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What could Tailings Facility Engineering look like in 2030?

¿Cómo podría ser la ingeniería de instalaciones de relaves en 2030?

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ABSTRACT: Over the past five to ten years, there has been a surge in many different aspects of tailings facility engineering as the mining industry pays more attention to the importance of their tailings facilities as part of the overall success of their mining operations. This has been partly related to the Global Industry Standard on Tailings Management (GISTM) that was released in 2020 but is also due to other initiatives by several mining companies and organizations around the world that are committed to safe tailings facilities. There are major initiatives occurring on many fronts, including:

- Tailings technology and deposition strategies.
- Characterization of tailings and foundation soils, slope stability assessment (including deformation analyses), liquefaction predictions, dealing with high stresses, closure, filtered tailings, and so on.
- Closure strategies.
- Surveillance techniques.
- Competency building.
- Guidance documents that bolster the capabilities of the engineers working on tailings facilities.

This paper presents a summary of key issues that are currently confronting tailings facility engineers, owners, and regulators for each of the above topics. It describes initiatives that are currently underway or planned to address these issues and provides a vision for 2030. A survey of leaders in tailings facility engineering was conducted and the results of the survey are summarized in the paper.

KEYWORDS: tailings, characterization, closure, surveillance, guidance, 2030

1 INTRODUCTION

This paper envisions what tailings facility engineering could look like in 2030. Significant advancements have been made in the field in recent years, and the pace of innovation is accelerating. Tailings volumes to be managed are also increasing, as mining operations are expected to increase production by about 3% per year until at least 2030[1] while ore grades are decreasing (requiring more volume to be milled to realize a unit of each desired commodity).

Major focuses of this paper include: improved tailings technology and deposition strategies, closure strategies, improved characterization methods for tailings and foundation soils, enhanced surveillance techniques, and the development of technical capacity and competency within the industry. Governance is a key aspect for safe tailings management that is also evolving, but is beyond the scope of this paper.

The authors have defined "tailings facility engineering" as covering the following areas of knowledge:

- tailings milling and processing,
- tailings storage facility design,
- closure design,
- geotechnical engineering,
- hydrogeological engineering,
- hydrotechnical engineering,
- geology,
- geochemistry,
- environmental protection,
- construction,
- operations,

[1] This percentage is based on information from (i) Mining. Com: Copper production, price rebound on the horizon — report, July 2022; (ii) expertmarketresearch.com: Global Precious Metals Market Size, 2022; (iii) Canada Energy Regulator: Canada's Energy Future, Raw Bitumen Production by Type – Evolving Policies Scenario, 2021, (iv) finance.yahoo.com: Investing in Gold: Global Gold Mining Market Size Is Projected to Grow at 3.5% CAGR, Exceed $260 Billion by 2030, September 2023

- surveillance,
- risk assessment, and
- governance.

This paper continues with some context and discusses the method used to gather supporting information related to the key topics noted above. The paper presents the authors' understanding of these key topics summarized under the subheadings: *Current Situation and Vision for 2030.*

2 CONTEXT AND WHY 2030?

Over the past five to ten years, there have been significant efforts to reduce the likelihood of catastrophic tailings failures through training, guidance documents, increased regulation, improved surveillance, etc. Increases in computing power have made complex analyses more efficient and have supported the use of artificial intelligence (AI).

Investors and insurance companies are paying close attention to the efforts to reduce risks associated with tailings storage facilities (TSFs). However, as these efforts drive the TSF risks to lower levels, a key challenge will be the demand for qualified people, as well as the demands on those qualified people. The demand for capable and experienced engineers of record (EoR), responsible tailings facility engineers/persons (RTFE/P), independent tailings review board (ITRB) members, and regulators is far greater than the supply, which is declining due to the age demographic of the people currently fulfilling these roles. The next 10 years will see a significant reduction in the number of senior tailings facility engineers practicing and there are not enough younger engineers available to backfill the current and expected demand.

The International Commission on Large Dams (ICOLD) has developed a world-wide registry of TSFs that has catalogued over 24,000 entries (Rana et al, 2024). As noted above, the volume of tailings to be stored will increase by more than 3% per year over the next six years, which means more TSFs and larger TSFs.

Repurposing or expanding older TSFs to meet storage needs with the aim to reduce additional disturbance area, as well as upgrading those that were not built to today's standards will be undertaken, which poses significant technical challenges. For example, demonstrating safety of existing TSFs, particularly those that employed classical upstream construction (i.e., upstream construction on unconsolidated fine tailings), is very complex. Furthermore, water conservation is becoming more important to operators and communities due to climate change and increasing regulation on the use of "clean water" and requirements on discharge of water to recipients.

From some perspectives, the year 2030 does not seem that far away, but, after reflecting on what has been accomplished in the past six years, the authors selected the year 2030 for this paper; six years from when this paper was prepared.

A number of guidance documents have been issued related to TSF safety. Table 1 shows that for the six-year period from 2011 to 2017, there were at least seven major guidance documents issued, whereas, for the following six years, 2018 to 2024, there were at least another nine (despite the industry navigating a global pandemic).

Table 1. Guidance documents for increased tailings dam safety within the mining industry from 2011 to 2024

Year	Organization[2]	Document Title
2011	ICOLD	Bulletin 138: Improving Tailings Dam Safety
2011	ECCC	Guidelines for the Assessment of Alternatives for Mine Waste Disposal
2012	ANCOLD	Guidelines on Tailings Dams
2013	ICOLD	Bulletin 153: Sustainable Design and Post-Closure Performance of Tailings Dams
2014	CDA	Mining Dams Bulletin (Revised 2019)
2014	OSTDC	De-Licensing of Oilsands Tailings Dams
2011-2024	MAC	Updates to Guides on Management of Tailings Facilities and Developing OMS Manuals
2011	ICOLD	Bulletin 138: Improving Tailings Dam Safety
2011	ECCC	Guidelines for the Assessment of Alternatives for Mine Waste Disposal
2019	ICMM	Integrated Mine Closure: Good Practice Guide
2020	GTR	Global Industry Standard on Tailings Management (GISTM)
2021	ICMM	Tailings Management: Good Practice Guide
2021	CDA	Bulletin: Tailings Dam Breach Analysis
2021	ICOLD	Bulletin 181: Tailings Dam Design, Technology update
2022	SME	Tailings Management Handbook
2022	ICOLD	Bulletin 194: Tailings Dam Safety Guideline
2022	ACR	Assessment Tool for Landforms in the Oilsands

[2] ICOLD = International Commission on Large Dams, ECCC = Environment and Climate Change Canada ANCOLD = Australian Commission on Large Dams, CDA = Canadian Dam Association, OSTDC = Oil Sands Tailings Dam Committee, MAC = Mining Association of Canda, ICMM = International Council on Mining and Metals, GTR = Global Tailings Review, SME = Society for Mining, Metallurgy and Exploration, ACR = Alberta Chamber of Resources.

2011-2024	MAC	Updates to Guides on Management of Tailings Facilities and Developing OMS Manuals

A major contribution to recent developments was Dr. Morgenstern's Victor de Mello lecture on Performance-Based Risk-Informed Design (Morgenstern, 2018), which has influenced and impacted many of the above guidance documents as well as regulations.

Additional key changes that have occurred over the past six years include:

- In 2018, there was significant trepidation associated with the EoR concept as a viable career path. Whereas in 2024, more young engineers see this as a career path (Prince and Boswell, 2023).
- In 2018, a limited number of dam safety surveillance programs had automation, but in 2024, there is extensive automation, remote monitoring, cameras, and monitoring centers.
- In 2018, AI was on the horizon, but in 2024, AI is being used to support complex surveillance data gathering and interpretation.

The authors believe that over the next six years, much can be done to maintain the momentum and do more than just "continuous improvement." This paper explores additional initiatives and advancements in the next six years presented as a collective vision for 2030.

3 METHOD

To support the creation of a vision of what tailings facility engineering could look like in 2030, the authors reached out to acolleagues and leaders in the tailings space around the world with a survey questionnaire to obtain a global perspective. An extensive questionnaire was issued to over 240 tailings practitioners covering the following topics:

1. Tailings technologies and deposition;
2. Closure strategies;
3. Characterization of tailings and foundation soils;
4. Surveillance of tailings facility performance;
5. Design approaches for slope stability assessment;
6. Guidance documents for tailings facility safety design; and
7. Building competency and capacity
8. Artificial Intelligence

Over 60 people responded to the questionnaire (as of the end of May 2024) from 15 countries; the majority of the responses were from Canada and the United States. Presentations were given in Canada in May and June 2024 on the vision for tailings facility engineering in 2030 and additional input was obtained from the audience members from those presentations. The authors also consulted with several key people and organizations within different areas of tailings facility engineering.

This paper will also be presented at ICOLD's annual conference in India in September 2024 and the Tailings and Mine Waste Conference in USA in November 2024. The questionnaire results and will be available at the end of 2024 through the ICOLD committee on tailings dams and waste lagoons (Technical Committee L).

In this paper, the authors endeavoured to summarize the results of the questionnaire and input from contributors. This paper was not prepared on behalf of ICOLD Committee L.

4 BUILDING COMPETENCY AND CAPACIT

4.1 Current Situation

As noted above, there is, and will likely continue to be a shortage of qualified engineers providing services for TSF safety and this topic was considered the most important from the respondents. Hence, this topic is presented first in this paper.

On the one hand, the field of tailings facility engineering is challenging, complex, interesting, and rewarding. It is no longer viewed as commodity engineering, and the professional contributions are viewed with value by mine owners and regulators. There are many training programs in place being offered by universities and technical associations. Consulting companies and mine owners are also providing in-house training.

However, on the other hand, with the growth in tailings, the limitations associated with how TSFs can be developed, and the higher expectations of regulators and stakeholders, the demands of tailings facility engineering will increase. Some universities are offering graduate degree programs in tailings engineering, but there is limited training at the undergraduate level and more master's level programs are needed.

Mining is not considered an attractive career opportunity to young people. McKinsey (2023) conducted a survey of people between the ages of 15 and 30 and asked if they would be interested in working in one of nine different sectors, including health care, financial services, construction, and mining. Mining ranked last among the nine sectors, with 70% of the respondents saying that they would not be interested in working in the mining sector. One of the potential reasons for this is that could be a disconnect between the value that mining provides and the perception of young people; that is, they do not realize that most of the conveniences and necessary infrastructure that they have comes from mining. That, these conveniences and infrastructure are taken for granted.

4.2 Vision for 2030

To help address the challenge of the human resource shortage, the authors recommend establishing the discipline of "Tailings Management Professional" (TMP) as a first step. In this context, tailings management includes the design, construction, operation, and closure of systems that are used to produce tailings and the facilities that are constructed to store tailings.

This would include the following facilities:

- Conventional slurry, thickened, paste, filtered tailings;
- Co-mingled, co-disposed, co-deposited, and co-placed mineral residue (e.g. tailings and waste rock, fines and coarse discards, etc.); and
- Containment facilities for sludge and sediment from process, water treatment plants, or runoff.

Ash lagoons for power generating plants could also be covered here.

The TMP should have knowledge in the areas listed in Section 1 as tailings facility engineering with a specialty in one or more of those knowledge areas and a general knowledge of the others.

ICOLD is forming a working group to develop the scope for the TMP discipline and will work with other organizations to define it.

With this discipline defined, it will be possible to identify the TMP discipline as a distinct career path for young engineers, rather than, as so many do now, "just fall into tailings engineering".

Further, it will be possible to develop focused training that supports the development of TMPs. As noted above, there is a significant amount of training occurring, but there is not a comprehensive database that captures this training. Such a database is being developed by the Society for Mining Metallurgy and Exploration (SME) that will allow organizations to list the training they are providing. For example, Organization X may be planning to conduct slope stability training in Africa and can post that training to this database, indicating if it is in person and/or virtual. Then, engineers from around the world can search the database for slope stability training, find the one in Africa and determine if it meets their requirements.

With the discipline of TMP defined and a database offering current available training, then a gap analysis can be done between what is required and what is currently being offered. Plans can then be developed to fill these gaps and provide additional opportunities to develop competency and capability.

One of the survey respondents provided a recommendation that graduate programs can be developed to focus on the development of TMPs, but not have a significant research component. This program would be course-based and structured to run for one year. Because it does not have a research component, it would not be funded by research grants, which would require funding from industry to help support students that are interested in taking this program. Colorado State University and the University of Alberta are both considering this approach and plan to work with other universities to advance this concept.

As a result of discussions held with colleagues in the industry, the authors included the following question in the questionnaire: "Should there be an international certification program for tailings facility engineers?" There was a wide range of responses, from "Yes, this is important" to "No, this is not required." The reference to certification was not in the context of receiving a certificate after having completed a set of courses. Rather, it was intended to be a certification that is received after having also obtained experience after course work. There are some advantages to certification, but there are several challenges with establishing an internationally recognized certification program that would require significant infrastructure to support. There was sufficient interest in this topic that ICOLD is creating a working group to explore the issue and provide a recommendation on whether such a certification is of value and, if so, then what such a program could look like. This would be done in concert with other key organizations to help decide whether certification should be pursued or not.

Given potential the disconnect between the perception of mining and the benefits of mining (and therefore tailings management), more work needs to be done by organizations such as ICMM, MAC, CIM, SME, etc. to educate young people about the benefits of mining to society and the value of being involved with responsible tailings management.

5 TAILINGS TECHNOLOGIES AND ALTERNATIVES TO SLURRY DEPOSITION

5.1 Current Situation

The vast majority of existing TSFs worldwide employ conventional slurry-deposited tailings. Slurry deposition often results in loose, saturated deposits that are potentially prone to liquefaction.

Filtered tailings technology has evolved but the actual number of filtered tailings facilities is not quantified. The TSF registry that has been developed by ICOLD and the general consensus from the survey is that dewatered tailings operations (including high-density thickened, paste, and filtered tailings) make up less than 1% of existing tailings operations. The authors' experience, reinforced by the survey responses, is as follows:

- Filtered and paste tailings technology initially developed in the 1990s, but widespread application of this technology has been limited by economics, operational challenges at high throughputs, and technical challenges in wet climates.
- Combined management of tailings and waste rock (i.e., co-mingling, co-disposal, co-depositing, co-placement, etc.) is gaining traction in research trials but has not been fully proven at operational scale (Burden and Wilson, 2023).
- For new tailings facilities, the general approach to technology selection often involves performing a structured multi-criteria alternatives analysis of feasible sites, technologies and strategies for tailings management (GISTM, 2020 – Requirement 3.2). However, this practice has not been widely adopted by the industry and is required by regulation in only a few jurisdictions, for example British Columbia, Canada (EMLI, 2024).
- Water management is a key driver in tailings technology selection, with arid climates opting to recover water in the process by dewatering to reduce evaporation losses while wetter climates tend towards conventional slurried tailings and managing surplus water via large supernatant ponds (MEND, 2017).
- Tailings geochemistry, including acid generation potential, leads to a generally binary choice between wet or dry cover solutions, but there is a movement toward dry covers for closure with respect to risk (post closure dam failure). Limited effort is put into designing tailings processing to reduce future risk, such as segregation of tailings into geochemically non-reactive and reactive streams and management of reactive streams in separate facilities. Tailings geochemistry is gaining much more importance in many mining districts with a focus on source control.

5.2 Vision for 2030

The consensus amongst the survey respondents is that conventional slurried tailings will continue to be the norm for new tailings facilities in 2030. However, the selection of conventional tailings technology as the best available technology (BAT) for a site will need to be objectively demonstrated through tailings alternatives assessments (ECCC 2011) supported by risk assessments to define design and operational controls. This position is based on a view that classical upstream construction methods will cease and be replaced by centerline construction, modified upstream construction (i.e., upstream construction that employes an engineered structural zone such as a compacted tailings beach), or downstream construction.

It is envisioned that filtered tailings will continue to gain popularity due to technological advances that allow scaling to throughputs of greater than 50,000 tonnes per day. However, filtered tailings will likely still represent a low percentage of future tailings facilities due to its high capital and operating costs, and the inability to match the scales of the worlds increasingly high throughput low-grade porphyry mineral deposits. Rather, it is likely that filtered tailings may find a place as a feasible companion technology to support a primarily conventional operation with the filtering process used to create dewatered tailings for use as a construction material for perimeter embankments or as a means to create smaller scale deposits of sulphide concentrates that would be managed outside of a larger conventional facility. Such applications would benefit from guidance documents specific to filtered tailings with emphasis on hydrotechnical, geotechnical, and geochemical considerations, including surface water management, unsaturated strength, dust control, and seepage behavior. Some have been developed but are not publicly available.

Multi-criteria alternatives analysis will move away from just focusing on the tailings facility, but will include the overall mine plan that optimizes the mining operation in concert with the tailings plan and closure plan. Factors such as water conservation and climate change will be given more prominence in these analyses.

Regardless of the tailings technology selection, we see tailings geochemistry taking a more active role in tailings-related decision making due to increasing regulation of surface water and groundwater and a perceived lack of appetite in the investment community for planned long-term water treatment in new mining propositions. The MAC tailing working group plans to update their Tailings Guide by 2026 which will include more emphasis on geochemical failure modes in its guidance on risk and alternatives assessment.

Combined, the above vision for tailings technology selection requires the adjustment of classical financial models (e.g., net present value, NPV) to capture the true lifecycle cost or benefit of the tailings technology without discounting long-term costs to low costs. Although the world financial system is unlikely to make such a step-change by 2030, it is hoped that the momentum achieved by PRI and UNEP through the development of the GISTM will continue.

6 CLOSURE STRATEGIES

6.1 Current Situation

In 2024, there is no one global definition of "safe closure". ICOLD's Bulletin 194 (Preprint) – Tailings Dam Safety defined closure as: *A planned, final cessation of tailings disposal and the modification/engineering of the tailings dam with the objective of achieving long-term physical, chemical, ecological, and social stability, and a sustainable, environmentally appropriate after-use* (ICOLD, 2022). GISTM defines safe closure as: *A closed tailings facility that does not pose ongoing material risks to people or the environment which has been confirmed by an ITRB or senior independent technical reviewer and signed off by the Accountable Executive.* (GISTM, 2020).

The ICMM GAP analysis of closure guidance documents for responsible closure (WSP, 2023) differentiates "responsible closure" from "safe closure". The definitions of the two are that:

- Responsible closure means a final closed state where environmental, ecological and social conditions are incorporated; and
- Safe closure is a physically and chemically stable final closed state.

Because there is not a consensus on the appropriate term at this time, the authors adopted the term "closure" for this paper, including all aspects of closure, i.e., both responsible and safe closure.

The survey responses indicated that the concept of TSF closure could encompass a broad range of considerations such as:

- Long-term vision;
- Alternative land use;
- Environmental and social integration;
- Regulatory compliance;
- Limiting risk to humans and the environment by long-term physical, chemical, ecological, and social stability;
- Principles related to ALARP (as low as reasonably practicable); and
- Limiting credible failure modes, i.e., elimination of potential failure modes or alternative ways to manage remaining risks / failure modes.

When it comes to care after closure, opinions on monitoring and maintenance differ. Some view safe or responsible closure as a state where no further human intervention is required, while others hold that, in some cases, there may be a need for ongoing monitoring and maintenance in perpetuity.

Many jurisdictions require closure plans and promote, or require, progressive closure at the permitting stage as well as financial guarantees for closure. Some jurisdictions require TSF closure plans as part of permitting conditions, prior to a mine starting or expanding. Efforts are being made by the industry to improve the dialogue with stakeholders with respect to closure, but to gain the trust required for a constructive and transparent dialogue, takes time.

At many facilities (particularly those that are not acid generating), tailings deposition plans include reducing water volumes as the operation proceeds and, ultimately, removal of impounded water after operations cease. Monitoring is planned to continue until the results show stabilized conditions, which in some jurisdictions are defined to be up to 30 years or so. Many companies are improving how they deal with closure, but implementation of today's ambitions varies across the industry.

The importance of tailings management and safe or responsible TSF closure, is gaining recognition. Research initiatives are ongoing in several specialized fields of closure. Some mining companies have developed their own closure guidance documents.

As mentioned in Section 5, many mining companies use the economic principle of net present value (NPV) to make decisions about whether to proceed with an operation or an option. NPV favors lower up-front capital and operating costs and encourages postponing costs and rehabilitation works, thus often creating significant liabilities at the end of a mining operation when there is no revenue or the mining company is not viable.

6.2 Vision for 2030

Based on the results of the survey, the vision for 2030 when it comes to TSF closure is as follows:

- There will be a global definition of "closure". This will help to achieve consensus on closure strategies.
- There is an engaged, open, and meaningful dialogue between all parties involved in TSF closure (i.e. mining companies, regulators and authorities, consultants, communities, NGOs, and other stakeholders) based on mutual trust and transparency.
- Global guidance documents and technical manuals will be developed that will provide guidance on goals to be achieved, closure criteria, acceptable levels of risk and the process of how to achieve closure as well as an appropriate level and detail of closure cost estimations to reach a suitable accuracy to be relied upon.
- The knowledge and understanding of TSF closure are improved and there is improved acceptance of closure practices among all parties involved, including involvement and collaboration with academia.
- It will be acknowledged that the TSF owner will likely not be the future land user and, therefore, not be solely responsible for the closure vision. Therefore, all parties involved will take part in the process, and take shared responsibility, in determining the vision through a meaningful dialogue and process.
- TSF closure will be an adaptive process from first planning through design and operation to post closure, where the design includes: a lifecycle perspective, processing methods to either limit tailings generation or produce benign tailings, integrated waste management (i.e. tailings, waste rock and possible other waste produced), long-term geotechnical aspects (including liquefaction, erosion etc.), geomorphological / landform design, chemical stability, water management (including surface water, acid rock drainage (ARD) etc.), climate change, and risk assessment and management.
- Large scale trial areas will be used in testing proposed closure designs.
- Financial models and systems will be developed for operating and new TSFs that support progressive closure, encompassing real costs and economic risks over time, and appropriate value will be paid to social benefits.
- All TSF operations have integrated closure into operations, meaning operation is equal to preparing for closure with the optimal goal being mining for closure, i.e. mining is done for two reasons a) to extract a metal / mineral and b) to create a new landscape / land use.
- There are effective monitoring and maintenance systems available for closure monitoring and maintenance in perpetuity.
- TSFs have a Reclamation Designer of Record (RDoR) who is responsible for closure design and progressive rehabilitation works over the life of the facility. The skill sets of an RDoR are different than the typical EoR. This framework may also include an Independent Reclamation Review Board (IRRB) like that of an ITRB but more multidisciplinary. Alternatively, the closure/reclamation discipline be included in an ITRB.
- Third party audits, covering technical, environmental, social and financial aspects, are done for closure plans and closure for all TSFs.
- Responsibility for historical TSFs that have been abandoned by irresponsible operators is allocated to bodies/parties with resources to properly close these (not just taxpayers) and there are cost-effective strategies for closure of abandoned and historical TSFs.

Integrating management of all waste materials produced, environmental sustainability, and economic development will be a prime milestone in the circular economy (CRC Press, 2024). Many actions are required to achieve the vision for 2030. The following initiatives, underway or planned, will not fully address the requirements, but will make important contributions:

- The CDA Mining Dams Committee are developing closure guidelines and criteria for when a dam is no longer a dam and is developing guidance on risk informed closure design.
- SME is developing a closure handbook that will provide comprehensive guidance and details related to closure. Many of the topics identified above will be addressed in this handbook.
- MAC and ICMM are developing their closure guidance.
- The efforts by MAC, ICMM, SME, and CDA will be coordinated.
- The LDI[3] is developing detailed guidance on landform design.
- Ten mining companies have established the GeoStable Tailings Consortium[4] where large scale closure field tests are run.

A change of the NPV financial model is required, but it is not clear at this time how the financial models can evolve to place more emphasis on low-risk closure solutions. This will require efforts by a number of stakeholders.

Despite current efforts, the challenges that are faced highlight the need for a comprehensive, transparent, interdisciplinary and multifaceted approach to achieve closure of TSFs (safe or responsible). To design with the end in mind, building TSFs to final landform designs from the beginning and viewing closure costs as part of the lifecycle of TSFs is necessary. In support of this, flexibility and continuous update of closure plans are required to adjust for changes in mine planning and development of good closure practices.

7 CHARACTERISATION OF TAILINGS AND FOUNDATION SOILS CURRENT SITUATION

7.1 Vision for 2030

The geotechnical community has made great strides over the past century, refining site characterization tools that were introduced starting in the 1930s, such as the cone penetrometer (now with many add-ons) and the triaxial compression test (now the standard for critical state line [CSL] testing). These tools, and others, allow

[3] The Landform Design Institute have a mission to make landform design routine in the mining industry by 2030 and focus on governance, leadership and education in landform design.

[4] Consortium led by Newmont with Antamina, Barrick, BHP, Freeport McMoRan, Gold Fields, Teck, and Vale.

for detailed engineering characterization of soil elements both in-situ, or in the laboratory, respectively. Fourie et al (2022) provides a detailed account of the standard of practice for characterization of mine tailings with detailed discussions on the applications of such tools. However, reliance on the tools alone without appropriate consideration for geological and geomorphological processes can lead to errors. Furthermore, lack of recognition of the fundamental mechanics of soil behavior (especially understanding of a critical state soil mechanics [CSSM]) has contributed to the propagation of what Dr. Morgenstern termed "weak engineering" (Morgenstern, 2018).

Historically, budgeting to support extensive site characterization efforts for tailings facilities was constrained by short-term operational mindsets (e.g., focusing on characterizing only the minimum requirements for a single dam raise). These constraints have now been largely removed in most parts of the world by evolving Owners' commitments and regulatory requirements to develop an integrated knowledge base for the whole TSF (GISTM Principle 2) underpinned by a detailed site characterization model.

The consensus amongst the survey respondents is that most of the tools required for adequate site characterization are already available today (e.g., piezocone, shear vane, piston sampling, advanced lab testing, etc.), but the toolbox could be better organized, and the tools sharpened. Specific challenges are:

- Methods for establishing potential for liquefaction, especially in the absence of a significant earthquake triggering mechanism. There are indirect methods available with the CPT and lab testing, but there is no direct method of discerning the in-situ void ratio of the tailings, which can be used to inform the liquefaction potential.
- Methods for discerning brittleness of tailings. As described in ICOLD preprint of Bulletin 194 (ICOLD, 2022), brittleness is a key aspect of discerning the risks associated with a TSF that has contractive and potentially liquefiable units in the dam and/or foundation. Methods for discerning brittleness are limited to lab testing that has challenges with respect to sample quality and extension of findings to field situations.
- Methods for assessing the post-liquefaction/large strain/residual strength of brittle materials
- Methods for characterizing and understanding the behavior (for both strength and seepage) of unsaturated tailings are severely limited, which will be essential for assessing and demonstrating that "safe/responsible closure" of tailings facilities can and has been achieved.
- Methods for understanding the evolution of geotechnical and hydrogeological properties of tailings (and mine wastes in general) in light of long-term geochemical weathering.

7.2 Vision for 2030

The vision for site characterization in 2030 is to fully embrace the principle of an interdisciplinary knowledge base for tailings management. This involves developing and regularly updating integrated site characterization models.

Site characterization should be treated as an iterative risk-informed process in concert with the design process where conceptual models of the foundation, tailings embankments, and tailings deposition process are developed based on a geotechnical, geological, geomorphological, and hydrogeological understanding of the site and the tailings depositional scheme. Involving more engineering geologists in this activity would be beneficial. Once this is done, uncertainty (both geological and depositional) can be characterized and used to inform site investigation targets and methods; each drill hole or laboratory test should have a clear objective linked to reducing model uncertainty or facility risk.

Liquefaction characterization and unsaturated soil mechanics was a specific theme in the survey responses. Based on the survey results, the vision for 2030 includes:

- Characterization of liquefaction potential and post liquefaction strength with the ability to accurately estimate in-situ void ratio will be standardized and common practice in the industry;
- Characterization of brittleness is standardized and common practice in the industry;
- The impact of fabric / layering on tailings behavior is understood; and
- Better methods for recovering "undisturbed" samples of fine and coarse tailings are developed.
- Use of robotics combined with artificial intelligence to conduct investigation programs.

In addition, for large facilities, methods will be developed to characterize the soil between discrete investigation points.

Several university and industry groups are currently tackling these challenges through ongoing research and guidance initiatives, for example:

- The University of Western Australia (UWA) recently completed a round robin on CSL testing involving 15 independent laboratories around the world. The results indicated the best reproducibility was obtained using end-of-test soil freezing to measure void ratio which has been accepted as the industry standard (Reid et al. 2021).
- The University of Toronto (UoT) is researching the impact of partial drainage conditions on CPT penetration using calibration chamber testing, which indicates the negative pore pressures observed in some tailings CPTs are indicative of dilative behavior (Lizhi et al. 2024).
- The ICOLD Bulletin 194 (2022) provides design guidance on soil brittleness and liquefaction potential with a flowchart on application of strength concepts (peak or residual) to factor of safety computation.
- Drilling contractors are adapting the nuclear and magnetic resonance technologies to in-situ tools for in-situ density (i.e., void ratio) and water content estimation.
- There is active research and development to incorporate pore pressure measurement on the electric vane shear test (eVSTu) to overcome the uncertainty of drained conditions during vane shearing.

To continue moving forward, there is a need for innovation in non-destructive/non-invasive technologies that can provide screening level information or reduce uncertainty in conceptual site characterization models. This could take many forms, but emphasis should be placed on vadose zone geophysical surveying from the surface to estimate degree of saturation in tailings deposits, stacks and cover systems.

To make this vision a reality, there also needs to be a focus on widespread sharing of common characterization data (e.g., adjacent operators in mining districts sharing data) and the formation of groups like the Canada's Oil Sands Innovation Alliance (COSIA) or the GeoStable Tailings Consortium to pool research funding and resources to develop solutions to common challenges.

8 SURVEILLANCE OF TAILINGS FACILITY PERFORMANCE

8.1 Current Situation

The importance of surveillance of TSFs has become more apparent to mine owners; not only to provide information on the performance of the TSF and provide early warning of potential concerns, but to support the adoption of the performance-based design approach. There is widespread use of "point" measurements (e.g., vibrating wire piezometers (VWPs), survey prisms, inclinometers, and seepage monitoring weirs) with automation of the instruments and data gathering becoming more of the norm than the exception. However, the data management interfaces can be cumbersome and there are challenges with false positives in so-called "real time" data.

Cameras are in place for many dams. Monitoring centers are being established that have computer monitors showing the view of the TSF and the dams and the instrumentation results. Alert levels are set for the instrumentation that can trigger a response to preserve the safety of the TSF.

Drones, often equipped with survey capability, are commonly used to observe the TSFs and INSAR [5] has proven to be an effective tool for monitoring features on a broader scale than "point" measurements.

Providers of surveillance methods have been at the cutting edge of developing new approaches and technologies with many owners embracing these innovative techniques.

The surveillance methods, though, are not necessarily linked to a comprehensive and realistic understanding of the potential failure modes, particularly for dams that have contractive elements in the structural body of the dam or foundation that can fail in a brittle manner. If the dam can fail by static liquefaction, then monitoring movements and pore water pressures to guard against static liquefaction may not provide adequate warning time in the event of a failure. Establishing trigger levels based on stability analyses alone can be misleading. Deformation models with appropriate constitutive models based on comprehensive field and laboratory testing programs can provide insight to the possible triggering mechanisms and a determination of whether an observational approach can be applied to this situation.

However, there have been instances of a "false confidence" being established that the surveillance will help to protect from failure in these circumstances. If a seismic event were to occur and cause a dam to fail by liquefaction, surveillance may be of little value other than to support the back analysis of the failure.

Internal erosion can occur at discrete points within a dam that are distant from where the instrumentation is established and cannot be discerned by point measurements.

8.2 Vision for 2030

By 2030, we anticipate the following to have been achieved:

- Surveillance programs will be targeted to address instability and internal erosion failure modes through the use of performance-based design to support slope stability assessment and seepage controls (refer to Section 8.1), Or, it will be demonstrated that surveillance cannot be effective to guard against those failure modes, that the observational approach cannot be used, and additional controls need to be implemented to preserve the safety of the facility. ICOLD is developing a new Bulletin on surveillance that will address these items.
- Automation and data management interfaces are improved to the point that the surveillance information can be directly integrated with engineering models to support calculations related to performance (e.g., deformations, factor of safety, seepage, etc.). AI will support the data acquisition and interpretation. Because of the massive amount of data that will be available, data scientists will be employed to assist with gathering and processing the data so that it can be interpreted effectively by engineers and operators. This will be led by service providers and data scientists.
- Methods of monitoring on a more areal extent will be commonplace. INSAR and drones are widely used, but other systems are evolving that can monitor performance over an aerial extent:
    - Fibre optic cable technologies can detect changes in temperature (which can provide indications of seepage), tension (to indicate deformations) and acoustic properties (to indicate changes in the material) and can be placed in critical positions of the dam section where seepage and deformations are expected and/or critical.
    - Permanent geo-electric monitoring of a dam and its foundation can be undertaken that can track the location of the phreatic surface over the length of a dam and identify areas where there may be concentrated seepage.
    - Deep penetrating radar and muon radiography from satellites can provide information on the internal configuration of a dam.

These initiatives are being advanced by service providers.

9 DESIGN APPROACHES

9.1 Current Situation

With respect to slope stability assessment, limit equilibrium methods (LEMs) are the most commonly used tool with conservative approaches adopted for dams that have contractive elements that are potentially liquefiable. However, there are a number of limitations with LEMs that need to be recognized when undertaking these analyses and establishing suitable targets for factor of safety (Krahn 2001).

In 2018, Dr. Morgenstern (Morgenstern, 2018) advocated for the adoption of performance-based design for slope stability

[5] INSAR = Interferometric Synthetic Aperture Radar

assessment that integrates a comprehensive understanding of the geotechnical conditions of the dam and foundation, performance information (deformations and pore water pressures), and deformation models to simulate the behavior of a TSF. Measurable performance objectives are established and, as a TSF is constructed and performance information is obtained, the performance is compared to the objectives and modifications made to the design, if necessary. "History matching" is done by updating the deformation model to match the performance information, which permits refinements to the understanding of the TSF and project future performance.

Performance-based design has proven to be effective on cases in western Canada (Gelletta 2023, Nguyen 2022, Nguyen 2023, and Quinn 2014) where water retaining dams built on pre-sheared clay shale have experienced significant deformation. Limit equilibrium analyses were not sufficient to represent the conditions and establish the potential for failure. Three-dimensional deformation analyses were able to demonstrate that the dam was safe and that the movements were tolerable.

For dams with contractive elements that are potentially liquefiable, case studies are being developed that show that the classical approaches for predicting liquefaction due to seismic events are possibly conservative. The use of deformation modelling, with appropriate constitutive relationships, may provide predictions of deformations that could occur as a result of a seismic event, rather than liquefaction (Kafash et al, 2021).

ICMM has provided training materials on performance-based design and CDA is also developing training materials.

LEM will still play an important role for stability analysis (when done properly and recognizing the associated limitations) and can be supplemented by performance-based design methods, particularly for complex geometries with multiple soil units.

Performance-based design can be extended to other facets of design such as flood control, seepage control, and internal erosion.

Risk informed design is an overarching philosophy that applies to all facets of design that accounts for the risks that are posed by a TSF. Because of the potentially significant losses to a mine owner and the downstream environment in the event of a TSF failure, ICMM recommends that extreme loading criteria be adopted for TSFs. The GISTM recommends that consideration be given to adopting extreme loading criteria. The GISTM states the following as Requirement 4.2:

A. *Develop preliminary designs for the tailings facility with external loading design criteria consistent with both the consequence of failure classification selected based on current conditions and higher Consequence Classifications (including 'Extreme').*
B. *Informed by the range of requirements defined by the preliminary designs, either:*
   1. *Implement the design for the 'Extreme' Consequence Classification external loading criteria; or*
   2. *Implement the design for the current Consequence Classification criteria, or a higher one, and demonstrate that the feasibility, at a proof of concept level, to upgrade to the design for the 'Extreme' classification criteria is maintained throughout the tailings facility lifecycle.*

Many owners have adopted this approach, but there are exceptions, particularly for TSFs that do not have life safety consequences.

Dam breach analyses are an important tool to understanding the potential consequences associated with a TSF, and thus the risks. Significant progress has been made in the past five years on this topic including the issuance of the Tailings Dam Breach Analysis Technical Bulletin by CDA in 2021 and the establishment of a consortium of universities in Canada to form CANBREACH (www.canbreach.ca). The University of British Columbia, Queen's University, and Waterloo University formed CANBREACH in 2019 with the goal of better understanding the tools and methods available to simulate a tailings dam breach. Part 1 of the research program was completed in 2023 and Part 2 is planned to commence in 2024. Part 1 advanced the understanding of the physical processes of a tailings dam breach and the outcome of a breach as well as the computer models that are available to predict the extent of a breach. Part 2 will continue this work with further research on computer modelling, the released volumes of tailings, and the behaviour of unsaturated tailings during a breach.

A key driver of TSF design can be the geochemical considerations, especially as they relate to closure and how the initial designs and operations need to account for this.

9.2 Vision for 2030

By 2030, we anticipate the following:

- Performance based design for slope stability assessment will be a widely recognized and accepted approach;
- Limit equilibrium analyses will still play an important role in design;
- Performance-based design for slope stability assessment and LEM will be viewed as complementary;
- Fully coupled deformation and seepage models will be able to achieve results closer to reality; and
- The concepts of performance-based design will be extended to other facets of design as noted above.

For performance-based design for slope stability assessment to gain widespread acceptance, additional case studies need to be developed and presented in the literature with a critical view to the limitations associated with deformation modelling. Conferences and training sessions should convene targeted sessions related to performance-based design and how it can be integrated with LEMs.

A challenge that will limit the advancement of performance-based design is regulatory capacity; the ability of the regulators to understand performance-based design as opposed to simply meeting a factor of safety requirement.

With respect to dam breach analyses, the CANBREACH consortium is initiating Part 2 of their research that will explore:

- Unsaturated soil behavior and how this should be considered in a tailings dam failure.
- Breach processes and how tailings dam breaches actually form, which will allow better predictions of failures associated with tailings dams that are buttressed with rockfill.
- Improved correlations between modelled failures and actual failures.

The geochemical aspects will be given greater prominence in the design in support of closure plans that will properly address these aspects and not simply result in pump and treat scenarios.

10 GUIDANCE DOCUMENTS FOR TAILINGS FACILITY SAFETY DESIGN

10.1 Current Situation

As noted in Table 1, there are many guidance documents available to support the design of TSFs and some respondents to the questionnaire stated that there was sufficient guidance, i.e., "we should use what we have." However, there is a recognition that the state of practice for TSF engineering is evolving rapidly and, hence, several organizations are modifying their current guidance or developing new guidance related to TSF safety. These include:

- CDA - modifying the Mining Dams Bulletin that was issued in 2014 (revised in 2019) and the overarching dam safety guidance.
- MAC – modifying the tailings management guidance.
- United States Society of Dams (USSD) – developing a tailings dam safety guidance for the US.
- CDA and USSD – developing guidance for the EoR role and for risk informed decision making.
- SAICE (South Africa Instiute of Consulting Engineers) – updating the Civil South Africa National Standard 10286 Mine Residue Code of Practice to be more aligned with GISTM.

A number of regulatory jurisdictions around the world have developed or updated their regulations related to TSF safety.

The questionnaire identified a number of gaps related to guidance, including:

- Closure (refer to Section 6.2)
- Filtered tailings
- Methods for characterizing tailings and foundation soils
- Spillway design

10.2 Vision for 2030

As noted above, a tailings closure handbook is in progress by SME that is expected to be completed before 2030. Also, the LDI will have developed their guidance on landform design. The following additional guidance documents should also be available:

- Updates to the MAC tailings management guides.
- A document on filtered tailings that integrates the process and geotechnical aspects. This is to be led by representatives from industry that specialize in filtered tailings supported by input from ICOLD and other organizations on the geotechnical aspects.
- Revised version of ICOLD Bulletin 194 that provides additional guidance on site characterization, hydrogeology and hydrology, spillways, undrained stability analyses, and brittleness.
- ICOLD Bulletin on surveillance of tailings dams.

There will likely be additional guidance documents developed in addition to these.

11 ARTIFICIAL INTELLEGENCE

11.1 Current Situation

Six years ago, AI was hardly discussed. Today, AI seems to be incorporated into our basic computer software (e.g., Microsoft Copilot). Regarding TSFs, AI is, in some cases, being used in surveillance activities to support the gathering and processing of large amounts of data. Discussion and research are ongoing regarding future possibilities and opportunities with AI. Some of the survey respondents are very interested and positive about AI, whereas others are more skeptical and negative and think AI is overhyped.

From the questionnaire there was a concern expressed with the increased computing power and AI as that might reduce emphasis on learning the fundamentals of tailings engineering. The authors agree that the use of AI does not replace the need for humans to understand how to do a task, but should be used as a means to improve efficiency of a task that the person already knows how to do well.

11.2 Vision for 2030

From the responses to the questionnaire there is no clear vision for 2030, and some emphasize a vision can only be for 2040 or beyond. The authors, however, believe that by 2030, we'll see AI used frequently within the industry and for TSFs within the following areas:

- Managing, processing and analyzing large data sets (weather, hydrology, monitoring – especially on-line monitoring) to identify trends and deviations to help understanding the TSF performance.
- Integration of data sets such as mineralogy, geology, hydrology, and seismology to provide a more multifaceted picture of the TSF conditions.
- Pre-processing of data and prediction operational aspects of tailings management to help identifying potential risks and predict future performance.
- Numerical modeling for stability and deformation analysis as well as breach inundation simulations.
- Enhanced adaptive management by monitoring real-time stability, identifying trends, anticipating risks etc.
- Training programs and live guidance and support for operations.
- Review of literature and documents, summarizing of information / reports and reporting to standards / regulators.

Overall, while there is cautious optimism about AI's potential in tailings facility engineering, there is also a strong emphasis on the need for human oversight and the importance of integrating AI as a supportive tool rather than a replacement for expert judgment. However, AI could be part of the solution to the coming challenge of fielding enough TMPs to meet the growing demand.

In order to reach the vision for 2030 the industry will have to have an open mind towards AI and invest time and money in developing methods to use this potential tool that in many ways can improve, speed up and simplify data analysis, predictive modeling, numerical simulations, surveillance, training and enhance decision-making and risk management in TSF engineering. In addition, we cannot lose sight of the importance of understanding the fundamentals of tailings engineering and the role that models should play.

12 CONCLUSIONS

Through this work and reviewing the provided information, the authors have been impressed by the overall developments and achievements in recent years and been even more impressed by the anticipated and possible developments ahead to 2030. All the people who contributed to this work through the questionnaire, interviews and discussions have shown a positive attitude to this work, and a general optimism to the change and improvements on the horizon. The aim is to keep the momentum of improving tailings facility engineering and with the support of ICOLD's Technical Committee L on Tailings Dams and Waste Lagoons and many other organizations work towards achieving the vision of what tailings facility engineering can look like in 2030.

We will publish a comprehensive summary at the end of 2024 of this work including further input from this and coming presentations during the autumn.

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