CHAPTER II
MINE TAILINGS FACILITIES: OVERVIEW AND INDUSTRY TRENDS

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1. INTRODUCTION

This chapter provides an overview of mine tailings and mine tailings facilities. It illustrates why and how mine tailings are produced, and the complexity involved in the long-term storage and management of this waste product. The call for a global standard for mine tailings management is a response to recent catastrophic facility failures. Mining companies, governments and communities all recognise the potential for unacceptable loss of life, livelihoods and long-term environmental damage that can result from such failures. There are lessons to be learned from past failures but if we cannot integrate these lessons throughout the industry, we will likely continue to witness these tragic events. The United Nations Sustainable Development Goals (SDGs) should underpin the mining industry's social licence to operate, ensuring that benefits from mining to society are not achieved at the expense of local communities or the environment. To realise this, the entire industry needs to commit to a standard of design, operation and innovation that solves the problem of tailings facility failures.

2. MINE TAILINGS AND TAILINGS FACILITIES: AN OVERVIEW

Mine tailings are the waste material that remains after the economic fraction has been extracted from the mineral ore. Tailings consist of a slurry of ground rock, and water and chemical reagents that remain after processing. The composition of mine tailings varies according to the mineralogy of the ore deposit and how the ore is processed.

The tailings are most commonly stored on site in a tailings storage facility. Storage methods for conventional tailings include cross-valley and paddock (ring-dyke) impoundments, where the tailings are behind a raised embankment(s) that then, by many definitions, become a dam, or multiple dams. However, a tailings facility can have an embankment function like a dam during some portion of its life cycle but not during another (e.g. closure). For this reason, it is more correct to refer to the entire tailings facility when discussing mine tailings. The tailings still exist during all life-stages but the 'dam(s)' may not, as there may no longer be a function for embankment(s) of that nature.

Raised embankments can be constructed using upstream, downstream or centreline methods (Figure 1) and even a combination thereof. The embankment needs to be designed, constructed and operated to withstand the loading conditions expected during the life of the mine, including post-closure.

While impoundment storage of tailings slurry is currently the most common storage method, tailings can also be deposited into a previously mined pit when available, filtered to produce dewatered stacked tailings, placed underground after adding a binder such as cement, or less commonly deposited into rivers or offshore (though the latter is increasingly limited due to jurisdictional and/or owner restrictions on the use of such practices). The approach taken in the design, construction, operation and decommissioning of the tailings facility will depend on many factors, including the owner's own governance approach, government regulations, nature of the ore, the local topography and climate, site geology, seismic risk and cultural context.

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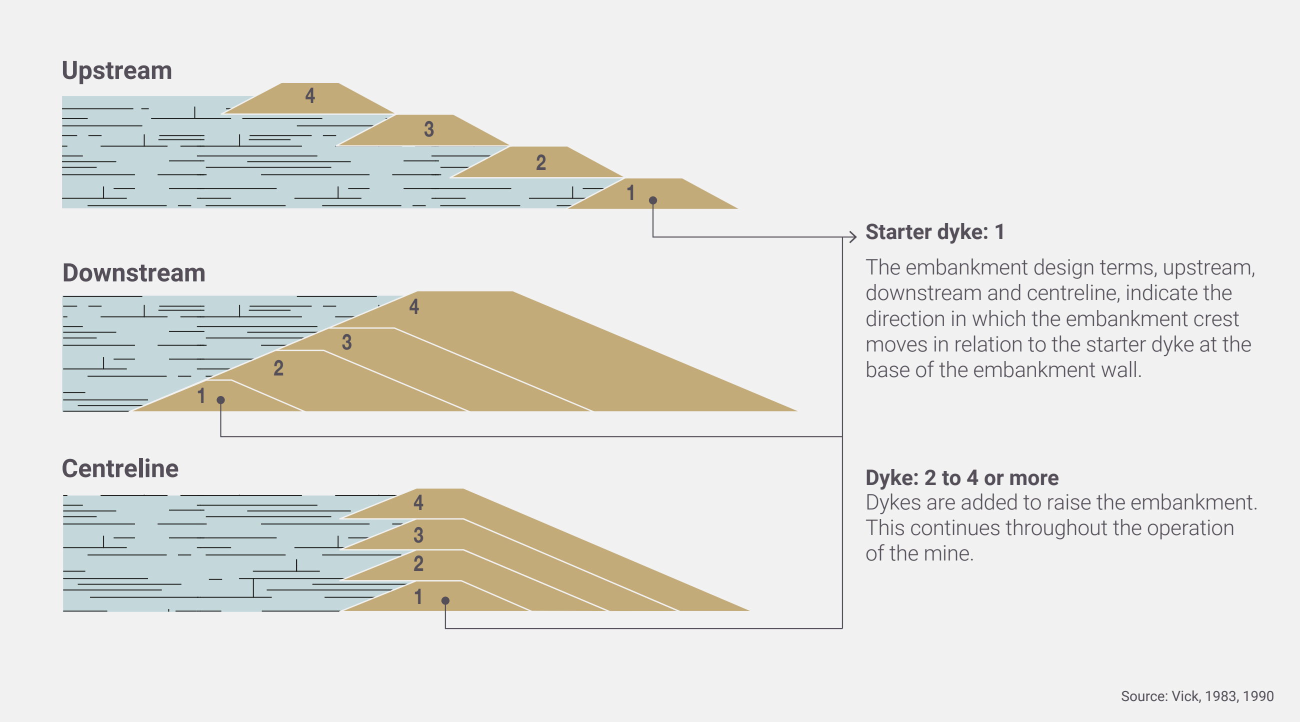


Starter dyke: 1
The embankment design terms, upstream, downstream and centreline, indicate the direction in which the embankment crest moves in relation to the starter dyke at the base of the embankment wall.

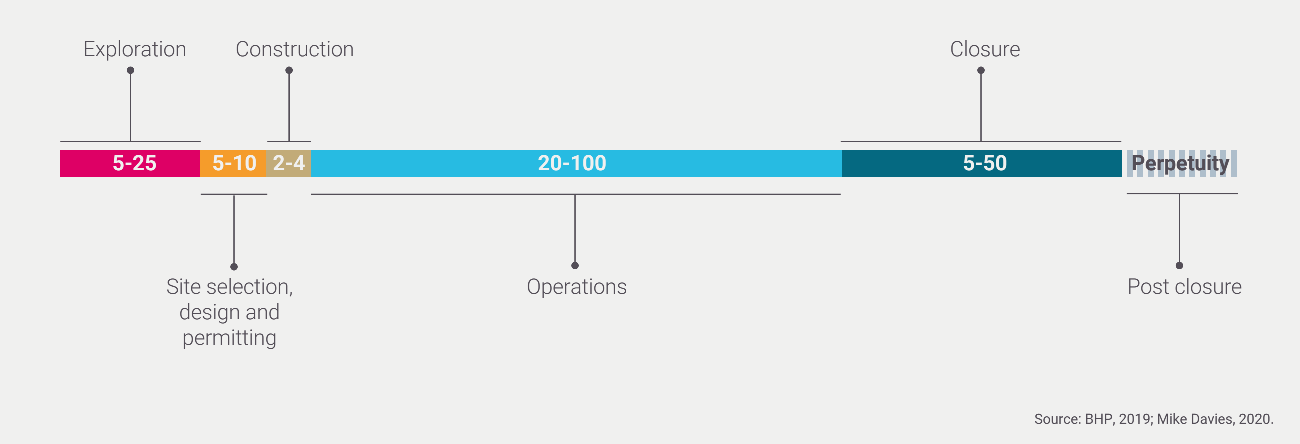
Dyke: 2 to 4 or more
Dykes are added to raise the embankment. This continues throughout the operation of the mine.

Source: Vick, 1983, 1990

Figure 1. Common methods of tailings embankment construction

Mine tailings management is a long-term process that starts well before any tailings are produced (Figure 2). It can be difficult to estimate the 'typical' cost of building, operating and closing a tailings storage facility as it depends on many factors, but examples suggest up-front capital costs can be around 15 per cent of mine development, with ongoing operational costs generally less than 5 per cent of the total cost of mine production.

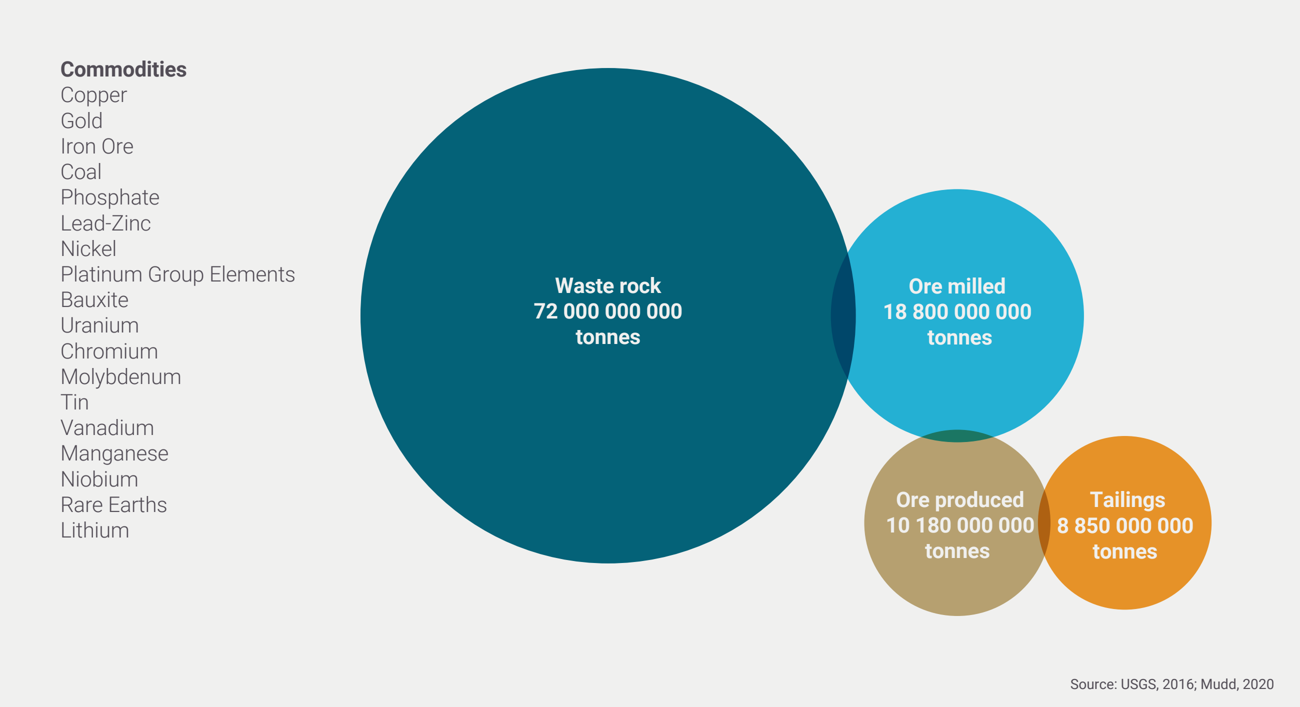
There is increasing scrutiny being placed on mine closure, with expectations of improved land rehabilitation and comprehensive water management planning (McCullough et al. 2018). A key take-out from Figure 2 is that by far the longest portion of a tailings life cycle (closure/post-closure) also occurs at the time when the mine is not generating revenue. For larger mining owners with multiple operations this may be addressed through sharing of resources, but for most tailings facilities it is critical that the facility is sufficiently prepared for closure/post-closure through investment during the operational phase.



Source: BHP, 2019; Mike Davies, 2020.

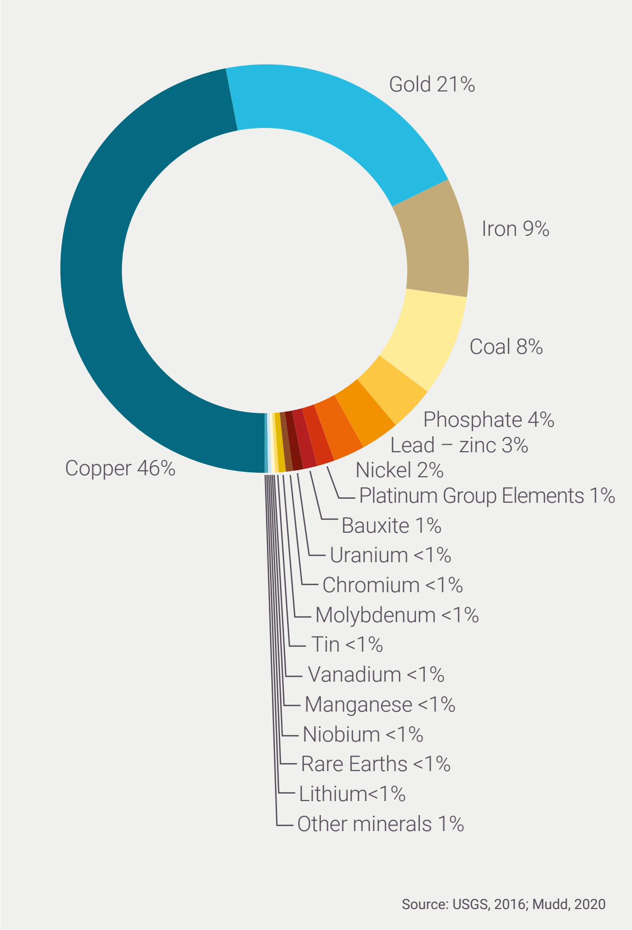
Figure 2. Life of a mine with a tailings storage facility – in average years

Tailings, other than perhaps waste rock dumps in some instances, generally have the single largest mine site footprint, both spatially and temporally (Werner *et al.* 2020). This is but one of the reasons why managing TSFs can be extremely complex. The volume of waste material produced per unit of commodity is increasing due to declining ore grades (Mudd 2007; 2010), so the challenges of operating and maintaining traditional tailings facilities are increasing. The largest facilities can have embankments designed to contain more than a billion m^3 of tailings. In 2016 it was estimated that more than 8 billion tonnes of tailings were produced from the extraction of metals and minerals (Figure 3). The largest volume of tailings, 46 per cent, is produced from copper mining (Figures 4 and 5).



Source: USGS, 2016; Mudd, 2020

Figure 3. Estimate of the volume of tailings and waste rock produced in 2016 in relationship to ore production (c.f. plastic waste weight and volume)

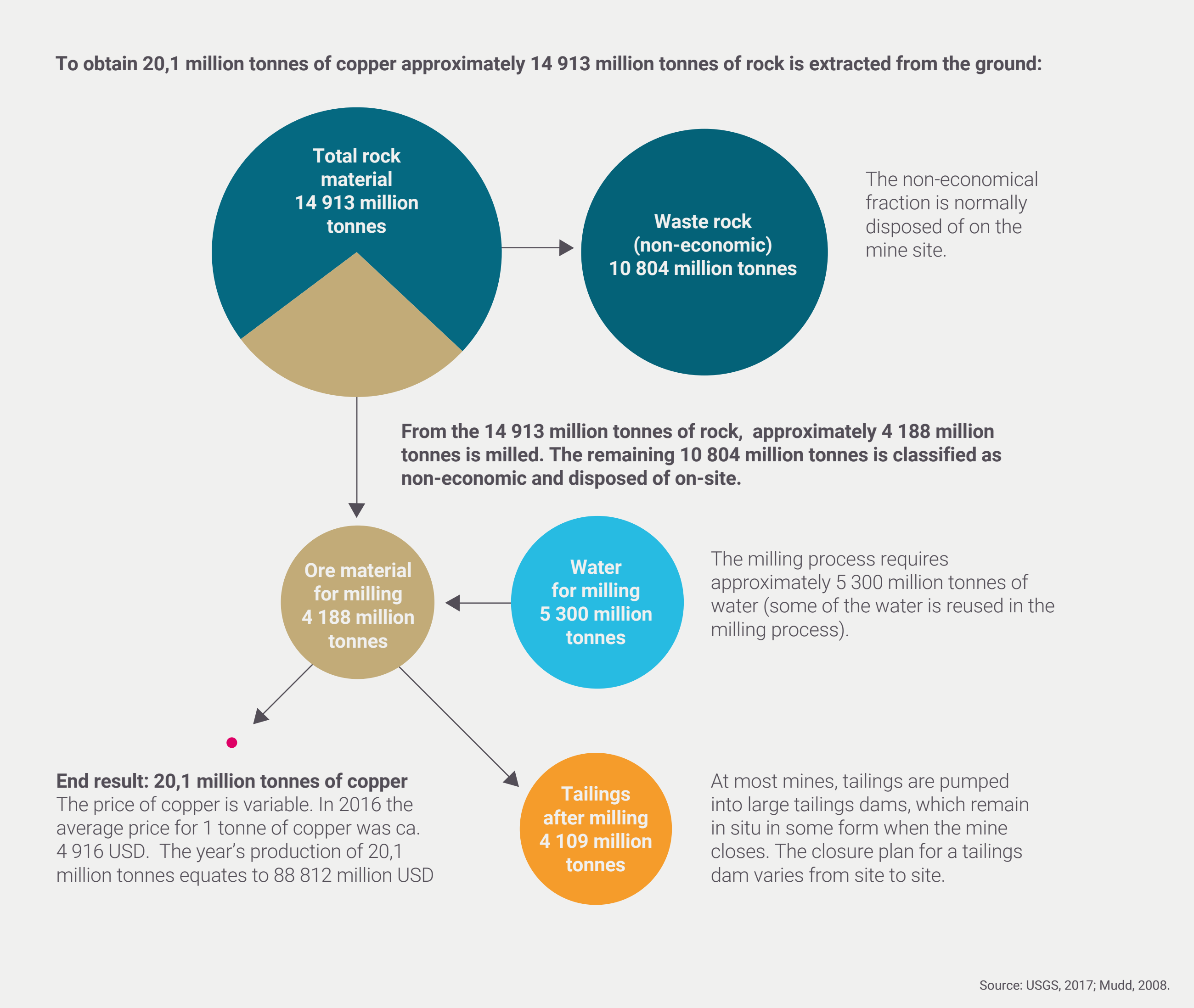


Source: USGS, 2016; Mudd, 2020

Figure 4. Percentage of global tailings volume per commodity in 2016

The precise number of active tailings storage facilities is currently unknown. Although incomplete, the Global Tailings Portal (see the chapters by Franks *et al.* and Barrie *et al.*, this volume), which includes information provided by publicly listed companies, currently records 724 active tailings facilities. More than half of these (364), were constructed in the last 10 years. The actual total of tailings facilities in the world is likely at least an order of magnitude greater than the 724 noted above when all of the active and legacy (closed) facilities are taken into account (see Franks *et al.* this volume, who estimate there are approximately 8,500 sites world-wide or which around 3,250 are active sites). Many of these other facilities may be quite small and relatively inconsequential, but that presumptive assumption should be confirmed over coming years.

The growth in resource consumption as a result of population increase and the continual expansion of the global economy has seen a steady increase in the extraction of metals and minerals (Figure 6). Mining of metal ores has grown on average by 2.7% per year since the 1970s, a reflection of the growth in infrastructure and manufacturing (International Resource Panel [IRP] 2019). Metals and minerals are essential to society and have a major impact on 11 of the 17 Sustainable Development Goals (UNDP and UN Environment 2018). The reduction in poverty in many parts of the world is underpinned by mineral resources and the move towards a low carbon economy points towards increasing demand for metals. For example, the shift to renewable energy, outlined in the scenarios developed to achieve the Paris Climate Agreement target, requires increased use of many metals, including copper, lithium, cobalt, aluminium, iron, manganese and silver. Increased material efficiency and recycling may offset some of this demand, but for many currently important metals the projected demand far exceeds the current production rates (Giurco *et al.* 2019).



To obtain 20,1 million tonnes of copper approximately 14 913 million tonnes of rock is extracted from the ground:

The non-economical fraction is normally disposed of on the mine site.

From the 14 913 million tonnes of rock, approximately 4 188 million tonnes is milled. The remaining 10 804 million tonnes is classified as non-economic and disposed of on-site.

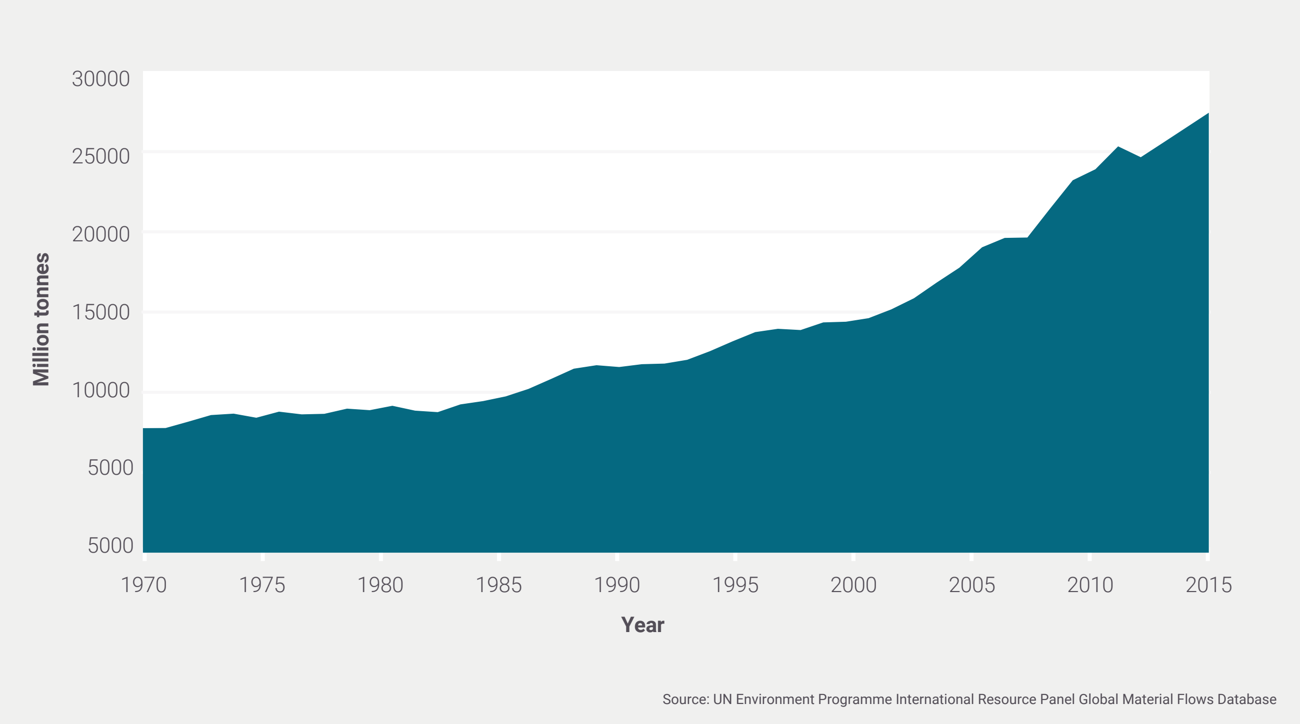
The milling process requires approximately 5 300 million tonnes of water (some of the water is reused in the milling process).

End result: 20,1 million tonnes of copper
The price of copper is variable. In 2016 the average price for 1 tonne of copper was ca. 4 916 USD. The year's production of 20,1 million tonnes equates to 88 812 million USD

At most mines, tailings are pumped into large tailings dams, which remain in situ in some form when the mine closes. The closure plan for a tailings dam varies from site to site.

Source: USGS, 2017; Mudd, 2008.

Figure 5. The relationship between copper, waste rock, tailings and water usage – Global footprint of copper production, 2016



Source: UN Environment Programme International Resource Panel Global Material Flows Database

Figure 6. The global extraction of metal ores (includes copper, iron, aluminium and other non-ferrous metals) from 1970 to 2017.

3. TAILINGS FACILITY FAILURES

The UNEP Rapid Response Assessment on mine tailings safety (Roche *et al.* 2017) noted that in the previous 10 years, significant failures of tailings facilities had been reported across the globe, including in jurisdictions with comprehensive regulatory regimes. The key point is that despite numerous interventions, failures continue to occur at an unacceptable rate. Various groups around the world have analysed and presented data on aspects of tailings facility failures, failure rates and consequences (e.g. WISE 2019; WMTF 2019; Owen *et al.* 2020) and all of these make useful contributions to highlighting the problem. The Global Tailings Portal (2020) provides a significantly updated database of tailings facilities and their consequence of failure. While not exhaustive, it illustrates the enormous volume of tailings that need to be safely managed.

In 2001 Davies reviewed tailings facility failures up to that time and observed that all were predictable in hindsight and could have been prevented during the design and/or operational phase. This is still the case for the many failures that have occurred in the intervening period, indicating that there has unfortunately not been sufficiently uniform commitment to the fundamentally sound design and operating concepts that were outlined in the review.

At the same time, while failures do continue to occur, and the rate and nature of those remain wholly unacceptable, on a per tonne basis the world's largest facilities have performed well and are not contributing to these events. Further, an increasing number of countries have adopted governance programmes and many owners, regulators, communities of interest (COIs) and designers continue to advocate for their use more broadly (e.g. Mining Association of Canada [MAC] 2017; MAC 2019a). Finally, we can say that failure modes remain within a tight band of technical root causes that have known engineering solutions (see below).

Poor governance practices (operating or regulatory) that contribute to failures can be addressed through more rapid adherence to frameworks like MAC's *Towards Sustainable Mining* (see MAC 2019b) or, where a jurisdiction does not have a sound governance model, the Global Industry Standard on Tailings Management ('the Standard'). When addressing the governance issues that can contribute to catastrophic failures, these frameworks are entirely consistent and are based upon the premise that eliminating catastrophic failures is the ultimate goal. In this respect there are similarities with how the mining industry approaches workplace safety. There are likewise parallels with other industrial sectors, such as the airline, and hydroelectric industries, where the aim is also zero fatalities and zero major incidents that cause severe public and environmental impacts.

In terms of what causes a tailings facility to fail, there are a number of design and/or operational flaws that can trigger a failure event. These triggers are well-represented in the failure case history record and, as such, are well known and commensurately should be able to be anticipated and addressed prior to any failure event. These common triggers include:

- **Operating and/or regulatory failures of governance.** A lack of attention to the key performance indicators that are required for the facility to perform as intended can lead to any of the common triggers that follow. While inadequate designs have occurred, in the majority of all case histories available there was clearly a failure of either operating governance or regulatory oversight which was at odds with adequate tailings facility management. Even the best designs may not be able to withstand poor governance.
- **Overtopping**, where the capacity of a tailings facility without a sufficiently sized spillway is insufficient to safely store water during operational upsets and/or extreme storm events. When this occurs in the most extreme cases, water eventually overtops a low point on the facility perimeter, often resulting in significant erosion and perhaps even, ultimately, catastrophic release of tailings.
- **Foundation failure**, where the soil and/or rock beneath the tailings facility is not sufficiently strong to safely bear the imparted stresses from the weight of the overlying embankment that forms the retention portion of the facility.
- **Piping**, which is initiated by excessive seepage through the embankment or the foundation of the tailings facility, which leads to sufficient erosion of embankment or foundation particles resulting in the development (sometimes very rapidly) of an erosion void that may ultimately facilitate extremely rapid discharge of tailings and process water. This is a more common failure mode in conventional (non-tailings) water reservoirs but has occurred for some tailings facilities as well.
- **Slope failure**, including where tailings are used to construct some or all of the tailings facility embankment(s). This type of failure can occur where the material used for any embankment(s) developed lacks the strength required for the loading conditions, inclusive of the slope of the embankment. Where tailings are used for embankment construction and they are not sufficiently compacted, a very sudden loss of strength called ‘liquefaction’ can occur and a catastrophic release of tailings can follow.

The triggering mechanisms mentioned here are certainly not exhaustive and there are many examples of less well-recognised triggering events, such as development of a sinkhole beneath the tailings facility sited in a karstic environment due to dissolution of underlying limestone or dolomite (e.g. Yang *et al.* 2015) or the upstream failure of another structure, such as a beaver dam (e.g. McKenna *et al.* 2009) that leads to a cascade failure event.

As evident from World Mine Tailings Failures (WMTF) database (2020), the number of tailings facility failure events is unacceptable to both the mining industry and society in general. Whenever a failure occurs, there tends to be a rush to investigate whether other facilities have a similar flaw to that identified in the forensic investigation of the most recent failure, whatever that might be. As an example, in the aftermath of the failure of the Mount Polley tailings facility in Canada, extensive field investigations were carried out around the world to determine if the possibility of the primary mechanism identified as being responsible for this failure (in this case related to inadequate shear strength of the foundation soils) could be a problem at other sites. Such reactive approaches can add some value but are prone to miss a number of key issues:

- It is very rare that a tailings facility failure is attributable to a single, isolated cause. Earthquake-induced failure may be an exception to this statement, but even these failures are now avoidable, as evidenced by the excellent performance of many large tailings facilities in Chile since the 1960s through many large seismic events including the very large (magnitude 8.8) earthquake in 2010. Rather, forensic investigations of tailings facility failures often point to a failure of governance as well as technical issues. Focussing on just the event that finally triggers a failure will likely only serve to ensure that failures that are more a function of poor governance will continue to happen. Good governance, for example the management approaches outlined by MAC (2017; MAC 2019a), is clearly defined yet not universally applied, as evidenced by the nature of failures that have continued to occur.
- Focussing on single cause mechanisms may disguise a deeper underlying malaise, which includes inadequate governance and inadequate or insufficient technical training of responsible personnel. Achieving the goal of sound tailings facility governance towards a future with zero catastrophic failures requires: (1) proper training in personnel management, regulatory management, engineering principles, facility operation and other roles that are key to ensuring that a facility is designed and operated safely; and (2) management systems to ensure that appropriate monitoring, surveillance and governance systems are in place and are adequately resourced.
- A single cause focus can also lead to the erroneous conclusion that solutions to ensuring stability are simple, e.g. ‘if failure occurs due to overtopping, all that is needed is monitoring of water levels’. Unless responsible personnel, including the designer, the facility owner and the regulator, are adequately trained and suitably skilled to recognise an evolving problem, monitoring protocols alone may well prove to be inadequate.

4. PREVENTING TAILINGS FACILITY FAILURES

The vast majority of active tailings facilities – and many that have been closed, – have operated without any issues of concern for society. However, the number of failures that continue to occur is rightfully deemed unacceptable by both those who own/operate them and by society in general. As described above, there has been a wide variety of facilities across broad geographies that have failed over the past 100 years (although record keeping has been sporadic and incomplete). The specific causes and triggers for the documented failures have varied, but there are similarities in each case in terms of fundamental loss of governance at some point to the degree that a failure did occur. ‘Governance’, as used here, includes the responsibilities of the owner and/or operator, the core competencies of the designer, the core competencies and role provided for any independent senior review and the competency/capacity of the regulatory processes within the jurisdiction of the facility involved. Certainly not all of these aspects of governance were lacking for each incident, but in all cases systems and processes in at least one or more of those areas were insufficiently robust.

The Standard provides recommendations that address largely the owner/operator but also has clear requirements related to engagement of appropriate design and independent review competence/capacity commensurate with the subject facility. Though far from a certainty, given the nature of the failures that have occurred, it appears a logical conclusion that if the recommendations in the Standard on governance issues related to design, operation and review had been followed, many of the failures that occurred in the past may not have happened, or at least would have had less severe impacts. This observation is necessarily speculative and is not intended in any way to address any single incident, either explicitly noted above or implied through connection. However, it broadly aligns with the published findings of incidents and the examples of best practices from well-governed facilities that together were used to inform the development process of the Standard; to that extent the conclusion appears well-justified.

5. CONCLUSION

The mining industry is extremely good at determining the cause of tailings facilities failures, and to date there have been no unexplained failures reported. The problem is that the events or conditions that lead to failures, although clear in hindsight, have not always been observed and/or are miscommunicated during the lead-up to the failure. There needs to be greater effort to identify high risk tailings facilities with a focus on preventing failures. Recent catastrophic failures have increased community awareness of mining risk. Communities which may potentially be impacted by the failure of a tailings facility deserve access to disclosure information that provides an understanding not only of the risk status of the facility, but also the broader risks to communities and the environment. Tailings facilities owners and their regulators that do prioritise safety and provide appropriate risk information need to be acknowledged and rewarded for their combined efforts to operate existing facilities and/or design new ones with no credible failure modes.

KEY MESSAGES

1. Mine tailings are currently an unavoidable waste product of mining.
2. There has been an increase in the volume of tailings produced for many mineral commodities, due to increased demand for minerals and the continuing decrease in ore grade.
3. The precise number of active tailings facilities is currently unknown, although initiatives are underway to determine both the location and status of these facilities.
4. Responsible mine closure is integral to mining companies' core business.
5. Mining conducted responsibly, is acknowledged as a key industry for achieving the United Nations Sustainable Development Goals (SDGs).
6. Failures of tailings facilities are continuing to be reported across the globe. These failures are unacceptable to both the mining industry and society.
7. The triggers for failures of tailings facilities are well documented and understood and, as such, should be anticipated and addressed, starting at the design phase and continuously during operation through to closure (and beyond if necessary).
8. Communities potentially affected by mining hazards are entitled to information that allows an understanding of a broad range of risks, as well as being informed about operator risk reduction strategies.

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