CHAPTER VI
THE ROLE OF TECHNOLOGY AND INNOVATION IN IMPROVING TAILINGS MANAGEMENT

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1. INTRODUCTION

While there is no 'silver bullet' to cover all tailings in all climatic, topographic and seismic settings, much can be learnt from recent high-profile and well-documented tailings facility failures which, while rare, continue to occur at an unacceptably high frequency in terms of both industry and societal expectations. A rethink is also required about the way in which many view tailings management in terms of economics, relying on a net present value (NPV) approach with a high discount factor, rather than a whole-of-life economics approach. There is scope for the further development and implementation of new tailings management technologies and innovations, and for the use of different economic models. Change is most readily achieved in new mining projects and hence change in tailings management for the mining industry as a whole will be generational.

For context, this chapter first describes conventional tailings management, arguing that applying NPV accounting to tailings management supports the transportation of tailings as a slurry to a facility, with insufficient consideration being given to the potential risks and long-term costs of this method of storage. While this conventional management approach can be the optimal NPV and life-cycle choice for a given operation, there is often a divergence when a whole-of-life approach is fully considered. The constraints under which a conventional surface tailings facility must operate are also described. The chapter then outlines the key causes of the unacceptable consequences of tailings facility failures and the threats posed to industry, regulators and society by such failures. Alternative approaches to tailings management are described in the main body of the chapter. Issues relating to the closure and rehabilitation of tailings facilities are also discussed.

The chapter draws on the author's own research, the work of other researchers active in this area, and a large and growing body of guidance documents on best or leading tailings management practice. An Appendix to the chapter lists the more significant of these documents.

2. CONVENTIONAL TAILINGS MANAGEMENT

The conventional approach to tailings storage is to thicken the tailings just to the extent that they can be pumped using robust centrifugal pumps by pipeline to a surface tailings facility, where the tailings are deposited sub-aerially (that is, above water and on the surface) forming a beach.

The forms of tailings containment and method of construction and facility raising varies from region to region. Upstream construction, using tailings where possible, is widely employed in southern Africa, Australia and the south-west of the USA, which have in common a dry climate. Centerline and downstream construction, by contrast, is usually employed in wet and/or high seismic regions. While the necessity for centreline or downstream construction is understandable in wet climates, the choice between upstream construction and other geometries is not so obvious. It seems that this is more a function of past experience and established regional practices, which vary and are difficult to change. Sand facilities, cycloned and/or compacted, are widely employed in South America and Canada, now usually raised by the centreline or downstream methods. Rockfill and/or roller compacted concrete facilities are finding favour for high tailings facilities in the deep valleys of the Andes in South America.

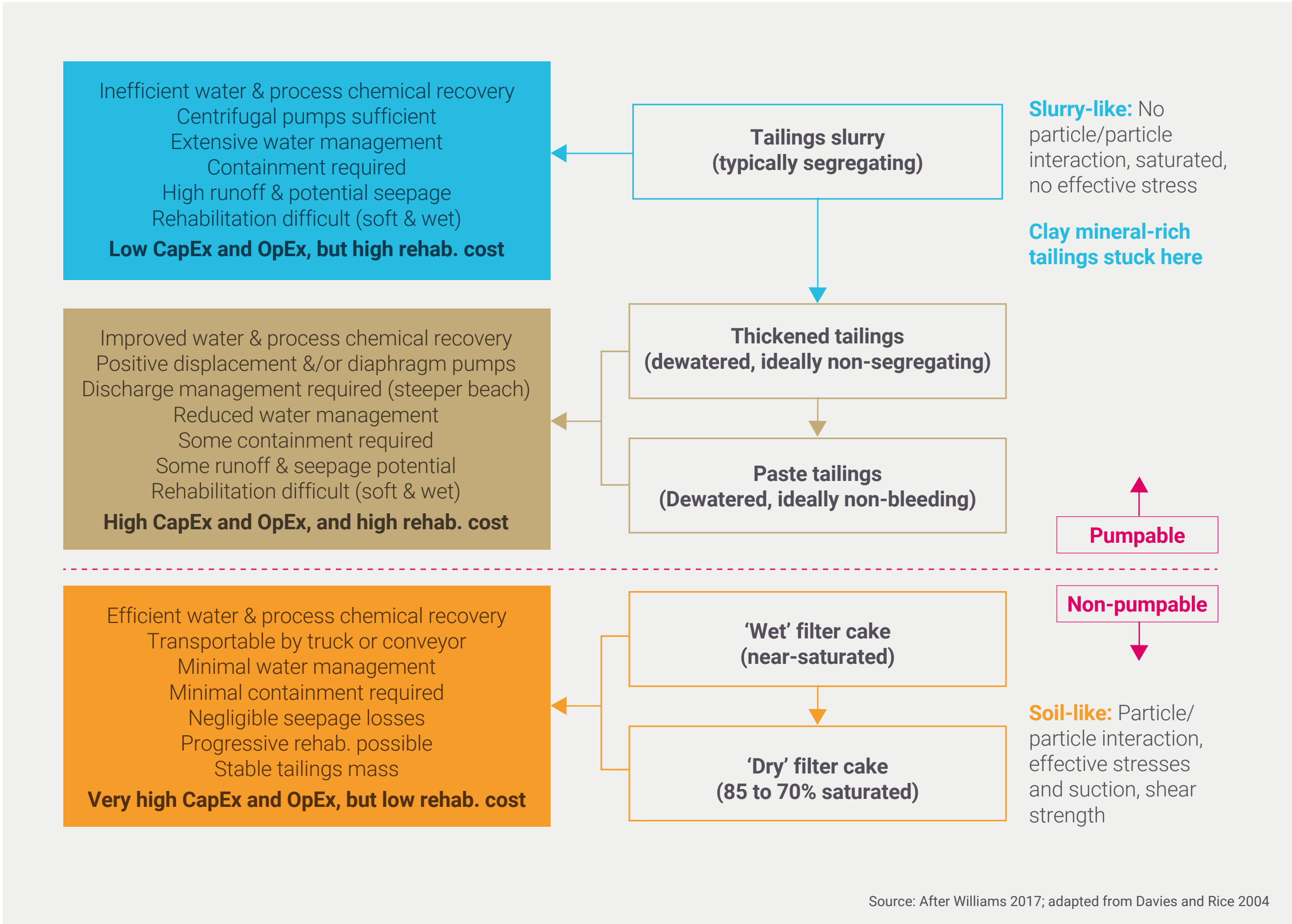
2.1 NET PRESENT VALUE ACCOUNTING APPLIED TO TAILINGS MANAGEMENT

There is a commonly held perception that transporting tailings as a slurry to a facility is the most economic approach. However, to a large extent this is because the costs of closing and rehabilitating the resulting tailings facility are discounted by the NPV accounting approach and are not considered to be significant. Instead, the NPV approach prioritises the minimisation of short-term capital costs (Williams 2014). While the best practices in the industry have moved beyond the NPV approach, with a growing number of owners and jurisdictions now embracing true full-life economics, there remains a substantive portion of global tailings practice that still uses the NPV approach.

This way of thinking leads to tailings being stored as a slurry in surface facilities that are often initially too small, leading to high rates of rise, and creating wet and soft tailings deposits that store excessive amounts of water. Operating costs tend to blow out, and the risk of tailings run-out on loss of containment increases. The wet and soft tailings can also be difficult and expensive to rehabilitate, due to the challenge of capping a 'slurry like' tailings. This is contrary to good practice, which aims to optimise tailings management by improving tailings dewatering, density and shear strength, and maintaining a safe, stable and non-polluting tailings storage (see Box 1).

Box 1: Limitations of the NPV Approach

The use of NPV and an artificially high Discount Factor result in apparent cost savings in tailings management in the short-term, but at the price of increasing operational and capital costs, and unintended cumulative detrimental impacts over time, and ever-increasing closure and rehabilitation risks and costs in the long-term. This is particularly the case in flat terrain, such as much of Australia, where there is limited free storage in valleys, resulting in containment walls extending around an increasing proportion of the tailings storage perimeter as they are raised, making high facilities too costly. As a result, facility heights are limited, and tailings storage footprints grow ever larger.



Source: After Williams 2017; adapted from Davies and Rice 2004

Figure 1. Tailings Continuum from slurry-like to soil-like as they dewater

Figure 1 shows five different tailings treatment options, the advantages and disadvantages of each option, and the relative levels of capital (CapEx), operational (OpEx) and rehabilitation expenditure required for each option. It can be seen that the NPV approach, which prioritises the minimisation of CapEx and OpEx over the minimisation of rehabilitation costs, favours what is often the least desirable option from a long-term management perspective.

Most tailings can be thickened mechanically, some to a paste or filter cake consistency. However, clay mineral-rich tailings, such as coal tailings, mineral sands tailings, tailings from some oxide ores, and residue from the processing of bauxite, nickel laterite and oil sands, are difficult to dewater mechanically, particularly where the unstable, moisture-reactive sodium smectite clay mineral is present, even in small proportions. As a consequence, dewatering tailings to a paste or by filtration has conventionally been seen as too capital intensive and too expensive to operate, and as being difficult to scale-up for large production rates. The long-term benefits of reduced storage volume occupied by tailings paste or filter cake, and the relative ease of capping 'soil-like' tailings have been discounted, as have the potential for a higher level future land use and/or improved ecological function.

3. CONSTRAINTS UNDER WHICH A CONVENTIONAL TAILINGS STORAGE MUST OPERATE

Conventional tailings storage remains the optimal solution for a wide-range of existing and proposed facilities. However, conventional tailings storage is not ideal for every site. For those locations where conventional facilities are both false economics and poor technical choices, there is a series of constraints that counter their use. The constraints under which a conventional surface slurried tailings storage must operate include the following (Williams 2014):

- the climatic, topographic, seismic and geological settings
- the nature of the tailings, and potential contaminants, including sulphides, salinity, radioactivity, cyanide, etc., and how these may change during the mine life
- the tailings production rate and solids concentration which must be accommodated, and how these change during the mine life
- the need to manage, store, and recycle, when possible, supernatant tailings water
- the need to minimise the risk of the release of tailings and tailings water through overtopping, tailings storage embankment instability, or excessive seepage
- the need to meet discharge water quality licence conditions
- the need to maximise the tailings settled dry density, and hence minimise wall raising and the required tailings storage volume
- the need to facilitate upstream wall raising, where appropriate
- the need to rehabilitate the tailings storage on closure to a safe, stable and non-polluting structure in perpetuity, and to achieve some post-closure land use or ecological function.

3.1 SETTING OF THE MINE SITE

Tailings management is typically easier, at least physically, in dry climates, where advantage can be taken of desiccation (that is, drying by exposure to the wind and sun) to naturally dewater, increase the density of the tailings and strengthen the tailings. However, on desiccation in a dry climate, sulphidic and otherwise potentially contaminating tailings can oxidise, potentially leading to acidic and otherwise contaminated seepage and runoff. On the other hand, the limited rainfall in a dry climate will reduce the transport of any contaminants that are generated. Unrelated to water transport, fugitive dust generation from tailings in arid climates is a significant contributor to off-site impacts in many regions.

High topographic relief provides 'free storage' in valleys, requiring a facility of limited width, but also results in a high embankment to create the storage for the facility, leading to initially high rates of rise and the need to divert steam flows. High seismicity can also dictate design, such as in Chile, which experiences about 40 per cent of global seismicity.

Different combinations of these aspects may dominate in particular geographical areas. For example, in much of Australia, apart from the humid and cold West Coast of Tasmania and the seasonally wet tropics, the climate is dry, the topography generally flat (which limits the height of tailings facilities but not their extent) and the seismicity generally low. The same is generally the case for southern Africa and the South-West of the United States of America (USA).

In Chile, by contrast, the climate is dry, but the topography and seismicity are extreme. Prior to 1965, the majority of Chilean mining companies, (which at the time, mainly operated in Central Chile, above Santiago) employed cycloning to form a sand facility that was constructed upstream. However, a magnitude 7.4 earthquake in 1965 caused a liquefaction failure of the cycloned, upstream tailings facility at El Cobre Mine, resulting in more than 200 fatalities. This failure occurred in a decade when world copper production, particularly in Chile, increased significantly.

The failure resulted in almost immediate industry-initiated changes to tailings facility construction in Chile. These included:

- using dozers to flatten the downstream slope to about half (from an angle of repose of wet sand of about 2.5 horizontal to 1 vertical to about 4 to 1), also inducing compaction
- moving from upstream to downstream and centreline construction
- the installation of centralised cyclone stations
- in some instances, the installation of a 'temporary' upstream liner to limit seepage from the slimes into the sand facility, and
- limiting the percentage of fines in the sand facility to a maximum of about 20 per cent.

The Chilean regulators followed the industry some years later with Decrees in 1970 and 2016 (see Box 2).

Box 2: Tailings facility performance in Chile

Since 1965, Chilean tailings facilities have increased in height to 200 metres or higher. There are currently about 740 tailings facilities in Chile, of which about 100, mostly downstream sand facilities with a dozed downstream slope, are active; about 470, mostly former upstream sand facilities, are inactive; and about 170, mostly former upstream sand facilities, are abandoned. The active Chilean downstream sand tailings facilities have performed well since 1965, due to improved construction methods. The large number of inactive or abandoned Chilean sand tailings facilities have also performed well since 1965, as they have drained down in the dry Chilean climate.

In western portions of British Columbia, the climate is wet, the topography extreme and earthquake loading can be high, if infrequent. In continental Canada, the climate is dry but seasonal, the topography low relief, and the seismicity low. Brazil has an extreme wet season and high topographic relief, but low seismicity. The 2015 Fundão and 2019 Brumadinho tailings facility failures in Brazil were influenced by the wet season rainfall and the high topographic relief.

3.2 NATURE OF TAILINGS

Tailings are typically mainly silt-sized (0.002 to 0.06 millimetres in size) but may also contain sand-sized particles (0.06 to 2 millimetres in size) and clay-sized particles or clay minerals (finer than 0.002 mm). Tailings particles can also have a range of specific gravities, ranging from as low as 1.8 for coal-rich tailings to 4.5 for iron-rich tailings. This compares with a specific gravity of about 2.65 for normal mineral matter. The variable particle size and specific gravity of tailings particles result in hydraulic sorting down the tailings beach on conventional sub-aerial deposition.

The presence of clay minerals in tailings, even in small proportions, can limit sedimentation and consolidation, and water recovery. Tailings can be hypersaline due to the chemistry of the ore and/or the process water; acidic due to the presence of sulphides and/or acidic process water; or alkaline as a consequence of caustic processing, such as for bauxite, nickel laterite and oil sands.

3.3 CONVENTIONAL SUB-AERIAL TAILINGS SLURRY DISPOSAL AND STORAGE

The conventional approach to tailings disposal and storage, supported by the NPV approach, is to thicken the tailings just to the extent that they can be pumped using inexpensive and robust centrifugal pumps by pipeline to a surface tailings storage, where the tailings are deposited sub-aerially forming a beach.

Conventional sub-aerial tailings slurry disposal to a surface tailings storage involves the processes of beaching, hydraulic sorting of particles down the beach according to their particle size and specific gravity, settling of particles, consolidation, desiccation if exposed to the sun and wind, and loading by an upstream raise or cover placed for rehabilitation purposes. Beaching and hydraulic sorting are best assessed on the beach. Settling involves very large deformation and little strength gain, consolidation involves large deformation and significant strength gain, and desiccation involves some deformation and substantial strength gain. Loading the tailings beach could cause 'bow-wave' failure of tailings with a desiccated surface crust, requiring that loading be progressive on a broad front, which will result in strength gain in the tailings as they drain over time.

3.4 KEY CAUSES OF TAILINGS FACILITY FAILURES

Tailings facilities continue to fail at an unacceptably high rate of about two per year (Rico *et al.* 2008). Recent high profile failures in Brazil in 2015 and 2019 resulted in significant fatalities and involved major mining companies.

Most tailings facilities that fail have marginal stability, and most tailings facility failures involve 'water', making drainage, clay cores and water management key. Many tailings are potentially liquefiable, either under earthquake or static loading, although not all fail since the facility usually has adequate stability. Further, tailings in the embankment shell of centerline and downstream facilities that have been placed with compaction and drainage (as in Chile and Canada), have been shown not to be susceptible to liquefaction. Another cause of tailings facility failure can be a weak foundation layer (often unidentified, possibly moving from over- to normally-consolidated on progressive raising).

Many tailings facilities that fail have been constructed upstream. Equally, there are many traditional tailings facilities that have used the upstream method of construction that are fully resistant to all external loads and will provide excellent operating and closure stability. Nonetheless, use of upstream construction takes a higher level of design, independent review and operating discipline than some facilities are afforded and unless all of the key elements of strong design, review and operating practices can be assured, upstream facilities do present a higher risk than centreline or downstream facilities.

In relation to the design of tailings facilities, reliance has traditionally been placed on stability analyses carried out using the deterministic Limit Equilibrium method, typically with a single set of design parameters (see Box 3). The key parameters include the annual rainfall, which typically varies from 50 to 200 per cent of the average annual rainfall. The site seismicity has a variability of perhaps ±20 per cent for operations to perhaps ±50 per cent for closure

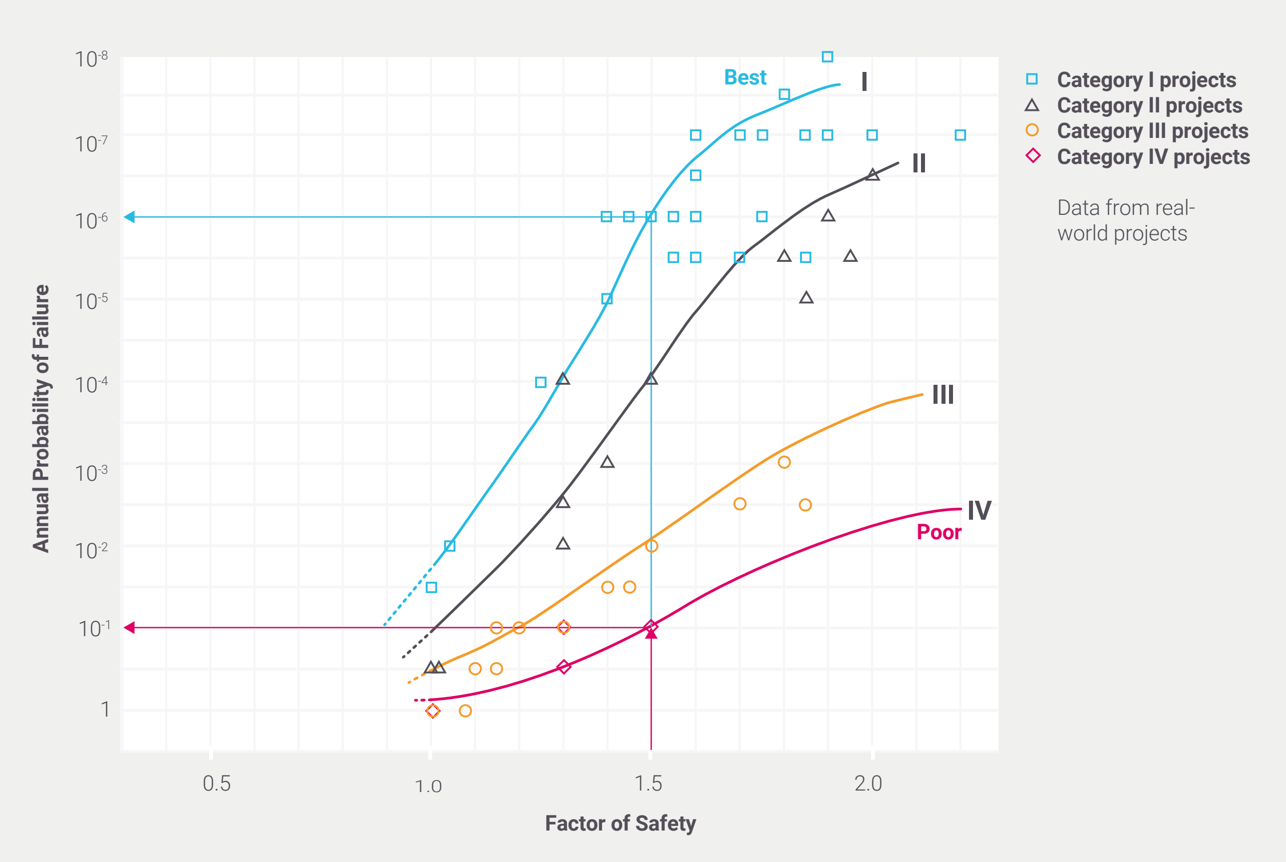
Box 3: Constraints of the Limit Equilibrium method

The calculated factor of safety does not warrant a precision of more than one decimal place. The Limit Equilibrium method also assumes that all points along the critical failure surface are at the same state (of failure), notwithstanding that brittle, cemented or bonded tailings resulting from desiccation and oxidation may be at different failure states.

(the higher variability for closure reflects the fact that closure is in perpetuity, nominally 10,000 years, requiring gross projections from available earthquake data in most cases). The undrained shear strength estimate for tailings may be ±50 per cent, while the estimated drained friction angle for tailings may be ±3 degrees. There is clearly a need to use conservative values in design and to carry out sensitivity analyses, but this has not always been the case in practice.

The relationship between the calculated factor of 'safety' and the corresponding probability of 'failure' must also be understood, particularly as it relates to the standard of design and construction. This is illustrated in Figure 2 (adapted from Silva *et al.* 2008). The figure shows that poor design and construction to a factor of safety of 1.5 corresponds to a very high and unacceptable probability of failure of 10^{-1}. By contrast, best design and construction, also to a factor of safety of 1.5, corresponds to a very low probability of failure of 10^{-6}, at the level of acceptability generally adopted for aircraft travel.

While attractive to many, the use of limit-equilibrium factors of safety are, at best, a guide and should not be the sole discriminator for the security of a tailings facility. Alternative approaches, for example deformation evaluations, may be far more appropriate for many facilities. Further, depending upon the parameters used, a factor of safety of 1.1 can be associated with a facility presenting zero risk of harm to society, whereas one with a much higher computed value (above 1.5) may present a high risk of harm. How a facility will strain under load (brittle versus ductile), along with the nature of the input parameters, are but two key reasons why the factor of safety is not as useful a tool as many consider it to be.



Source: Adapted from Silva et al. 2008

Figure 2. Relationship between calculated factor of safety and corresponding probability of failure, as it relates to standard of design and construction

While considerable work has been devoted to risk assessment, there is relatively little guidance on the acceptability of risk. Whitman (1984) attempted to plot the annual probability of failure against lives lost and dollars lost (in 1984 $). Key findings from this analysis are reproduced in Figure 3. Whitman assigned bubbles to represent different activities and types of infrastructure such as civil aviation (assigned an 'acceptable' annual probability of failure of about 10^{-6}), water facilities (at about 10^{-4}), buildings (at between 10^{-5} and 10^{-4}), foundations (at between 10^{-3} and 10^{-2}), mine pit slopes (at about 10^{-1}), and shipping (at between 10^{-3} and 10^{-2}). Whitman also added possibly upper bounds for 'acceptable' and 'marginally acceptable'. To Whitman's plot has been added the wide range for tailings facilities (from 10^{-4} to 1), based on the high tailings facility failure rates and consequences. Implications for tailings facility design are given in Box 4.

Box 4: Implications for Tailings Facility design

Clearly, tailings facilities can be built to a similar margin of safety as water facilities, at a probability of failure of about 10-4. If this were done, it would prevent many tailings facility failures, and the associated loss of life, damage to infrastructure, and environmental harm.

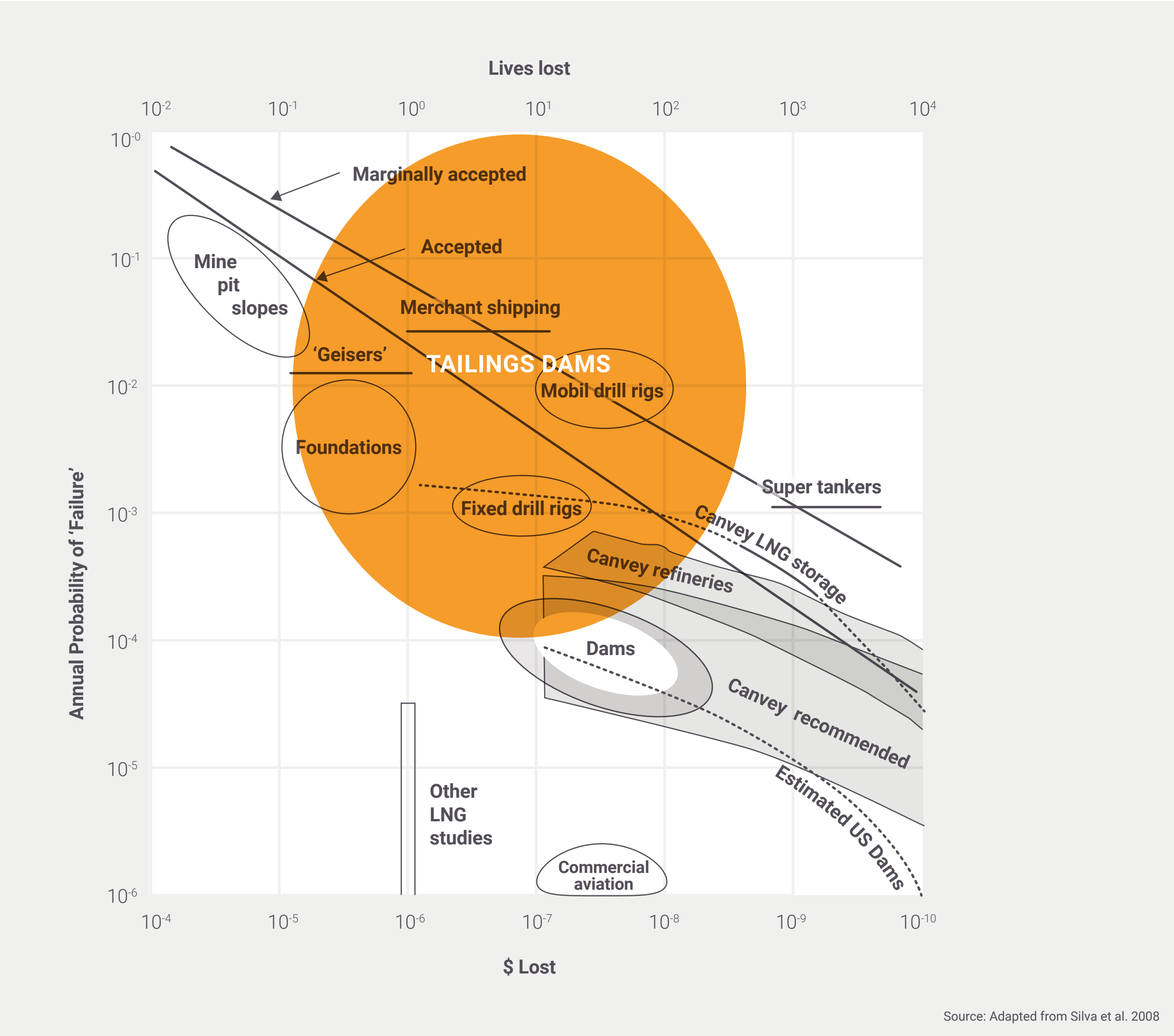


Figure 3. Acceptability of failure

3.5 CONSEQUENCES FOR INDUSTRY

As a result of the unacceptably high rate and severe consequences of ongoing tailings facility failures, there has been a loss of trust and confidence in the industry's ability to safely manage tailings. While the vast majority of tailings facilities do not fail, the failure rate is still beyond that deemed acceptable to both the industry and society. Further, the very clear lessons from failures indicate that there is an ability to reduce the rate of failures considerably towards a goal of zero catastrophic incidents. The track record to date, however, has created threats to the mining industry's financial and social licences to operate, coming from:

- an instantly 'social media-connected', although not necessarily well-informed, community
- major investors, such as the Church of England, BlackRock and the United Nations-supported Principles for Responsible Investment international network (PRI)
- insurers, who are making cover more difficult to obtain and more expensive, leading to self-insurance by major mining companies and creating difficulties if not near impossibility for mid-tier mining companies in securing cover
- regulators, who are imposing stricter requirements (for example, outlawing upstream construction

in Chile following an earthquake-induced tailings facility failure in 1965 that killed more than 200 people, and in Brazil following the Brumadinho tailings facility failure in 2019 that killed 270).

3.6 ALTERNATIVE APPROACHES TO TAILINGS MANAGEMENT

'Leading' or 'best' current practice in tailings management has been documented in numerous guidance documents, guidelines and handbooks (see the Appendix to this chapter). Conventional storage methods can be a 'best practice' for the right site conditions, but for many sites, alternative technologies would be a better option. Alternatives to current tailings management practices are described in several of these documents.

The following sections consider a range of alternative tailings management options, most of which use currently available technology (Williams 2015). The innovative aspects of these technologies lies mainly in their application to tailings management. Sound management practices are also essential for conventional tailings deposition.

3.7 ACHIEVING PHYSICAL STABILITY AND WATER RECOVERY VIA DEWATERING TAILINGS

Achieving physical stability of tailings via dewatering (how dry is possible, and how dry is dry enough) must be balanced against the need to ensure their geochemical stability. The latter requires maintaining the tailings near-saturated and preferably permanently under water, requiring a permanent impoundment and water supply.

The recovery of water in-plant is the most effective means of maximising water return for recycling and the retention of any residual process chemicals. Tailings are conventionally thickened prior to disposal to a surface tailings storage. The slurry concentration achievable by conventional thickeners varies with the type of tailings, typically ranging from 25 per cent solids by mass for coal tailings and alumina residue (red mud), and up to 40 to 50 per cent solids for metalliferous tailings. Smaller diameter high rate and high compression thickeners raise the solids concentration further, but with less torque than conventional thickeners.

Water recovery from the tailings storage itself is generally limited to the recovery of supernatant water[1] (the water that pools at the end of the tailings beach), although seepage through the wall may also be collectable. Other tailings water is lost to entrainment within the tailings, evaporation from the decant pond[2] and wet tailings, and seepage into the foundation and through the embankment.

In order to maximise the recovery of supernatant water from the tailings storage, good design, construction and management of the water return system is required. This should include the planning and implementation of tailings disposal to direct supernatant water to the decant pond, minimising the size of the decant pond and the rapid return of supernatant water to minimise evaporation losses, and maintaining the decant pumps and water return pipelines.

The overall tailings water recovered as a proportion of the total water used in processing is typically 50 to 60 per cent for tailings disposal as a slurry. This increases to 60 to 70 per cent for tailings disposal as a high-density slurry.

3.8 ON-OFF TAILINGS CELLS

As an alternative to in-plant dewatering, desiccation and harvesting of black coal tailings in 'on-off' tailings cells has been employed at a number of mines, including at Charbon Coal Mine in New South Wales since 1990 (see Figure 4). This method can be effective provided that the tailings are deposited in thin sub-layers, preferably no more than 600 milimetres thick, since desiccation by solar and wind action drops off exponentially with depth. Sufficient time (of the order of several weeks) must also be allowed for desiccation of each sub-layer before further sub-layers are added, to a maximum depth of about 3 metres, and before the full depth of dried tailings is harvested. This necessitates a large number of cells covering a large footprint -although probably no larger a footprint than would ultimately be needed for a conventional surface slurried tailings facility. The harvested dried tailings can be co-deposited with coarse wastes, so that ultimately there is no dedicated tailings storage facility.

1. Supernatant water is the water that pools at the end of the tailings beach.
2. The decant pond is the body of supernatant (process) water that has separated from the tailings solids, plus any rainfall runoff collected on the tailings facility. (Department of Industry 2016, p.110).

Insufficient desiccation   Full-depth drying   Dumping

Source: Author

Figure 4. On-off coal tailings cells, employing solar and wind drying, harvesting and disposal with coarse reject

3.9 THICKENING – IS THERE A PRACTICAL LIMIT?

If conventional thickening and slurry disposal fails to achieve adequate settling and consolidation and supernatant water recovery, secondary (inline) flocculation[3] can be applied just prior to tailings discharge to re-flocculate conventionally thickened tailings that have been shear-thinned by pumping.

The practical limit to thickening is considered to be a consistency that is just pumpable by inexpensive and robust centrifugal pumps. However, this consistency will vary with the particle size distribution of the tailings and, particularly, with the clay mineral type and proportion.

3.10 'FARMING' OF TAILINGS

Some forms of wet and soft tailings, particularly clay-rich tailings or process residue, may benefit from 'farming' by the use of equipment such as an amphirol or scroller, and/or later by a D6 Swamp Dozer. Farming is widely applied to red mud in Australia, and has been trialled on other tailings, including on coal tailings and fly ash in Australia, and oil sands tailings in Canada.

An amphirol (shown in Figure 5, Williams 2014) has a very low bearing pressure of 3 to 5 kilopascals and is used first. The principles of tailings or residue farming by amphirol are as follows:

- The tailings or residue can be poured to a thickness of 700 to 900 mm, up to three times the thickness if surface desiccation only was allowed.
- Some drying and strengthening of the tailings or residue surface is required to allow safe and efficient amphirol operation.
- Too heavy a bearing pressure from the amphirol and/or too soft a tailings or residue surface leads to bogging of the amphirol. An amphirol will only achieve minimal consolidation or compaction of the tailings or residue since its bearing pressure is low.
- An amphirol should:
    - essentially 'float' over the tailings or residue surface
    - create trenches down the tailings or residue beach to facilitate the drainage of surface water
    - maximise the tailings or residue surface area exposed to evaporation and strengthening, and
    - expose undesiccated tailings or residue on further farming.
- An amphirol should not over-shear the tailings or residue by excessive or repeated farming; about four amphirol passes is optimal.

A D6 Swamp Dozer has a bearing pressure of about 35 kilopascals and can be used once the tailings or residue has gained sufficient shear strength and bearing capacity to safely support it (see Figure 6). A dozer could be used after amphirolling or simply after the tailings or residue has desiccated naturally on exposure. Dozing improves the already desiccated tailings by compaction, leading to a further increase in dry density and shear strength.

3. Flocculation is a process widely used in mineral processing whereby small particles in suspension are aggregated to make larger clusters (flocs) that are more easily separated than the original particles.

Red mud has a specific gravity of about 3.0 and is difficult to densify due to it forming a loose 'card-house' structure of low permeability. Without farming, the dry density achieved is typically limited to about 0.7 tonnes per cubic metre, and desiccation is limited to a depth of about 300 mm. Amphirolling or scrolling can increase the dry density to about 0.9 tonnes per cubic metre, and dozing can increase it further to 1.3 to 1.4 tonnes per cubic metre.

Figure 5. Amphirol or scroller on red mud

Source: Author

Figure 6. D6 Swamp Dozer on red mud

3.11 PASTE TAILINGS

Paste thickeners raise the percentage of solids to between 45 per cent (for red mud) and 75 per cent for metalliferous tailings. The relative consistencies of high-density thickened slurry and high and low slump paste metalliferous tailings are illustrated in Figure 7.

Pumping paste tailings to a surface tailings storage requires piston pumps, which are about an order of magnitude more expensive than centrifugal pumps, cost more to operate, and are more sensitive to variable input feeds. Also, piston pumps discharge a 'toothpaste-like' consistency, which requires that the discharge point be constantly moved. However, paste tailings can be delivered under gravity as underground backfill (usually with cement added) or into a pit if the dewatering facility is located close to the discharge point, possibly on a mobile skid that can be moved. Underground tailings paste backfill will generally reach its intended destination under gravity, provided that the angle between the discharge and final points is steeper than 45 degrees.

The overall tailings water recovery as a percentage of the total water used in processing increases to about 80 per cent for tailings disposal as a high slump paste, and to 85 to 90 per cent for tailings disposal as a low slump paste. However, to date the practical applications of paste tailings have typically been limited to gravity deposition in-pit or as a cemented underground backfill.

High density slurry   High slump paste   Low slump paste

Source: Author

Figure 7. Consistency of thickened and paste tailings

3.12 FILTRATION AND DRY STACKING

If a consistency greater than is readily pumpable by centrifugal pumps is desirable, filtration may be preferable to producing paste tailings. Centrifuges or belt press filters can produce a 'wet' filter cake, while plate and frame or screw filtration can produce a 'dry' filter cake. The filter cake can then be transported by truck or conveyor. Centrifuged filter cake may still flow, while dry filter cake can be compacted.

Filtration of tailings can be achieved by vacuum, belt press, plate and frame, or screw (although screw filters have not been taken up for tailings) methods. While centrifuging and filtration can produce a cake of similar moisture content or the percentage of solids, the greater pressures imposed by filtration will create a 'structure' that makes the filtration cake more 'permanent', more readily transportable by conveyor or truck without inducing flow, and more manageable (see Figure 8).

Centrifuged (wet cake) Filtered (dry cake)

Source: Author

Figure 8. Consistency of centrifuged and filtered tailings

Dry tailings filter cake better lends itself to dry stacking, although even then compaction may be required to form a stable stack, and to limit oxygen ingress and rainfall infiltration into potentially contaminating tailings in order to minimise contaminated seepage. Dry stacking, sometimes involving compaction, has found most favour in dry climates such as northern Chile. Dry tailings filter cake can also be co-disposed with coarse-grained wastes, as shown in Figure 9 for coal tailings. It is essential to avoid confusion around the nomenclature adopted for these filtered tailings: although termed 'dry', they do retain moisture after processing and when placed. The more correct term would be 'unsaturated' stacked tailings, but the existing terminology is well-established and should be understood by most in the industry.

Belt press filter Conveying Co-disposal in spoil piles

Source: Author

Figure 9. Belt press filtering of coal tailings, transportation of filter cake and coarse reject by conveyor, and end-dumping in spoil piles

3.13 BRIQUETTING

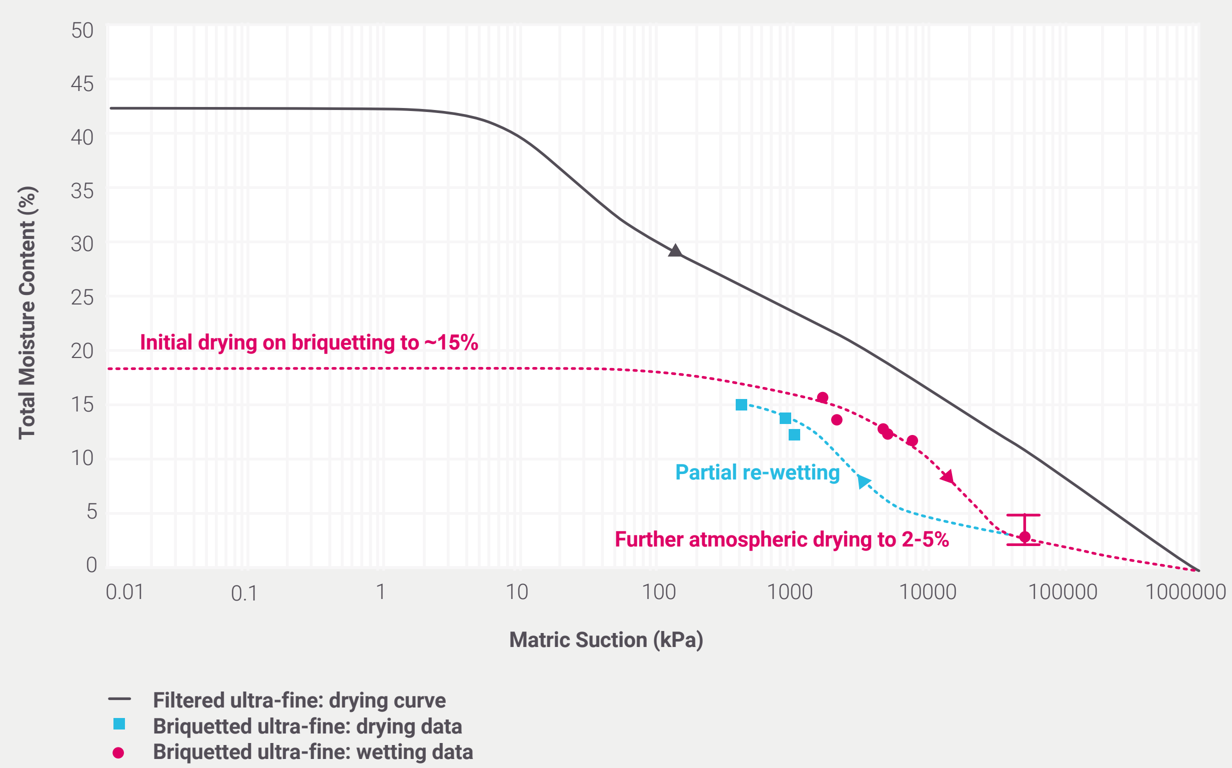
Briquetting has been shown in trials to be very effective in dewatering ultra-fine black product coal (Williams 2012). This technology can also potentially be applied to tailings. In the trials, ultra-fine product coal that was initially at 40 to 45 per cent total moisture content was dewatered to about 15 per cent total moisture content (85 per cent solids) by squeezing the slurry between two rollers under very high stress (of the order of 50 megapascals). The very high stresses imposed over very limited duration resulted in further dewatering of the briquettes formed, in a dry atmosphere, to about 2 to 5 per cent total moisture content (95 per cent solids). The air-dried briquettes can re-wet in a humid atmosphere, but only to about 15 per cent of total moisture content, and they retain their 'briquette' lumpy structure. This sequence of drying and re-wetting is illustrated in Figure 10. However, the high initial CapEx and high OpEx of briquetting have discouraged its application to either ultra-fine black product coal or tailings.

3.14 CO-PLACEMENT OF TAILINGS AND COARSE-GRAINED WASTE

Co-placement of fine coal (tailings) rejects and coarse rejects into a material that is transportable by truck has been practiced in British Columbia. This results in a compactable material that can be used to develop stable stacks that more resemble a conventional mine waste dump than a tailings facility.

The pumped co-placement of combined coal tailings and coarse coal rejects has been practiced at a numerous coal mines in Australia and Indonesia, since this method was first introduced at Jeebropilly Coal Mine in the Ipswich Coalfields of South-East Queensland in about 1990.

Pumped co-disposal in-pit at Jeebropilly Coal Mine is shown in Figure 11 (Morris and Williams 1997; 1999). Unfortunately, in order to avoid pipeline blockages, the combined washery wastes are pumped at a low 25 to 30 per cent solids and at high velocity (up to 4 m/s). This results in the unintended segregation of most of the fines and the generation of an undesirable flat (at about a 1 in 100 slope) fines beach (mostly tailings) beyond the desirable steep upper coarse-grained beach (at about a 1 in 10 slope). In addition, the inclusion of the coarse rejects results in high pump and pipeline wear.



Source: Williams 2012

Figure 10. Briquetting trial on ultra-fine black product coal

Source: Author

Figure 11. Pumped co-disposal of combined coal tailings and coarse coal rejects

3.15 PIT TAILINGS STORAGE

Storing tailings in completed pits is gaining favour, particularly as permitting of new surface tailings storages meets with increasing community opposition. This option can be attractive when pit backfilling does not sterilise potential future ore reserves. It can be very attractive financially as it eliminates the need for the construction of a containment structure and does not require further thickening of the tailings. It also fills the void, albeit with wet and soft tailings that are very difficult to rehabilitate.

A challenge with implementing this option is that the rate of rise will be high in-pit due to its small footprint, particularly in the early stages. It is also difficult to manage the supernatant water due to the steep pit slopes limiting access to pumps, and the reduced evaporation of water by sun and wind (by up to 2-fold compared with surface ponds). This will severely limit dewatering, consolidation and strengthening of the tailings through desiccation. Consolidation of the tailings will be high and ongoing, causing the tailings surface to 'dish', reflecting the shape of the pit. A further disadvantage could be the potential for the contamination of any groundwater resources surrounding the pit, if contaminated pit water rises above the surrounding groundwater level. In addition, the stability of underground mining operations in the vicinity may be jeopardised. A further consideration is that, in a dry climate, a final pit lake over tailings will inevitably contain water of increasingly poor quality due to the concentration of salts and contaminants through net evaporation.

3.16 WASTE LANDFORMS

Integrated waste landforms are being employed in Australia, particularly at coal and iron ore projects, including new projects. This involves either the construction of a robust containment for thickened tailings using waste rock, or the co-disposal of mixtures of filtered tailings, and waste rock or coarse-grained processing wastes, delivered by combined pumping (such as for coal washery wastes), or by haul truck or conveyor. This method has also been employed in the wet tropics to encapsulate potentially acid forming tailings and waste rock behind a robust containment of more benign waste rock constructed in compacted layers.

3.17 'PASTE ROCK' AND 'ECOTAILS/GEOWASTE'

Another approach has been to combine filtered tailings with waste rock. Examples include:

- 'Paste Rock', patented by Golder Associates, which has been trialled in Canada for mine waste covers (Wilson *et al.* 2008)
- 'EcoTails/GeoWaste', patented by Goldcorp, which incorporates filtered tailings and screened or crushed waste rock (Burden *et al.* 2018).

The practical and economic challenges that must be overcome to promote the combination of filtered tailings and waste rock include:

- Minimising the extent to which the tailings must be dewatered, in order to save costs, while not compromising the stability of the tailings/waste rock mixture.
- Minimising the crushing or screening of the waste rock to allow mixing with the filtered tailings and transportation. The top-size of the waste rock for conveying is about 200 to 300 mm, while coarser-grained waste rock can be trucked.
- Achieving adequate mixing of the filtered tailings and waste rock. This is unlikely to occur on a conveyor or on dumping from a haul truck, but may be achieved by a number of drop points into hoppers along a conveyor line.
- Compaction of the mixture may be required to produce a stable deposit, although this could be restricted to the perimeter of the emplacement.

The benefits of combining filtered tailings and waste rock can include improved geotechnical parameters, including increased shear strength, reduced compressibility and a permeability that is lower than that of waste rock alone, but higher than that of tailings alone.

3.18 REDUCED TAILINGS PRODUCTION

While it is not the major focus of this chapter, it should be noted that more attention is now being paid to finding ways of reducing tailings production. This is in response to the ever-increasing production of tailings, due to decreasing ore grades and increasing demand for minerals. Another driver has been the rising cost of energy and other mining and processing inputs. The primary focus of innovation has been on coarse particle or dry processing. New technologies that are being applied to facilitate these alternatives include ore sorting using magnetic resonance technology, and 'precision mining'.

Box 5: Challenges of closing conventional tailings facilities

Post-closure, surface tailings facilities are required to remain physically and chemically stable in perpetuity, which can be mutually exclusive objectives. Some conventional wet tailings facilities have soft tailings deposits that are difficult and expensive to physically cover and rehabilitate, particularly at the end of the mine life when it is no longer producing revenue and construction equipment is being demobilised. Further, the presence of wet and soft tailings at some locations will limit the future land use potential of the tailings storage. On the other hand, their high degree of saturation will limit the oxidation of any sulphides present in the tailings.

4. CLOSURE CONSIDERATIONS

Surface tailings storage closure should be developed with community input and address the agreed post-mining land use. Irrespective of the use(s) agreed upon, considerations for all facilities entering their closure phase will include:

- facility geotechnical instability – Tailings are expected to drain down on cessation of deposition, but may be recharged by high rainfall (in the absence of a spillway)
- facility erosional instability, particularly in a dry climate if the slope is flattened and topsoiled
- differential tailings settlement, affecting slope profile and drainage
- poor water quality (saline, and/or acidic, or alkaline), after a lag:
  - ponded water, and in any spill ponding below the tailings facility
  - emerging at low points around toe, and/or
  - infiltrating to any groundwater resource.

Box 5 summarises the challenges involved in closing facilities containing wet and soft tailings deposits.

The rehabilitation of tailings can range from direct revegetation of benign tailings, to soil covers, and also water covers, depending on the climatic setting. The Global Acid Rock Drainage [GARD] Guide (INAP 2009) recommends that the choice between cover types based on climatic conditions should be guided by the following considerations (Figure 12):

- water covers are appropriate for wet climates as effective oxygen barriers
- water-shedding soil covers are appropriate in moist climates to promote rainfall runoff and limit net percolation of rainfall
- store and release soil covers, which store wet season rainfall, releasing it through evapotranspiration during the dry season to sustain revegetation, are appropriate for dry or seasonally dry climates to sustain vegetation and limit net percolation of rainfall.

In seasonally dry climates, store and release covers are more robust than rainfall-shedding covers since they better sustain vegetation and limit erosion. Store and release covers require a base sealing layer to limit the breakthrough of rainfall infiltration, and may take advantage of the natural tailings beach slope to direct clean excess rainfall infiltration towards a collection point, avoiding breakthrough into the underling tailings.

Any soil cover over tailings is necessarily relatively thin, and hence is prone to breakthrough. Also, all soil covers have some 'store and release' function. Historically, soil covers were limited in thickness and were placed primarily to support revegetation. Over time, an increase in cover thickness was seen as an 'improvement'. Rainfall-shedding covers followed the approach taken to cover landfills, but are prone to failure in dry or seasonally dry climates due to erosion. Too thin a cover lacks the capacity to store rainfall infiltration, can dry out during prolonged dry periods, and can be punctured by erosion. Store and release

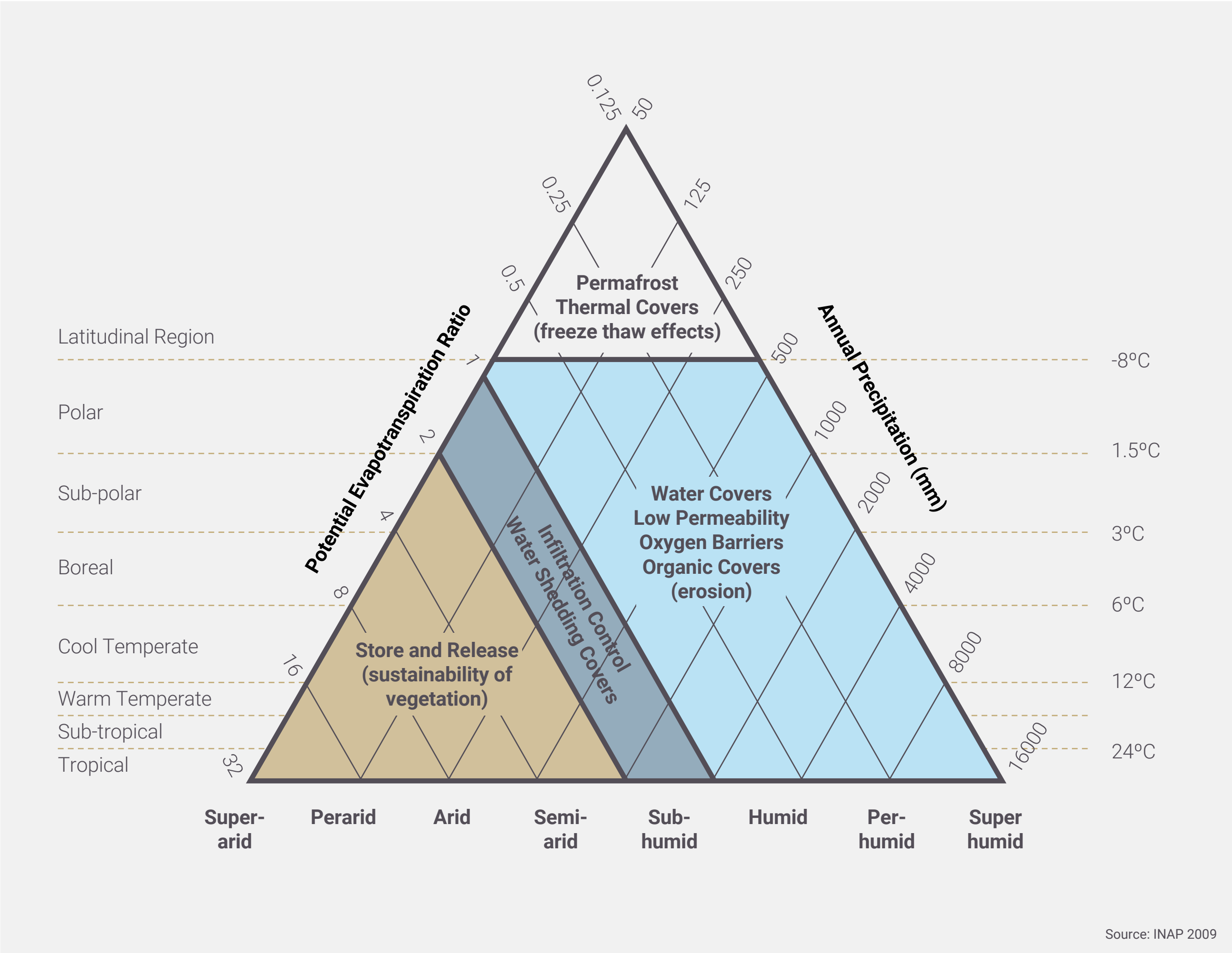


Figure 12. Choice of cover related to climate

covers gained popularity for dry climates but have not always been well designed and constructed. A composite cover is seen by regulators to be 'better', but by operators to be more costly.

Tree death (when tree roots reach contaminated tailings) and/or blow-down of shallow-rooted trees, due to roots spreading laterally across a compacted layer or contaminating tailings, can threaten the integrity of a cover over tailings. However, excluding tree growth is unsustainable. To address these issues, use may be made of shallow-rooted plants or plants that can survive on toxic tailings and/or take-up contaminants.

Store and release covers are designed to have sustainable tree, shrub and grass cover to transpire moisture. There is an optimal store and release growth medium thickness, of the order of 1.5 to 2 m. Too thin a layer does not store sufficient rainfall infiltration delivered by the climate, while too thick a layer makes it difficult for roots to extract deep drainage, leading to a wetting-up of the cover and increased risk of breakthrough.

Exposure to the atmosphere of potentially acid generating or otherwise potentially contaminating tailings may require that they be maintained under water, preferably from disposal onwards. The downside is that this will leave slurry tailings soft and wet. In wet climates and valley topographies, it may be possible to maintain the tailings underwater in perpetuity, provided that the stability of the facility's containment embankment can be assured. In dry climates and in flat terrain, the focus will need to be on minimising rainfall runoff over exposed contaminating tailings and the net percolation of rainfall that would transport contaminants. Alternatively, potentially contaminating tailings could be placed in a completed pit or underground mine and maintained underwater, or contaminants could be removed by additional processing, such as desulphurisation.

Without proper management, differential consolidation settlement of tailings can disrupt any constructed surface drainage features on a tailings cover, particularly as they are gently sloping (typically less than one per cent). This will also result in surface ponding of rainfall runoff on the tailings, recharging and exacerbating seepage. However, the hydraulic conductivity (permeability) is generally low due to the fine-grained particle size of most tailings, and particularly those that contain clay minerals or sulphides that hardpan. Consequently, consolidation can be slow and difficult to predict, and clay mineral-rich tailings may remain under-consolidated.

The treatment of the side slopes of a tailings facility is often given only limited attention. While slope flattening will increase geotechnical slope stability, it may not be required for this purpose. A downside of slope flattening is that it will likely increase the potential for erosion due to the increased slope catchment and runoff, particularly if erodible topsoil is placed on the slope to facilitate revegetation. Further, contour and downslope drains on tailings facility embankment slopes concentrate rainfall runoff and are prone to failure due to overtopping and piping failure.

The reality is that in many regions in the world, few surface tailings storages have been successfully rehabilitated, due to the associated costs, with reprocessing and in-pit storage being increasingly considered as alternatives. As argued above, the conventional cost-based approach to surface tailings storage rehabilitation is often at odds with the potential for value-added rehabilitation, as described in Table 1 (Williams 2019). A focus on the costs of tailings storage rehabilitation by operators and regulators discourages rehabilitation activities post-closure, which in turn is likely to lead to increased impacts over time, exacerbating the situation. By contrast, identifying and realising potential opportunities for value-added rehabilitation and post-closure land uses sets the rehabilitation budget and is a potential win for all stakeholders.

Table 1. Conventional cost-based rehabilitation versus value-added rehabilitation

Conventional Cost-Based Rehabilitation	Value-Added Rehabilitation
Production rules	Post-closure 'value' is identified upfront
Rehabilitation is seen by operator and regulator as a 'cost' Operator discounts cost over time, discouraging rehabilitation Infrastructure such as power lines and buildings are stripped for little financial gain Rehabilitation is limited to 'smoothing' and 'greening' (where sustainable)	Examples of post-closure value include: • Re-processing of tailings to extract metals of value, depositing the residual tailings in-pit and reducing the rehabilitation liability • Industrial land use • Renewable energy– solar, wind and pumped storage, delivered to the grid via mine transmission lines • Agriculture and/or fishery impoundment • Tourism and heritage (older the better)
Post-closure land use and function are limited	'Value' sets rehabilitation budget
Operator is threatened with loss of financial and social licences to operate	Potential wins for operator, future land user and Government

4.1 BARRIERS TO IMPLEMENTATION OF INNOVATIVE TAILINGS MANAGEMENT

Conventional slurried tailings deposition remains a best practice option for many sites. However, the industry currently has a range of options beyond this conventional approach and for those where conventional deposition and storage is not the best option. This begs the question of what is stopping adoption of alternative tailings management. Barriers to the implementation of innovative tailings management include the following:

- The continued reliance on NPV accounting and the use of a high discount factor (typically 6 to 10 per cent, which is three to five times the consumer price index). This approach favours tailings management options that are cheap in the short-term (particularly for CapEx), and delays necessary expenditure on rehabilitation. These factors together are likely to exacerbate impacts and blow-out rehabilitation costs.

- Alternative tailings management options, such as mechanical dewatering and co-disposal, are seen as too costly. This view is reinforced by NPV accounting.
- There are perceived and real technical difficulties associated with mechanical dewatering and co-storage (for example, high clay mineral content, and handling coarse-grained wastes).
- Uncertainty – and perceived higher risk – of new approaches also serve to discourage innovation.

Underlying all of this is an inherent resistance to change, which is often disguised as unsubstantiated claims about perceived high costs, perceived technical obstacles, and perceived uncertainty.

CONCLUSIONS

Tailings management must take into account the nature of the tailings and, importantly, the climatic, topographic and seismic settings of the mine. The ongoing rate of tailings facility failures is unacceptable to both industry and society, and there is a need to restore trust and confidence in the industry's ability to safely manage tailings. A rethink is required about the way in which tailings management is costed. Too many jurisdictions continue to rely largely on a net present value (NPV) approach with a high discount factor, rather than a whole-of-life cost approach. There is scope for the further development and implementation of new tailings management technologies and innovations, and for the use of different cost models, but this must overcome the natural resistance to doing things differently to the way they are usually done in those jurisdictions.

Tailings facilities can be built to a similar margin of safety to that of water dams, at a probability of failure of about 10^{-4}. This would prevent many tailings facility failures, and the associated loss of life, damage to infrastructure, and environmental harm. It would also restore the industry's financial and social licences to operate. The implementation of existing and new technologies to tailings management could help to eliminate the risks posed by a subset of conventional tailings facilities, possibly removing them altogether. Such technologies include:

- optimising in-plant dewatering of tailings, particularly by thickening or filtration
- 'farming' deposited tailings that consolidate poorly
- dry stacking of filtered tailings
- co-disposal of tailings and coarse-grained waste
- in-pit tailings disposal, particularly if final pit lakes containing water of diminishing quality can be avoided by complete back-filling
- integrated waste landforms that re-combine tailings and coarse-grained wastes
- reduced tailings production through coarse or dry processing
- value-added tailings rehabilitation post-closure.

As discussed, there are several barriers to the implementation of innovative tailings management where they are indicated by site-specific conditions, particularly where existing facilities are concerned. Change will be more readily achieved in new mining projects and hence change in tailings management for the mining industry as a whole will necessarily be generational.

KEY MESSAGES

1. If tailings facilities were built to a similar margin of safety to water dams, this would prevent many tailings facility failures.
2. There is a commonly held perception in the mining industry that transporting tailings as a slurry to a facility is the most economic approach, but this fails to factor in the true cost of closing and rehabilitating the resulting tailings facility.
3. A rethink is required about the way in which tailings management is costed. A substantial portion of global tailings practice still uses the Net Present Value (NPV) approach with a high discount factor. What is needed is a whole-of-life cost approach.
4. In practice, not enough tailings facilities have been successfully rehabilitated, due to the difficulty of capping a 'slurry-like' (wet and soft) tailings deposit and the excessive cost involved, particularly at a time when the mine is no longer producing revenue.
5. The implementation of existing and new technologies to tailings management could help to eliminate the risks posed by the nature of conventional tailings facilities that have been responsible for the failures that have occurred, possibly removing them altogether.
6. A fundamental barrier to the implementation of innovative tailings management at those sites that would benefit from these technologies is people's resistance to change, which is often disguised as unsubstantiated claims about perceived high costs, technical obstacles and uncertainty.
7. Change is more likely to be achieved in new mining projects than existing operations. Hence, change in tailings management for the industry as a whole will necessarily be generational.

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APPENDIX – GUIDANCE ON BEST OR LEADING TAILINGS MANAGEMENT

Global references to best or leading tailings management include (but are not limited to):

- ICOLD bulletins:
  - 44: Bibliography: Mine and Industrial Tailings Dams and Dumps (1982)
  - 44a: Bibliography: Mine and Industrial Tailings Dams and Dumps (1989)
  - 45: Manual on Tailings Dams and Dumps (1982)
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