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Don't let the tail(ings) wag the mine: guiding tailings storage facility closure designs for compliance

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Abstract

Navigating the choppy waters of tailings storage facility (TSF) closure is no simple feat — it's a bit like teaching an old dog new tricks, but with more environmental regulations. TSFs can be some of the most complex mine closure components, as they pose significant environmental, social and economic risks if not properly designed, constructed and rehabilitated.

The Global Industry Standard on Tailings Management (GISTM) provides a framework for the safe management of TSFs throughout their lifecycle, from planning to closure and post-closure. This paper presents some of the lessons learnt and challenges encountered while undertaking engineering closure designs of TSFs for GISTM compliance, with a focus on aligning with the United Nations Sustainable Development Goals (UN SDGs).

The paper discusses the closure hierarchy that is typically considered for TSFs, which serves as a foundational framework for identifying appropriate post-closure land uses and for developing robust engineering designs. It suggests that it is possible to design and implement closure strategies for TSFs that not only meet GISTM standards but also contribute to achieving several UN SDGs.

Additionally, the paper examines strategies to reduce both initial investment and ongoing costs associated with monitoring and maintenance post-closure. Some of the challenges that are highlighted in the paper include the knowledge base, uncertainties regarding the long-term performance and behaviour of TSFs, and the design life of the closure components.

By sharing insights and experiences from TSF closure design projects, which sometimes feels like trying to tame a beast before it hibernates, this paper aims to provide some recommendations and best practices for future projects.

Keywords: *closure designs, GISTM, UNSDG, tailings, TSF*

1 Introduction

1.1 Importance of tailings storage facility closure

According to Veiga et al. (2001), an increasingly important consideration in mine planning is the impact and legacy the mine leaves on the community after its closure, as there are numerous examples where the legacy fails to meet acceptable standards.

Integrating closure planning from the onset of tailings design and operations is crucial. Early planning helps identify potential challenges and allows for modifications that can prevent difficulties and reduce costs over the lifecycle of a tailings storage facility (TSF). This proactive approach ensures that closure strategies are aligned with operational goals, leading to more efficient and sustainable outcomes.

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Although the closure of a TSF is a crucial step towards mitigating environmental and safety risks, it does not inherently guarantee that the TSF is safe. Roche et al. (2017) highlight that while failures are more common at active sites, chronic problems at legacy sites are well-documented. Studies have shown that inadequate or poorly maintained closure systems can lead to increased risks of dam failure, environmental contamination and other hazards (Aubertin et al. 2002; Sanchez et al. 2015).

1.2 Overview of the Global International Standard on Tailings Management

The International Council on Mining and Metals (ICMM), partnering with the United Nations Environment Programme (UNEP) and Principles for Responsible Investment (PRI), developed the Global International Standard on Tailings Management (GISTM) (Global Tailings Review 2020) following the Brumadinho TSF failure in 2019.

The purpose of the GISTM is to enhance the safety of TSFs while improving transparency and disclosure practices (ICMM 2020).

According to Requirement 5.5 of the GISTM Conformance Protocols (ICMM 2021a), 'Closure designs are recommended to be completed to a pre-feasibility study (PFS) level'. This requirement is intended to cover existing TSFs but also applies to new facilities that currently exist only on paper or 'in the cloud'. To comply with this requirement for new TSFs, closure should preferably be included from the onset, i.e. closure slopes should be built and progressively rehabilitated (where possible), not only implemented when the TSF approaches its golden years. However, the level of closure planning and design will need to be refined during the life of the TSF.

1.3 Alignment with United Nations Sustainable Development Goals

Set out by the United Nations, the Sustainable Development Goals (UN SDGs) constitute 17 integrated goals that act as a framework to foster a more prosperous and ecologically sustainable future for every individual.

The closure of TSFs can significantly align with multiple UN SDGs, demonstrating a commitment to sustainable development and responsible mining practices. For instance, aligning TSF closure strategies with various UNSDGs would ensure the prevention of water contamination, promote the health and safety of local water bodies, restore habitats, prevent land degradation, foster biodiversity, and lead to the implementation of resilient infrastructure that minimises waste and optimises resource use.

Through these efforts, the closure of TSFs not only mitigates environmental and societal risks but also positively contributes to broader sustainable development objectives, thereby enhancing the overall positive impact of the mining sector.

1.4 Purpose of the paper

This paper presents the closure hierarchy typically considered in TSF closure designs, providing a foundational framework for identifying suitable post-closure land uses and developing robust engineering solutions.

The author discusses lessons learnt from involvement in various TSF closure projects, focusing on designing and implementing closure strategies that meet GISTM standards and contribute to achieving several UNSDGs. Challenges encountered during these projects are also included to help streamline future closure design initiatives.

Additionally, various strategies for reducing the costs and efforts related to closure implementation and ongoing maintenance are presented.

Following the analogy contained in the title of this paper would result in quite a lengthy tail wag!

2 Tailings storage facility closure methodology

2.1 Framework for tailings storage facility closure hierarchy

Responsible mine owners will often (hopefully!) have an idea in their minds as to what closure will 'look' like. These pictures are often subjective and likely to focus on different components such as community involvement, aesthetics, etc.

Various closure principles exist, with the ICMM Integrated Mine Closure Good Practice Guide (ICMM 2019) advocating the following principles:

- safety
- physical stability
- chemical stability
- socio-economic transition
- ecological stability
- risk limitation
- cost-effectiveness
- long-term care.

For the purposes of this paper, the hierarchical approach has been abbreviated and is presented in Figure 1. This approach is used when developing closure plans for TSFs.

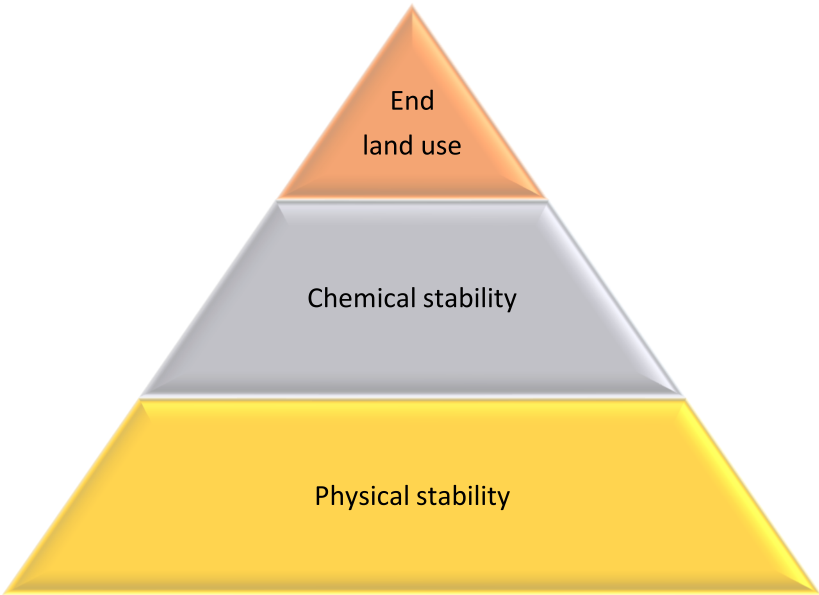


Figure 1 Closure design hierarchy

This hierarchy looks to first establish a stable landform (in terms of global stability and erosion resistance) and then prevent, or at least minimise, pollution or degradation of the receiving environment. Once confident in achieving these two key principles, the end land use (ELU) is determined, which ideally should be informed by all interested and affected parties (I&APs).

A converse approach is to determine the ELU and then 'reverse engineer' the landforms to achieve the desired objectives. This is more likely to result in an acceptable ELU, but the exact ELU might need to be tempered by practical engineering considerations.

2.2 How do we know when the facility is 'closed'?

While the closure of a mine can be likened to a journey with unexpected detours, delays and memorable (or forgettable) pit stops, it is essential to recognise that no-one would willingly embark on a journey with no defined end destination, which would effectively become a journey in perpetuity. So, how do we know if we have successfully closed a TSF?

To determine if you have reached your end destination, it must be clearly defined. In the context of a TSF, the destination is likely to be one that is expected to be stable — there is little value in a beautifully reshaped TSF covered in endemic vegetation if it fails and flows down the valley a few years later. It should also be non-polluting and have a productive ELU. To define these aspects for establishing relinquishment criteria, one might propose the following:

- physical stability — an acceptably low probability of failure, including erosional stability
- chemical stability — the degradation of the environment is either non-existent or acceptably low
- ELU — land use that is accepted by the communities and regulators.

These agreed-upon relinquishment criteria should form the basis for the closure design criteria, and should be specific, measurable, achievable, relevant and time-bound — often referred to as SMART.

In the author's opinion, a fair degree of humility is required in successful closure planning. While the best science, engineering and international guidelines may provide a good 'global' road map, a site-specific map is required to understand the local topography, climate, geology, communities and biodiversity. Integrating remote desk-based expertise with local knowledge will almost always outperform exclusively external plans and designs.

Furthermore, the potential benefits of undertaking trials and/or concurrent rehabilitation on site are unlikely to be fully appreciated until implemented and monitored. Trial covers or slopes can inform the final cover designs, with appropriate adjustments made if needed. Full-scale concurrent rehabilitation (or progressive reclamation, as per GISTM terminology) is likely to reveal the good, bad or even ugly long-term performance of the planned closure measures.

2.3 Design life

Most civil engineering designs are intended to last for decades, but the post-closure life of TSFs far exceeds these timelines. This is schematically shown in Figure 2, with the last portion of the timeline including a not-to-scale break to illustrate the unknown life beyond the closure of the TSF.

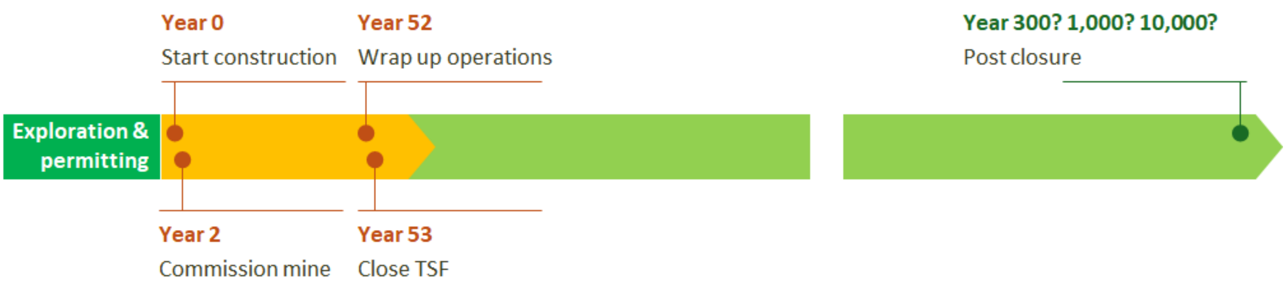


Figure 2 Typical tailings storage facility timelines

The design life of the closure measures has been a hot discussion topic. The underlying intention of designing for closure is to have a truly engineered landform with lower long-term monitoring and maintenance requirements (ICMM 2021b). However, engineers prefer to have a defined design life to inform the design process, while accountants need to have a timeline to calculate the associated costs.

The International Commission on Large Dams (ICOLD) acknowledges the variation in accepted design life periods globally, as presented by Bjelkevik (2011). The general regulatory and best practice focus is on achieving long-term stability for hundreds (Aubertin et al. 2002) to 1,000 years (ICOLD 2016), to ensure negligible risk to the environment and human health.

2.4 Importance of upfront closure planning

Integrating closure planning at the earliest stages of tailings design and operations is vital. This approach allows for the identification of potential challenges and the implementation of modifications that can prevent difficulties and reduce costs. By considering closure requirements from the beginning, mining operations can align their strategies with both operational and closure goals, ensuring more efficient and sustainable outcomes. Early planning not only mitigates risks but also enhances compliance with the GISTM and supports the achievement of UNSDGs.

3 Global Industry Standard on Tailings Management compliance and United Nations Sustainable Development Goals overlap

3.1 Current Global Industry Standard on Tailings Management compliance levels

The ICMM members disclosed their levels of GISTM compliance for their Extreme and Very High Hazard Consequence Category TSFs in accordance with the August 2023 deadline. The disclosures were summarised and presented at the Global Roundtable Investor Mining and Tailings Safety Initiative on 24 January 2024. The results indicated that ~60% of the 238 TSFs are compliant, with the remaining 40% not yet being in full conformance — although most of these facilities have at least identified gaps and are implementing plans to allow the gaps to be closed. It was noted that the main compliance gaps are ‘associated with Principles 4 and 5 (assembly of design/design criteria/knowledge base)’, which is reasonable considering the extensive history of certain facilities.

To be fully GISTM-compliant would mean that those TSFs have at least PFS-level closure designs in place, with some of the TSFs in a state of partial compliance potentially also having closure designs.

3.2 United Nations Sustainable Development Goals-related tailings storage facility closure

All the UNSDGs can be related to the closure of TSFs, with the goals relevant to the discussions in this paper highlighted in Table 1 and the relevance explained in the second column.

The GISTM aims to ensure TSFs are built, operated, maintained and closed in a sustainable and responsible manner. Several UNSDGs align with the principles and requirements promoted by the GISTM, especially concerning the closure of TSFs, with the overlaps relevant to this paper presented in the third column of Table 1.

Table 1 United Nations Sustainable Development Goals (GISTM) relevant to tailings storage facility closure (TSF) designs

Goal	Relationship to TSF closure	Overlap with the GISTM
Goal 3: Good Health and Wellbeing	Ensuring a safe and effective closure of tailings dams helps to prevent the release of contaminants, protecting the health and wellbeing of local communities and ecosystems.	The closure of TSFs following the GISTM helps in reducing environmental contamination, thereby ensuring healthy lives.
Goal 6: Clean Water and Sanitation	Proper closure of TSFs helps prevent contamination of water resources, ensuring the availability and sustainable management of water and sanitation for all.	The GISTM emphasises safe water management of TSFs to prevent contamination of water sources. Ensuring clean water and sanitation aligns with responsible closure practices that prevent leakage or spillage of hazardous materials.
Goal 9: Industry, Innovation and Infrastructure	Developing innovative and sustainable methods for TSF closure contributes to building resilient infrastructure and promoting inclusive and sustainable industrialisation.	Establishing resilient and sustainable infrastructure for tailings management is crucial. The GISTM promotes innovation and proper engineering practices, which contribute to building resilient infrastructure.
Goal 11: Sustainable Cities and Communities	Ensuring that TSFs are safely closed and rehabilitated helps make cities and human settlements inclusive, safe, resilient and sustainable.	Both promote the development of safer infrastructure and effective disaster risk management practices, thus ensuring that communities near TSFs are protected from potential tailings failures and environmental harm.
Goal 12: Responsible Consumption and Production	TSF closure practices that minimise waste and promote the safe disposal of mining byproducts align with responsible consumption and production patterns.	The GISTM encourages processes that reduce waste and pollution, echoing the UN goal of responsible consumption and production. Proper closure involves minimising environmental footprints and promoting recycling and reuse of materials where possible.
Goal 13: Climate Action	Effective TSF closure can mitigate the release of greenhouse gases and other pollutants, contributing to efforts to combat climate change and its impacts.	Climate resilience is a key aspect of the GISTM during the closure phase. The standard includes measures to manage TSFs under changing climatic conditions, thereby contributing to broader climate action goals.
Goal 14: Life Below Water	The prevention of leachate entering water bodies is crucial in protecting marine ecosystems and in support of efforts to conserve oceans, seas and marine resources.	Both emphasise pollution prevention, ecosystem protection, sustainable resource use and effective regulatory frameworks, demonstrating an interlinked commitment to environmental sustainability.
Goal 15: Life on Land	Proper closure and rehabilitation of TSFs help protect, restore and promote sustainable use of terrestrial ecosystems, combat desertification, halt and reverse land degradation, and halt biodiversity loss.	Protecting, restoring and promoting the sustainable use of terrestrial ecosystems is a shared objective. The closure of TSFs under GISTM guidelines aims to minimise land degradation and support biodiversity conservation.
Goal 17: Partnerships for the Goals	Collaboration between mining companies, governments and communities in the closure of TSFs fosters partnerships that are essential for achieving sustainable development goals.	Effective closure of TSFs often requires multi-stakeholder partnerships involving governments, industry, communities and other stakeholders to ensure compliance with closure standards and community safety.

3.3 Integration of early closure planning with the GISTM and UNSDGs

Early closure planning is essential for aligning TSF operations with GISTM guidelines and UNSDGs. By incorporating closure strategies from the outset, mining operations can ensure compliance with international standards and contribute to sustainable development goals. This proactive approach not only addresses regulatory requirements but also fosters environmental stewardship and community wellbeing, enhancing the positive impact of the mining sector.

4 Lessons learnt

The author has participated in several PFS-level closure designs and has provided closure inputs for detailed designs of TSFs. These experiences form the basis for the discussions presented in the subsections below. Some of these studies were initiated by the mine owner’s desire to be GISTM-compliant, necessitating the disclosure of a closure design. Others were driven by the owner’s proactive approach, which is the preferred motivator. However, GISTM compliance is raising awareness among owners about the need for advance closure planning before the end of a facility’s life. Lessons learnt from closure projects should be shared publicly to advance industry knowledge, thereby reducing the risk of inefficient methods being perpetuated.

4.1 General lessons learnt

It is crucial to establish a comprehensive knowledge base and address any knowledge gaps promptly during the life of the TSF, rather than postponing studies with potentially long lead times until later stages. Insufficient data typically necessitates conservative assumptions, resulting in higher closure cost estimates.

In addition to the calculated costs for implementing closure measures, the owner is generally responsible for ongoing monitoring and maintenance of the site until a closure certificate is issued by the regulator. These ongoing costs can be significant, particularly if extensive maintenance is needed (such as replacing a concrete spillway every few decades), especially when the period of responsibility spans centuries or millennia.

Engaging with regulators and communities early and regularly allows the owner to present a clear picture of the ELU while encouraging the constructive involvement of all I&APs. This approach should also help mitigate the impact of changing neighbouring land uses that could impose different demands suddenly.

Simple yet accurate representations of closure options help explain technical concepts in an accessible manner or, in GISTM terms, in ‘meaningful engagement’. For example, the use of rain-on-grid modelling shown in Figure 3 (Van der Colf et al. 2024) effectively illustrates how an intense rain event can cause a pool to build up in the paddocks on the TSF basin and the associated flow vectors, which are then drawn down using the spillway, highlighting areas that may require additional armouring or energy dissipaters.

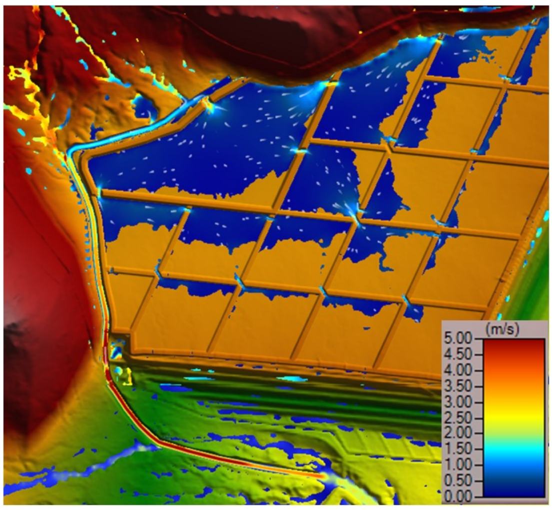


Figure 3 Spatial velocity and flow vectors map from rain-on-grid modelling (adapted from Van der Colf et al. 2024)

As discussed above, the post-closure life far exceeds the planning and operational phases, making it difficult to accurately predict what stressors are likely to be applied to the closed TSF over centuries or millennia. Redundancy and nature-based solutions (NBS) are likely to outperform systems that rely on a single piece of hard, grey infrastructure. NBS are also often more favourably received by communities, while some regulators may prefer proven grey infrastructure due to its established track record as the regulators will need to assume responsibility for it in the long-term. NBS are starting to gain credibility for their ability to rehabilitate, or even regenerate, the mining environment (Howard 2022).

Short-term assessments, such as the apparent establishment of self-sustaining vegetation, should not be extrapolated to indicate long-term performance. Factors like bushfires, climate change, the cessation of irrigation or the migration of salts can harm or kill vegetation (Gan et al. 2012) previously considered established and self-sustaining.

All terraces remaining post-closure will still require active monitoring and maintenance. The likelihood of a terrace overtopping at some point during the post-closure phase is high, considering factors such as climate change, inadequate monitoring or maintenance, and the development of low points on the bunds due to foot traffic or water and/or wind erosion. Overtopping of these bunds will likely result in a cascading failure down the outer slope of the TSF, as illustrated by the red polygon in Figure 4. Extensive basin erosion with a dendritic drainage pattern is highlighted in Figure 4 using a blue polygon.

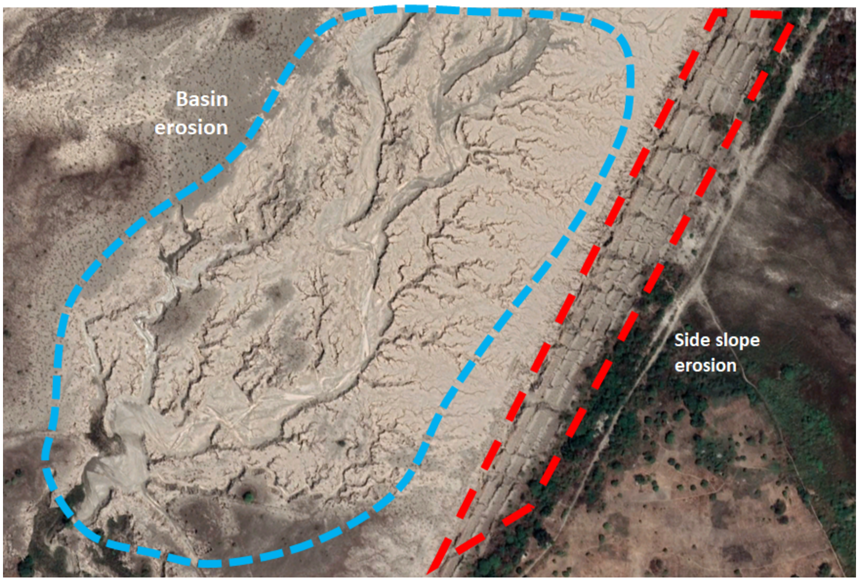


Figure 4 Extensive erosion features on an old tailings storage facility (Google 2024; image dated 5 February 2023)

To mitigate the risk of terraces overtopping it is possible to flatten the steeper slopes to fill in the terraces and create a near-constant overall slope. This is relatively straightforward for lower TSFs, but taller ones may require some form of intervention to shorten the flow path slope length. The degree of intervention would be highly dependent on the overall slope angle, climate, vegetation, and properties of the soil and/or rocks in the cover.

Potential interventions to limit the flow path down the slope could include armoured valleys or stormwater channels. Banded vegetation, such as strategically planted grasses and shrubs, can significantly reduce erosion rates on the side slopes of TSFs by stabilising the soil with their root systems and reducing the velocity of surface runoff (Morgan 2005; Valentin et al. 2005).

4.2 Lessons learnt from engineering closure designs for existing facilities

Clients do not always know what they want, nor are they aware of the implications of what they are asking to be undertaken. This can lead to incomplete or incoherent scopes of work being requested.

Historically, the planning for the closure of a TSF often did not extend much beyond managing catastrophic credible failure modes. Consequently, it has been necessary to convince clients that closure planning is more involved (and has evolved) these days. This mindset shift is most challenging for facilities that have been in operation for decades, where everyone involved previously believed that appropriate closure plans were already in place.

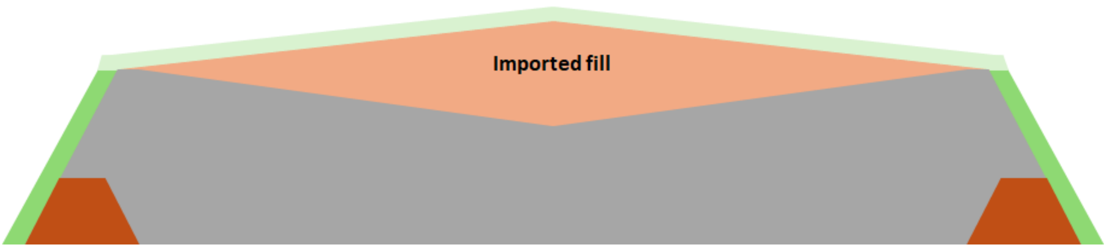
As discussed above, a hierarchical approach is typically used when undertaking closure designs. This approach resulted in the stability of an existing TSF being assessed as the first step. The geotechnical modelling indicated that a buttress would be required to adhere to the GISTM stability requirements. This buttress was incorporated into the closure planning for the TSF when considering erosion modelling and water management. A workshop was held with the relevant client team members to document the post-closure risks and develop ELUs.

Clients often anticipate that a first-principle design and cost estimate at the PFS level will yield a lower closure cost for the TSF compared to an estimate derived from a framework based on unit rates. In South Africa, the traditional framework has primarily relied on the Department of Mineral Resources (DMR 2005) guideline to assess financial requirements. The author has had experience presenting closure costs based on facility-specific designs, which often leads to client surprise and necessitates budget applications or long-term financial planning. However, it is important to emphasise that a PFS-level closure design using first-principle, facility-specific rates offers a significantly more accurate estimate than guidelines based on hypothetical scenarios.

Planning for closure early, ideally during the design phase or early operational years, can lead to design or operational modifications. This proactive approach often reduces the capital costs associated with initiating closure only at the facility's end. For example, a project undertaken midlife allowed for proposed adjustments over the remaining decades. These adjustments are expected to lower closure costs and enable concurrent or progressive implementation of closure measures. Planning and adjusting operations in this way most often reduces long-term closure costs and leads to better closure outcomes.

One such modification proposed for a TSF with decades of operation remaining was to switch the deposition from being around the perimeter to a central deposition. This modification could be made in the last years of the operational life to dramatically reduce the volume of imported fill otherwise required to dome the TSF basin. Figures 5a and 5b schematically indicate the discharge of tailings from the perimeter and the associated imported fill volume, respectively. Figures 6a and 6b show how switching to a central deposition system could partially fill in the basin, thereby reducing the required volume of imported fill, respectively.

(a)



(b)

Figure 5 Typical section through a tailings storage facility showing: (a) Discharge from the perimeter; (b) The resulting volume of imported fill required

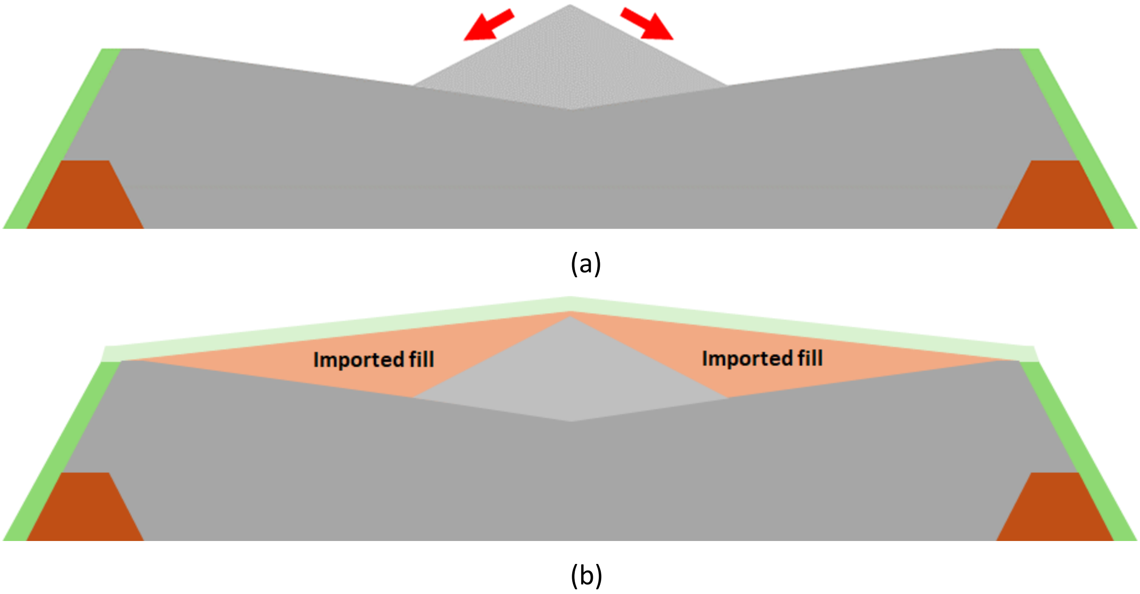


Figure 6 Typical section through a tailings storage facility showing: (a) Central discharge; (b) Reduced imported fill volume following central deposition partially filling the basin

4.3 Lessons learnt from engineering closure designs for new facilities

As discussed above, the GISTM requirements (ICMM 2021a) call for closure designs to be completed to at least a PFS level.

Incorporating actual closure components into the design and operation phases of a TSF is recommended, rather than deferring all measures to the end of a TSF's life (or even the life of the mine). However, in the author's experience, the industry often hesitates to modify existing familiar designs and methods early in the TSF lifecycle, despite the presence of a comprehensive long-term plan.

Such challenges were encountered as part of the design of a new TSF at an existing mine. It was proposed to construct the TSF at a constant slope instead of incorporating terraces and slopes. This change would not impact the overall TSF storage capacity but would prevent the duplication of rehabilitation efforts (i.e. prevent the need to flatten intermediate slopes and avoid the need to vegetate the steeper temporary slopes) and simplify the piping system (as the distribution lines up the slope would not need a variety of bends and make-up pieces) — and all of this would be part of the ongoing operational expenditure. However, the client was hesitant because it would require the surveyors to provide batter boards up the slope to ensure correct overall outer slope raising. The consultant designing the deposition system also had concerns, which they admitted were intangible because there was no reason why a constant slope couldn't work for the piping.

Figures 7a and 7b show a TSF raised using traditional terraces and at a constant slope, respectively. The terraces are likely to require a pushdown of the slope towards the end of the TSF life, making any cladding and vegetation of the outer slope most probably a waste of effort. Conversely, constructing a TSF at the final closure profile allows progressive rehabilitation, with the darker shades of the cover indicating the greater age of the lower slope with larger vegetation, while the lighter colours indicate a younger cover with smaller vegetation.

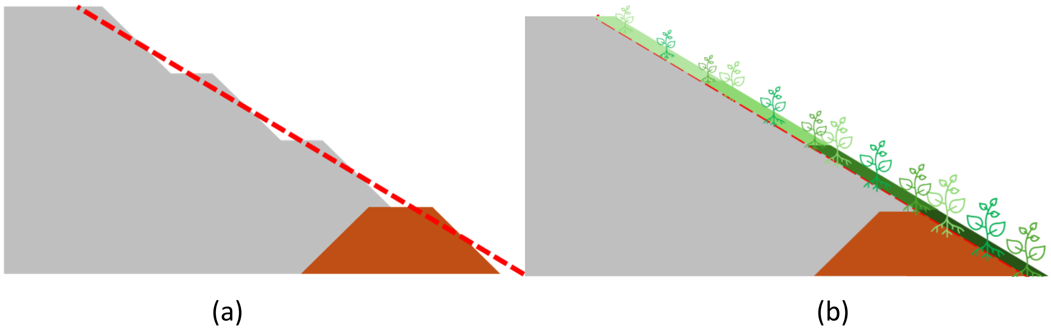


Figure 7 A tailings storage facility constructed with;(a) Terraces; (b) A constant outer slope

Natural slopes offer a useful reference for designing the outer slope of a TSF because their shapes are typically more resistant to erosion compared to straight or rectilinear geometries (Slingerland et al. 2019), especially under site-specific climatic conditions and vegetation types. However, it is important to consider differences between the TSF cover materials and natural materials, which may include features such as a resilient rock cap or other characteristics that may not exist on the TSF.

4.4 Challenges encountered

4.4.1 Material shortages and cost implications

One mine faced the challenge of insufficient material for constructing a buttress due to limited waste rock stockpiles from its underground operations. This significantly increased the projected cost. Efforts are now focused on additional geotechnical investigations to enhance parameter confidence. Elevated drainage features are being installed within the TSF to improve stability, reducing reliance on an expensive rock buttress initially based on conservative assumptions.

4.4.2 Field trials and implementation

Recommendations often include conducting field trials for reshaping and cover materials, yet such trials are rarely implemented. Trial slopes are cost-effective, especially when using available onsite equipment. They can be monitored, assessed and adjusted as needed, providing confidence in the design. Trials also demonstrate the intended closure profile, offering a chance to engage local communities and regulators.

4.4.3 Joint venture ownership conflicts

Mines with joint venture ownership can benefit from diverse inputs but disagreements may arise. At one mine, the controlling owner was an ICMM member while the partner was not. The non-ICMM member viewed certain components as overly conservative, questioning the necessity of fully complying with the GISTM.

4.4.4 Exclusion of interested and affected parties

Closure work to date has involved only the client team, excluding I&APs. While this speeds up planning, it can overlook valuable community input. Including I&APs is recommended for meaningful engagement and potentially beneficial ideas.

4.4.5 Limitations in consultant scope

A review of a closure plan by another consultant revealed significant limitations. The plan aimed for GISTM compliance but was restricted by the client’s limited scope, covering only a few GISTM requirements. The consultant lacked access to the necessary documentation, hindering the assessment of technologies and stability. Consequently, the closure plan was theoretical and not robust enough for sustainability.

4.5 Strategies for cost clarity

Acquiring additional high-quality and appropriate data typically allows for the refinement of designs. It is common to conclude the PFS design phase with a comprehensive list of required studies to inform subsequent design stages. A lack of data forces designers to apply conservative assumptions, potentially leading to more expensive design proposals, such as the size or even the necessity of a buttress. The cost of constructing a buttress often far exceeds the expense of conducting additional investigations, modelling and design steps, likely resulting in overall cost savings.

NBS that rely on natural processes and redundancy can be more cost-effective and potentially outperform traditional infrastructure in terms of longevity. This improved performance of mobile channel base sediment compared to a rigid (armoured) base was demonstrated through modelling by Slingerland et al. (2019).

Certain tailings streams have the potential to contaminate water on and around the mine site. While pumped and chemical water treatment systems exist to manage pollution, they require long-term inputs and human oversight. Passive treatment systems, such as wetlands, have been successfully used to manage specific contaminants (Kadlec & Wallace 2009; Sheoran & Sheoran 2006). Although wetlands might not be entirely free from monitoring and maintenance, depending on the contaminants of concern, they require significantly fewer inputs and monitoring, thereby reducing costs.

Involving local communities in supporting long-term closure solutions provides the added benefit of utilising community members for certain monitoring activities while upskilling those involved. Local involvement allows for more frequent monitoring at lower costs.

Consultants are often perceived as expensive and overly theoretical. However, reducing the scope or budget of a consultant undertaking a closure design will almost certainly result in higher expenses in the future when implementing the closure design, and require additional monitoring, maintenance or even repairs in the ensuing years or decades. The author believes that conducting additional investigations, field trials, modelling and design is likely to result in long-term cost savings due to design refinements. Consequently, saving money on consulting fees is unlikely to reduce overall costs and should not be considered a strategy for cost reduction.

4.6 Lessons on the importance of upfront planning

The importance of incorporating closure planning early in the design and operational phases cannot be overstated. Projects that delayed closure considerations faced increased complexity and costs. By integrating closure strategies from the beginning, mines can better manage risks and enhance sustainability. These lessons highlight the value of proactive planning in achieving efficient, cost-effective and compliant closure outcomes.

5 Conclusion

Navigating the complexities of TSF closure design is akin to managing a delicate balance between engineering precision, environmental stewardship and regulatory compliance. This paper has underscored the importance of adhering to the GISTM to ensure that TSFs are closed in a manner that is safe, sustainable and compliant with international guidelines.

The hierarchical approach to TSF closure, prioritising physical and chemical stability followed by an acceptable post-closure land use, provides a robust framework for developing effective closure strategies. Aligning these strategies with the UNSDGs can achieve broader environmental and societal benefits, enhancing the mining sector’s positive impact.

Key lessons from TSF closure projects emphasise the importance of:

- early and comprehensive planning
- meaningful stakeholder engagement
- integration of innovative and NBS.

These practices mitigate risks and reduce long-term monitoring, maintenance and costs.

Challenges such as knowledge gaps, long-term performance uncertainties and the need for site-specific solutions highlight the necessity of tailoring each TSF closure project. Emphasising humility and adaptability in planning is crucial; leveraging global expertise and local knowledge is essential for resilient and sustainable closure designs.

In conclusion, guiding TSF closure designs for compliance with the GISTM ensures regulatory adherence and fosters sustainable development and responsible mining practices. Emphasising early closure planning is crucial for achieving effective, cost-efficient and sustainable outcomes. By integrating closure strategies from the beginning, mining operations can mitigate risks and align with broader environmental and societal goals.

This paper aims to contribute to the ongoing dialogue and improvement of TSF closure methodologies, leading to safer and more sustainable mining operations. Just as it takes a village to raise a child, it takes a community of stakeholders to effectively close a TSF — but hopefully it involves fewer sleepless nights.

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