

Review

A Review of Tailings Dam Safety Monitoring Guidelines and Systems

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Abstract: The awareness of tailings dam safety monitoring has widened due to the recent disasters caused by failures of such structures. The failure rate of tailings dams worldwide (i.e., the percentage of failed dams out of total) is estimated at 1.2%, compared to the 0.01% rate for traditional water dams. Most of the tailings dam monitoring guidelines suggest that the owner develops a robust surveillance program to detect possible indicators of potential failures. This paper presents a thorough review of major guidelines on tailings storage facility (TSF) monitoring and surveillance, the visual parameters to be monitored, as well as good practice in the development of monitoring systems. This paper reviews the recent literature with an emphasis on the development of monitoring systems utilizing sensors, unmanned aerial vehicles (UAVs), and satellite images that may be considered as supplementary guarantees against failure events.

Keywords: tailings dam; safety; stability; monitoring system



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1. Introduction

The topic of tailings impoundments' safety has been trending in the mining industry. The catastrophic failure of the Córrego do Feijão tailings dam in Brumadinho, Brazil, in early 2019 made the industry take an even closer look at this issue. Tailings impoundments (also referred to as tailings storage facilities—TSFs) require constant maintenance and monitoring throughout their life cycles (including post-closure). The public tends to associate tailings dam failures with catastrophic events that cost lives and cause environmental damage. These significant accidents are usually related to a type of stability failure.

Failure is always a concern with TSFs. The failure rate of tailings dams worldwide (i.e., the percentage of failed dams out of total) is estimated at 1.2%, compared to the 0.01% rate for traditional water dams, based on data covering 100 years [1,2], that found that active tailings dams contributed over 90% of dam failures in the world (mostly occurred in European countries) at that time. The current high metal demand is projected to require more mining, which will lead to more active tailings dams. Damage is prone to happen on tailings dam walls compared to water retention dam walls for the following reasons [1]:

- (1) The use of tailings material or waste rock for embankment construction;
- (2) A linear relationship between the dam height and the amount of wastewater deposited along with tailings that needs to be managed;
- (3) Minimum regulations are provided in the dam design standards;
- (4) The high monitoring cost when the dam is active and post-reclamation, throughout and after the active life of the mine ends.

This paper focuses on a thorough review of the major guidelines on TSF monitoring and surveillance, the visual parameters to be monitored, as well as good practices in the

development of monitoring systems. A brief background of tailings dams and associated instabilities and statistics is also presented. This study can be useful to researchers and industry practitioners by gathering and summarizing most of the works in these areas.

2. Background

2.1. Tailings Disposal

The Canadian Dam Association (CDA) considers a dam as a barrier which can retain a minimum of 30,000 m³ of water, tailings, or another substance containing water [1]. It is essential to know that this structure can be addressed with a couple of different names such as residue disposal area, tailings impoundment, tailings management facility, or TSF.

Tailings disposal methods can vary depending on the site location. ICOLD (1996) [2] presented five ways of disposal, including economic utilization, river or sea release, underground storage, filtering and storing on land, and building a containment structure. The utilization of tailings for economic purposes currently is commonly related to underground deposition, where tailings are mixed with cement to serve as backfill material. This is especially useful for operations with weak rocks. Subaqueous disposal is another name used for river or sea disposal after being treated, which is exactly as the name implies. In-pit tailings deposition is also considered as another form of subaqueous disposal, where an operation sub-aqueously stores material in an old, inactive pit. Dry or filtered tailings disposal on land is an option where, ideally, no impoundment structure is needed. Water is filtered out for reuse in the mining process, and the dewatered tailings can be mechanically placed in a specified area. Lastly, tailings containment in a dam structure is what is commonly used in the industry to retain tailings material on the surface with multiple variations of how to retain it. Another name used for this method is subaerial. Paste tailings would also be categorized in this class for it still requires a containing dam, though smaller than for slurry. The containment facility usually requires a large area to fit all the tailings produced, so tailings are typically transported and deposited some distance away from the processing plant. Ref. [3] explains that the optimal distance between the tailings dam and mill facility is within five miles of the facility. The subaerial method is where most accidents have occurred, so the focus from this point forward is on this disposal method.

Proper containment of tailings is a vital aspect of ensuring the material will not flow out and disturb the surrounding area. Therefore, this correlates with the health and safety of the employees, the environment, and the operation itself. Two typical tailings discharge types for surface impoundment are rotational spigotting and single-point discharge. Many operations employ spigots to control material distribution and reduce workload because single-point discharge is less flexible [4].

2.2. Tailings Failures

ICOLD (2001) [5] summarizes the causes of reported tailings dam failures around the world, which sparked the interest to create a database of failures posted on a website entitled www.worldminetailingsfailures.org (accessed on 4 March 2024). An additional source where TSF failures are frequently recorded is a website by the World Information Service on Energy [6]. It focuses on uranium mines, but it provides a compilation of major tailings dam failures from 1960 to the present day and gives details of the incident type, the amount of material released, and the impact of the failure. After compiling reviews from the TSF guidelines, papers, and databases, many failures were caused by seepage, foundation failure, overtopping, and earthquakes. This list is also reflected in the data shown in Figure 1. Out of these causes, this study is directed toward overtopping to see how well we can detect its leading features for better tailings dam monitoring using image analysis.

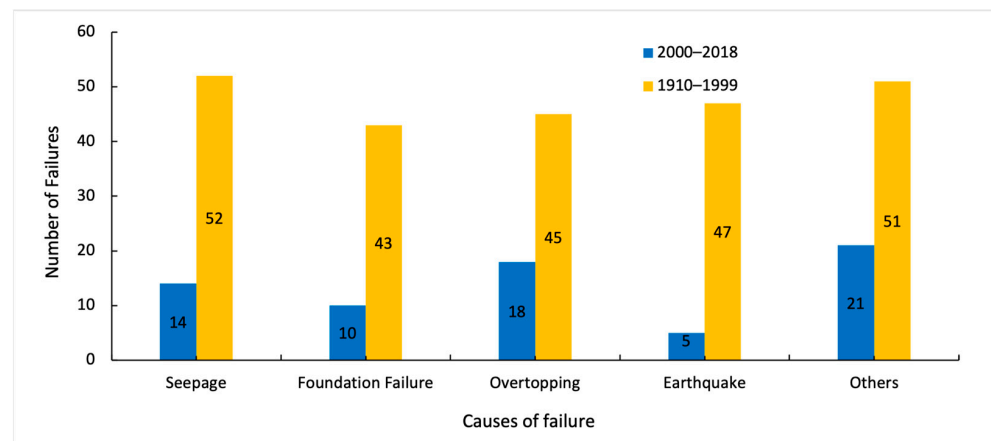


Figure 1. Main causes of failure in TSFs based on 100 years of data. Data from [7].

The identification of these failure causes can be made through several performance parameters. Table 1 presents a compilation of some essential categories summarized in [8]. This list indicates that there are ways of preventing these failures. A study recorded in a review paper [7] found that the initial stages of overtopping can be mistaken as signs of water erosion. The Federal Emergency Management Agency (FEMA) recognizes that a small failure can lead to a more significant event [9].

Table 1. Compilation of key visual performance parameters. Adapted from [8].

Category	Visual Parameters
Tailings Surface	Slurry flow rate and density
	Size and position of the decant ponds
	Reservoir level and freeboard requirements
	Tailings transport conditions
	Beach slopes
	Persistent vortex (whirlpool) in the reservoir
Ancillary Infrastructure	Decant facility integrity and access
	Cracking in any concrete structure
	Erosion in roadways and access routes
	Return water storage capacity and infrastructure
	Condition of gates, fencing, and signage
	Pump and pipeline systems condition
	Vegetation clogging drainage ditches
	Discharge tunnel or conduit condition, seeps, and cracks
Emergency Preparedness	Status of the leak detection system
	Performance of automatic flow measurement
	Status of fault alarms
Seepage Flow	Trench flow efficiency
	Density and flow rate of slurry
	New development or changes in seepage areas
	The color of seepage water
	Quantity, location, and clarity of flowing water
Instrumentation	Water levels in permanent monitoring stations
	Condition of monitoring instruments and data reading quality
Embankment/Berms	Cracking
	Bulging at the toe of slope
	Weeping
	Piping
	Sloughing
	Subsidence at the crest or downstream embankment
	Sinkholes at upstream face of the dam
	New vegetation or changes in quantity
	Surface erosion of any type
	Wave erosion on the upstream embankment
Miscellaneous	Animal burrows

The final goal is to prevent failure from occurring. Once an impoundment fails, it damages the environment and takes human lives [7]. Armstrong et al. (2019) [10] recommended technical and managerial level incentives that might prevent failure, such as the use of new processing technology, imposing significant penalties, and adopting the Mining Association of Canada's (MAC's) guidelines. They suggest that the MAC guidelines' inclusion of higher-level officials will push more care to tailings operations. It is common in the mining industry to go through changes in ownership and TSF personnel, so another challenge is to make sure that proper maintenance and high safety standards are carried out throughout the life of the facility.

The current advancement in technology had incentivized mining and consulting companies to employ UAV (unmanned aerial vehicle) and UAS (unmanned aerial system) technologies. They have been proven to effectively combine the traditional monitoring processes both while dams are active and post-reclamation [11,12]. Therefore, the aim is to couple the automation of monitoring systems with new technologies which could assist mine sites with continual monitoring data gathering that can be flexible enough during these changes.

3. Existing Guidelines and Standards for Tailings Dam Management

This section presents a general review of the guidelines and their contribution to the monitoring system of tailings dams.

An assessment of the case histories indicates that the rate of failure for tailings dams is higher than other types of dams. Further, the statistics indicate that, on average, three tailings dams fail annually [8]. This high failure rate had incentivized many organizations and countries to provide better tailings dam design guidelines to follow. Currently, two countries are known to publish such guidelines, Australia and Canada, which have high mining activity and tailings dam inventories [13].

There are multiple guidelines currently available in tailings dam construction. Ref. [13] summarized those guidelines based on the country of origin and some independent organizations, such as Canada, Australia, South Africa, the International Commission on Large Dams (ICOLD) and its member countries, the United Nations Environmental Program (UNEP), the International Council on Metals and the Environment (ICME) [14], the International Institute for Environment and Development (IIED), and the International Organization for Standardization (ISO). However, IIED only deals with safe disposal into natural bodies of water, and ISO serves as an extra layer of certification since it was the guide for the MAC guidelines.

In April 2021, the Church of England released a requested disclaimer from all mining companies on their list of active and inactive tailings dams in response to the recent tailings dam failure disaster [15]. Table 2 shows the results of this survey, where only 114 out of 721 contacted companies were willing to disclose the full list of their tailings impoundment.

Table 2. Results of survey conducted by the Investor Mining and Tailings Safety Initiative (as of May 2021). Data from [15].

Classification	Amount
Total Number Contacted	721
Overall Number of Responders	341
Responders Declared no TSF	188
Responders with Full TSF Disclosures	114
Total Number of Disclosures (Partial Included)	153
No Response	183
No Response but No TSF Confirmed	197

The following subsections consist of a brief explanation of well-known existing guidelines as well as additional standards that are periodically used in the mining industry. Due to the nature of this study, the documents discussed are the ones specified for tailings dam monitoring. Most monitoring systems need to be installed at the beginning of the dam's life; therefore, good planning will result in efficient data gathering. The next section will dive into some guidelines that are commonly used during the design, operation, and maintenance of TSFs. Tailings dam design is very site-specific, so countries publishing guides will include common practices in their respective locations and climates. Also, some of these guides can be utilized for both tailings and general dams in the construction process [16,17].

3.1. Mining Association of Canada (MAC)

The MAC is an organization that focuses only on sustainable mining in Canada and helps support its members and partners. The organization consists of 41 companies that are considered as full members and 57 associated companies. There are two main documents that have been published and revised throughout the years, i.e., the tailings guide and the operation, maintenance, and surveillance (OMS) manual. The tailings guide has had three editions published, where the latest edition was updated in 2019 (version 3.1) [18,19]. The OMS guide has two editions, and the second edition was revised in 2019. All guide documents are available online for download at MAC's main website.

The OMS guide provides information and details how to create a surveillance program. The term surveillance in MAC covers both inspection(s) and monitoring. The idea behind monitoring is to see a possible trend within the recorded data and inspect the performance of the facility. The parameters suggested for monitoring are:

- Pond level and freeboard;
- Deformation (bulges, cracks, sinkholes, etc.);
- A new or expanding area of erosion;
- Piping or unexpected water movement;
- New seeps formation, changes in seeps, or changes in seepage characteristics;
- Spigot or material discharge instrument and pump condition;
- Possible leakage of water lines from the decant pump;
- Condition of water reclamation infrastructure;
- New or change in wildlife activity;
- New or changes in vegetation;
- Condition of the ground instruments.

3.2. Canadian Dam Association (CDA)

The CDA guidelines and technical bulletins are the most utilized of the guidelines in the mining industry based on the survey from the Church of England. The documents recognize routine inspection as an important aspect of facility management. Figure 2 presents this as the first step of the dam safety analysis process, but notice that the system should run as a closed loop.

This guideline recommended that dam surveillance can only be effective when the site safety personnel understand the possible failure modes, signs of failure to look for, and the proper monitoring or inspection measures to detect such processes. Principle 4a of the guideline suggests that “A safety review of the dam shall be carried out periodically”. It advises an evaluation and systematic review of all aspects, including visual inspection of various dam components, since warning signs usually appear as dam failures develop [1]. To put it simply, the parameters that should be routinely visually monitored are:

- (1) Leakage;
- (2) Erosion;
- (3) Sinkholes;
- (4) Boils;
- (5) Seepage;

- (6) Slope slumping or sliding;
- (7) Settlement;
- (8) Displacements or cracking of structural component;
- (9) Clogging of drains and relief wells.

The frequency of inspection is greatly dependent on the regulatory requirements, the consequence of failure, season, development time, etc.

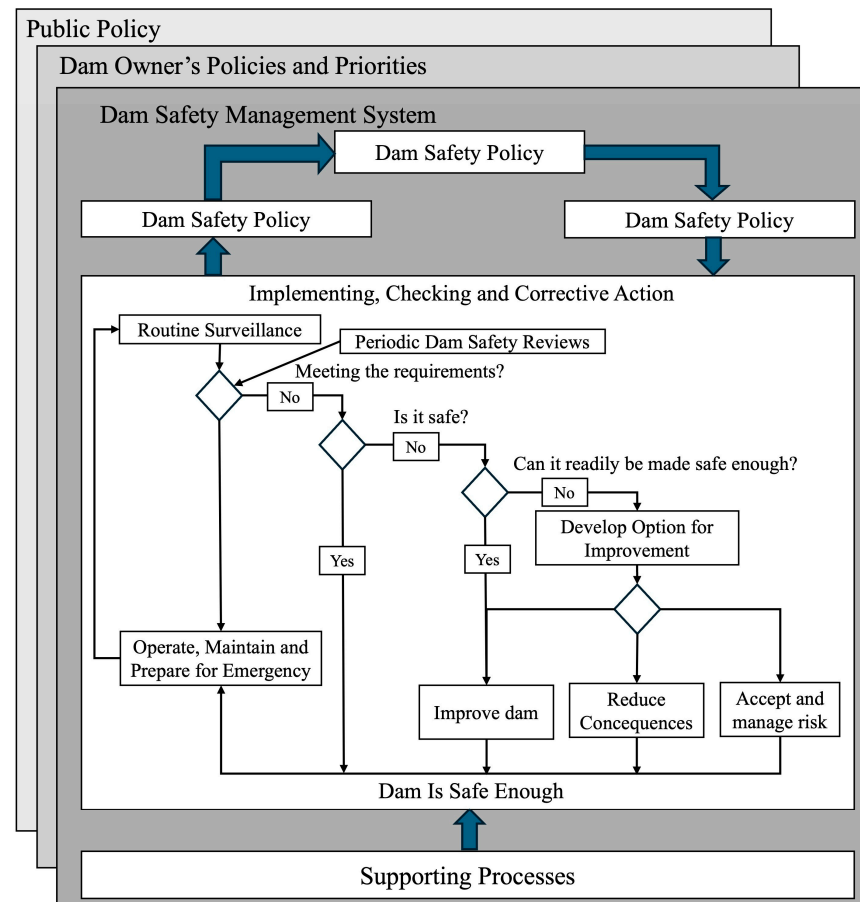


Figure 2. Tailings dam safety management system suggested by the CDA. Redrawn from [1].

3.3. International Commission on Large Dams (ICOLD)

ICOLD is an international organization with more than 100 member countries from all continents. Member countries often have their own internal extension. Each member country can publish their guidelines created specifically for their specific law and geological condition. For example, the United States is a member country, and their internal organization is known as the United States Society on Dams (USSD). The general publications on dams from ICOLD are released in bulletins, with topics ranging from design to operations to surveillance. To name a few, it covers challenges in dam engineering, concrete dams design, surveillance, safety management, water storage, regulations, material selections, inspection guidelines, risks, lessons learned from past cases, etc. The bulletin numbers published specifically on tailings dams are 181, 139, 121, 106, 104, 103, 101, 98, 97, 74, 45, 44 [2,5,20–22].

Out of these 12 bulletins, 4 covered the area of monitoring/surveillance (bulletins 74, 103, 104, and 139). Seven bulletins specifically on dam surveillance are also available for review, these are bulletin numbers 60, 68, 87, 118, 138, 158, 180 [22–24].

Most of the specified bulletins do not list the exact parameters to be monitored visually. However, this might be due to the lengthy explanation given within the general dam surveillance documents. Bulletin 180 is currently in a preprint format, but it summarizes

both bulletins 118 and 158 on the idea of surveillance. Figure 3 shows a chart representing areas of surveillance and tying it to the dam assessment process. It should be noted that this document indicates how visual inspection only has an analysis section since no instrument is used but human eyes.

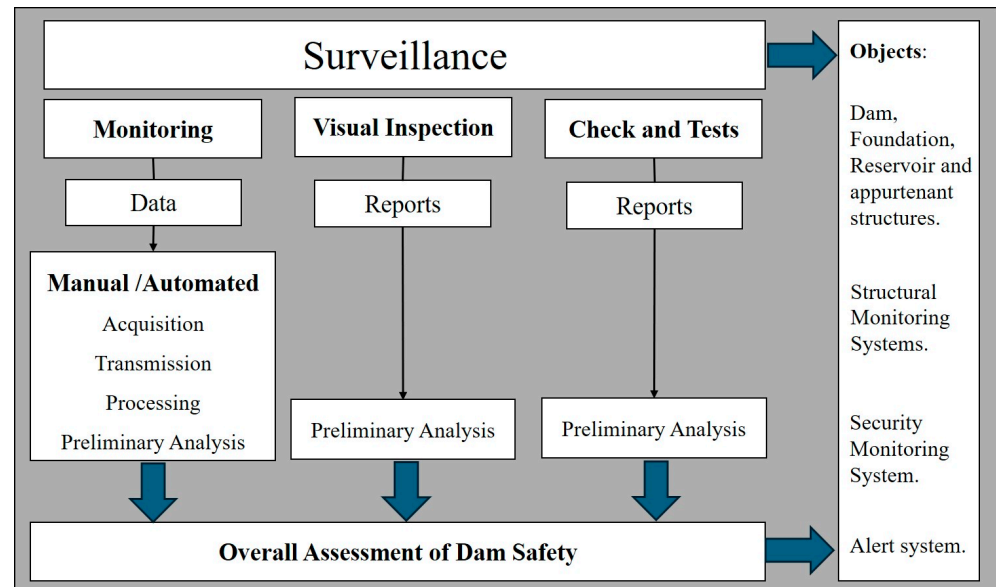


Figure 3. Graphical representation of surveillance on the tailings dam. Redrawn from [24].

Detailed surveillance guidelines can be found in bulletin 158 as the most recent publication on the topic. Four main items suggested for visual inspection are the following:

- (1) Seepage;
- (2) Displacements and deformations;
- (3) Cracking;
- (4) Erosion, weathering, and clogging.

Table 3 recommends the most important visual inspection parameters for different sections of a tailings embankment dam. The changes summarized in this table can be considered as the ones detectable with UAV systems. The document then mentions the case of special inspections. UAV applications are more suitable for inspection of areas without direct access. The inspection frequency is recommended to be weekly but daily inspections might be necessary after a major or extreme event [24]. The great addition of this bulletin is how it provides recent developments and applications of new technology in monitoring. There is also a separate section especially on creating automation of the monitoring system.

Table 3. The extent of visual inspections for an embankment dam type. Adapted from ICOLD bulletin 158 [24].

Dam Section	Changes Inspected
Downstream face	Seepage water surfacing
	Cracks, local settlements
	Erosion (development of gulling)
	Vegetation
Dam crest	Animal burrows
	Cracks, local settlements
	Erosion
	Vegetation
	Animal burrows
	Road condition

Table 3. Cont.

Dam Section	Changes Inspected
Upstream face (accessible section only)	Vortex formation on the water surface Cracks, local deformations, local slides Bulging of surface sealing elements Damages in the surface sealing element Displacement or riprap Vegetation Animal burrows

3.4. Australian National Committee on Large Dams (ANCOLD)

As the name implies, this guideline was developed by the ICOLD member country of Australia. Like ICOLD, this organization deals with concrete dams, earth embankments, and also tailings dams [25]. Practices for tailings initially published in May 2012 were considered the standard in Australia, and they were used heavily in Australia and around the world. They were revised in 2019 to include new practices learned from failures since 2012. The most significant addition in this new publication is related to earthquakes, where they learned that they could induce failure due to static liquefaction. Sites outside of Australia are advised to use these guidelines alongside the original ICOLD guidelines to create a specified document that follows the local natural conditions.

ANCOLD suggested a few types of inspection levels such as comprehensive, intermediate, routine, special, and emergency. The application of drones could fall into the routine inspection whose frequency depends on the failure consequence category. Furthermore, the following is the list of visual inspections recommended [25]:

- (1) Overtopping;
- (2) Burrowing;
- (3) Flora attack (root penetration);
- (4) Flora colonies;
- (5) Erosion;
- (6) Cracks;
- (7) Sinkholes;
- (8) Subsidence;
- (9) Piping;
- (10) Seepage;
- (11) Movement;
- (12) Misalignment;
- (13) Deformation;
- (14) Settlement;
- (15) Freeboard levels;
- (16) Beach width;
- (17) Pond location;
- (18) Storage capacities.

The guideline itself is not as detailed as an ICOLD bulletin; however, it is concise enough to serve well as a foundation to create a site-specific guide.

3.5. Dam Safety Management Guideline

The purpose of this guideline is to delineate best practices for the construction and management of referable dams [26]. Its primary objective is to aid dam owners in ensuring the safe management of their dams while also protecting the environment and the surrounding community. The overarching goal of the dam safety management program is to mitigate any potential risks associated with the dam, thereby preventing possible failures. This guideline is specifically tailored for referable dam owners, operators, employers, and consultants. While designed with referable dams in mind, it can be adapted for the devel-

opment of a dam safety management plan for other dams. The comprehensive program encompasses various key components, including:

- (1) Investigation;
- (2) Design and Construction Documentation;
- (3) Standard Operating Procedures;
- (4) Operation and Maintenance;
- (5) Inspection and Evaluation Reports;
- (6) Dam Safety Review Reports;
- (7) Emergency Action Plan;
- (8) Emergency Event Reports.

By addressing these components, the dam safety management program aims to establish a robust framework for effective and secure dam operation while minimizing potential risks and ensuring environmental and community protection.

3.6. United Nations Economic Commission for Europe (UNECE)

The provided guidelines have been formulated by the UNECE member countries that decided to jointly develop safety guidelines and good practices for tailings management facilities under two UNECE conventions. Their purpose is to provide assistance in the effective management of tailings facilities for the benefit of the public, operators, and ECE member countries. The application of these best practice guidelines aims to minimize the occurrence of accidents at these facilities and mitigate the severity of their impacts. The document comprises two key components: recommendations and technical and organizational considerations.

The recommendations encompass safety principles and guidance directed towards member countries, authorities, and operators [27]. Meanwhile, the technical and organizational aspects address the entire lifecycle of mining facilities, outlining proper procedures to be followed. Authorities, tailings management facility operators, and the public have been invited to apply these guidelines and good practices, which are intended to contribute to limiting the number of accidents at tailings management facilities and the severity of their consequences for human health and the environment.

3.7. South Africa National Standard (SANS 10286)

The requirements listed in this guideline are special for the tailings dams located in South Africa where this document was published. The South African Bureau of Standards published this guideline in 1998 in response to the Merriespruit failure. It was first known as the Code of Practice for Mine Residue Deposits [28], which was later renamed to SANS 10286. This guideline was also recommended as one of the resourceful documents by the MAC guidelines.

The purpose of this guide was to talk about concerns about structure-related issues and preventative measures. The following are the suggested principles in the guidelines:

- (1) Continual management: Emphasized for on-going processes;
- (2) The minimization of waste and the impacts of waste: Reduce waste production and its footprint;
- (3) Precautionary principle: Use a conservative risk analysis;
- (4) Internalization of costs: Cost description should be true to all levels of risk;
- (5) Assessment of the full cycle of implications: Waste management should be considered throughout the whole mine cycle, even after closure.

3.8. International Organization for Standardization (ISO)

The ISO is widely known as the extra layer of credibility companies want to achieve to show their commitment to safety and/or quality. The technical committee (TC) within the ISO, that specializes in mining, covers the standardization of areas such as [8]:

- (a) Specification of specialized mining equipment for surface and underground operations;
- (b) Best practices in the presentation of mine survey plans and drawings;
- (c) Mineral reserve calculation methods;
- (d) Management of mine reclamation;
- (e) Design of structures for the mining industry;
- (f) Special refuge/rescue chambers;
- (g) Shaft boring machines.

It is worth mentioning that the ISO has a special subcommittee dedicated only to mine closure and reclamation management. They are currently in the process of developing four standards in this area. On the other hand, there are 49 published ISO standards, especially for mining within the seven areas above. However, the common certifications in the organization's best practices for managing risk, quality, and the environment are ISO 9000, ISO 14000, and ISO 31000 [8]. These standards are also listed in the MAC guidelines as great sources to develop a site-specific OMS manual.

The ISO 9000 family addresses criteria ensuring the quality of the management system. Tailings facility management constantly comes up in multiple tailings dam guidelines, so this certification ensures proper management of the dam operation. There are three standards in this family:

- (1) ISO 9000:2015—Fundamentals and vocabulary;
- (2) ISO 9001:2015—Quality management systems—Requirements;
- (3) ISO 9004:2018—Quality of an organization—Guidance to achieve sustained success.

The ISO 9000:2015 provides some vocabulary to apply as the foundation of defining the monitoring system. Monitoring is about “determining the status of a system, a process, a product, a service, or an activity.” This definition is fitting with what we are trying to accomplish in terms of detecting how stable the tailings dam is. Additionally, when we look at the terms, inspection is about the consistency of the design specification.

On the other hand, ISO 14000 is an environmental management practice. This certification is highly sought after because tailings dams are closely related to the environment. This certification is voluntary, but it increases the credibility of the site to show that they are environmentally responsible. Listed below are the published standards in this family:

- (1) ISO 14001:2015—Requirements with guidance for use;
- (2) ISO 14002-1:2019—Guidelines for using ISO 14001 to address environmental aspects and conditions within an environmental topic area—Part 1: General;
- (3) ISO 14004:2016—General guidelines on implementation;
- (4) ISO 14005:2019—Guidelines for a flexible approach to phased implementation;
- (5) ISO 14006:2020—Guidelines for incorporating eco-design;
- (6) ISO 14007:2019—Guidelines for determining environmental costs and benefits;
- (7) ISO 14008:2019—Monetary valuation of environmental impacts and related environmental aspects.

The ISO 14001:2015 provided some guidance on monitoring, measurement, analysis, and evaluation of the environmental performance. The methods used by the organization to monitor and measure, analyze, and evaluate should be defined in the environmental management system, in order to ensure that:

- (a) The timing of monitoring and measurement is coordinated with the need for analysis and evaluation results;
- (b) The results of monitoring and measurement are reliable, reproducible, and traceable;
- (c) The analysis and evaluation are reliable and reproducible and enable the organization to report trends.

Reliability and reproducibility are some major components when working with UAVs, thus the standard provides a proper foundation for visual inspection with image processing.

Finally, there is the ISO 31000 family for risk management. Constant optimization plays a major part across any field, and when we look at the mining industry we can almost

predict that managing risk is a part of the daily effort. Better risk management allows stakeholders to be at ease with the project. Three standards included in this family are:

- ISO 31000:2018—Principles and guidelines on implementation;
- ISO/IEC 31013:2009—Risk management—Risk assessment techniques;
- ISO Guide 73:2009—Risk management—Vocabulary.

The risk involved with tailings dam failure is very significant financially; therefore, risk treatment options given in ISO 31000:2009 include:

- (a) Avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk;
- (b) Taking or increasing the risk to pursue an opportunity;
- (c) Removing the risk sources;
- (d) Changing the likelihood;
- (e) Changing the consequences;
- (f) Sharing the risk with another party or parties;
- (g) Retaining the risk by informed decision.

Most of the other tailings dam guidelines use ISO 31000 as an essential framework in creating their risk management programs.

3.9. Global Industry Standard on Tailings Management

As a result of a convention of three entities including the International Council on Mining and Metals (ICMM), the United Nations Environment Programme, and the Principles for Responsible Investment (PRI or UNPRI, a United Nations-supported international network of investors), the most recent guidelines for tailings management were published in August 2020 [29]. The Global Industry Standard on Tailings Management (The Standard) aims to achieve the ultimate goal of ‘zero harm to people and the environment with zero tolerance for human fatality’, requiring the disclosure of relevant information to support public accountability. It is arranged in three layers: ‘topics’, ‘principles’, and ‘requirements’. The six main topics covered in this standard are summarized as follows.

Topic I: Affected Communities

This subject places a strong emphasis on upholding the rights of those impacted by the project and actively involving them at every stage of the tailings facility lifespan, including closure, demonstrating adherence to the United Nations Guiding Principles on Business and Human Rights (UNGP), consulting with those affected by the project in management decisions, responding to complaints and grievances over the tailings facility, and doing so in a way that complies with the UNGP. Additionally, obtaining and maintaining Free Prior and Informed Consent (FPIC) is required if a new tailings facility may affect the rights of indigenous people. This can be achieved by demonstrating compliance with established international standards and best practices.

Topic II: Integrated Knowledge Base

This subject requires adherence to two concepts, one of which is the creation and upkeep of an interdisciplinary knowledge base to facilitate safe tailings management. This principle calls for documenting information about the context (social, environmental, and local economic), capturing uncertainties due to climate change, site characterization (climate, geomorphology, geochemistry, and hydrology), and a breach analysis based on site conditions and slurry properties to estimate the physical area impacted, flow arrival times, depth, and velocities in case of a potential failure. All of this information must be updated at least every five years. The second principle is that decisions should be made throughout the lifecycle of a tailings facility by using all knowledge-base components (social, environmental, local economic, and technical). To reduce the hazards in new tailings facilities, the operator should perform a multi-criteria alternatives analysis. Utilizing adaptive management best practices, it is possible to update assessments of the social, environmental, and local economic impacts and adjust the management of the tailings facility to reflect the new information.

Topic III: Design, Construction, Operation, and Monitoring of the Tailings Facility

In order to reduce and manage risk at all stages of the tailings facility lifecycle (including closure and post-closure), four principles are included in this discussion, including (1) developing plans and design criteria, determining the consequence of failure, and classifying the tailings facility. Preliminary designs for a new tailings facility should consider both failure classification consequences based on existing conditions and higher consequences in order to maintain flexibility, optimize costs, and prioritize safety. All design requirements (factors of safety for slope stability and seepage control) should be determined explicitly in order to reduce risk for all plausible failure modes at all stages of the tailings lifetime. The Engineer of Record (EOR) must create a design basis report (DBR) outlining the design assumptions and criteria to serve as the foundation for the design of all phases of the tailings facility lifespan if upgrading an existing tailings facility is not feasible. (2) To reduce the risk of failure to people and the environment, a resilient design must be developed and integrated. Technical, social, environmental, and local economic contexts, and a demonstration of the feasibility of safe closure of the tailings facility, including progressive closure, should all be included in a robust design for each stage of the tailings facility's construction. The possibility of improving tailings technologies and design strategies for current tailings facilities to reduce threats to humans and the environment should be looked into. The Responsible Executive shall attest that the design satisfies a level as low as practically possible in every Dam Safety Review (DSR) or at least every five years if the existing tailings plant is classed as high, very high, or extreme in terms of potential damage. On the other hand, the results of the multi-criteria alternatives analysis should be incorporated into the design of new tailings facilities. The Responsible Executive must ensure that the design satisfies a level as low as reasonably practical and must authorize any further actions that may be taken downstream to lessen potential repercussions if the new tailings facility is classed as high, very high, or extreme. (3) Establishing, maintaining, and running the TSF to control risk at every stage of the lifecycle. Using certified staff, an appropriate methodology, equipment, and procedures, and constructing, operating, monitoring, and closing the tailings facility in accordance with the planned design. As part of a quality control, quality assurance, and construction vs. design intent verification (CDIV) process to monitor quality and sufficiency during the construction and operation phase, the operator must guarantee that the intended design is carried out. Any time the tailings facility, its infrastructure, or its monitoring system undergoes a significant alteration, a thorough construction records report should be developed. For all levels of staff working in the tailings management system, an operations, maintenance, and surveillance manual is required. (4) Developing, implementing, and operating monitoring systems to check specified assumptions and to monitor probable failure mechanisms. Establishing precise and quantifiable performance goals, metrics, standards, and performance parameters over the whole lifetime of the tailings facility. Additionally, data should be collected and evaluated at suitable intervals to update the monitoring program and guarantee its efficacy in managing risk. These data could be used as proof of any performance variance from what was anticipated and any performance deterioration over time.

Topic IV: Management and Governance

The fourth topic, which is the most crucial component of this most recent standard, highlights managerial principles and solutions in the following five categories.

- Establishing policies, systems, and accountabilities to support the safety and integrity of the tailings facility, creating systems, rules, and accountability measures to support the tailings facility's integrity and safety. A policy for the safe management of tailings facilities, emergency readiness, and failure recovery must be adopted and published by the Board of Directors. Choose one or more Responsible Executives who will be directly responsible to the CEO for the safety of the tailings facilities and the program for training tailings management personnel. The Responsible Executives are also in charge of preventing or lessening the effects of a tailings plant failure on society and the environment.

- Choose an engineering company with knowledge and experience in the planning and building stages. Additionally, the company must designate a senior engineer with the required qualifications to serve as the Engineer of Record (EOR), who must be accepted by the operator. In the alternative, the operator may name an inside engineer to act as the EOR; in this case, the EOR may assign the design to a company but must remain intimately knowledgeable. Use a written agreement outlining the EOR's authority, function, and duties for the duration of the tailings facility's life to give them more influence. Also, the Responsible Executive will determine the EOR, and if it changes, a thorough plan must be made for the transfer of all data, information, knowledge, and experience.
- At least every three years, and more frequently whenever there is a substantial shift in the social, environmental, or regional economic context of the tailings facility, risk assessments with a qualified multidisciplinary team must be revised. To ensure the efficacy of the management systems, a frequent evaluation of the tailing management system and the elements of the environmental and social management system must be performed. The Responsible Executive, Board of Directors, and those affected by the initiative must also be informed of the results. A review must be carried out at least every three years for TSFs designated as having high, very high, or extreme implications.
- Every member of the staff working on any aspect of the tailings plant needs to be informed about the steps they must take to prevent failure. Putting in place procedures that take into account the knowledge that comes from workers' experience in planning, designing, and operating; encouraging cross-functional cooperation to efficiently share data and knowledge; and praising, rewarding, and shielding from retaliation staff members and contractors who report issues or spot opportunities for bettering tailings facility management. Recognizing and putting into practice lessons learned from relevant external incident reports or internal event reports that concentrate on organizational and human elements.
- The Responsible Executive must establish a formal, private, and documented procedure for gathering, looking into, and quickly responding to employee or contractor complaints that jeopardize the integrity of the tailings facility. Also, the operator is prohibited from firing, treating unfairly, or taking any other adverse action against a whistleblower.

Topic V: Emergency Response and Long-Term Recovery

The first principle in topic V deals with preparing for emergency responses to failures, and the second principle deals with preparing for long-term recovery in the case of a catastrophic failure. According to the first rule, a site-specific emergency preparedness and response plan (EPRP) for a tailings facility must be developed and put into action depending on the potential repercussions of a flow breakdown. The strategy must include how often the EPRP is tested and updated. Moreover, to develop an emergency preparation that is community-focused, and meaningfully educate the EPRP with those who are impacted by the project. Collaborate with public sector organizations, first responders, local governments, and institutions to assess their emergency preparedness against the threats listed in the TSF and pinpoint any gaps to assist the creation of a cooperative strategy to boost readiness. The second premise calls for collaboration with public sector organizations and other groups that would take part in medium- and long-term post-failure social and environmental response initiatives. The public should have access to the post-failure results. In the event of a catastrophic TSF failure, it is crucial to assess the social, environmental, and local economic effects right away. Additionally, plans for reconstruction, restoration, and recovery must be created in collaboration with the public sector and other stakeholders in order to fairly address the medium- and long-term effects.

Topic VI: Public Disclosure and Access to Information

This topic is broken down into three requirements: (1) to publish and routinely update information; in the case of new tailings facilities, a plain-language summary of the design; and to conduct multi-criteria analysis. The following must be made public for existing

tailings facilities: a summary of the significant findings of the annual performance and environmental or social monitoring program, a summary of the EPRP, dates of the most recent and subsequent independent reviews, and an annual confirmation that the operator has the necessary financial resources. (2) To promptly and methodically reply to inquiries from interested and impacted stakeholders. (3) To pledge support for reputable international transparency projects aimed at building databases on the security and reliability of tailings facilities.

The Standard also incorporates flood and earthquake design guidelines, as well as consequence classification tables made up of a consequence classification matrix. Also, it includes a list of important files and a summary of the major responsibilities of the individuals working on any TSF project.

3.10. European Commission: Best Available Techniques Reference Document for the Management of Waste from Extractive Industries

This document summarizes the current informational exchange on best available techniques (BATs) for the management of extractive waste and related monitoring that the commission convened. Current information and statistics on the management of extractive waste should be made available to the extractive industries, responsible authorities, and other relevant stakeholders. A list of identified BATs to prevent or lessen any negative effects on the environment and human health is also provided to assist decision-makers.

BATs can be divided into two categories: risk-specific BATs and general BATs. The latter is relevant to places where specific risks have been determined through an environmental risk and impact assessment.

3.10.1. Generic BATs

To improve the overall environmental performance of the extractive waste management, operators make use of the following techniques:

- (a) Organizational and Corporate Management System (O&CMS): Includes quality assurance and control, mass balances, and risk management during the planning phase. It must be updated during the operational period, and it must adapt to the particulars of the closure phase;
- (b) Environmental Management System (EMS): Asks for the creation of an environmental policy that covers ongoing improvements in operators' management of extractive waste. It must be updated during the operational period, and it must adapt to the particulars of the closure phase.

The following methodologies will be used as BATs to enable the identification of potential environmental risks and impacts linked to the features of extractive waste.

- (a) Initial extractive waste characterization examining the traits of representative extractive waste samples in accordance with EN criteria. Use an ISO, national, or other international standard if EN standards are not available for certain parameters;
- (b) Review and verification of the extractive waste characteristics based on the environmental risk and impact assessment and the initial characterization.

3.10.2. Risk-Specific BATs

The following methods are used as BATs to help assure the extractive waste dumping area's structural stability over the short and long terms.

- (a) Investigation of the supporting strata's geotechnical characteristics;
- (b) Choosing the right materials for a dam based on the suitability of materials for the specific geotechnical and environmental conditions;
- (c) Geotechnical analysis of ponds and dams, taking into account every mechanism that could have a detrimental impact on the full or partial structural stability of dams and ponds, e.g., seismic conditions;

- (d) Geotechnical analysis of heaps, addressing every mechanism that could have a harmful effect on the full or partial structural stability of heaps.

3.11. Limitations

The existing guidelines on dam safety management and tailings dam monitoring exhibit several notable gaps and limitations. For instance, while the ICOLD publications cover various aspects of dam surveillance, including bulletins dedicated to monitoring and surveillance, they often do not provide detailed instructions on specific parameters for visual inspection. In addition, the Dam Safety Management Guidelines provides a comprehensive framework for dam management, but it does not offer detailed guidance on tailings dam-specific monitoring practices. While it addresses key components like investigation, design, and operation, it may overlook tailings dam-specific risks and monitoring requirements, which are essential for ensuring the safety and integrity of these structures. Additionally, the South Africa National Standard focuses primarily on structure-related issues and preventative measures, but it may lack clarity on the incorporation of advanced monitoring technologies and international best practices, limiting its applicability. Furthermore, although the Global Industry Standard on Tailings Management highlights the importance of controlling risk throughout the lifecycle of tailings facilities, it lacks explicit recommendations for integrating emerging monitoring technologies. Similarly, the European Commission's BATs require more clarity on incorporating advanced technologies into monitoring systems. These gaps hinder the adoption of innovative monitoring solutions that could enhance the effectiveness and efficiency of dam safety monitoring, particularly in the context of tailings dams. Addressing these gaps would require comprehensive guidance on incorporating emerging technologies into routine monitoring practices to ensure the safety and integrity of these critical structures.

4. Tailings Dam Stability Monitoring Indicators and Systems

This section presents and explains important indicators to be monitored in tailings dam impoundments as suggested by the guidelines. Some surveillance items are shown to be common for all, or most, of the tailings guidelines, and other parameters that are not common to all the guidelines are based on the level of detail within each guide.

4.1. Visual Indicators

Any introduction of instrumentation within the dam could alter the material around it, so visual inspections are generally required. This section will touch on a variety of suggested visual parameters.

4.1.1. Vegetation

Plants, trees, or anything that can grow are the collective components of the vegetation parameter. The ANCOLD, ICOLD, and CDA guidelines suggest visual inspection of vegetation in and around the dam area.

Though suggested by multiple guidelines, it is helpful to understand why vegetation should be monitored. ICOLD bulletin 158 suggested visual vegetation inspections on the downstream face, dam crest, and upstream face (when accessible). This bulletin and Ref. [4] tied the overgrowth on the dam to seepage detection or excessive capillarity. Refs. [1,4,19] also used this approach as a part of the maintenance program. This applies when growth is detected on spillways or outlet channels, where it can impact discharge capacity or instrumentation. The blockage of water discharge can lead to serious failure mechanisms such as overtopping. Also, the obstruction of equipment can lead to reading errors. The visual monitoring of vegetation is commonly related to the post-mining operation, where revegetation is desired. However, sites and the Engineer of Record (EOR) would still pay attention to vegetation while the TSF is active, through manual visual monitoring. Logically speaking, the presence of *unjustifiable* vegetation on an active TSF should raise a red flag.

CDA uses the lushness of vegetation to inspect any detected anomalies related to distress symptoms or maintenance.

Based on the previous clause, the main cause of vegetation growth is the presence of water. Also, nutrients will support plant growth, so supplies can come from leaking water. On the other hand, the same leaked water can disturb the mineral supply, causing a lack of vegetation.

A study was performed in [30] applying the inverse of vegetation detection. Schimmer's literature research found that copper mill tailings contain three main characteristics including a non-organic environment, homogeneous grain size, and wetness. They utilized remote sensing and GIS methods to detect the active copper TSF area in Arizona through the combination of those three components. The NDTI (normalized difference tailings index) threshold was modeled on the normalized difference vegetation index (NDVI). This method came out positive and effective when tested since it was able to identify and distinguish 17 mine-tailings features. This study does not use the method to detect possible instability events, but it can be expanded further.

4.1.2. Decant Pond

There are many types of tailings, but the majority of TSFs in the United States employ thickened or slurry tailings types. These two tailings types consist of large water quantities, thus will produce a decant pond on the surface. A decant pond is a pool of water on the tailings surface where tailings water and stormwater are collected [25]. The collected water is commonly recycled and re-used for the operation, especially for areas where water is scarce.

The extent of the pond is related to the beaching of material after discharge. Evaporation, site temperature, and permeability are also within the variable. Furthermore, the location and allowable size of the decant pond are determined during the design process. It ties back into the chosen control method of a floating barge with a pump or a decant tower. There are two material discharging directions recorded within ANCOLD: downslope and upslope discharge. Figure 4 shows how to differentiate them visually with regards to the location of the embankment. Upslope is the common setup used in the industry. It is favorable because it reduces the risk of seepage and high phreatic surface [25].

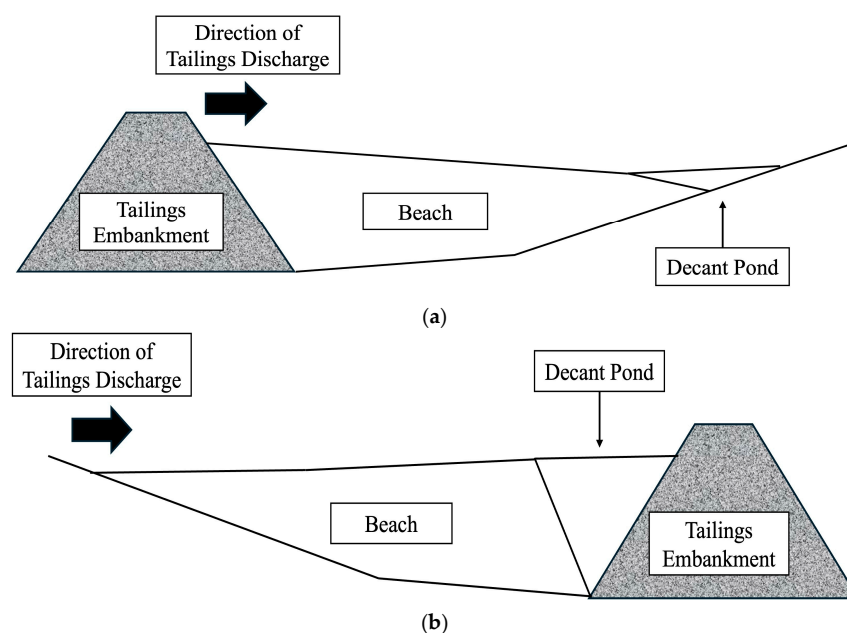


Figure 4. Two discharge directions of tailings: (a) Upslope discharge; (b) downslope discharge. Adapted from [25].

The pond location and quantity of water are some of the influential factors in tailings dam stability. MAC and ANCOLD suggest frequent inspection of this parameter. The monitoring of a pond's water quantity is important for water balance purposes and freeboard availability. Pond location monitoring is related to the pump or decant tower's location for the water balance requirement. Steven Vick also described how the location of the pond relative to the embankment crest is one of the factors that influences the phreatic surface location.

The monitoring of the pond's water quantity and location are being advanced by merging aerial drone surveys and remote bathymetry surveys. These provide accurate data that helps in optimizing the operation [31].

4.1.3. Deformation and Displacement

In terms of deformation in TSFs, sites generally look for cracks, depressions, settlement, bulging, and scrapes. Close monitoring of this indicator is suggested by most of the guidelines. These deformations are related to the stability of walls, contained materials, and the dam foundations. Crack development is a major indicator of failure. Bulletin 106 from ICOLD connected the presence of tension cracks on top of the crest as a sign of instability due to shear failure (see Section 3.3). The development of new cracks can cause further seepage problems that directly impact the dam safety [24]. However, TSFs are commonly built as earthen embankments and cracks are usually tough to discern in this type of embankment.

The inevitable occurrence of many deformations requires the designer to perform all kinds of analyses to lower the risk of failure. The factor of safety is one of the engineering parameters utilized to create an acceptable range. Furthermore, stability analyses are performed during the design process, where multiple scenarios are analyzed to predict the risk involved with the TSF. The MAC guidelines provide several levels of displacement and the level of risk it possesses. Note that this was designed to serve as a guideline to then expand for any specific site. There are four levels of risk: acceptable situation, low risk, moderate risk, and high-risk. It is acceptable when deformation or displacement is not visible or within the designed range. When it starts to become visible and exceeds the designed limit, then it becomes low risk. Moderate is when the toe has been displaced in the form of sloughing, and movement exceeds historical data. Lastly, sloughing occurs and travels more than 3 m from the original location. Furthermore, it is better to detect displacement as soon as possible when there is less risk involved.

Some possible causes of displacement and deformation are earthquakes, settlement, and traffic (if applicable). Earthquakes possess the highest risk of movement due to our inability to prevent them and estimate their time of arrival and magnitude. The analyses suggested by the guides involve the strength of material sustaining different loads. In the same way, proper tailings deposition could help in controlling how the material settles. It is not ideal to have traffic on the dam surface or walls, but extra precautions should be put in place or possibly it should be avoided altogether.

As previously mentioned, there are multiple causes of deformation and displacement, so sites can only detect and monitor them. Bulletin 158 [24] mentions that "displacement and deformations of the dam body are critical indicators of dam stability." The inspection needs to keep track of the location, direction, and geometry of movement. Proper personnel should be notified immediately when a drastic change is identified, thus allowing quick action to be taken. Fractures created through these kinds of activities are the leading reasons for foundational failures [7].

There are multiple ways available to monitor this parameter properly. Deformation and displacement deal with an extreme relationship with the dam foundation, but there is no way to visually inspect the foundation. Bulletin 158 [24] suggested the use of cameras, thick gauges, hand levels, measuring tapes, etc., to aid field inspections. A well-known instrument for this parameter is an inclinometer. A proper installment in the right place could alert the personnel. On top of that, the current technologies have allowed mines to

utilize LiDAR data to detect any changes. A study shows the advantage of this method, especially for a small mining operation and in developing countries [32]. However, this usually leads to a longer report period due to the limited rotational capacity of the satellite. To combat this issue, some mines have been taking advantage of drones to survey the mines for quick data acquisition. It is very easy to compare the latest data and the previous data to measure new movement. An issue is the difficulty in realizing a slow trend that is occurring. This requires proper analysis by experienced personnel.

4.1.4. Seepage or Leakage

Water is a material that can always seep its way through small cracks or porous material. When this path is established, a wet spot can be easily identified on the dam wall. Most tailings dam guidelines strongly suggest proper monitoring of seepage. A concise definition of seepage in the CDA guidelines is when “contaminated fluid escapes to the natural environment” (2013). Similar to deformation and displacement, seepage is inevitable for an embankment dam, so it can only be controlled. Furthermore, seepage can potentially develop not only through the embankment, but also the foundations and floor of the entire structure [25].

The cause of seepage is simple yet tricky. Two laws can explain elementary reasons behind seepage. The first one is the law of osmosis, which is a spontaneous event of selective molecule transfer through a permeable membrane. In this case, the dam acts as the permeable membrane. The ANCOLD (2019) guide [19] mentions that the second law is how fluid tends to flow from higher pressure to lower pressure. The build-up of pressure within the dam is the location of high pressure, and the other side of the dam has lower pressure (atmospheric). Therefore, the combination of these two natural phenomena is the main driver of seepage. It could become worse when cracks are involved in the equation as these provide the path of least resistance for water.

The most sensitive issue on an impoundment is seepage [3] because the liquid inside the dam is contaminated with reagents, metals, and materials that are dangerous to the environment. A recent comprehensive review of tailings dam failures from around the world determined that seepage is one of the main causes [7]. Also, the best way to qualitatively measure dam performance is by looking at the seepage data [4]. All the tailings dam guidelines list seepage as one of the indicators that needs to be visually inspected regularly. Seepage left to develop further will end up in internal piping. Therefore, the site should have proper measurement and observation of seepage location, quality, quantity, etc. The most famous failure caused by seepage happened back in 1974 at the Bafokeng, South Africa, where 12 lives were lost and tailings materials flew 45 km downstream [6].

An important step in TSF design is water management, especially maintaining the water balance. Even though seepage might not contribute significantly to the calculation, the concern comes from its environmental impact. Bulletin 106 argued for the importance of seepage collection ponds as an alternative [2]. These allow for easy management and tracking of the amount of water present. Suggestions given by guidelines for controlling seepage are through adding barriers between tailings and walls, creating a return system, or utilizing liners [3].

Due to the certainty of seepage occurrence, many studies mostly focus on finding ways to better predict the quality and quantity of seepage. However, the literature shows a lack of studies on monitoring and detecting this parameter. The common monitoring technique is through the installation of multiple piezometers around the TSF. The relationship between the phreatic line and seepage was briefly explained earlier. A study was performed at three tailings dams in Sweden (Kiruna, Aitik, and Kristineberg) back in 2015 using the geoelectrical method to monitor potential seepage locations. Two methods were studied: self-potential (SP) and electrical resistivity. The SP method looked at finding locations with high electrical streaming potential since water followed the same principle of flowing from high to low potential places. On the other hand, the electrical resistivity method was found to be better for detecting the water level, dam core, dam material type,

inhomogeneity, and saturation [33]. A famous analytical method that relates the saturation line with seepage is Darcy's Law, thus saturation line monitoring can boost understanding of seepage monitoring. A study proposing an on-line monitoring method to connect the in-field instrument and central data monitoring through an optical signal, disclosed the possibility of real-time monitoring [34]. However, this study did not include a field test that could support the methodology. It looked at the methodology of applying vibrating wire technology that can detect pore pressure change based on the wire tension. The issue with this method is the use of a ground-disturbing instrument, which impacts the dam stability.

4.1.5. Freeboard

From the Australian guidelines, ANCOLD, a general definition of freeboard is the distance between the critical designed water level and the current water level in the dam. This distance is profoundly related to the location of the dam facility because extra measures should be put in place to account for extreme conditions such as a storm or wet season. Therefore, the total freeboard is a bit more complex to calculate. Figure 5 illustrates possible water levels for different purposes of analysis.

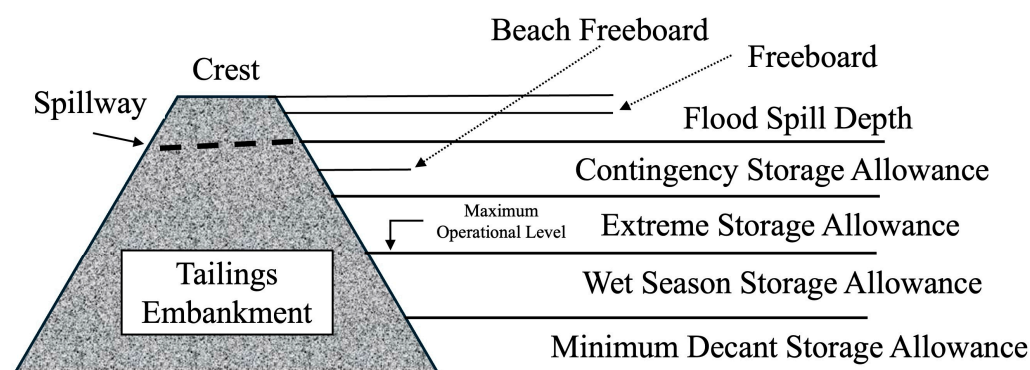


Figure 5. Freeboard design parameters in a typical dam impoundment. Adapted from [25].

A detailed explanation of each element of the freeboard criteria is presented in the ANCOLD guidelines; however, some of the elements worth mentioning are:

- Minimum decant storage allowance: The minimum amount of water expected to be held within the dam to achieve the required discharge condition;
- Wet season storage allowance: The water volume allowed during the wet season that includes input from rainfall and water from processing;
- Operational freeboard: The distance between the crest and the top of the tailings material;
- Maximum operating level: The highest extent where the water level can rise under normal conditions before activation of the site's emergency plan.

Freeboard distances give safe ranges of the water level. The CDA recorded that overtopping failure usually starts with water going over the dam crest, so it is very important to keep it not only below the maximum level but also above the minimum recommended level after discharge [1]. It is revealed that overtopping is the greatest cause of failure, so freeboard monitoring can have a high potential for preventing this failure mode.

The common method of freeboard monitoring is through a regular survey and visual inspection. Mines are starting to employ UAVs/UASs to aid this process, similar to for decant pond monitoring. The paper from NewFields mentions survey advantages when these technologies were used together. It is advised that the monitoring is more regular in the case of high precipitation or possible storm occurrence.

4.1.6. Beach Width and Distance

Almost every reviewed set of guidelines recommended monitoring of the beach width and distance. Beach development is based on the material's segregation process as it travels away from the discharge point(s). In general, particle size decreases with distance from the deposition point. The beach width is influenced by the amount and location of the tailings discharge points. The beach width and distance design are tied to many different aspects such as tailings rheology, temperature, required beach angle, deposition rate, etc. Rheology is a crucial factor, especially for higher-solid-concentration tailings [25]. ICOLD Bulletin 181 [22] collected beach slope data from around the world and analyzed its correlation to the beach length. This study proved how beach length is the inverse of the beach slope, as expected. The guidelines suggested that the overall beach slope should be within the range of 1%–4% for uniform material distribution. The reader is referred to [22] for the correlation between beach length and beach slope based on different tailings types.

Material segregation, settlement, and water management are some of the closely watched parameters. The MAC (2017; 2019) [18,19] guidelines suggested the control of the beach angle for better tailings placement, and the control of the beach width for water management. Due to the segregation nature of tailings previously mentioned, the beach angle is especially crucial for the upstream raise method. The distance should be long enough to create more surface area for water evaporation since the next embankment cannot be constructed on a wet surface. Delayed material settlement will create embankment collapse, shown by the development of tension cracks. Another risk coming from incorrect beaching is dusting. A large amount of mine operations are located in arid areas, so these small particles need to be suppressed. This issue is why the reclaim pond location and extent are also monitored.

The monitoring of beaching is crucial to ensure conformity between field performance and design criteria. Visual inspection is highly recommended to ensure proper material distribution. On the other hand, manual calculation of the beach distance is discouraged if it requires stepping inside of the dam. Therefore, mines have also utilized UAVs and LiDAR applications to obtain better aerial surveys and views. A computer simulation study was performed on a TSF in Arizona employing drones. It correlates the design FoS and the current beach distance to calculate the critical distances for safe operation. They simulated different weather conditions and found its usefulness in checking the dam performance [11]. This study was for an upstream TSF, thus further studies should be performed to expand this application. The approach serves as a good foundation for future expansion of precise monitoring and continual risk analysis.

4.1.7. Erosion

The natural process of erosion will always take place on any embankment dam. Erosion itself is the process of soil being removed and transported elsewhere. Note that internal erosion of piping is different from this topic since it is hard to visually inspect. Erosion process monitoring was recommended by the majority of guidelines. External erosion is considered the main topic, which is also different from the weathering process. ICOLD (2018) [24] identified weathering as alternating actions from drying to wetting or freeze to thaw.

Erosion can occur via constant impact with the wind, water, or other natural agents. Wind and water erosion are the two common occurrences in tailings dams. Typical forms of water erosion are rills, gullies, and sheets (see Figure 6). Rill erosion is presented as branch-like lines on the dam wall. Gullies are the much deeper advancement of rills. Sheet erosion removes a wide area of soil at once. On the other hand, wind erosion can look similar to rills but is differentiable by the ripple effects created. Wind can only pick up small particles, so it is less likely to develop on TSFs. Moreover, the factors influencing erosion are precipitation, soil strength, length, slope angle, exposure time, etc.

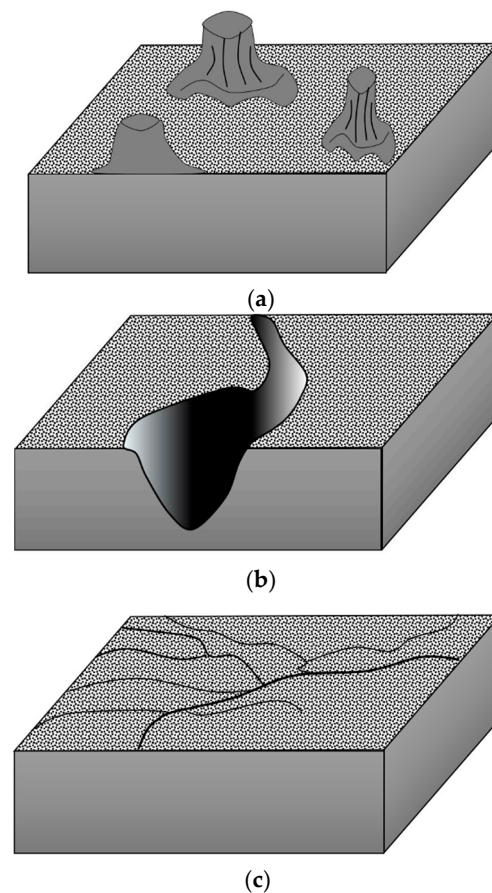


Figure 6. Schematic of three common types of water erosion: (a) Sheet erosion; (b) rill erosion; (c) and gully erosion. Adapted from [35].

Erosion is considered as one of the main causes of failure in tailings embankments. ICOLD (1996) [2,20,21] explains that “the slow deteriorative processes or progressive degradation may lead to overall failure and may have severe adverse long-term environmental consequences.” This statement applies to the erosion process. Erosion causes dam material to be transported somewhere else, thus reducing the strength of the designed walls. Early signs or progression discovery through proper monitoring is important. This will allow proper repair actions as soon as possible. Extra precautions are needed especially after a heavy rain season. The steepening event of toe erosion can lead to rotational failures. Occurrences of these events are recommended to be considered during the initial engineering analysis [36]. Protection against erosion during the active period is less desirable for most mining operations. Documents commonly suggest cover utilization when going into the reclamation step for a lasting effect.

Erosion is a visible problem, but it can be time-consuming to identify, particularly for large impoundments. Compared to the mining industry, erosion detection for agricultural purposes is progressing much more rapidly. Although LiDAR and aerial images are primarily used after site reclamation, there is currently no specialized instrumentation to aid visual inspection [12]. Therefore, adapting methods used in agriculture could be beneficial for mining purposes. High-quality aerial images from mine surveys can also be used to help with erosion detection. Recent work by Nasategay (2020) [37] has focused on using semantic segmentation with the UNet architecture and a weighted cross-entropy loss function to detect rills on tailings dams. The resulting model demonstrated promising results, achieving a precision, recall, and F1-score of 83.3%, 72.0%, and 77.2%, respectively.

4.2. Monitoring Systems

Monitoring systems can cover multiple instruments and layers of surveillance. ISO defined a system as the “set of interrelated or interacting elements.” The system itself will be site-specific, thus each might have a slight composition difference. A performance-based monitoring system is a system where it seeks possible hazards, possible failure mechanisms, signs to look for, and how to detect them [1]. Several documents included a guideline on how to build a proper system. A surveillance program is described as consisting of monitoring the performance of multiple factors, such as [1]:

- Comparison between the actual and design performance to identify deviations;
- Detection of changes in performance or the development of hazardous conditions;
- Confirmation that reservoir operations are following the dam safety requirements;
- Confirmation of adequate maintenance is being carried out.

A common requirement of a monitoring system is its ability to be carried out continually. Items related to stability could resort to FoS as the assessment basis.

A challenge with monitoring is the time constraint. The warning time determined from the surveillance system can range from days, months, years, even hours or minutes [1]. The failure of Mount Polley in Canada was extreme for there being no warning signs. Therefore, real-time monitoring is favorable for even better operation. There have been many studies performed in the past to test different monitoring methods for tailings impoundment. A brief summary of these studies is listed in Table 4.

Table 4. Notable recent studies on tailings dam monitoring.

Author(s) and Year	Article Title	Case Study Location	Monitoring Method	Parameters Monitored	Description of Work	Scale of Study
Adriaan Basson et al., 2021 [38]	TD-DAQ: A Low-Cost Data Acquisition System Monitoring the Unsaturated Pore Pressure Regime in Tailings Dams	South Africa	Hardware TD-DAQ	Negative pore pressure, moisture content, and temperature	This paper describes the construction, experimentation, and verification of a data acquisition system for measurements of the unsaturated pore pressure regime in tailings dams over extended periods of time. The data are saved and delivered in wireless networks.	Full TSF
Dong et al., 2017 [39]	Pre-Alarm System Based on Real-Time Monitoring and Numerical Simulation Using Internet of Things and Cloud Computing for Tailings Dam in Mines	China	Piezometers, extensometer, transducer, strain gauge	Hydrostatic pressure, dry beach length, internal deformation, stress monitoring, horizontal displacement	A pre-alarm system for tailings using cloud computing to calculate the limit state equation, phreatic line, and a numerical simulation based on instrumentation data, with output including three pre-alarm levels, safety factors, and reliability scores.	Full TSF
Dong et al., 2022 [40]	Anomaly Identification of Monitoring Data and Safety Evaluation Method of Tailings Dam	China	Seepage field	Depth of saturation line	Cloud computing and artificial neural networks (ANNs) were utilized to identify outliers in seepage monitoring data. A real-time safety assessment was performed based on the relationship between the depth of the saturation line and the safety factor.	Full TSF
Du et al., 2020 [41]	Risk Assessment for Tailings Dams in Brumadinho of Brazil Using InSAR Time Series Approach	Brazil	InSAR images	Ground displacement	A new method that allows for selecting more accurate pixels from InSAR images to create time series and acquire ground displacement in synthetic and real data in tailings dams.	Full TSF

Table 4. Cont.

Author(s) and Year	Article Title	Case Study Location	Monitoring Method	Parameters Monitored	Description of Work	Scale of Study
Duan et al., 2023 [42]	Retrospective Monitoring of Slope Failure Event of Tailings Dam Using InSAR Time-Series Observations	China	InSAR time series	Deformation rates	The surface deformation map of the tailings dam before a failure event was obtained using the InSAR time-series method. A GPU-assisted InSAR processing method was applied to 91 images from 2019 to 2022. Rainfall was found to significantly influence tailings pond deformation, with a delayed peak deformation rate of about one month compared to the maximum rainfall.	Full TSF
Gama et al., 2019 [43]	Advanced DINSAR Analysis on Dam Stability Monitoring: A Case Study in Germano Mining Complex (Mariana, Brazil) with SBAS and PSI Techniques	Brazil	Advanced differential SAR interferometry	Deformation	The feasibility of a satellite imaging system in tailings dam monitoring was studied. The SBAS technique showed the best deformation detection capability. The use of satellite data provided a cheaper rate compared to the installation of full ground movement equipment, especially for small companies located in developing countries.	Full TSF
Hu & Liu, 2011 [44]	Design and Implementation of Tailings Dam Security Monitoring Systems	China	Sensors, GPS, video surveillance	Saturation line, water level, internal horizontal and vertical displacements, and surface displacement	The authors created a software to automate streamlining data acquisition, presentation, and alert systems. One shortcoming of their research is the lack of result analysis to see the accuracy of these data compared to manual data.	Full TSF
Jeong & Kim, 2020 [11]	A Case Study: Determination of the Optimal Tailings Beach Distance as a Guideline for Safe Water Management in an Upstream TSF	USA	UAV	Beach distance	A digital model was created using drone data. This study found an optimal safe beach distance to maintain the factor of safety requirements (FoS = 2.0). The model is valid for the geometry it is created for, hence constant updates are required.	Full TSF in a computer simulation
Li et al., 2011 [34]	Tailings Dam Breach Disaster On-Line Monitoring Method and System Realization	China	GPS, vibrating wire sensors	Displacement and saturation line	This study proposed a method of creating an on-line monitoring system using GPS to detect displacement and vibrating wire sensors to find the saturation line. The data were gathered in situ through ground instruments and transferred as an optical signal to the data monitoring and alert center. No numerical results were given since this was a proposed method only.	Full TSF
Lumbroso et al., 2021 [45]	DAMSAT: An Eye in the Sky for Monitoring Tailings Dams	Peru	InSAR, GNSS	Ground displacement	A new system that uses earth observation technology for modules of visualization, movement detection, hydrometeorological forecasting, emergency planning, and leaching detection.	Full TSF

Table 4. Cont.

Author(s) and Year	Article Title	Case Study Location	Monitoring Method	Parameters Monitored	Description of Work	Scale of Study
Lumbroso et al., 2019 [32]	The Potential to Reduce Risk Posed by Tailings Dams Using Satellite-Based Information	Peru	Satellite information	Displacement, deformation	The need for a low-cost and efficient monitoring system for developing countries and small mining operations drove the development of this system. Software using satellite images for tailings dam monitoring was presented, which was in testing stages at mines in Peru with acceptable performance.	Full TSF
Mainali et al., 2015 [33]	Tailings Dam Monitoring in Swedish Mines Using Self-Potential and Electrical Resistivity Methods	Sweden	Geoelectrical: self-potential (SP), electrical resistivity	Seepage on wall	Geophysical methods were used for tailings dam monitoring. These methods showed great success in detecting potential seepage in embankments.	Full TSF
Nie et al., 2022 [46]	3D Visualization Monitoring and Early Warning System of a Tailings Dam	China	GIS	Phreatic line changes	Geographic Information System (GIS) and autoregressive integrated moving average model were utilized to predict deformation and phreatic line changes in the tailings dam.	Full TSF
Ouellet et al., 2022 [47]	Advanced Monitoring of Tailings Dam Performance Using Seismic Noise and Stress Models	Canada	Geophones array	Soil stiffness	Ambient noise interferometry (ANI) was utilized to monitor performance of an active tailings dam, combining it with recordings of pond levels and shear wave velocity profiles. Fluctuations in seismic velocity were found to be strongly associated with changes in water levels in a nearby tailings dam.	Full TSF
Rauhala et al., 2017 [48]	UAV Remote Sensing Surveillance of a Mine Tailings Impoundment in Sub-Arctic Conditions	Finland	UAV	Surface displacement	Four measurement campaigns were performed in a sub-Arctic environment when the mine was temporarily inactive during the summer. Stable areas around the perimeter were used as ground control points. Detected displacements were related to a combination of tailings settlement, erosion, and possible consolidation of an underlying peat layer.	Full TSF

Table 4. Cont.

Author(s) and Year	Article Title	Case Study Location	Monitoring Method	Parameters Monitored	Description of Work	Scale of Study
Slingerland et al., 2018 [12]	Identification and Quantification of Erosion on a Sand Tailings Dam	Canada	LiDAR, aerial photos	Erosion	The objectives were to investigate the tailings erodibility of the site, obtain a better understanding of future design based on the current state, and test the possibility of sourcing LiDAR and aerial photos to identify and quantify erosion signs after reclamation. An in situ assessment was performed on rills and gullies appearance on site. The study showed that both water and wind erosion were present. The authors evaluated the applicability of LiDAR and aerial photography models to identify, classify, quantify, and determine the causes of erosion. The digital stereo aerial photography was found to be superior in most assessments but limited when quantifying erosion.	Full TSF
Song et al., 2021 [49]	Influence of Control Point Number on UAV Low-Altitude Photogrammetry and its Application	China	Photogrammetry	Surface subsidence	A surface subsidence map of the tailings dam was obtained using a high-precision mapping method based on low-altitude aerial photogrammetry. To analyze the subsidence of the study area, the elevation differences values of corresponding points from the digital elevation model were extracted.	Full TSF
Zwissler et al., 2017 [50]	Thermal Remote Sensing for Moisture Content Monitoring of Mine Tailings: Laboratory Study	USA	Thermal remote sensor	Moisture content	Variables measured are mass, penetration depth, spectral reflectance, atmospheric temperature, humidity, and thermal emissivity. The recorded gravimetric moisture content and penetration depth plot show an exponential relationship with a different coefficient for each site. Regression models were created where sample temperature and atmospheric humidity were found to be the most significant parameters.	Laboratory-scale tests

5. Conclusions

TSFs require extra attention to prevent dam failures. Too many failures associated with any kinds of dam result in financial loss, environmental damage, and loss of lives. Most TSF guidelines suggest creating a monitoring program. Visual inspection is a highly recommended aspect of surveillance because it is perceived as the best way to identify issues. This paper reviewed the major guidelines and standards on TSFs from the stability monitoring point of view. They were found to be similar at some points, yet very different in treating multiple instability causes as well as surveillance strategies. The gaps and limitations in safety guidelines were generally discussed. These gaps were found to hinder

the adoption of innovative monitoring solutions that could enhance the effectiveness and efficiency of tailings dam safety monitoring. Addressing these gaps would require comprehensive guidance on incorporating emerging technologies into routine monitoring practices to ensure the safety and integrity of these critical structures. Works from the recent literature on the development of innovative monitoring systems were also covered to emphasize best practices in this regard.

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