co-disposal of tailings consists of mixing other materials, such as waste rock, in a single storage area. This approach allows the tailings to be "stacked" by filling in the voids within the waste rock or other media. Figure 5 presents an example of comingled tailings.

Courtesy of Teck Mining Company

Figure 2 Cross-valley tailings storage facility

Source: Hore and Luppnow 2015, reprinted with permission from the Australasian Institute of Mining and Metallurgy

Figure 4 In-pit disposal at Langer Heinrich mine, Africa

Courtesy of Newmont Mining Corporation

Figure 3 Paddock tailings storage facility

Figure 5 Comingled/co-disposal tailings

TSFs may incorporate a liner for environmental containment and/or to reduce loss of process water via seepage into the foundation. Some may have a compacted soil liner; compacted native or imported soils that provide a low-permeability layer. Other TSFs may have a composite liner (e.g., a geomembrane liner in combination with a compacted soil liner). Choosing the need for a liner and liner type depends on site conditions, quality of the tailings, geochemical characteristics, and environmental/social risks.

TSFs are seldom constructed for the life-of-mine tailings storage needs up front. Rather, they are periodically raised (i.e., the containment dams or embankments are constructed to a higher elevation) over time to provide additional tailings storage. This allows capital expenditures to be deferred until additional storage is needed. The first dam or embankment that is constructed in a TSF is often called the starter dam.

Three primary methods are used to raise TSF embankments (see Figure 6):

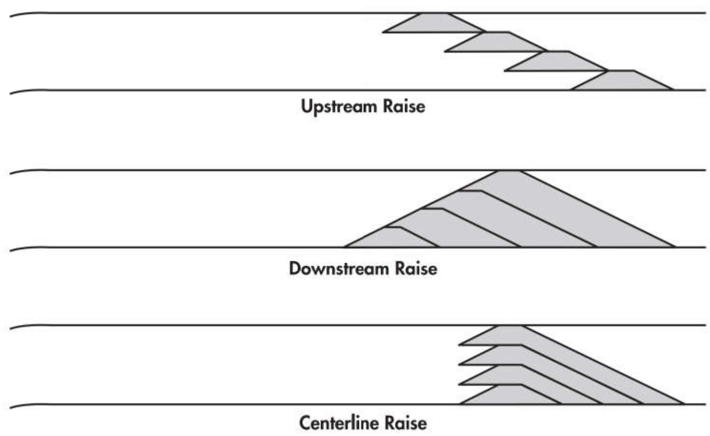
1. **Upstream raise.** The embankment is constructed over deposited tailings, upstream of the starter dam.
2. **Centerline raise.** The embankment is constructed so that the centerline remains more or less the same as the starter dam. In a modification of a centerline raise, the embankment can be constructed so that the centerline moves slightly upstream or downstream of the starter dam.
3. **Downstream raise.** The embankment is progressively constructed on the downstream end of the starter dam and TSF.

Strengths and weaknesses are associated with each of these TSF raise methods, as presented in Table 1.

The design and method of raising a TSF (for both existing and greenfield projects) requires input and discussion from many functions, including project execution, mine engineering, process engineering, environmental, geotechnical engineering, water management, land, and social. It is recommended to include these functions into the TSF planning and design stage so that the design and any associated risks are discussed and agreed on prior to finalizing the design.

Tailings Storage Facility Failures

Over the past several decades, the mining industry has experienced many TSF failures and incidents. The lessons learned from these events are improving safety and continue to support the development of enhanced practices in tailings management. International Committee on Large Dams (ICOLD) Bulletin 121 (ICOLD 2001) and Rico et al. (2008) provide a summary of TSF failure modes and lessons learned from the failures. Figure 7 presents a chart of the most common modes of failure for TSFs.



Source: Vick 1990

Figure 6 Tailings storage facility raise methods

Table 1 Tailings storage facility raise-method strengths and weaknesses

Upstream Raise	Centerline Raise	Downstream Raise
Strengths • Requires the least amount of earthwork, so often the lowest cost option. • Has the smallest area footprint compared to the other methods. • Allows concurrent reclamation.	**Strengths** • Has a smaller area footprint than a downstream raise. • Can be designed for water retention, if internal drainage is provided in containment embankment. • Generally, better seismic stability than upstream method.	**Strengths** • Each raise buttresses the previous raise, thereby providing a greater degree of stability. • Can be designed as a water retention structure. • Accommodates a composite liner, if required.
Weaknesses • Potentially susceptible to failure under seismic loading. Not recommended in highly seismic areas. • Cannot be used for water storage. Reclaim pond area must be minimized to maintain long, dry beaches. • Generally, limited to <3 m/yr rate of rise. • Must have sufficient underdrainage and/or internal drainage to maintain a drained condition in the containment embankment. • Very sensitive to deposition planning and water management. • Cannot have steep slopes on outer face of embankments (generally 3 horizontal to 1 vertical or flatter).	**Weaknesses** • Very difficult to implement a composite liner. • Can be susceptible to upstream slope failure, particularly in seismic events. • Requires internal drainage within containment embankment.	**Weaknesses** • Requires a greater volume of earthwork and fill. • Has a greater footprint compared to the other methods. • Requires internal drainage within containment embankment.

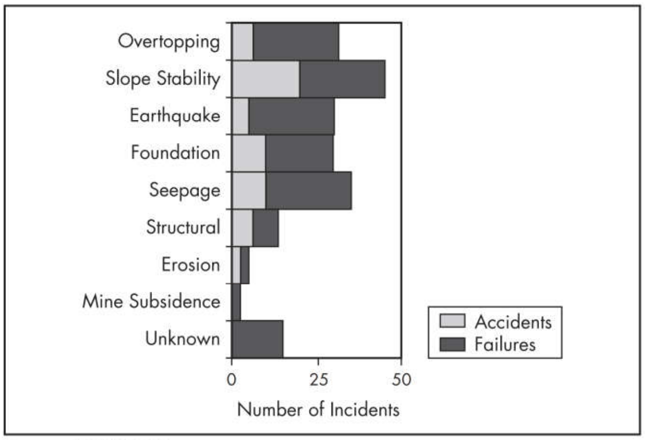
As noted in Figure 7, the top failure modes for TSFs are

- Slope stability issues resulting from poor construction or design, inadequate water management (excessive water in facility), and poor TSF management (e.g., incorrect beaching or reclaim pool location);
- Seismic events causing liquefaction of foundation and/or seismic instability because of inadequate design, construction, or lack of geotechnical investigation; and
- Overtopping because of storage of excessive water in the facility and/or poor reclaim pool management (e.g., location).

Failures of TSFs generally occur if there is a deficiency in the design, construction, and/or operation of the facility. Past TSF failures have shown that a well-designed and constructed TSF can still fail through poor operation. Therefore, it is important that all aspects (design, construction, and operation) of the facility be scrutinized to identify fatal flaws or weaknesses. Any flaws or weaknesses in the facility must be corrected to ensure safe operation. In addition, TSFs are designed for life-of-mine of the operation; however, changes in operation (e.g., throughput, process method, ore type, or mine plan) can occur during the life-of-mine that may be incompatible with the original TSF design. Care must be taken to assess the original intent of the TSF design with respect to anticipated operational changes so that, if needed, the TSF design can be modified. This process is referred to as *change management* and is key to successful TSF operation.

TSF DESIGN

A robust TSF design typically requires input from several functions, including process, environmental, social, operations,



Source: ICOLD 2001

Figure 7 Common tailings storage facility failure modes

mine planning, geology, geotechnical, and mine water management. It is important that representatives from each of these functions be involved throughout the design stage so that the design and performance of the facility meets the desired intent.

Since the majority of TSFs are engineered aboveground structures, the design requires that sufficient knowledge be obtained regarding

- Subsurface geologic and geotechnical conditions,
- Subsurface hydrogeologic conditions,
- Surface water hydrology (rivers, streams, lakes, etc.),
- Geohazards (avalanches, landslides, sinkholes, etc.),
- Seismicity,
- Current and projected climatic conditions, and
- Tailings characteristics.

In addition, testing will be required on the tailings as well as foundation and construction materials to define the engineering parameters to support design.

Design Criteria

Design criteria define the basis for the TSF design. The criteria are generally established with input from the functions listed in the previous section and considered to be "fixed" throughout the design. If a change in criteria occurs (during the design stage or after the design is completed), the design must be reevaluated, and modified if needed, to ensure the facility meets the project objectives and can be safely operated.

Typically, TSF design criteria include the following (as applicable):

- Storage capacity
- Average tailings density
- Average tailings percent solids (by weight)
- Tailings delivery schedule
- Tailings deposition concept
- Design storm events (containment and emergency spillway)
- Stability (static and seismic) acceptance criteria (such as factor of safety and/or reliability)
- TSF lining system (if needed)
- Drainage elements (underdrains, embankment/dam internal drains, etc.)
- Average beach slope
- Seismic load
- Minimum embankment/dam crest width
- Regulatory and social requirements and constraints
- Closure considerations

The design criteria feed directly into engineering analyses that form the basis of the TSF (basin, embankments/dams, decant, spillway, etc.). Engineering analyses for the design of a TSF would generally include stability, seepage, liquefaction (static and seismic), settlement, and erosion. In addition to these engineering analyses, a water balance for the TSF must be developed. A TSF water balance is a critical element in *both* the design and operating phase of a TSF and is used to size the decant/reclaim system, establish operating thresholds, and estimate water demand from external sources. A TSF water balance also plays a critical role in the site-wide water management plan. The section on TSF operation and management later in this chapter presents a more thorough discussion on water management and water balances.

Operating Criteria

Operating criteria define the anticipated life-of-mine operating conditions for the facility. Operating criteria should be explicitly defined during the design stage so that the design is compatible with the anticipated operating conditions. Also, any changes in the operating criteria, before or after the design has been completed, should be evaluated against the design to identify potential conflicts or impacts to the desired facility performance.

Typically, the operating criteria for a TSF include the following (as applicable):

- Tailings delivery rate
- Tailings percent solids (by weight) operating range
- Tailings rheological parameters
- Maximum rate of rise (tailings)
- Maximum embankment/dam height
- Maximum reclaim pool extent
- Minimum freeboard
- Minimum beach widths
- Pore pressure or piezometric level thresholds
- Embankment/dam acceptable deformation threshold
- Seepage collection rate and threshold
- Decant operating criteria (maximum height, water level thresholds, structural thresholds)
- Hydraulic conveyance maximum pressures and flow rates

The operating criteria are also used to form the basis for the facility monitoring program. The TSF monitoring plan is discussed later in this chapter.

Geotechnical

The geotechnical components of a TSF design consist of field and laboratory work to characterize the TSF location, availability and characteristics of potential construction materials, and tailing characteristics.

Field Investigations

Geotechnical field investigations are required to gather information on the subsurface conditions beneath a TSF. The subsurface conditions will influence the type and design of a TSF that can be constructed. The most common geotechnical field investigation methods include the following.

Site reconnaissance and mapping. Site reconnaissance and field mapping consists of conducting a visual survey of the TSF area to identify surface features and geohazards that may affect the TSF design or performance.

Borehole investigation. A borehole investigation program consists of advancing a borehole to a specified depth, logging the borehole, conducting in situ testing, and collecting disturbed and undisturbed samples for geotechnical laboratory testing. Standard procedures, such as ASTM D1586 and AS 1289.6.3.1, are often used to guide the drilling, sampling, and testing procedures. Drilling methods may include auger, coring, and rotary methods. In situ testing typically consists of a standard penetration test, although other methods (e.g., large penetration tests or soil pressuremeter tests) may be used. Undisturbed samples are generally collected using a sampling tube, such as a split-spoon, Modified California Sampler, Shelby tube, and piston samplers.

Piezocone probes. Piezocone probes (often referred to as cone penetration tests, or CPTs) consist of pushing an instrumented cone into the ground at a controlled rate. CPTs are often used in active tailings impoundments to characterize the tailings deposit (e.g., density and drainage). Standard procedures, such as ASTM D5778 and AS 1289.6.5.1, are often used for CPT programs. The information from a CPT program can provide an estimate of shear strength, pore pressure gradients, pore pressure response to shear, susceptibility to liquefaction, and postliquefaction residual shear strength. The piezocone data also provide a discrete pore pressure profile (based on pore pressure dissipation tests during pauses in piezocone penetration) and a direct measurement of the in situ hydraulic conductivity (horizontal direction).

Test pits. Test pits are excavated holes or trenches dug into the ground to provide a detailed visual examination of the near-surface soil profile. Test pits can also be used to determine the depth to groundwater and bedrock. Both disturbed and undisturbed samples may be gathered from test pits.

Geophysical methods. Geophysical methods provide an inexpensive way to gather subsurface information (geologic profile, underground voids, depth to bedrock) over large areas. Commonly used geophysical methods include seismic reflection, seismic refraction, seismic tomography, resistivity, electromagnetics, and multichannel analysis of surface waves. A review of geophysical applications to geotechnical field work is presented in Anderson (2006).

Photogrammetry. Photogrammetric methods (aerial photographs or high-resolution satellite photographs) can be used to identify areas of existing or historic instability (e.g., landslides), surface subsidence, floodplains, and surface ruptures because of seismic events.

Geotechnical Laboratory Testing

Samples gathered from the geotechnical field investigation are typically submitted to a laboratory for characterization, strength, and hydraulic testing. The data from the laboratory testing program are used in basis for the TSF design. A typical laboratory test program would include the following.

Particle size analysis (ASTM C117/C136). A particle size analysis describes the distribution of particle sizes for a material (soil or tailings). This information can be used to characterize and qualitatively assess the behavior of a material.

Atterberg limits (ASTM D4318). Atterberg limits measure the critical water content of a soil at points where distinct changes occur in behavior or consistency. These tests are useful to qualitatively characterize the shear strength and permeability of a soil.

Moisture content (ASTM D2216). A moisture content test measures the amount of moisture or water in a soil or tailings sample. These tests are often correlated to the Atterberg limits to determine the state of the in-place soil. They can also be used to assess a potential source for construction materials.

Dry density (ASTM D7263). These tests are used to quantify the dry-state density of a soil or tailings sample. They are used to assess a potential source for construction materials or the density of the exposed tailings beach material.

Moisture–density relationship (ASTM D698/D1557). These tests correlate the maximum dry density of a soil to its moisture content. The moisture–density curve is a critical tool to guide earthworks and construction of earthen structures, such as dams or embankments.

Permeability (ASTM D5084). Permeability tests are conducted to measure the soil or tailings hydraulic conductivity. These tests are often conducted at varying pressures and are used in engineering calculations to estimate seepage through a foundation or dam.

Consolidation (ASTM D2435). A consolidation test measures the time-dependent settlement of a soil or tailings sample under an applied load. Consolidation test data is used to estimate settlement of the soil foundation beneath a TSF and the settlement of tailings after deposition.

Shear strength (ASTM D2850/D4767/D7181/D3080). Shear strength tests measure the strength of a soil sample under an applied load. The shear strength of a soil is used in the design of the dams or embankments. Shear strength tests typically include triaxial compression (drained and undrained) and direct shear testing methods.

Hydrological Field Investigations

In addition to geotechnical field investigations, hydrological field investigations should be conducted to support the TSF design work. Hydrological investigations should include both surface water and groundwater. The field investigations are conducted to evaluate

- The depth to groundwater,
- The permeability of the subsurface units,
- Groundwater gradient and/or flow paths,
- Surface water flows, and
- Surface water/groundwater interaction.

Groundwater field investigations typically consist of the installation of instrumented piezometers within and downgradient of the TSF location, installation of monitoring wells for sampling water quality and to measure changes in the water level, and installation of groundwater wells to conduct hydraulic testing to derive aquifer properties.

Surface water field investigations typically consist of stream/river gaging, water quality sampling, and establishing rainfall-runoff factors.

Tailings Characteristics Testing

Tailings characterization tests are typically conducted as part of the ore processing work effort. Typical tailings characterization test work includes

- Density (dry and slurry);
- Particle size analysis;
- Atterberg limits (including shrinkage limit);
- Percent solids (by weight) of the slurry, thickened, or paste tailings;

- Slurry consolidation testing;
- Tailings shear strength, from drained and undrained triaxial compression testing;
- Permeability at various loads;
- Slurry settling/flocculant tests; and
- Geochemistry.

If the tailings are to be discharged to the TSF via a pipeline or trench, then rheological tests are also conducted. Tailings rheology tests are used to quantify the viscosity of the tailings as a function of temperature, solids concentration, and applied shear. Tailings rheology tests typically consist of specific gravity, rotating viscometer tests, capillary tube viscometer tests, and loop tests.

Tailings rheological test results are used as input into pump and pipeline designs. Tailings rheology may also be correlated to beaching angles for thickened and pasted tailings. The details of tailings rheology cannot be covered in a single subsection. Several good references provide details of tailings rheological testing methods and data interpretation (Weir Minerals Division 2009; Laskowski 2001; Boger et al. 2006).

If filtration is being considered for tailings disposal, then bench-scale and pilot-scale tests are often conducted using vacuum belt and/or mechanical press technologies. The filter cake is then tested for

- Density (dry),
- Cake moisture content,
- Moisture–density relationship,
- Shear strength from drained and undrained triaxial compression testing,
- Settlement under load,
- Permeability at various loads (unsaturated hydraulic parameters via pressure-plate testing, may also be needed), and
- Geochemistry.

Other Considerations

Other considerations for the design of a TSF include the following.

Construction. An integral part of the design of a TSF is the development of construction technical specifications, issued-for-construction (IFC) drawings, and a construction quality assurance/construction quality control (CQA/CQC) plan. Technical specifications are developed as part of the design process to define which materials are to be used for construction of the TSF and how they are to be used. The intent of technical specifications is to ensure that the constructed facility will perform as per the design intent. IFC drawings are also developed as part of the design process. IFC drawings provide details on the layout, plans, sections, and survey control for construction of the TSF and all appurtenant structures. The CQA/CQC plan is developed to outline the testing, monitoring, and reporting requirements to ensure construction quality.

Water management. The TSF is just one component of a site-wide water management plan. In the effort to reduce overall water consumption, the TSF design and water balance should be integrated into the overall site-wide water management plan. This approach allows the development of a water management strategy that considers the efficient use of water resources.

Environmental and social impacts. Environmental and social impacts must also be considered so that the TSF design can be modified to be compatible with environmental and/or social constraints.

Operation, maintenance, and surveillance. All TSFs should have a prepared tailings operation, maintenance, and surveillance (OMS) manual that includes an emergency response plan (ERP). The ERP details roles, responsibilities, and contact information; monitoring thresholds and alarms that trigger a response; response details and protocols; and a clear communication plan.

Change management. Finally, there is the consideration for change management that may occur during the life-of-mine. Although it is not possible to predict change management, it is possible to add robustness to a design, through redundancies or additional capacity, so that the facility can accommodate potential operational changes in the future. Regardless, it is critical that the TSF design documentation be complete and clearly state the design basis, intent, and operational constraints so that any potential future changes are compatible with the original design.

TSF CONSTRUCTION QUALITY

Construction of a TSF often involves the management of several disciplines and contractors, such as earthworks, concrete, structural steel, geosynthetics, pumps, and pipelines, to execute the project. Successful project execution requires establishing clear battery limits, instituting lines of responsibility and accountability, and managing construction quality. Critical components to managing construction quality are the CQA and CQC plans that are developed as part of the TSF design. The primary objectives of the CQA and CQC plans are to ensure that the construction of the various TSF components complies with the project specifications and to demonstrate that the regulatory requirements for the construction are achieved.

A CQA program is independent of the CQC programs conducted by the manufacturers, installers, and contractors. A CQA program provides independent third-party verification and testing to demonstrate that the manufacturers, installers, and contractors have met their obligations in the supply and installation of TSF construction materials according to the design, project specifications, and contractual and regulatory requirements. A CQA program also identifies problems that may occur during construction and provides the means for resolution of these problems.

The CQA plan must address the following items:

- **Quality management structure.** Defines how the CQA plan fits within the construction project and how it will be managed.
- **Project definitions.** Clear and consistent definitions to be used throughout the project.
- **Roles, responsibilities, and inspecting authority.** Clear lines of authority, communication, and management.
- **Testing requirements.** Types of tests to be conducted, where the tests are to be conducted, and the names and qualifications of the testing personnel.
- **Testing frequencies.** Define the threshold (time, volume, weight) that triggers a test.
- **Surveying requirements.** Identify areas to be surveyed, acceptable survey tolerance, and qualifications of the surveyor.
- **Surveying frequencies.** Define the threshold (time, area, volume) that triggers surveying.

- **Nonconformance process**. A clear process on reporting nonconformance tests or survey and evidence of repair or resolution.
- **Reporting requirements and document control.** Documentation and reporting of testing results, survey results, approved changes or modifications to the design and/or technical specifications, and a summary of nonconformance resolution.

The objective of a CQC program is to ensure that proper materials, techniques, and procedures are used by manufacturers, installers, and contractors to meet the TSF design requirements. A CQC program is independent of the CQA program conducted by the third-party CQA organization. CQC testing may be performed at the point of manufacturing, processing, or stockpiles, or at the place of installation. This is in contrast with CQA testing that is mostly performed at the place of installation.

At a minimum, the CQC plan must address the following:

- **Quality management structure.** Defines how the CQC plan fits within the construction project and how it will be managed.
- **Project definitions.** Clear and consistent definitions to be used throughout the project.
- **Roles and responsibilities.** Clear lines of authority and communication.
- **Testing requirements.** Types of tests to be conducted, and where the tests are to be conducted and by whom.
- **Testing frequencies.** Define the threshold (time, volume, weight) that triggers a test.
- **Reporting requirement.** Documentation and reporting of testing results, approved changes or modifications to the design and/or technical specifications, and a summary of issues.

Upon completion of the TSF construction, an as-built report with drawings should be produced by the CQA organization. The as-built report represents the official record of what was constructed, how it was constructed, and any changes or modifications that occurred during the construction period. The as-built report should also include documentation from the CQA and CQC programs, reports on nonconformance and nonconformance resolution, and a discussion on site conditions that differed from the original design assumptions.

TSF OPERATION AND MANAGEMENT

An OMS manual must be completed for the TSF as part of the design stage. The manual should address the design intent, operating criteria, predicted behavior of tailings, daily operations and inspections, water management procedures, criteria for mechanical and electrical works (including pumps), surveillance, and maintenance and reporting requirements. Furthermore, the OMS manual should specify all requirements for operators and the minimum level of operator training. This section highlights the TSF operational aspects of the OMS. Monitoring and surveillance aspects of OMS are covered later in this chapter.

General Philosophy and Stewardship

Successful operation and management of a TSF focuses on four key areas, as applicable:

1. Controlled deposition of the tailings solids to form beaches that are consistent with the design geometry and design criteria
2. Management of the water within and around the TSF according to the conditions set forth in the design and operational criteria
3. Phased raising of the TSF dam(s)/embankment(s) to maintain sufficient storage capacity of storm events per the design
4. Frequent monitoring the performance of the TSF with respect to the design assumptions

These key areas are elements of a tailings management framework. The operation and management of a tailings facility should be governed by a tailings management framework that is site and operation specific.

The Mining Association of Canada (MAC) provides excellent guides for the management and monitoring of tailings facilities (MAC 2017, 2011a, 2011b, 2011c). The MAC guides provide information on safe and environmentally responsible management of tailings facilities; help companies develop tailings management systems that include environmental and safety criteria; and improve the consistency of application of sound engineering and management principles to tailings facilities.

In addition to the MAC guides, ICOLD has published several bulletins with respect to tailings dams. ICOLD publications pertaining to tailings dams include the following:

- Bulletin 74, *Tailings Dams Safety Guidelines* (ICOLD 1989)
- Bulletin 97, *Tailings Dams" Design of Drainage: Review and Recommendations* (ICOLD 1994)
- Bulletin 101, *Tailings Dams: Transport, Placement and Decantation* (ICOLD 1995)
- Bulletin 103, *Tailings Dams and Environment: Review and Recommendations* (ICOLD 1996a)
- Bulletin 104, *Monitoring of Tailings Dams: Review and Recommendations* (ICOLD 1996b)
- Bulletin 106, *A Guide to Tailings Dams and Impoundments: Design, Construction, Use and Rehabilitation* (ICOLD 1996c)
- Bulletin 139, *Improving Tailings Dam Safety: Critical Aspects of Management, Design, Operation, and Closure* (ICOLD 2011)
- Bulletin 153, *Sustainable Design and Post-Closure Performance of Tailings Dams* (ICOLD 2013)

The United Nations Environment Programme (UNEP) and the International Council on Metals and the Environment (ICME) have also published guidance related to tailings management (UNEP–ICME 1997, 1998). Key topics covered that relate to management of tailings dams include

- Corporate policies and procedures regarding stewardship of tailings facilities,
- Evolving regulatory climates and trends,
- Definitions of roles and responsibilities,
- Application of risk assessment techniques,
- Environmental management systems,
- Emergency preparedness and response, and
- Education and training.

These, and other guidelines, should be used to develop the tailings management framework for a specific TSF.

Tailings Deposition

The deposition of tailings into a TSF requires some forethought on the type of tailings to be deposited and the site conditions that may affect deposition. Tailings deposition considerations include but are not limited to the following:

- Variations in climate and climate change may have a significant impact on water management within the facility. For example, at start-up many operations run a negative water balance (e.g., the operation consumes more water than it has available, requiring makeup water from external sources). However, the water balance may become neutral or positive over time because of climatic conditions or changes in the mine plan (e.g., mining below the water table). Changes in the water balance need to be identified well in advance so that a water management strategy can be developed and implemented.
- Geometry of the tailings basin should be considered. For example, deposition in narrow valleys or rapid deposition in a confined area may result in a high rate of rise, impeding beach formation and beach drying. This can be an issue if the TSF was designed assuming beach formation and drying between deposition cycles.
- Paddock deposition using several separate cells is common in arid regions. This approach allows active deposition to be rotated between the cells, so that one cell is active while the others are allowed to "rest" and dry out. This approach has several benefits: (1) it provides a source of material that can be used for future raises; (2) by dividing deposition across several cells, seepage through the base of the facility is reduced; and (3) having multiple deposition cells distributes the "slimes" uniformly rather than from a central location, which may be difficult to reclaim at the end of the mine operation.
- Point of discharge flocculation may also be a consideration for slurry deposition. Dosing with flocculent at the point of discharge from a pipeline may result in a higher initial settled density and better water recovery.
- Many TSF designs are predicated on achieving a specific deposition geometry (e.g., beach length, slope, or slimes location). The inability to achieve the desired geometry may affect the performance and stability of the facility. Reconciling the actual geometry against the design is required so that potential impacts to performance or stability are identified early and appropriate risk mitigation efforts are implemented.

Three basic deposition methods are subaqueous, subaerial, and hydrocycloning. *Subaqueous deposition* is where the tailings surface is wholly or partially submerged below free water. In subaqueous deposition, the separation of the solids from the liquid phase occurs by sedimentation and submerged consolidation only. Subaqueous deposition is generally used where climatic conditions and/or operational controls ensure reliable year-round coverage by water, and where submerged tailings is determined to be essential for environmental or health and safety reasons dictated by the physical and/or chemical properties of the tailings. If subaqueous deposition is adopted, the TSF *must* be designed to account for water being in direct contact with the dam(s)/embankment(s). The TSF also must always have enough capacity to safely contain the design storm event to prevent discharging to the environment. Figure 8 presents a photograph of a subaqueous deposition facility.

Subaerial deposition is the most common method of deposition. Subaerial deposition occurs where placement of tailings forms an exposed beach over most of the storage area, with a reclaim pool at the end of the beach. With low solids content slurries, subaerial deposition promotes segregation of coarser particles from the finer particles (Blight 1994). This segregation occurs toward the top of the beach while finer particles (often referred to as "slimes") accumulate in the reclaim pool. The beach is exposed to evaporative drying, which increases the density of the beach tailings. The "slimes" generally remain submerged or partially submerged in the reclaim pool. Average beach angles for slurried tailings generally range from 0.2% to 1.0%. The coarser particles on the upper part of the beach may also be removed and used for dam/embankment construction. Thickened and paste tailings are also deposited subaerially; however, particle segregation does not occur in these materials.

Hydrocycloning is commonly used with low solids content slurry to produce sand for construction along the TSF dam/embankment (Figure 9). Kujawa (2011) provides practical guidance on potential sand production using hydrocyclones.

Figure 8 Subaqueous deposition facility

Figure 9 Hydrocycloning

Courtesy of Phibion

Figure 10 Mechanical drying of tailings

In higher solids content tailings (e.g., thickened and paste tailings), very little particle segregation occurs and only a minimal amount of free water may be present. With thickened and paste tailings, the achievable "beach" angle is a function of the tailings characteristics and deposition rate (McFayden 1998). The achievable beach angle for thickened and paste tailings may range from 1.0% to more than 5.0%. One of the many advantages of thickened and paste tailings (besides reduction in water consumption) is the ability to achieve a steeper beach as compared to low solids content slurries. The steeper beach angle can help reduce the TSF footprint and construction cost provided the topography and climate are suitable.

Some tailings, such as "mature fine tailings" in the oil sands industry, phosphate, and bauxite tailings, are composed mainly of clay-sized particles that remain in suspension in the process water. These materials can be very challenging as they retain moisture for long periods of time and are very difficult to consolidate, or densify (Caughill 1992; Kasperski 1992). These materials may require special flocculants or polymers (Li et al. 2008) and/or mechanical working (Munro and Smirk 2012), such as amphi-rollers (Figure 10), to achieve some level of densification.

Dry stacking involves dewatering the tailings (e.g., using vacuum or mechanical filters) so they can be stacked using earthmoving machinery or conveyors. Tailings that are dry stacked can be placed at slopes of up to 30% or more, if the material is compacted as placement occurs (Lupo and Hall 2010). The steep slopes that can be achieved by dry stacking can significantly reduce the TSF footprint and reduce construction costs, provided the topography and climate are suitable.

Deposition issues with dry stacking include material handling and scheduling, dust generation from the dry stack, erosion and water pooling on the surface of the stack, and static liquefaction (stacking at high rates).

Water Management

Water management within and around a TSF is a critical component to the overall management of the facility. As noted earlier in this chapter, poor water management has played a significant role in past TSF failures. Water management within a TSF is managing not only the size of the reclaim pool but also its location. Both the size and location of the pool can influence the stability of the TSF embankments/dams as well as seepage rates, beach geometry, tailings density, and the performance of the decant system.

The size and location of the decant pond can be affected by the method and direction of deposition, the geometry of the tailings facility, the climate, the decant recovery rate, and the settling characteristics of the tailings. For these reasons, the tailings deposition plan (discussed earlier in this chapter) must be integrated with the water management.

Two primary tools are used for effectively managing water in a TSF. These tools are (1) a water balance and (2) reconciliation/monitoring of the TSF performance.

Water Balance

A water balance is a methodology used to describe and quantify the flow of water into and out of a system. For a TSF, the primary components of a water balance include the following.

Inflows:

- Direct rainfall within the footprint of the facility
- Catchment runoff of precipitation into the facility
- Deposition water delivered within the tailings from the process plant
- Groundwater discharge into the facility (if present)

Outflows:

- Return/reclaim water from the TSF to the process plant
- Evaporation from the supernatant pond and beaches
- Water entrained in tailings
- Seepage capture from underdrains and leachate collection and recovery systems

A generalized schematic of a water balance for a TSF is presented in Figure 11.

It is common practice to develop a water balance during the design stage of a TSF. At this stage, the water balance is often based on limited climatic and site data, and assumed operational information; however, this is usually sufficient to provide an estimate to "bound" the water requirements for the operation. After the TSF goes into operation, the water balance should be updated annually and maintained using actual site information (daily precipitation, evaporation rates, production rates, percent solids, reclaim rate, etc.) as it becomes available.

A water balance is based on several simplifying assumptions. For example, the evaporation rates (which can be a significant outflow component) from the reclaim pool, wet beach, and dry beach are all different, yet the size of the pool, wet beach, and dry beach are constantly changing. So there is no practical means to estimate the loss to evaporation other than

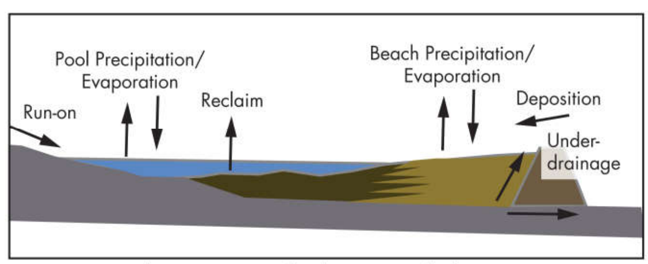


Figure 11 Tailings storage facility water balance

Figure 12 Tailings storage facility survey prism setup

Figure 13 Inclinometer (next to pickup truck)

using assumed areas and effective evaporation rates. Even though there are practical limitations to water balances, they are still important tools for water management. For example, water balances can be used to

- Assess potential changes in water management because of changes in processing (rate, percent solids, etc.),
- Estimate when changes in water demand and/or the buildup of excess water may occur,
- Estimate treatment requirements and/or discharge rates should the site have a positive (e.g., gaining) water balance, and
- Assist in managing external water resources.

TSF Reconciliation

A TSF is an engineered facility, and therefore, the performance of the facility should be reconciled against the original design intent and assumptions. TSF performance reconciliation is important to identify potential flaws in the design (e.g., when what was assumed conflicts with actual conditions) and to provide input should the TSF design need to be modified.

The reconciliation of the TSF performance is typically conducted via monitoring and surveillance programs. These programs should be developed as part of the TSF design stage and consider stability, settlement, seepage, beach configuration, reclaim pool location and size, and decant performance.

TSF MONITORING AND SURVEILLANCE PLAN

The objective of the TSF monitoring and surveillance plan is to define the requirements for monitoring the performance of the TSF through life-of-mine. The plan must cover all aspects of the TSF so that the "health" or performance of the facility can be evaluated.

Dam/Embankment Monitoring

Critical elements of a TSF are the containment dam(s) or embankment(s). These are the primary engineered structures that prevent uncontrolled discharge to the environment. TSF dams/embankments are typically constructed of earthen materials, tailings, rockfill, and/or concrete. A typical monitoring program for TSF dams/embankments consists of the following instruments.

Survey prisms. Prisms are reflective devices mounted on poles and are located along the dam/embankment to monitor surface deformation (vertical and lateral movements) of the structure. Prisms are useful for monitoring changes along the surface of the dam/embankment that may indicate a stability issue. Prisms can be surveyed by manual means or by a robotic total station. Figure 12 presents a typical prism survey setup for a TSF.

Inclinometers. Inclinometers are instruments that are placed within the dam/embankment and used to measure deformation within the structure. Inclinometers consist of a grooved casing and the inclinometer instrument that runs along the grooves (see Figure 13). The casing is installed in the dam/embankment by drilling a hole and grouting the casing within the hole. The inclinometer is lowered and raised in the casing and measures deflections along the casing. The deflections along the casing can be plotted with depth to show potential movement within the structure. Alternatively, shaped acceleration array inclinometers may also be considered. An example of inclinometer data is shown in Figure 14.

Piezometers. Piezometers are instruments that measure water pressure and are used to determine the hydraulic pressure (piezometric) heads within the dam/embankment, which is critical to assessing the stability. Piezometers are installed within the dam/embankment, either as direct placement within the fill during construction or grouted in borings after construction is complete (see Figure 15). It is recommended that multiple piezometers be installed with the dam/embankment at different elevations (including the foundation) and along the structure to monitor hydraulic conditions.

A recent development for TSF monitoring is the use of satellite-based interferometric synthetic aperture radar (InSar). InSar is a radar technique that can map surface deformations (millimeter scale). This remote sensing method is very effective for covering large areas and providing high-quality data. InSar is not meant to provide real-time monitoring but does provide an efficient means to gather periodic deformation information. Figure 16 provides an example of InSar output for a tailings facility.

Drones may also be employed for surveillance of TSFs to measure deformation. Infrared cameras may be used with drones to scan the facility for the presence of shallow seepage.

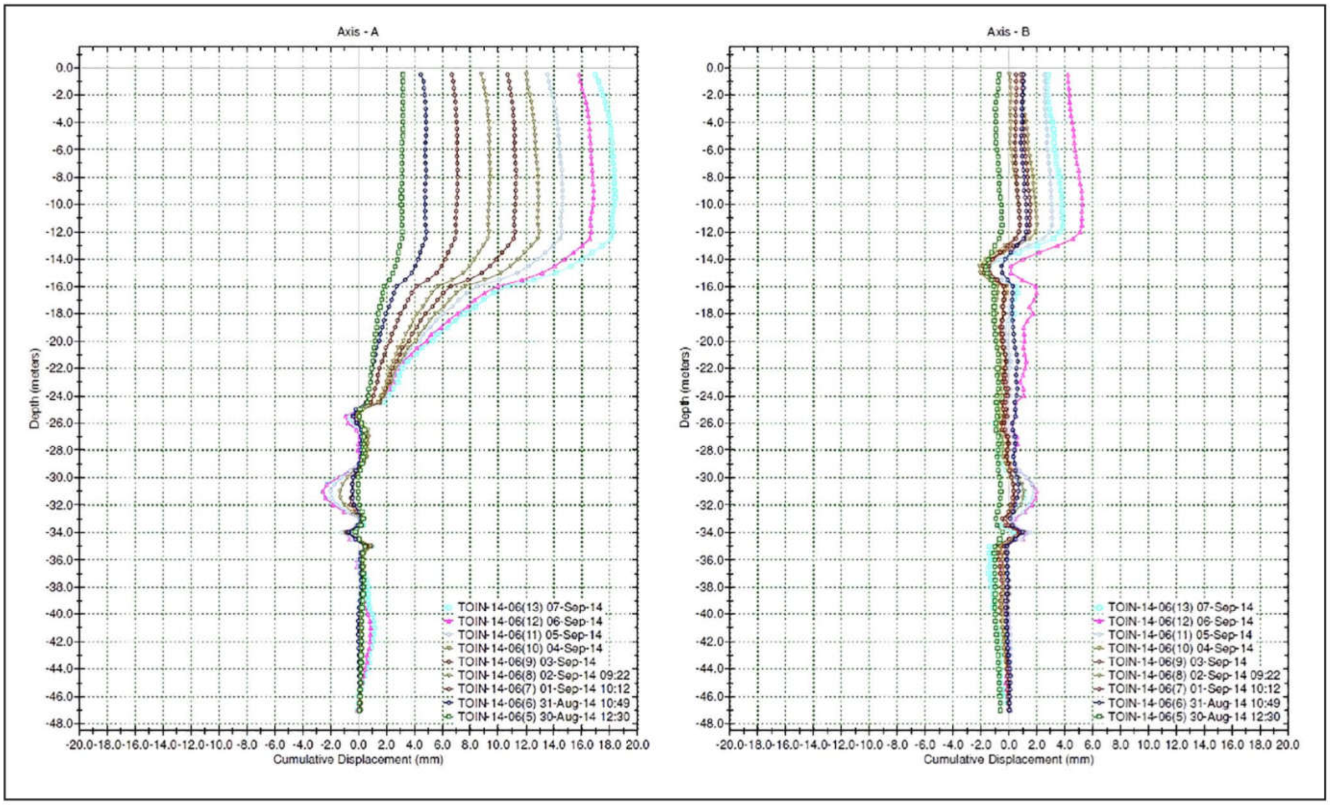


Figure 14 Inclinometer data example

Courtesy of Newmont Mining Corporation
Figure 15 Typical piezometer (fitted with a telemetry system)

Seepage Monitoring

Seepage monitoring from a TSF may consist of several elements, depending on the TSF design and site conditions, and generally consists of measuring both flow and water quality. Seepage monitoring provides critical information that relates to internal drainage of the facility, which can impact not only stability but also the effectiveness of the environmental containment.

Seepage monitoring of a TSF may include the following (as applicable):

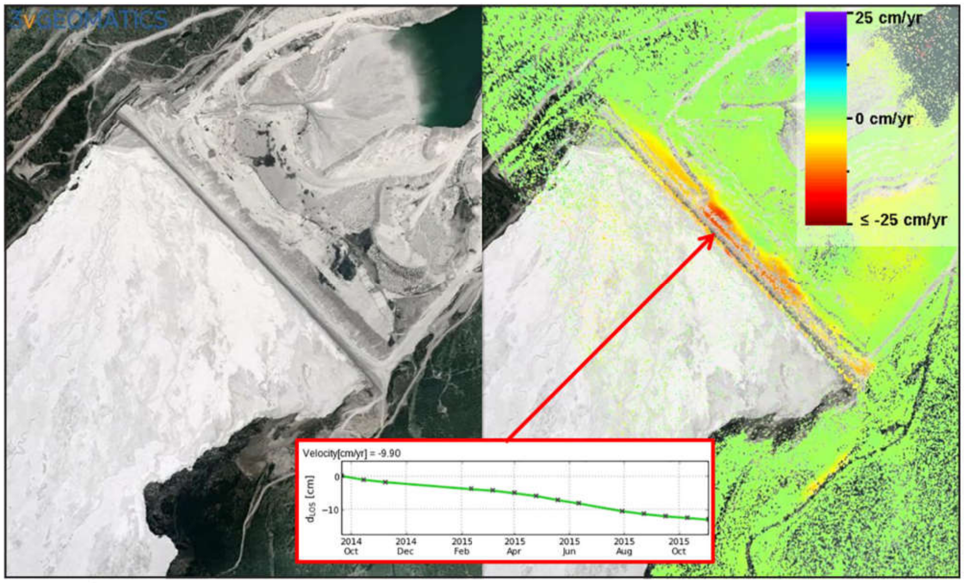
- **Foundation underdrains.** Drainage systems within the foundation to control seepage pressures
- **Internal underdrains.** Drainage systems that may be placed on the surface of the storage basin to enhance consolidation of the tailings
- **Dam/embankment drains.** Drainage constructed within the dam/embankment to control seepage through the structure, such as blanket drains and chimney drains
- **Monitoring wells.** Located downgradient of the TSF to monitor water levels and water quality.

Seepage monitoring data should be analyzed routinely to look for trends (e.g., increasing flows or increasing constituent concentrations) that may affect how the TSF is managed.

Deposition Monitoring

Deposition monitoring is used to ensure that the performance of TSF operations meets the criteria set forth in the TSF design (see the discussion earlier in this chapter). At the TSF, deposition monitoring consists of visual inspections and surveying to quantify the following (as applicable):

- **Beach or stack quality (uniformity and condition), length, area and slope.** Used to reconcile with the design assumptions and available storage capacity.
- **Rate of rise.** Used to assess the rate of rise with respect to the design.
- **Reclaim pool size and location.** Used to estimate the pool volume and location to critical structures.



Courtesy of 3vGeomatics

Figure 16 InSAR tailings storage facility application

- **Available freeboard.** Used to quantify and verify the available dry freeboard to contain the design storm event and protect against overtopping because of wave runup.
- **Tailings deposit gradation.** Used to measure the effectiveness of cyclone operations. It can also be used to assess the effectiveness of spigot shapes and spacing.

At the process plant, deposition monitoring consists of measuring discharge rates to the TSF, percent solids, rheological parameters (primarily used for thickened and paste tailings), and water recovery rate.

Inspection and Review Program

A formal inspection and review program must be established for every TSF. This program should detail the level of inspections and reviews to be conducted, frequency of inspections, and documentation requirements. Inspection reports should be kept up to date and readily accessible so that changes in the TSF behavior can be identified.

The Australian National Committee on Large Dams recommends that an inspection program include the following (ANCOLD 2012):

- Groundwater monitoring with special emphasis on the environmental impacts of the TSF on groundwater (e.g., geochemical processes)
- Surface drainage and seepage monitoring, both visual observations and seepage measurement as a minimum, with chemical analysis also of value (e.g., acid drainage generation)
- Capacity monitoring (tailings, process water, water recovery, evaporation)
- Tailings monitoring (e.g., beach development, drainage, density, desiccation)
- Monitoring of instrumentation and instrumentation readings
- Monitoring of equipment and pipework
- Monitoring of dam movements, stresses, cracking and seepage
- Inspection reports (i.e., times, dates, observations)
- Incident reports (i.e., time date, nature, actions)
- Annual audit

The frequency of inspections is often dictated by regulatory or permit requirements. Table 2 presents suggestions from ANCOLD.

EMERGENCY RESPONSE PLANS

All TSFs where any persons, infrastructure, or environmental resources could be at risk if the facility collapses or fails should have an ERP. The ERP should be based on an appropriate dam break study with the conservative assumption of liquid tailings flow in the event of failure (unless a more sophisticated analysis of water and/or tailings flow can be justified).

ERPs are often developed following the guidance set forth in framework presented in *Awareness and Preparedness for Emergencies at Local Level* (UNEP 2015). ERPs should be tailored to suit the regulatory requirements, site conditions, operation, and local community involvement.

The basic elements of an ERP include clearly defined roles, responsibilities, and contact information during an emergency; emergency response guidelines and procedures (internal and external); detailed communications systems; and incident investigation procedures. ERPs should be periodically tested to evaluate effectiveness and potential gaps in the plan.

TSF CLOSURE AND RECLAMATION

This section discusses the closure and reclamation of TSFs, including closure objectives and constraints that may affect closure design and activities. According to the guidance set forth in ANCOLD (2012), the closure of a TSF should embrace the following objectives:

- Provide long-term physical, chemical, ecological and social stability.
- Minimize ongoing maintenance and expenditures other than normally required for similar land use.
- Not pose a risk to human health and safety.

Table 2 Recommended frequency of inspections

TSF Failure Consequence Category	Inspection Type			
	Comprehensive	Intermediate	Routine	Special
Extreme or high	After first year of operation, then every second year	Annual	Daily to three times per week	As needed
Significant	After first year of operation, then every fifth year	Annual	Twice a week to weekly	
Low	—	After first year of operation, then every fifth year	Monthly	

Source: ANCOLD 2012

- Not pose an unacceptable environmental risk.
- Provide an appropriate and sustainable land and water use, which meets stakeholder and community objectives and supports a sustainable ecology.

In addition, the TSF closure must also comply with local or regional regulatory requirements as well as corporate internal standards that may apply.

A preliminary TSF closure plan should be developed during the design stage. A closure plan sets forth the details on how the TSF will be closed and meets the overall closure objectives. This is done to ensure that the TSF design is compatible with the desired closure objectives. Over the life-of-mine, the closure plan should be revised to take into account any changes in operation or management that may impact closure. Robins (2004) provides an excellent review of current TSF closure practices and case histories. The basic design and control considerations for the closure of a TSF are summarized in Table 3. A cover for the TSF may be required as part of the closure. The details of cover design are beyond the scope of this chapter; however, the Mine Environment Neutral Drainage (MEND) program discusses the results from several case histories and provides insight on actual cover performance as well as lessons learned (MEND 2004b).

Physical and Climate Constraints

The closure of a TSF and its final landform is closely tied to the site physical and climate conditions. A closure plan for a TSF should be developed that incorporates the site physical and climate conditions, and the necessary design elements, to meet the objectives stated in the previous section.

Physical constraints that may be considered for a TSF closure include legal land boundaries, sloping ground, high seismicity, surface water bodies, public roads and land, national or protected forests, and nearby towns. These physical constraints can impact surface grading and resloping configuration, surface water diversion and controls, seepage collection, cover design, and the availability of suitable construction materials. It is important that during the TSF design phase, suitable attention is paid to the impact to closure as a result of the site physical constraints. Changes can often be made in the design stage that can simplify closure of the facility and reduce postclosure risk.

Site climate conditions will also play an important role in how a TSF will be closed. For example, a TSF in a wet climate will require more water management controls than one located in an arid region. Climate also plays a role in cover design and performance. Wide swings in temperature and precipitation are often difficult to accommodate in a cover design, resulting in poor performance (e.g., high infiltration rates or cover erosion) and requiring periodic maintenance to repair the cover. It is very common to conduct cover trials to assess the performance of different cover designs. Typically, cover trials are conducted several years prior to closure so cover performance under site conditions can be monitored and documented. This will reduce the uncertainty of the cover's suitability with site conditions.

Environmental and Social Constraints

Environmental and social concerns must be addressed in the TSF closure plan and design. Stakeholder engagement during the design phase is recommended so that the TSF design and postclosure use addresses concerns and desires for future land use, water quality, and visual/aesthetics impact.

The environmental and social constraints are unique to each site, so it is key that the driving environmental and social issues be clearly identified and discussed, preferably before or during the design work for the facility. These discussions should address any constraints or commitments to be considered in the design and operation of the facility.

Tailings and Cover Material Characteristics

The characteristics of the tailings will affect closure and cover design. MEND provides some guidance and the suite of testing

Table 3 Tailings storage facility closure considerations

Issues	Desired Outcome	Control
Physical stability • Dust • Erosion • Embankment/Dam • Drainage • Radon gas	• Dust control • Sediment control • Structural stability • Radon gas emission control	• Site selection • Facility design • Deposition method • Tailings characteristics • Cover characteristics and design • Water management and drainage control
Chemical stability • Metal leaching • Acidic drainage • Reagent drainage	Discharge of acceptable quality water (surface and groundwater)	• Cover design to control reactions • Effluent collection and treatment • Pretreatment of tailings • Facility liner design • Water management and drainage control
Land use • Loss of land use • Visual impacts	Restore to appropriate land use	• Landform design • Cover design • Revegetation

Adapted from MMSD 2002

that may be required to support cover design (MEND 2004a). The primary tailings characteristics that should be considered include the following.

Metal/reagent leaching potential. Often the leaching potential of tailings is assessed using the toxicity characteristic leaching procedure. Alternatively, the synthetic precipitation leaching procedure can be used. Both tests are used to simulate potential leaching and metals/reagent release under field conditions. The data from these tests can be used to understand what metals or reagents may be released and if the leachate would impact groundwater and vegetation growth.

Tailings and cover mineralogy. The mineralogy of the tailings and potential cover materials should be evaluated to identify minerals that may influence cover design. For example, the presence of expansive clays, such as smectite, can expand and shrink significantly, damaging a soil cover. Tailings that are radioactive from uranium processing require special cover designs to mitigate or attenuate radon gas emissions.

Hydraulic properties. The majority of TSF closure covers are designed to minimize infiltration and, in some cases, oxygen egress into the tailings. These types of covers require knowledge of the soil–water characteristic curve (SWCC) for both the tailings and the cover materials. The SWCC defines the relationship between soil suction and moisture content within a material. This relationship can then be used to derive the unsaturated hydraulic conductivity. The SWCC is used in engineering calculations to estimate the infiltration rate and saturation of the cover materials and tailings under site conditions. Often the SWCC is measured for several cover materials, so that a suitable cover design can be developed.

Soil organic matter. Most tailings do not contain any organic content nor nutritive value to support vegetative growth. Numerous studies have been conducted to evaluate amending various types of tailings with organic carbon and other materials to increase the ability of tailings to support vegetative growth (Lindsay et al. 2011; Fang 2015; Pitchel et al. 1994). Cover materials should also be evaluated for organic/carbon content and nutritional value to assess their suitability for use.

CLOSING COMMENTS

This chapter provides the reader with an appreciation for tailings disposal and management. Although tailings are a waste product from mining, the disposal of tailings carries significant cost and risks to a mining operation. These risks can be mitigated by completing a thorough design of the TSF; implementing a high-level of quality control during construction of the facility; and operating the facility fully within the design and operational criteria. TSFs are highly engineered structures and should be treated as such.

The material presented is meant to provide basic knowledge on the disposal and management of tailings, from design to closure. Readers are encouraged to read the references provided and conduct their own literature search of this topic as there are numerous pertinent and excellent resources available. Finally, the reader should understand that tailings disposal is unique for each operation around the world. The nuances for each operation must be understood so that a safe and reliable facility can be designed, constructed, and operated.

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