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A closure practitioner's perspective on paste, thickened and filtered tailings

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Abstract

Tailings storage facilities are typically the largest features to remain at a mine following cessation of operations. As they will likely become part of the post-mining landscape in perpetuity, they need to be safe, stable, non-polluting and able to support the next land use agreed for these facilities. If these structures underperform post-closure, there is potential for significant social, environmental and economic risk. However, there is also opportunity to optimise closure outcomes as part of a sustainable and positive legacy.

Closure planning is a fundamental requirement for all existing and planned mines and is at its best when conducted in a collaborative and integrated manner, commencing in the early stages of project planning. With the average lead time for mines continuing to rise, and with the average resource life for existing mines in some commodities stretching to beyond 100 years, a closure plan is the primary instrument for capturing and communicating closure data, closure designs and other information relevant to closure of tailings facilities as part of a mine site.

One of the challenges facing closure planners is how to use often highly technical information to frame both closure risks and opportunities, and to solve complex multi-factor problems, and then to communicate these to both technical and non-technical audiences. This paper begins by outlining the role of a closure planner before reviewing some key closure terminology. It then outlines key tailings closure challenges and discusses how closure planning is addressed during all phases of the life cycle of a tailings facility. With reference to international case studies, this paper also provides practical suggestions on how the mining industry can do better in developing innovative and long-term solutions, sustainable outcomes and positive legacies when closing tailings facilities.

Keywords: *tailings closure risks, tailings closure planning, stakeholder engagement, closure outcomes, collaboration, integrated closure planning*

1 Introduction

Mapping of mining land use by Maus et al. (2022) indicates that more than 100,000 km^2 of land globally had been directly affected by large-scale, artisanal and small-scale mining up to 2019. Not all mines produce tailings, but it has been determined that there are at least 30,000 tailings storage facilities worldwide and that approximately 12.7 billion tonnes of tailings are produced every year (Holley et al. 2025). Further, there has been an increase in the volume of tailings produced for many mineral commodities due to increased demand for minerals and continuing decrease in ore grades (Baker et al. 2020). With mining activity anticipated to increase by 60% from 2020 levels by 2060 (United National Environment Programme 2024), increased production of tailings is inevitable.

Tailings comprise a combination of the fine-grained material remaining after recoverable metals and minerals have been extracted from treated ores and any remaining process water. The way in which tailings are stored or otherwise disposed depends on their physical and chemical properties, and the environmental and social

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setting of the site (Bennett & Lacy 2012). Their physical and chemical properties will also affect the degree to which tailings can be dewatered. Depending on these properties and the type of dewatering technology used, the resultant material ranges from thickened tailings (segregating slurry) at typically around 50–65% solids, to paste (non-segregating slurry) typically at 70–80% solids, and finally dry stack (filter cake) at >80% solids (Vietti 2021; Burden & Wilson 2023). In most cases, tailings are dewatered to a 'thickened' state with a low density, low yield stress and segregating consistency suitable for disposal in storage facilities constructed using conventional methods (i.e. upstream, downstream and centreline) (Vietti 2021). By comparison, 'paste' tailings have been dewatered to a high-density state with high yield stress and are non-segregating, and are suitable for disposal using central thickened discharge and down-valley discharge. However, where additional techniques such as vacuum or pressure flotation or centrifugation are applied, tailings can be further dewatered to form a 'dry' state suitable for dry stacking construction methods (Vietti 2021; Burden & Wilson 2023).

Tailings facilities are among the largest features to remain at a mine following cessation of operations, typically occupying 10–40% of the area of a rehabilitated mining landscape (McKenna & Van Zyl 2020). As they will likely form a permanent part of the post-mining landscape, these facilities need to be safe, stable and non-polluting, and able to support the next land use agreed and approved for these facilities (Schafer et al. 2020). The underperformance of these structures in the long-term can result in significant risks to public and environmental safety as well as impacts on the future land use and possibly local economies. However, there is limited published information on how these structures will age over time, closure practices vary widely according to a suite of engineering, environmental, social, economic and other factors, and closure expectations and practices are constantly evolving (McKenna & Van Zyl 2020; Schafer et al. 2020). Consequently, closure of tailings facilities presents a significant challenge for the mining industry.

This paper begins by outlining the role of a closure planner before reviewing some key closure terminology. It then outlines some of the closure challenges associated with different types of tailings before discussing how closure planning should be addressed during all phases of the life cycle of a tailings storage facility. Finally, this paper suggests ways in which the mining industry can do better in developing innovative and long-term solutions, sustainable outcomes and positive legacies when closing tailings facilities.

2 Role of the closure planner

When someone asks me what I do for a job, I tell them that I'm a mine closure planner, a generalist and an integrator, and that I do jigsaw puzzles for a living. This is not intended as a flippant comment, but recognises that, much like a jigsaw puzzle, closure planning involves connecting irregularly shaped pieces to eventually form a complete picture or design. According to the Games Learning Society (2024), compiling a jigsaw puzzle involves "assembling a picture or design by fitting together interlocking pieces. The puzzle pieces are typically cut into various shapes and sizes, making it a challenging and engaging activity..." and the same can be said for closure planning.

To pull together the closure puzzle, closure planners draw on multidisciplinary teams as these provide the different pieces of the puzzle. Figure 1 provides examples of the way in which closure planning for tailings facilities is informed by input from geotechnical engineers and others.

The challenge for closure planners is to facilitate closure planning and implementation in a way that makes sense for a site given its environmental and social setting, company drivers, technical and other challenges and opportunities, and other factors. It requires strong collaboration across disciplines which can be challenging to achieve but will improve efficiency of process and strengthen closure outcomes, and could significantly reduce closure costs. For example, a case study from Nevada, USA, has shown that if closure plans were refined in conjunction with the planning and mining teams, then the concurrent closure and other initiatives conducted during the operation (in this case in relation to open pits and waste rock dumps) could potentially reduce closure costs by USD 200–300 million (van Coller et al. 2024).

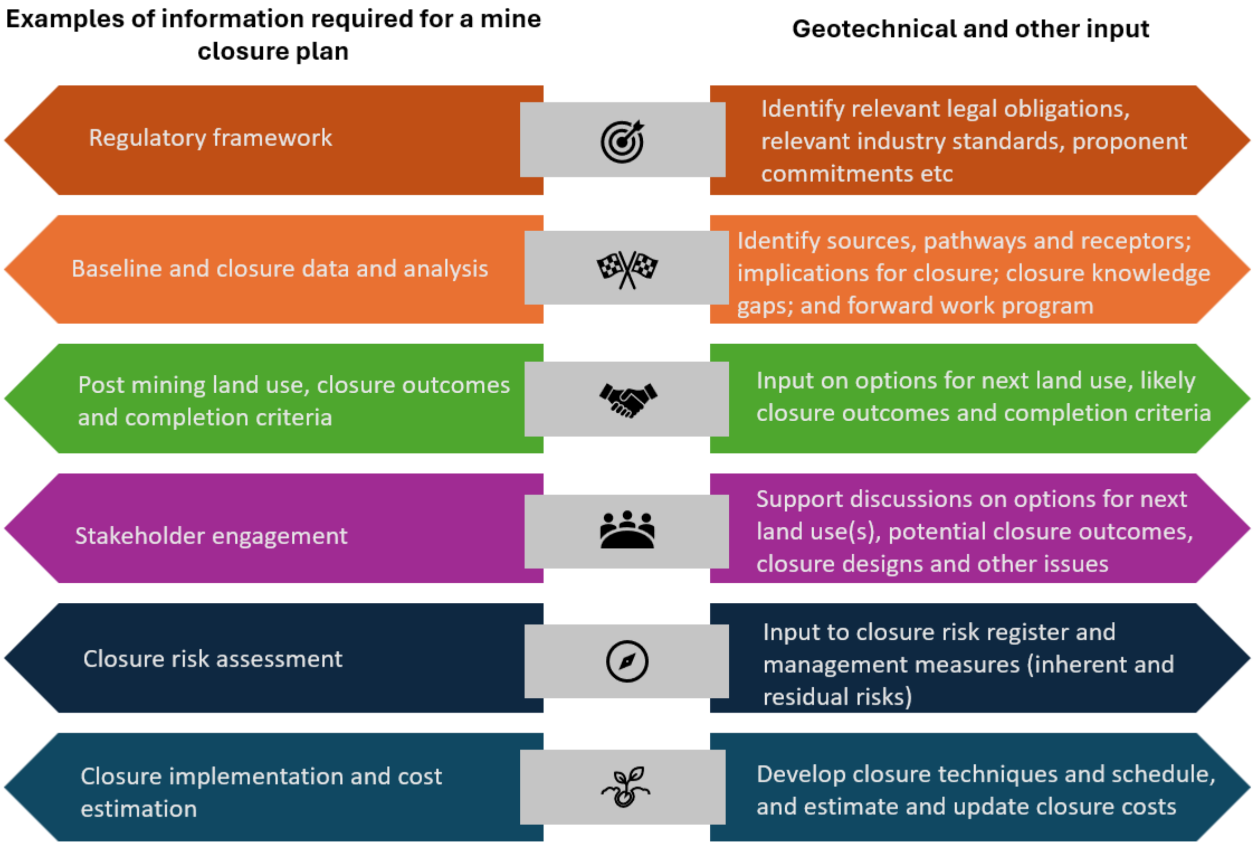

Figure 1 Examples of where geotechnical and other input on the closure of tailings facilities is needed for preparation and update of a mine closure plan (adapted from Finucane 2024)

Despite the importance of collaborating with multidisciplinary teams during closure planning, it's usually a closure planner who acts as the primary author of the closure plan itself. Consequently, in addition to being the doer of jigsaw puzzles, I'm also a teller of stories. At its core, storytelling is about connection, and closure planners (and closure plans) need to be able to communicate sometimes quite complex concepts and narratives in a clear and efficient manner that allows both technical and non-technical audiences to understand the mine closure narrative and respond in an informed manner.

Beyond integration and collaboration, closure planners raise awareness and educate our teams, corporate management, the community and other stakeholders. In doing so, it is important that closure challenges and opportunities are framed using the language that all parties understand and to which they can relate. As discussed by Ferguson (2025), "If risk is your business language, talk in risk. If cost is your business language, talk in cost."

3 Closure terminology

There is no doubt that language matters in mine closure, yet there is no universally accepted, jurisdictionally neutral definition for mine closure (O'Kane 2025). Instead, organisations tend to focus on those aspects of particular concern to them as influenced by site or industry history, or other factors. For example, Baker et al. (2020) and Teck Resources Limited (n.d) refer to "responsible mine closure" while Rio Tinto promotes leadership in "sustainable mine closure" (Rio Tinto 2025a). Further, ISO 20305:2020 (the standard for mine closure vocabulary developed by the International Organization for Standardization [ISO]) focuses on post-mining land use, defining mine closure as "planning for, and implementation of, strategies associated with the completion of mining activities and the establishment of the agreed post mining land use" (ISO 2020).

By comparison to the above, the *Global Industry Standard on Tailings Management* (GITSM) focuses on "safe closure". This is unsurprising given that the GITSM was developed after the catastrophic failure of a tailings facility at Brumadinho, Brazil, in 2019 and strives to achieve "the ultimate goal of zero harm to people and the environment with zero tolerance for human fatality" (International Council on Mining and Metals [ICMM] et al. 2020). However, a facility may be in a state of "safe closure" without necessarily having achieved all the requirements for responsible closure such as achievement of post-closure land use objectives (ICMM 2025a).

In one of its good practice guides, the ICMM focuses on 'integrated mine closure', defining this as "a dynamic and iterative process that considers environmental, social and economic factors from an early stage of mine development and throughout the life of an asset" (ICMM 2025b). In taking this approach, the ICMM recognises the importance of closure as an integral part of a mining company's core business. On this basis, this definition of mine closure has been adopted for the purposes of this paper.

The mining industry commonly uses terms such 'leading practice', 'good practice' and 'best practice' when describing its approach to closure planning and implementation. These terms are often used interchangeably, but they're not switchable. So, what should a mining company be aiming to achieve? In the past, companies were encouraged to commit to best or leading practices, but these tend to be moving targets so it's difficult, if not impossible, to measure progress in a meaningful way and to achieve the consistency needed to see tangible results. In addition, what is considered to be best or leading practice at one site may not be the best that can be achieved at , or even relevant to, another site. By comparison, good practice tends to be context-aware and comprise flexible approaches appropriate to the environmental, social and other factors relevant to a site. Further, while 'best' can be aspirational, 'good' is achievable (Ferguson 2025). In this regard, it seems appropriate to follow the lead of the ICMM which badges its guidance on integrated mine closure as a good practice guide that intends to promote a disciplined approach to integrated closure and increase uniformity of good practice across the sector (ICMM 2025b). It is noted that the ICMM guidance on tailings management is also badged as a good practice guide (ICMM 2025a).

The terms 'rehabilitation', 'reclamation' and 'restoration' are also often used interchangeably. In addition, the way that these terms are defined and used varies across the mining industry, between regulatory jurisdictions and within academic and professional literature, which has blurred some important distinctions (Poulton & Maron 2025). Further, some definitions have an anthropogenic focus that does not well match how the term is often used by many closure practitioners and in mine closure guidance (Gerwing et al. 2022). These include the Society for Ecological Restoration's definition of reclamation which refers to "the process of making severely degraded land fit for cultivation or a state suitable for some human use" (Gerwing et al. 2022). This paper uses the term 'rehabilitation' in preference to 'reclamation' or 'restoration'.

The lack of consistent closure terminology between states and countries, and the way in which terms are often used interchangeably, creates confusion for industry, regulators and communities, and can stymie effective communication. It's important to not contribute to this terminological confusion or fall victim to it (Poulton & Maron 2025), but more work is required before there is universal agreement on closure terminology. However, having a common understanding within an organisation or across a project is achievable. In fact, it's critical in enabling better identification of closure goals and methods, and ensuring consistency, clarity and effective communication across teams and disciplines.

4 Tailings closure challenges

Globally, more than 95% of tailings facilities store unthickened and thickened slurry tailings, but there is pressure to reduce the risks associated with unthickened tailings by finding alternative tailings management methods such as filtration (Amoah 2024). Selected examples of closure risks and opportunities are provided in Table 1. From a closure perspective, we're particularly concerned about the long-term challenges associated with residual risks (i.e. the ongoing risks that remain after closure after all mitigation measures and controls have been implemented).

Table 1 Selected examples of closure risks and opportunities for different tailings facility types

Aspect	Conventional tailings facilities	High-density thickened/ paste tailings facilities	Filtered tailings
Landform design and stability	Higher risk of erosion and instability of embankment surfaces due to size of tailings facility. If designed appropriately, can be closed as a 'dry' facility (Klohn Crippen Berger [KCB] 2017) Consequences of failure can be large, and significant effort is needed to reduce risks to an acceptable level (KCB 2017)	Less potential instability of embankment surfaces due to lower containment embankments (Jones & Watkins 2015) If designed appropriately, can be more easily closed as a 'dry' facility than a conventional tailings facility (KCB 2017) If failure occurs, this would more likely comprise local slumping unless material slumps into a water body (KCB 2017)	Much reduced risk of instability as discharge results in a low conical pile without the need for extensive embankments (Williams et al. 2008) Most amendable to 'dry' closure and landform development, though not meeting material specifications consistently during construction increases the likelihood of slope failures (KCB 2017) Amenable to progressive rehabilitation which helps to control residual risk of erosion (KCB 2017) If failure occurs, this would more likely be highly localised unless material slumps into a water body (KCB 2017)
Rehabilitation	Increased requirement due to typically larger size of conventional tailings facilities, with large surface areas. Poorly consolidated tailings with large central pond with long drying times delay start of works (New South Wales Resources Regulator 2020) Often require significant volumes of fill material to attain a final shape compatible with site closure objectives (Thompson & Moreno 2017)	Reduced earthworks due to smaller facility (Thompson & Moreno 2017) Improved water recovery results in earlier tailings consolidation and access (improved trafficability) (Jones & Watkins 2015) High-density material can present a very deep and highly compacted profile resistant to plant root development. Substrate with a largely uniform texture will have few of the physical structure that aid plant establishment such as fissures (Jones & Watkins 2015)	Placing tailings at higher density allows for a smaller footprint area for the tailings facility and minimises time-dependent consolidation (Hogg 2010) Rehabilitation can commence very early in mine life due to improved accessibility (WSP 2025), though trafficability can be challenging depending on tailings moisture contents and climate conditions (KCB 2017) Reduced earthworks and simpler cover systems reduce closure risks (WSP 2025)

Aspect	Conventional tailings facilities	High-density thickened/ paste tailings facilities	Filtered tailings
Post-closure mobilisation of tailings/ liquefaction	Loose saturated tailings have potential to mobilise if tailings facility fails, especially under seismic conditions (KCB 2017)	Potential for mobilisation as tailings not compacted and not fully contained by the facility in the event of structural failure (KCB 2017)	Lower moisture content of tailings reduces vulnerability to seismic events (Sanchez et al. 2023)
Geochemical risks	Highest risk during both operations and closure (KCB 2017) Can provide saturated conditions for management of potentially acid-generating tailings (KCB 2017), though wet covers can be difficult to maintain in drier climates	Highest risk during both operations and closure (KCB 2017) Large-scale operations have a higher risk of acid and metalliferous drainage than small-scale operations or conventional tailings facilities (KCB 2017)	Lower risk during closure than operations (KCB 2017) Reduced risk of acid generation due to reduced potential for air voids/ oxidation, but low saturation of materials can make it difficult to control acid drainage (KCB 2017)
Seepage and contamination	Higher risk due to higher volume of entrained water in tailings (Kemp & Chapman 2024)	Lower risk due to less supernatant liquor and overall drier tailings (Jones & Watkins 2015)	Much reduced risk due to lack of tailings pond and very low (if any) appreciable seepage (Davies 2011)

While there are multiple guidelines that provide a good 'global' road map to tailings closure planning such as the ICMM good practices guides, the GITSM and the Australian National Committee on Large Dams guidelines, what each mine needs is a site-specific closure plan that integrates technical expertise with local knowledge as this combination will almost always outperform exclusively external plans and designs (Walls 2024).

A discussion on closure challenges would not be complete without comment on the cost of closing and rehabilitating tailings facilities as these consistently represent the closure domain with the highest cost share. For example, recent analysis of 8 Brazilian mines found that tailings facilities represent 37% of the total costs during closure execution compared to 14% for open pits and 8% for waste rock landforms. Interestingly, dry stack tailings represented 8% of the total costs, reflecting the benefits of dry disposal methods including improved accessibility for progressive closure, reduced earthworks and simpler cover systems where required (WSP 2025). The high cost of closing tailings facilities is due to many reasons including closure complexity, long-term risk profile, evolving regulations, cost inflation and increased societal focus (Moody's 2024; WSP 2025). With these costs currently at USD 78 billion and rising, and a forecast that these could top the mining industry's debt obligations by 2033 (Moody's 2024), this is cause for serious concern.

5 Closure planning within the life cycle of a tailings facility

5.1 Overview of phases and tasks

Closure planning is a fundamental requirement for all existing and planned mines that ideally commences at the project conception phase and extends seamlessly through the design, construction, operation, closure and post-closure phases of a project (Figure 2). This approach reflects the principle of "designing for closure" introduced by John Gadsy in the 1970s and provides a framework for land stewardship and continual improvement as a site transitions to subsequent land uses (ICMM 2025a; O'Kane 2025).

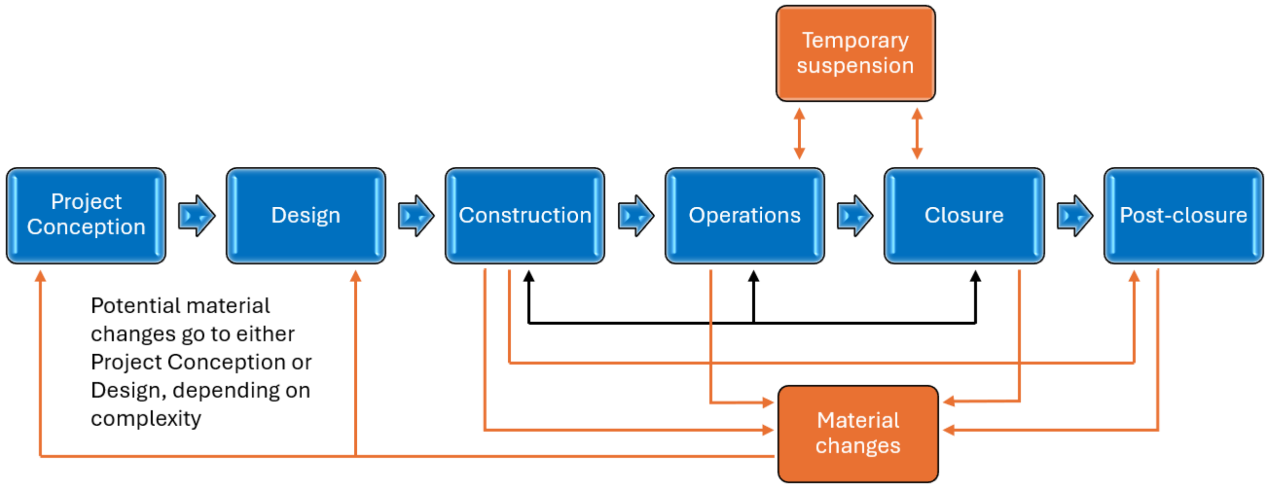

Figure 2 Relationship between life cycle stages of tailings storage facilities with the blue boxes and lines indicating activities/relationships that are expected to occur for all facilities and the orange boxes and lines indicating activities/relationships that may occur (modified from ICMM 2025a)

While closure is a discrete phase in the life cycle of tailings facilities, these facilities need to be planned and designed from the outset with closure and post-closure challenges and solutions in mind. Consequently, closure planning should begin as early as possible and be conducted iteratively through the life of the facilities. Early consideration of closure makes it easier and more cost-effective to reduce closure risks and liabilities, achieve final closure objectives and improve opportunities for site relinquishment and/or transfer to the next landholder or land use (ICMM 2025b). The importance of this cannot be understated as decisions made during the conception phase may prove to be some of the most important in the entire life cycle of a tailings facility (ICMM 2025a).

It is important to recognise that the relationship between the phases of a tailings facility's life cycle, and the activities within these phases, is dynamic (ICMM 2025a) (Figure 2). With Baker et al. (2020) indicating that the duration of a mine's operations phase could range from 20–100 years, it is likely that significant change will occur during the life of the project which could influence how each phase of the life cycle plays out. Further, life cycle phases are rarely linear (ICMM 2025a). For example, it is possible that a facility which had been closed could return to operation if, for example, storage capacity is still available, the facility is extended, or tailings are removed for reprocessing or used for other purposes. It is also possible that a mine will enter a period of care and maintenance where tailings production is suspended and then restarts when the mine returns to production. Alternatively, temporary suspension may lead to closure. Therefore, it is important that proponents plan for a dynamic life cycle, particularly as change can be a key source of risk for effective closure of a tailings facility.

The good practice guides for integrated mine closure and tailings management published by ICMM (2025a, 2025b) describe the steps for planning and managing closure during the life cycle of the tailings facility. Key aspects are discussed in Sections 5.2–5.7.

5.2 Project conception

The project conception phase includes initial baseline studies and analysis of alternatives related to site location, tailings technologies and other factors. This analysis needs to be informed by the project's preliminary closure vision, principles and objectives along with targeted stakeholder engagement. In particular, closure risks and opportunities should be key considerations in decision-making regarding options for facility location, design and technology (ICMM 2025a). Preliminary closure designs and an initial closure cost estimate should be developed for each of the project options to determine the feasibility and economic impact that closure could have on each option.

In addition to the above, it is important that the mine plan, management plans and closure plan developed during the project conception phase be aligned and that project decisions are made with the next land use for the mine and the tailings facility in mind so that eventual construction and operation of the facility are undertaken in a manner that is consistent with, and supports, effective closure (ICMM 2025a). The right decisions early in a mine's life can lead to better environmental, social and economic outcomes.

Once the preferred project option has been selected, it advances to the design phase. During this stage, all aspects of that option are designed in detail and life cycle cost estimates are refined (see Section 5.3).

5.3 Design

Historically, tailings facilities have been designed primarily with consideration of the mine's active life rather than with closure in mind. In these instances, the aim is usually to maximise tailings storage in a cost-effective manner. This is problematic if long-term closure challenges are overlooked despite the lifespan of these facilities far exceeding the life of the mine itself (Schafer et al. 2019, 2022). Consequently, primary objectives of even preliminary closure designs include attaining long-term physical and chemical stability, and achieving an agreed post-closure land use.

An updated closure knowledge base is needed to inform selection of methods to achieve these objectives. Consequently, a range of baseline and impact modelling studies are conducted during the design phase (including characterisation of tailings geochemistry, underlying geology, and tailings embankment and foundation construction material) along with stakeholder engagement (ICMM 2025a, 2025b). Any gaps in closure knowledge need to be identified and a forward work program included in the closure plan (ICMM 2025b).

The geometry of a tailings facility plays a significant role in defining possible closure outcomes and future land uses, and therefore strongly influences its closure design. It is important that design considerations for outer slopes and top basin areas align with surface water management plans and infiltration design. For example, determining whether concave, constant or stepped slopes are best suited for erosion resistance is a critical decision. Similarly, the top basin geometry must be evaluated for its water-retaining or water-shedding properties. These considerations incorporate geotechnical parameters, appropriate capping materials and vegetation selection to ensure stability and resilience against erosion forces, which again require multidisciplinary input (Walls 2025). In addition, potential modes of failure that could occur post-closure need to be identified and addressed (ICMM 2025a).

A critical component during the design phase is to continue to ensure alignment between the mine plan and tailings plan. It is important to select mining, processing and tailings technologies that enable progressive and final closure of the tailings facility, and that proponents seek opportunities for co-design of the facility with key stakeholders. Important aspects include locating a tailings facility to avoid sterilising mineral resources and contamination of water resources; identifying sufficient sources of suitable material for embankment construction and capping, and locations in which these can be stored as they become available; planning for closure and post-closure site water management requirements (including adaptive water management approaches and climate-specific cover systems); and sufficient salvage and effective storage of growth media and other materials for use in future rehabilitation (Bennett & Lacy 2012; ICMM 2025a, 2025b).

The design phase often includes procurement of environmental approvals and permits. These include approval for the closure plan so this is updated during this phase to reflect changes to the proposed project configuration and domain definition, proponent commitments and other obligations, baseline and other data, stakeholder feedback, closure risk assessment and management measures, closure strategies and designs, monitoring programs and the forward work program proposed to address any gaps in the closure knowledge base or other aspects. Note also that the closure plan may be appended to other environmental approval applications, so consistency across these documents is likely to be required.

5.4 Construction

Construction of a tailings facility is a recurring activity that results in a commissioned facility for use during site operations, as well as subsequent development of the facility (including capacity expansion) during operations. It is common for a contractor to undertake initial construction, but subsequent construction and expansion could be conducted by either a contractor or a site team. Regardless of who undertakes these works, it is critical that a strong quality assurance/quality control program be implemented to ensure compliance with the approved design, including closure features and controls (ICMM 2025a).

Having said that, it is not uncommon for situations to arise during construction or subsequent modification of a tailings facility (such as differences in foundation conditions or characteristics of construction materials from those anticipated during the project conception and design phases) that necessitate a deviation from the original design or construction specifications. While some deviations are quite minor, others can have significant consequences (ICMM 2025a). For example, KCB (2017) highlights that not meeting material specifications consistently during construction of filtered tailings facilities increases the likelihood of slope failures. Therefore, a process for change management is required to ensure that the potential impact of proposed deviations (including implications for the feasibility and cost of progressive rehabilitation and closure) is assessed and understood before any deviation is approved. Approved changes also need to be incorporated into the closure designs and closure plan, risk management plan and other relevant management plans (ICMM 2025a, 2025b).

Accurate documentation of as-constructed conditions is critical, including the volume of topsoil and other rehabilitation materials recovered during the construction phase and storage location(s) for these materials.

5.5 Operations

The operations phase of a tailings facility comprises the transport of tailings to, and deposition within, the facility. In-pit tailings disposal or backfill of former underground workings may also occur. In some cases, tailings will be redirected during the operations phase for reprocessing or other uses.

During the operations phase, it is expected that the risk profile and closure design of a tailings facility will be updated and refined to reflect proposed changes at the site, updated regulatory requirements, learnings from operational and monitoring data, changes in stakeholder concerns and feedback, updates to the post-closure land use of the tailings facility along with changes to the closure vision, principles, outcomes and criteria, and other aspects. The closure plan should also be updated regularly during the operations phase in response to these changes to ensure ongoing alignment of operational goals and closure strategies (Walls 2024), and a smooth transition to closure. In addition, the closure cost estimate for the tailings facility needs to be reviewed and updated as this typically rises as closure approaches and there is a risk that insufficient funds will be available for closure works.

One of the challenges associated with changes occurring during operations is striking a balance between short-term financial or operational priorities and optimal design, and operational practices that lower long-term impacts, complexity or risks (ICMM 2025a). These changes could include modifications in mine schedules, processing efficiencies, material balances, availability of growth media, water management requirements, contractor pricing and other factors. These variations can create uncertainty and highlight the importance of adaptive management in planning and implementing closure and rehabilitation.

The operations phase may also provide opportunities for progressive closure and rehabilitation. This is not always practical (McKenna & Van Zyl 2020), but is encouraged when a tailings facility ceases operation during the life of the mine. Progressive rehabilitation during the operations phase not only allows closure work to proceed while operational cash flow, management and resources are available, it provides the opportunity to test closure concepts, improves the likelihood of successfully meeting closure objectives and can reduce closure risks (including financial risks) such as those associated with final closure geometries (Bennett & Lacy 2012; ICMM 2025a). As many of the elements that underpin successful post-closure transition of a mine to the next land use start long before operations, progressive rehabilitation and closure of tailings facilities during operations may support implementation of a mine's post-closure transition plan (Gagen et al. 2024). Further, where rehabilitation bonds are in place, progressive rehabilitation enables partial bond releases as completed areas fulfil their completion criteria. This allows the return of capital to operations and reduces the total financial assurance requirement that would exist if all rehabilitation was deferred to the closure phase (ICMM 2025a).

5.6 Closure

Tailing facilities are often viewed as the most difficult features to resolve in mine closure, as closing these typically involves addressing multiple risks and ensuring long-term stability and environmental protection (Bennett & Lacy 2012).

Closure and rehabilitation practices vary widely depending on the closure risk profile for the facility including potential failure modes; the proponent's own governance approach; regulatory framework; nature of the ore that was mined and processed; operational practices and challenges; the environmental and social characteristics of the site and cultural context; agreed post-closure land use and transition plan; approved closure objectives, outcomes and criteria; learnings from monitoring and research programs; and other factors (McKenna & Van Zyl 2020; ICMM 2025a, 2025b). Prior to closure execution, mining companies are typically required to review and finalise their closure designs, plans and budgets, and ensure that no unmanageable residual risks exist (ICMM 2025a, 2025b).

Closure of a tailings facility is typically one of the longest phases in a mine's life cycle, with Baker et al. (2020) indicating that this could take up to 50 years to complete. It is also the most complex and resource-intensive phase (ICMM 2025a) and occurs at a time when the mine is not operating and therefore not generating revenue. While mining companies are responsible for ensuring adequate funds are available to meet their environmental and social obligations when ore-extraction activities and company profits cease (Finucane & Beckett 2024), concern has been raised that mining companies deliberately postpone mine closure as a way of avoiding closure obligations and that this could result in mines being abandoned and becoming public liabilities (Bainton & Holcombe 2018; Dela Azumah et al. 2026). This concern is alleviated where financial assurance systems are sufficiently robust to ensure adequate funding of closure and rehabilitation works, and that closure costs are not externalised to taxpayers (Dela Azumah et al. 2026).

Execution of the closure plan results in significant change on site, so it's important that proponents continue to be diligent through this phase and maintain governance structures, with accountability and responsibility appropriately assigned. Robust change management continues to be required as processes and personnel transition from the operations phase to the closure phase, and subsequently to the post-closure phase (ICMM 2025a).

5.7 Post-closure

The post-closure phase commences when closure works for the tailings facility have been completed and the facility enters a period of long-term monitoring and maintenance. For some mines, a post-closure objective is for the tailings facility to be declassified as a dam and become a landform that can be certified and transferred back to government with this being perceived as a maintenance-free, walk-away closure scenario (Schafer et al. 2020). In this context, ICMM (2025a) defines landforms as "long term, stable earth structures which are capable of being closed with surveillance and limited management or maintenance requirements. To be considered a landform rather than a dam, the facility cannot develop a credible catastrophic failure scenario." Regardless of the types of tailings stored therein, a tailings facility must be able to cope post-closure with stochastic events and changes likely to be encountered over an extended period determined as per the design life, potentially of 1,000 years or longer (Bennett & Lacy 2012). If a closed facility has credible failure modes, residual risks will inevitably remain and require ongoing management (ICMM 2025a). The complexities involved in declassifying a tailings facility from a dam to a landform and managing any associated contamination underscore the need for innovative and robust closure planning and implementation strategies (Kemp & Chapman 2024).

Although many organisations would like to achieve a state where the site requires no ongoing maintenance or long-term monitoring, Bocking et al. (2009) note that this is typically not feasible so it's not surprising that some authors such as McKenna & Van Zyl (2020) state that the post-closure phase could last in perpetuity. This is primarily due to the persistent risks associated with inactive and closed tailings facilities including structural instability, potential for dam failure and environmental contamination that can leach into groundwater and surface water systems. This contamination can have long-lasting impacts that can be difficult to manage (Kemp & Chapman 2024) and could result in the need for management in perpetuity. See Section 6.2 for further discussion.

6 How can we do better?

Mine closure practices have advanced significantly over the past few decades, but there is still room for improvement, particularly in relation to developing innovative and long-term solutions, sustainable outcomes and positive legacies when closing tailings storage facilities. This section of this paper discusses 6 topics in this regard.

6.1 Closure integration and collaboration as part of core business

Mine closure is inherently multidisciplinary and is impacted by decisions made across the business, throughout the mine's entire life cycle, and about features of a mine including any tailings facilities, yet the integration of multidisciplinary factors to scope, design, execute and monitor closure planning and implementation over project stages that may span many decades remains one of the key challenges for mine closure (de Graaf et al. 2021). Awareness and adoption of integrated mine closure practices have advanced over the past 4 decades, but a persistent disconnect remains, resulting in operational inefficiencies, regret costs and underfunded closure liabilities (O'Kane 2025).

Tailings production and management do not occur in isolation from other activities occurring at mining sites, but are a function of mining and ore processing techniques and the wide range of decisions made in this regard (ICMM 2025a). Despite this, at most mines, the design, construction and operation of a tailings facility is conducted separately from closure and rehabilitation (McKenna & Van Zyl 2020). Further, closure is not often considered to be part of a mining company's core business (O'Kane 2025), with Martín Duque & Lacy (2025) describing this as a "value chain paradox" where mining focuses on early profit, and closure is often treated as an afterthought. This situation has arisen despite the ability of mine closure to impact a company's reputation, investor outlook, cash flow and time frames (Ferguson 2025).

Inadequately implementing or ignoring a company's closure obligations once a site is operational can also have significant repercussions on its ability to maintain its statutory approvals. For example, on 18 September 2025, Indonesia's Energy and Mineral Resources Minister ordered the suspension of 190 mineral and coal mining permits due to a mining company's failure to meet rehabilitation obligations under Indonesian Law No. 3/2020 on Mineral and Coal Mining. In Indonesia, companies whose mining permits have been revoked or expired, and/or who fail to place reclamation and/or post-mining guarantees, can face criminal penalties including imprisonment for up to 5 years and fines of up to IDR 100 billion (around USD 6.04 million) (Pribati 2020; Susanti 2025). In addition, companies can be subject to an additional sanction in the form of payments to carry out their rehabilitation and other post-mining obligations (Pribati 2020).

With nearly 240 mines expected to close by 2040 in Australia alone (Commonwealth Scientific and Industrial Research Organisation 2023), integration of closure considerations into wider business units and processes is essential for optimising closure outcomes for tailings facilities (ICMM 2025a). Suggestions to facilitate this include, but are not limited to, the following:

- breaking down disciplinary silos to allow development of holistic assessment methods and workflows for decision-making (Holley et al. 2025)
- ensuring that project designs are developed with closure timeframes, rather than operational timeframes, in mind (Schafer et al. 2019, 2022)

- recognising that profitability and sustainability are not mutually exclusive (Martín Duque & Lacy 2025)
- ensuring that governance structures are in place to facilitate effective communication and collaboration between tailings, closure and other relevant personnel (ICMM 2025a)
- matching decision-making tools to project complexity and timing (O'Kane 2025)
- leveraging experience-based insights and lessons learned to strengthen implementation of mine closure across an asset's life cycle (O'Kane 2025).

6.2 Long-term and holistic thinking

As discussed in Section 5, tailings facilities should be planned, constructed, operated and closed on the assumption that they will become permanent landforms. When tailings facilities are designed for closure and these designs are implemented effectively, these facilities can become true future-engineered landforms intended to remain physically and chemically stable for the long-term while enabling the post-closure land use(s) to be achieved (ICMM 2025a). However, building durable legacies for future generations requires long-term thinking and a holistic approach (Mackenzie & Smedley 2024).

It is important for mining companies to understand the way that tailings facilities will perform in the long-term. This requires forecasting of long-term performance under different scenarios, including the way in which failure modes could change over time (Schafer et al. 2019), and ensuring that a tailored closure design that responds to the key drivers for long-term performance, site-specific conditions and the constraints of the mine plan is developed and implemented (Mackenzie & Smedley 2024). In doing so, we need to understand that we cannot develop a structure and expect it to be the same forever, but instead need to build capacity into our systems so that they behave naturally in the long-term (Schafer et al. 2019) and are durable (Mackenzie & Smedley 2024), without loss of containment.

It is also important to understand what the long-term performance of a closed tailings facility means for transitioning to the next land use in terms of technical efforts, time and budgets. Schafer et al. (2020) report that there appears to be a disconnect between actual and envisioned timelines for closure by senior management and an expectation that the more expensive active care period during the closure and post-closure phases will be shorter than the less expensive passive care period. Therefore, there is concern that a company will choose to default or be forced to abandon a site before it can transfer the site to the next land use or land user, and that there may be insufficient systems in place to protect the public purse (Schafer et al. 2020).

As discussed in Section 5.7, the end game for many mining companies and some jurisdictions is walk-away closure with no ongoing management requirements or other liabilities, but this is not a realistic expectation for all mines, particularly when it comes to water management and treatment (van Coller et al. 2024). Even low-risk mines that close with minimal residual liabilities will typically require some degree of active management in perpetuity (Mackenzie & Smedley 2024). This could be undertaken by the mining company (see, for example, Ayres 2023), but not all companies have sufficient experience, expertise or resources to do this. In these instances, it may be appropriate to consider alternative funding and other mechanisms, and/or to work with third parties who can take full responsibility for the site or at least help realise the full post-mining potential of a site (Standing Committee on State Development 2025).

6.3 Managing uncertainty

Closure planning is often fraught with uncertainties (Walls 2025), sometimes to the point where we are "perplexed in uncertainty" (Latham 2025). For example, it is considered essential in closure planning to anticipate shifts in environmental conditions, but there are often uncertainties associated with baseline studies and modelling, particularly with parameters subject to variability such as climate and ecology. In addition, it can be difficult to quantify the risk of a tailings facility in the long-term because failure probabilities and consequences along with risk tolerance change over time (Schafer et al. 2020). Gaps in and changes to the regulatory framework and evolving stakeholder expectations add further layers of complexity (Walls 2025), making it difficult for proponents to know what regulators and other stakeholders will deem acceptable and therefore where to invest in closure (Schafer et al. 2020).

ICMM (2025a) states that uncertainty is inherent in the analysis and evaluation of risks associated with tailings facilities and may be related to many factors, but in essence is the result of imperfect knowledge about the present or future state of a system, event, situation or population under consideration. Having a robust knowledge base dataset makes the difference between guesswork and informed action; it holds us accountable and, more importantly, enables us to do better (Dhawan 2025).

Implementing a risk-informed approach is key to managing uncertainty in the management and closure of tailings facilities. It is important to not only recognise and acknowledge uncertainties, but also to manage risk within the limits of uncertainties and to work to reduce uncertainty (ICMM 2025a). This includes research into the way that tailings facilities age and further assessment on the viability of walk-away solutions (Schafer et al. 2019, 2020).

In our pursuit of technical solutions and reduction in uncertainty, it’s important that we conduct robust research, publish meaningful data and share our closure stories. This not only supports formal benchmarking processes, but also increases industry and stakeholder awareness and understanding of closure challenges, processes and potential solutions. However, there is often a lack of willingness among mining companies to publicly share information about their sites which can severely limit the availability of comparable published information on such aspects as the long-term physical behaviour of tailings facilities (Schafer et al. 2020). Where this information exists, there are limitations on how it can be used. For example, Schafer et al. (2020) report that there is public access to dam safety reports for the Sullivan Mine and other closed mines in British Columbia, Canada, that provide information on how facilities are aging, but the information has not been collated and synthesised so considerable time is needed (and no doubt specialist technical expertise) to conduct meaningful review. Further, some of the performance monitoring information is not clear in some cases which may draw readers to reach incorrect or incomplete conclusions.

During preparation of this paper, it became apparent that there are limited published examples on the closure and long-term performance of thickened, paste and filtered tailings facilities. Publication or other distribution of industry experience will help address knowledge gaps associated with the closure and next land use of tailings facilities and other relevant factors, and assist in de-risking closure projects. In addition to publishing case studies supported by robust databases, it is important that industry experience be leveraged into documented guidance to enhance development and evaluation of closure proposals and plans (Schafer et al. 2020).

In addition to the above, it is critical that mining companies collate and manage their data so that it can be analysed and evaluated efficiently, and action can be taken if necessary. Effective and efficient data management becomes increasingly important as we move into much longer timeframes in excess of 100 years, during which the mine and its ownership are likely to change (Schafer et al. 2020). It is critical that we avoid not only the loss of knowledge, but also information on how that knowledge was obtained and applied. This includes why decisions regarding tailings management and closure were made by the proponent, regulators and others using the data and other knowledge available at the time.

6.4 Initiating and responding to change

The average lead time for mines continues to increase with Manolo (2025) noting that the lead time for mines that became operational between 2020 and 2024 has reached 17.8 years, which is nearly 3 times longer than the lead time for mines that began operations in the 1990s. For 20 non-operational mines undergoing feasibility studies, Manolo (2025) indicates that a lead time of 28 years is possible, which is almost 5 times the lead time observed in the 1990s. Further, the average resource life in some global commodities stretches to beyond 100 years (Geoscience Australia 2025). With such long development periods and life of assets, change is inevitable and, as standards and practices evolve and new knowledge emerges, our approach to closure planning and implementation needs to change too.

ICMM (2025b), Walls (2025) and others recognise that the long-term performance of a mine feature depends on closure designs that maintain flexibility and address changes triggered by regulatory reform, stakeholder feedback, monitoring data, research findings, changing closure practices and other factors. For example:

- The evolution from conventional landform design to geomorphic landform design (as described by Martín Duque & Lacy 2025) is a good example of an emerging science that is an exciting development towards achievement of positive post-mining legacies.
- Our thinking in terms of what we can do with a mine site following cessation of operations is changing, and there is increasing innovation in this regard. This has allowed the mining industry to extend beyond traditional post-mining land uses and encompass biodiversity projects (Rio Tinto 2025b), recreational opportunities (Gräpel 2025), renewable power generation (Williams et al. 2022), agribusiness (Whitbread-Abrutat & Lowe 2024) or other sustainable land practices. Such initiatives ensure that post-closure landscapes retain value and purpose, contribute positively to local communities and ecosystems, and strengthen socio-environmental post-closure transitions (Walls 2025).
- There is strong interest in the recovery of metals from tailings to reduce environmental liabilities and contribute to the circular economy, even though implementation is still limited (Holley et al. 2025).
- Mining companies regularly commit to post-mining land uses several decades before their planned closure and set closure outcomes and commitments during the early phases of project development. However, these uses may be considered sub-optimal in the future when considering the mounting global challenges of water, energy, food and livelihood security, as well as climate change (Simpson et al. 2025), and may need to be modified in the future.
- There is now greater recognition that mine closure is no longer simply a means to site relinquishment and that more focus is needed on processes to enable transition to the next land use (de Graaf et al. 2021; Measham et al. 2024). These need to recognise that the community will have to live with the closure landscape long after the mine has closed (Schafer et al. 2020) and provide opportunities for co-creation of a closure vision and closure designs (O'Kane 2025).

With our understanding of what constitutes good closure constantly evolving, mining companies update closure plans on a regular basis as part of a commitment to continual improvement. However, it is important to recognise how challenging it can be to materially change closure designs or other aspects of a closure plan once these have been agreed or approved, particularly if closure implementation is already underway. For example, tailings facilities designed for 1:100 or 1:1,000 years may not be able to be readily retrofitted to accommodate 1:10,000 years post-closure if, for example, they are located too close to a lease boundary or permanent infrastructure to allow reprofiling of the slopes of the facility (New South Wales Resources Regulator 2020).

In an effort to maximise the benefits of new perspectives, knowledge and techniques, and to achieve transformative change, mining companies need to be clear on the enablers and barriers to change relevant to their context, identify key priorities and determine where they will invest their time, budgets and resources.

6.5 Communicating about closure

Communities and other stakeholders potentially affected by mining hazards including those associated with tailings facilities are entitled to information that allows them to understand the broad range of risks and associated risk-reduction strategies (Baker et al. 2020). The closure plan is the primary instrument for capturing and communicating closure data, closure designs and other information relevant to closure of tailings facilities as part of a mine site. One of the challenges facing closure planners when preparing a closure plan is how to use often highly technical information to frame both closure risks and opportunities and solve complex multi-factor problems, and to then communicate these to both technical and non-technical audiences.

Risk communication can be particularly challenging. There are measurable differences in how technical specialists and community stakeholders define and assess risk (Beecher et al. 2005), and it is possible that stakeholders will interpret the same information very differently (van der Linden & Lewandowsky 2015) which can result in stakeholders over- or under-estimating risks, both of which can have undesirable consequences. Consequently, it is important that all communication in relation to closure risks (and other closure aspects) is clear, concise and relevant, and uses appropriate language. Language is not merely a tool for communication – it moulds the way we convey knowledge, influences our thought processes, shapes our perceptions and impacts how we make decisions (Altun 2023). In communicating with both internal and external parties, particularly non-technical personnel, it is important to avoid use of industry jargon, nested definitions and circular definitions (Gardiner & Scrase 2025) and assumed knowledge.

At this point, it is worth noting that any effort to communicate risk will likely be enhanced by the use of visual tools in addition to data and information. As stated by Beckett & D'Urso (2024), "As the saying goes, a picture says a thousand words. Across contexts, cultures and time, images share knowledge, inspire emotion, envision the future and build connections." Visual tools are useful and often necessary in enabling stakeholders to understand and provide input to closure plans, but these need to be selected carefully to ensure effective and meaningful communication, especially in relation to closure risks.

It is important to ensure that all communication is transparent, open and honest. This not only builds trust and credibility, it allows misinformation to be addressed and corrected. As reported by Schafer et al. (2020) in relation to risk communication regarding the closure of tailings facilities, "The biggest challenge is the perception that we are building these monstrous toxic death traps. The longer we hesitate [to talk] about these structures, the harder it's going to be to convince people that they are okay. We have to start embracing more public discussion and start eliminating the untrue facts. We need to be transparent and present the facts and numbers."

7 Conclusion

Tailing facilities are likely to become part of the post-mining landscape in perpetuity, but are often viewed as the most difficult features to resolve in mine closure (Bennett & Lacy 2012). This is because closing these facilities typically involves addressing multiple and multidisciplinary risks and ensuring long-term stability, public safety and environmental protection.

Tailings production and management do not occur in isolation from other activities occurring at mining sites, but are a function not only of mining and ore processing techniques, but also the wide range of decisions made from project conception to post-closure. Closure and rehabilitation processes vary according to the type of tailings facility and the characteristics of the tailings contained therein (McKenna & Van Zyl 2020), but they typically have a common goal which is to create a landform that is safe, stable and non-polluting in the long-term and able to support the agreed next land use(s). Consequently, there is significant focus within the mining industry on developing innovative and long-term closure solutions for tailings facilities that can achieve durable and ideally sustainable outcomes, and create positive and long-term environmental and socio-economic legacies.

Designing and operating a tailings facility for closure requires a long-term and holistic view, and is at its best when conducted in a collaborative and integrated manner, commencing in the early stages of project planning and continuing through to the post-closure phase. To achieve this, we need common ground – common values, beliefs, goals and direction – and recognition that there is usually no shortcut to success. It takes commitment, time, patience and creativity, and relies on dedicated mining professionals from a wide range of disciplines, including those with an ability to do complex closure jigsaw puzzles and tell comprehensive and coherent closure stories.

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