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RISK CONTROL PRACTICE: SPECIAL HAZARDS

Tailings & Tailings Management Facilities (TMF) Handbook

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SCOR
The Art & Science of Risk

As a founding signatory of the United Nations Environment Programme's Principles for Sustainable Insurance, and a member of industry Net-Zero Alliances, SCOR is committed to engaging with policymakers and other stakeholders to identify and implement the required measures to tackle climate change. Through the review of our underwriting and investment policies and guidelines and future targets and commitments under the Net Zero frameworks, we seek to enable and indeed accelerate society's shift to a net-zero carbon economy by 2050.

Our conviction is that we have an important role to play in insuring the transition and will actively support our clients in their own commitments to follow credible transition pathways as they transform their business model toward net zero.

Important notices and disclaimer

This Handbook | Guidance Note has been prepared to identify and flag issues a prudent Underwriter and Risk Engineer ought to consider and evaluate relating to the industry involving tailings risk selection and determination and calculation of loss estimates when deciding whether to accept a risk and, if so, on what terms.

Although this Handbook | Guidance is detailed and deals with a number of hazards, it is not intended to be a comprehensive analysis of every peril and potential scenario an Underwriter may be requested to provide cover for. Any estimation or projection of an MPL and final loss amount must be based on reliable, accurate and current values, applicable scenarios, and consideration of the relevant perils.

SCOR accepts no responsibility or liability for any use of this handbook by any party to underwrite any particular risk or to determine a Loss Estimate or final loss amount – it is the responsibility of the relevant Underwriter and (Re)insurer to independently determine whether to accept, or not, any particular risk and the contract terms and price to be required.

CONTENT

SCOPE

The purpose of this Handbook | Guidance Note is to provide basic comprehensive technical support to Underwriters and Risk Control Engineers when dealing with Tailings and Tailings Management Facilities (TMF).

The intention is not to become an expert in Tailings and Tailings Management Facilities (TMF) but to gain sufficient basic expertise in order to be able to adequately question the experts when on site. This entails looking at key basic indicators of management, practice, regulations, governance, design, potential deviations and failures, amongst others.

The structure of a Tailings Management Facility and related special hazards are described. Standard recommendations based on recognized international standards and good practices are proposed.

In line with the insurance industry statement jointly developed by the Principles for Sustainable Insurance (PSI), WWF and the UNESCO World Heritage Center, SCOR committed in September 2018 to develop and implement risk management, insurance and investment guidelines and processes that prevent or reduce the risk of knowingly reinsuring and directly investing in the construction and the expansion of mining infrastructure projects that would damage World Heritage Sites, whenever possible.

As tailings production is inherent to mining and minerals processing so is coverage for TSFs under property policies.
Underwriting policy is reinforced on:

- Risk selection as a pre-requisite condition to offer coverage for TSFs
- Preference for audit conducted on a regular basis by third party professional experts (with reports or conclusions disclosed to underwriters)
- In parallel in the long-term it is paramount that insurance coverage for TSFs remains relevant for mining companies either under property policy or through the deployment of a dedicated stand-alone insurance product. Either way introduction of any broadened coverage shall be conditioned by an independent safety certification of TSFs.

This special hazard handbook was implemented with:

- A Chartered Mining Engineer
- Xavier Dubois - Mining Property Underwriter at SCOR SE Paris
- Amanda Langer - Global Practice Leader for Construction Claims at SCOR Services UK Limited.
- Tim Chapman - Regional Construction Manager for EMEA at SCOR Services UK Limited.

Many thanks to them for their invaluable and extensive contribution.

I - OVERVIEW & RISK SUMMARY

1. THE CHALLENGE

Tailings are the materials left over after the process of separating the valuable fraction from the uneconomic fraction of an ore.

Note that tailings are distinct from overburden: i.e. waste rock or other material (*) that overlies an ore or mineral body and is displaced during mining without being processed.

(* e.g., within coal mines: a "spoil tip", also called a boney pile, culm bank, gob pile, waste tip or bing is a pile built of accumulated spoil – waste material removed during mining. These waste materials are typically composed of shale, as well as carboniferous sandstone and various other residues).

The extraction of minerals from ore can be done in two ways:

- Placer mining using water and gravity to concentrate the valuable minerals

  or
- Hard rock mining pulverizing the rock containing the ore and then relying on chemical reactions to concentrate the sought-after material. The extraction of minerals (i.e., ore processing) from ore requires comminution (i.e., grinding the ore into fine particles to facilitate extraction of the target element[s]). This generates a slurry made of fine particles mixed with water.

High-volume ore mining and processing operations generate a high volume of residue called tailings. The amount of tailings generated can be greater than 90% of the product being mined, especially when mining precious and trace minerals.

In the past, different methods were developed for the disposal of tailings such as:

- **Riverine Tailings Disposal (RTD)** disposing tailings downstream using running water or down drains. This method is used in some cases due to seismic activity and landslide dangers which make other disposal methods impractical and dangerous.
- **Submarine Tailings Disposal (STD) or Deep-Sea Tailings Disposal (DSTD)**: Tailings are conveyed using a pipeline, then discharged on the seabed.

Because of concerns about these sediments in the water and other issues, Tailings Dams and ponds came into use:

- **Tailings Dams and ponds**: an area bounded by impoundments (a dam). Large earthen dams may be constructed and then filled with tailings. The tailings themselves may be used for the impoundments- also called embankment dams. (See Handbook "Embankment Dam" for details). The slurry is pumped into the pond to allow the sedimentation (physical separation) of solids from the water. The ponded water is of some benefit as it minimizes the possibility of fine tailings being transported by wind into populated areas. There are many different variations of this method including: valley impoundments, ring dikes, in-pit impoundments, and specially dug pits. The most common is the valley pond, which takes advantage of the natural topographical depression in the ground. Dewatering is an important part of pond storage ensuring stability. As the tailings are added to the storage facility the water is removed. The water removed can thus be reused in the processing cycle.

- Once a storage facility is filled and completed, the surface can be covered with topsoil and revegetation can commence. However, drainage needs to be maintained unless a non-permeable capping method is used. Moreover, consideration should be given to the potential contamination of the underlying water table.
- Tailings may also be dumped into exhausted open pit mines. A certain quantity of tailings may also be mixed with waste aggregate and cement, creating a product that can be used to backfill underground voids and stopes (so-called High-Density Paste Fill [HDPF]).

In order to minimize water and energy inputs and the surface footprint of waste, tailings were sometimes mixed with other materials such as bentonite to form a thicker slurry that slows the release of water. This leads to:

- **Paste tailings**: Conventional tailings slurries are composed of a low percent of solids and a relatively high-water content (normally ranging from 20% to 60% of solids for most hard rock mining) and when deposited into the tailings pond the solids and liquids separate. In paste tailings the percent of solids in the tailings slurry is increased through the use of paste thickeners to produce a product where a minimal separation of water and solids occurs and the material is deposited into a storage area as a paste (with a consistency somewhat like toothpaste). More water is recycled in the processing plant and therefore the process is more water efficient than with conventional tailings. The cost of the thickening is generally higher than for conventional tailings and the pumping costs for the paste are also normally higher than for conventional tailings (positive displacement pumps are normally required) to transport the tailings from the processing plant to the storage area.

As water management is high up on the mining industry agenda, and sustainable tailings management is becoming an ever-bigger challenge for the industry, dry stack(ed) tailings is the prevailing solution for tailings storage:

- **Dry stacking**: there is a growing use of the practice of dewatering tailings using modern technologies so the tailings can then be stacked. This allows water to be recycled, pollutants to be recovered and it minimizes the surface area for tailings storage. Dry stacked tailings are often more expensive than other methods which may be due to the increased capital cost of purchasing and installing the filter systems and the increase in operating costs (electricity consumption and consumables such as filter cloth) of such systems. This is especially true for high-output operations.

Considerable effort and research continue to be made into discovering and refining better methods of tailings disposal, including (but not limited to):

- **Phytostabilization**: using so called “hyperaccumulator” plants for long-term stabilization and containment of tailings, by sequestering (adsorption or accumulation) pollutants in soil near the roots and reducing wind and water erosion (i.e., dry environments subject to wind and water dispersion).
- **Combining tailings products with coarse waste rock and waste muds** to create a product that can be stored on the surface in generic-looking waste dumps or stockpiles.
- **Tailings reprocessing**: as mining techniques and the price of minerals improve, it may be cost efficient to reprocess tailings using new methods for recovering additional minerals.

2. KEY TERMINOLOGY & ACRONYMS

Collectively, tailings, extractive waste and residues are mine waste and are stored in Mine Waste Facilities (MWF).

The following definitions are taken from the current European Codes [Directive 2006/21/EC]:

- **Mine Waste Facility (MWF):** an engineered structure which, together with all necessary appurtenant works, is designed to retain or confine in safety the extractive waste resulting from industrial processing of naturally occurring soil, ore or rock and to store and recycle, where appropriate, process and flood waters.
- **Tailings**: the waste solids or slurries that remain after the treatment of minerals by separation processes (e.g. crushing, grinding, size-sorting, flotation and other physicochemical techniques) to remove the valuable minerals from the less valuable rock [Directive 2006/21/EC].
- **Tailings dam:** (see also Tailings Management Facility (TMF), Tailings Storage Facility (TSF) and Mine Waste Facility (MWF): an engineered structure, together with all necessary appurtenant works, for ensuring stability, tailings, water and environmental management, and designed to retain or confine the tailings resulting from ore processing and for recycling the process water.
- **Extractive waste** - Waste resulting from the prospecting, extraction, treatment and storage of mineral resources and the working of quarries, but excluding waste which is generated by the prospecting, extraction and treatment of mineral resources and the working of quarries, but which does not directly result from those operations; waste resulting from the off-shore prospecting, extraction and treatment of mineral resources; and excluding injection of water and re-injection of pumped groundwater as defined in the first and second indents of Article 11(3)(j) of Directive 2000/60/EC, to the extent authorized by that Article. [Directive 2006/21/EC]

The common difference between tailings and residue is the grain size, where we typically see residue as a fine-grained material whereas tailings can be coarse-grained.

Slimes is another word we see which is also fine-grained material but mixed with water.

Note that the following acronyms are commonly used for designating an area / facility occupied for the storage and containment of tailings although TMF (Tailing Management Facility) is currently the accepted term.

- TSF – Tailings Storage Facility
- RSF – Residue Storage Facility
- DST - Dry Stacked Tailings
- TDW - Tailings Dam Work (mostly in the USA)
- TDF - Tailings Dam Facilities (mostly in the USA)

Other acronyms:

ANCOLD	Australian National Committee on Large Dams
CDA	Canadian Dam Association
ICMM	International Council on Mining and Metals
ICOLD	International Commission on Large Dams
IFC	International Finance Corporation
UNEP	United Nations Environment Program
UNGP	United Nations Guiding Principles on Business and Human Rights

See also Section 5. Glossary of Terms

3. THE BASICS

The type of storage mainly depends on the ability of the material to reconsolidate or not.

Some material may allow water to move quickly and reconsolidates relatively quickly (e.g., phosphogypsum) as well as forming a solid mass.

This is highly dependent on the chemical composition of the material. Some chemical reactions may occur when material is dehydrating forming a solid structure (“big cake”).

If the material/residue were not a solid structure, it would be like a ‘blancmange’ which would result in a dangerous structure that would fail under its own weight.

Material that is able to reconsolidate may provide its own containment.

Other material that is not able to reconsolidate (e.g., sand) will need a containment made of more solid material or compaction and blended with other materials to create a competent engineered structure.

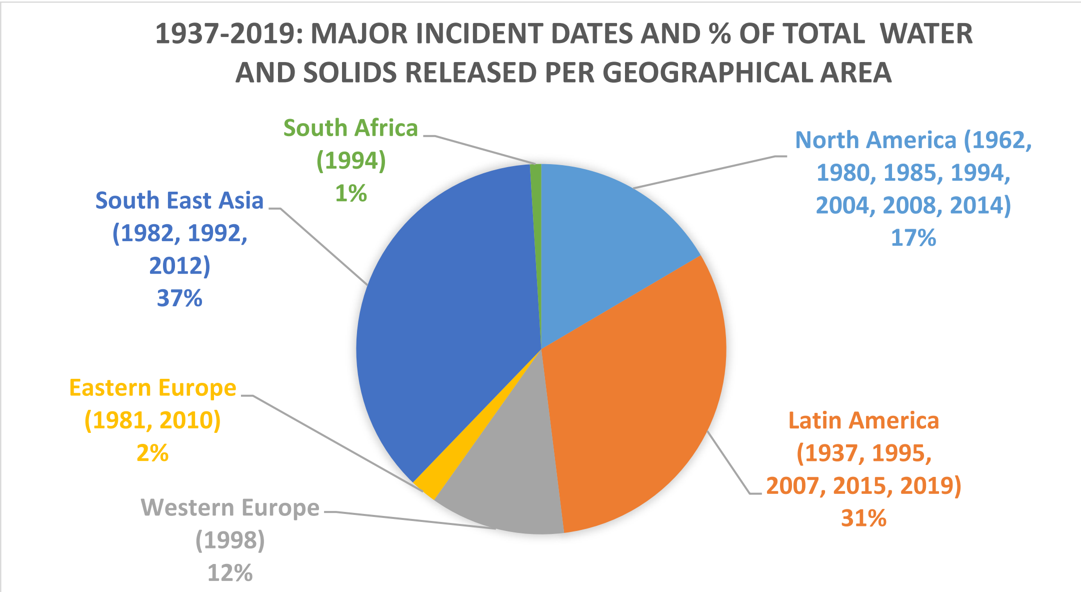
4. LOSS STATISTICS

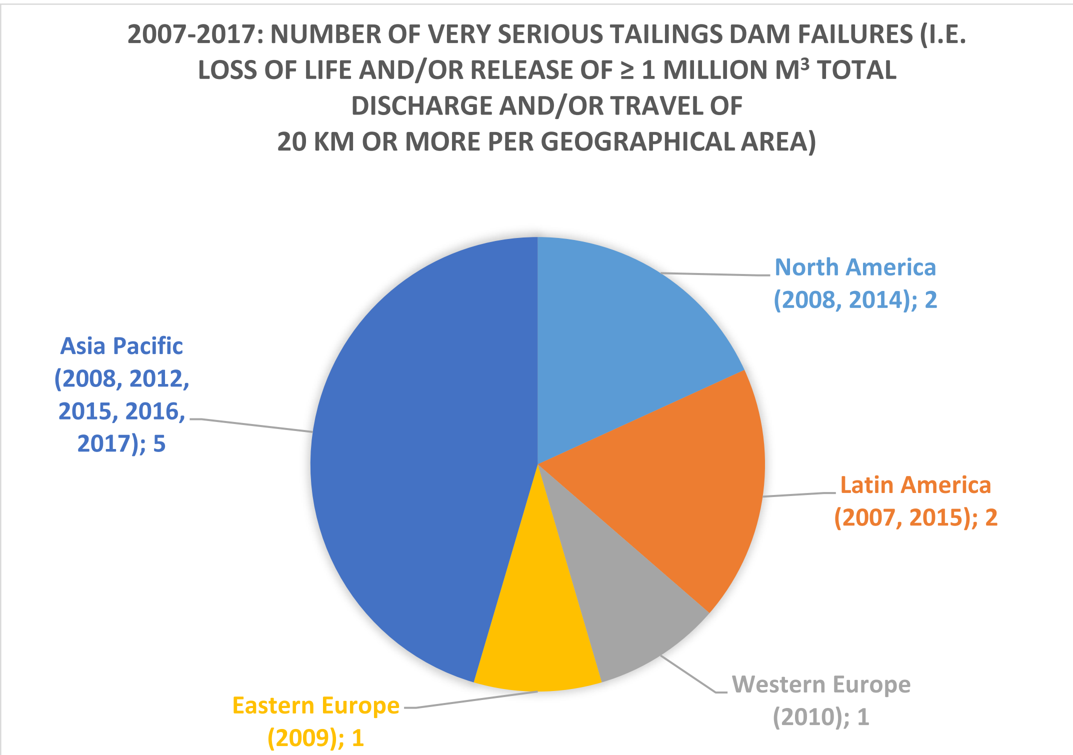
Information about tailings dam failures and tailings-related accidents is fragmented and sometimes even mixed together with non-tailings-related incidents involving groundwater, waste rock ground deformation or subsidence.

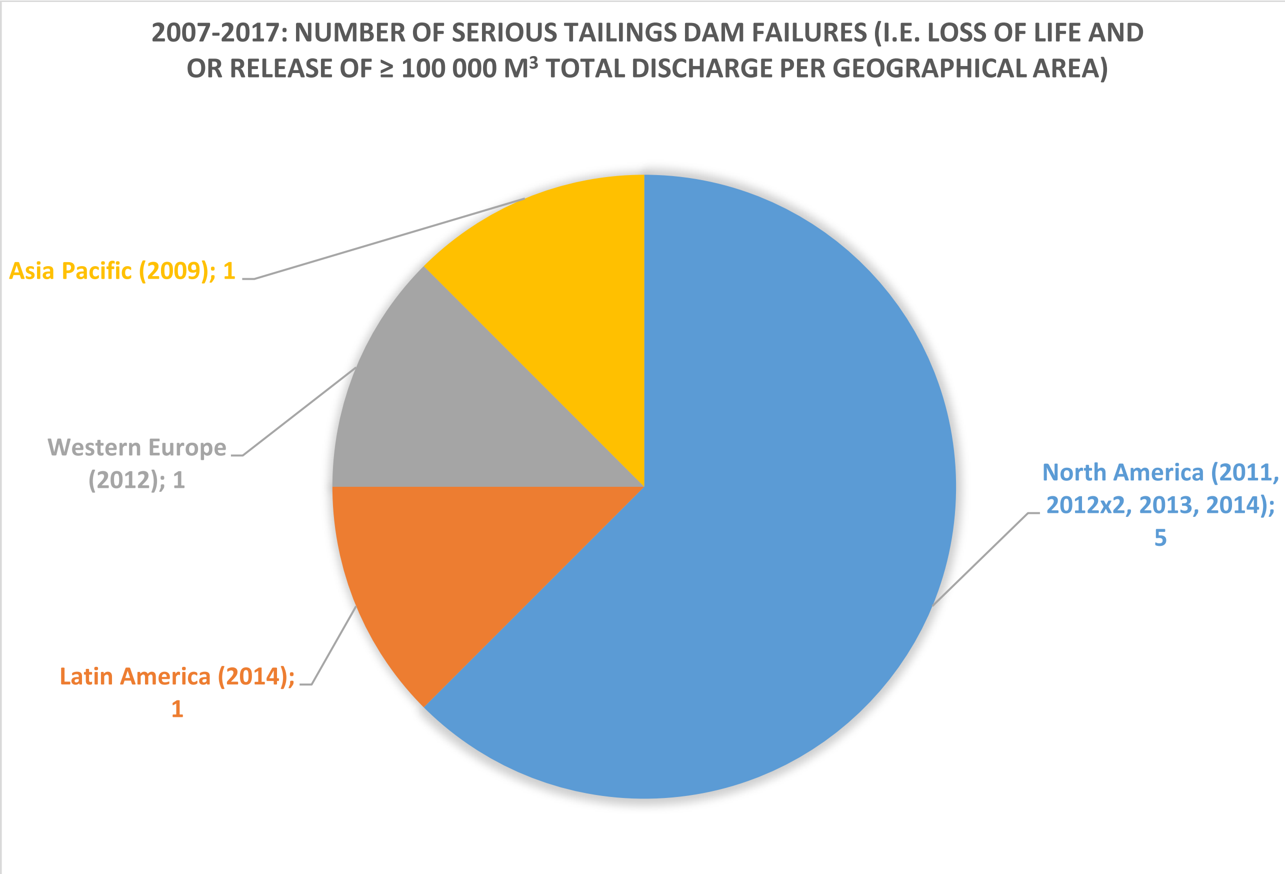
Moreover, different periods are usually considered so that the data are difficult to compare and may even show some inconsistencies.

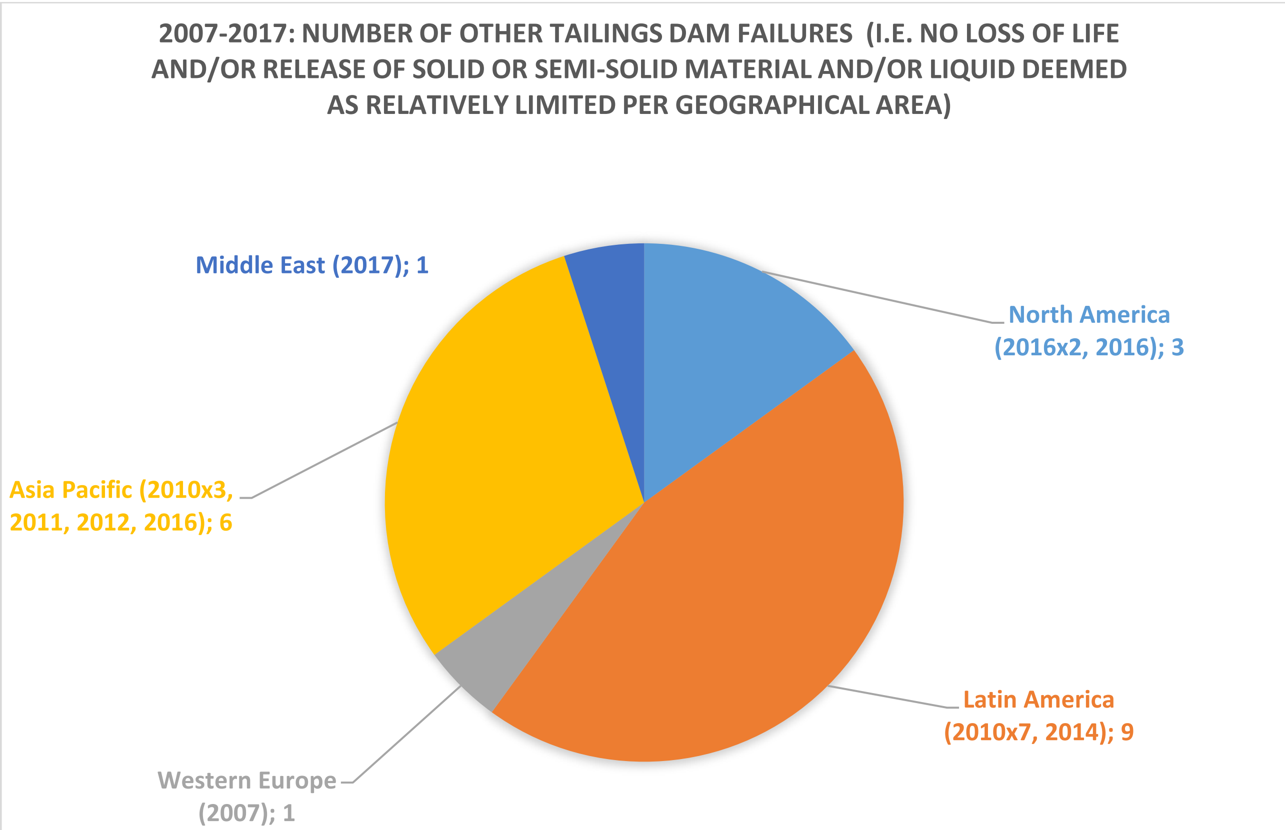
As a result, there are various sources available, and the accuracy of data is difficult to establish.

The following diagrams intend to give an overview of the largest tailings dam failures and tailings- related incidents reported worldwide:

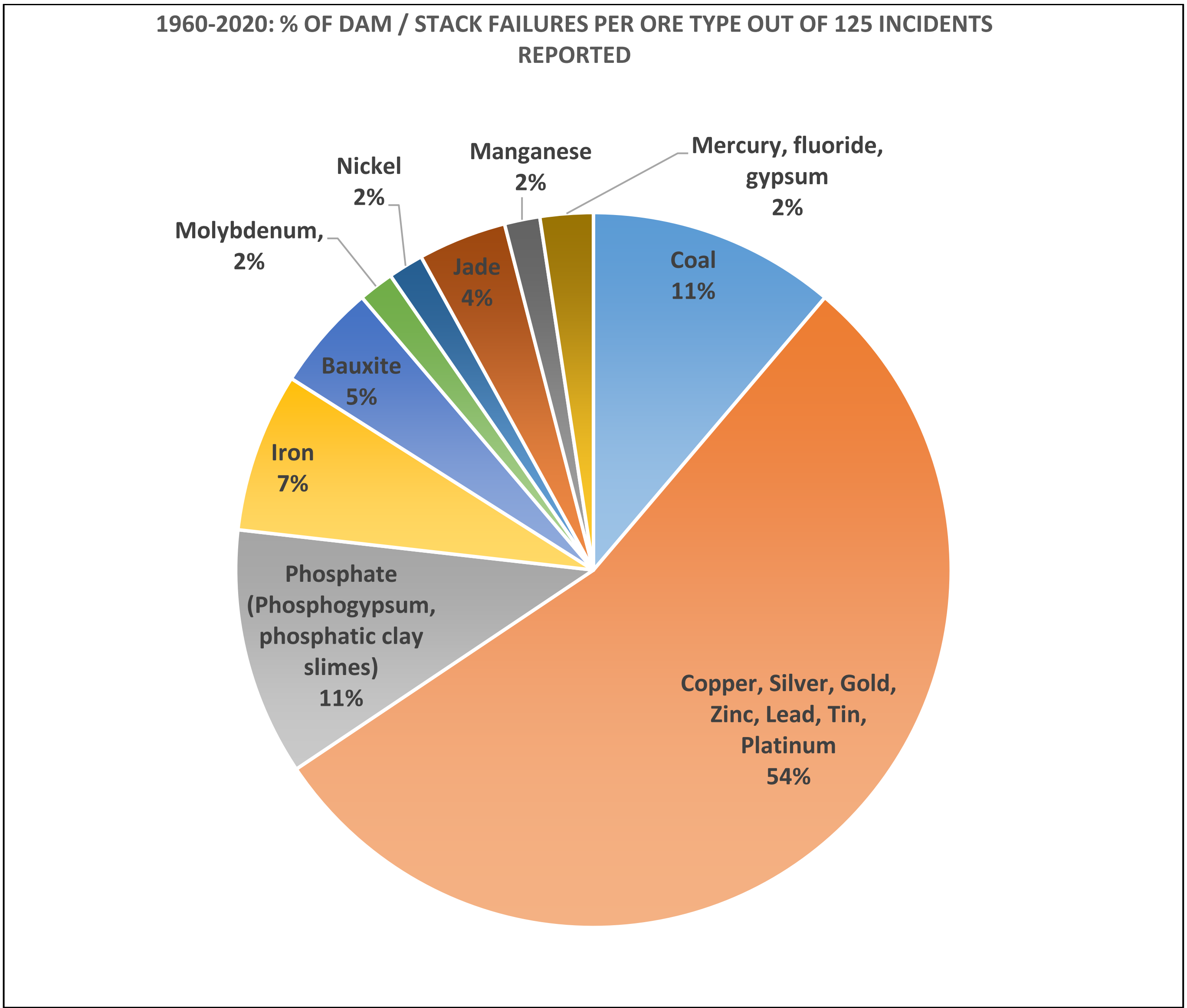





2007-2017: NUMBER OF SERIOUS TAILINGS DAM FAILURES (I.E. LOSS OF LIFE AND OR RELEASE OF ≥ 100 000 M³ TOTAL DISCHARGE PER GEOGRAPHICAL AREA)
Asia Pacific (2009); 1
Western Europe (2012); 1
North America (2011, 2012x2, 2013, 2014); 5
Latin America (2014); 1


2007-2017: NUMBER OF OTHER TAILINGS DAM FAILURES (I.E. NO LOSS OF LIFE AND/OR RELEASE OF SOLID OR SEMI-SOLID MATERIAL AND/OR LIQUID DEEMED AS RELATIVELY LIMITED PER GEOGRAPHICAL AREA)
Middle East (2017); 1
North America (2016x2, 2016); 3
Asia Pacific (2010x3, 2011, 2012, 2016); 6
Latin America (2010x7, 2014); 9
Western Europe (2007); 1

Other sources intend showing a chronology of major tailings dam or stack failures per type of ore from 1960 up to 2020, as follows. Again, the accuracy of data is difficult to establish:



5. SOME TAILINGS DAM FAILURES & TAILINGS INCIDENT CASES

5.1. Tailings Dam failure – Iron mine

Collapse of a tailings dam and release of around 12 million cubic meters of tailings.

The mud hit the mine's administrative area and a small community about 1 kilometre from the mine before reaching the nearest river supplying water to one third of the region. 270 people died as a result of the collapse and 11 others were reported missing.

The design of the tailings dam was of the upstream type.

This disaster was reportedly set in motion by several factors, including poor internal drainage and intense rain that gave rise to excess water.

5.2. Tailings Dam failure - Copper and gold mine

A tailings impoundment was breached, resulting in the release of an estimated 17 million m^3 of water and 8 million m^3 of tailings solids that flowed into two lakes and a creek.

The overall design of the TSF incorporated a zoned construction approach using a combination of centerline and modified centerline methods. The Perimeter Embankment (PE) design included a core zone consisting of a glacial till, an upstream zone of sand, a coarse bearing layer, and/or tailings, as well as a downstream zone of rockfill. Filter and transition zones separated the core and the rockfill.

The site geology is complex with multiple glacial tills and glaciolacustrine layers deposited during several advances and retreats of glacial ice sheets over 10,000 years ago.

The dam ultimately failed on a weak high plastic clay layer in the foundation referred to as the Upper Glaciolacustrine Unit (UGLU). This clay layer is only 2m thick and is located 10m below the dam.

5.3. Tailings Dam Failure – Red Mud

Failure of the corner of a red mud reservoir, operated by an Aluminum Production and Trading Company: as a result of the dam rupture, hundreds of thousands of cubic meters of highly alkaline red mud and technological water flooded the surroundings including various parts of the municipalities in the valley. The catastrophe resulted in casualties, more than 300 properties lost and covered more than 1,000 hectares of land.

On the morning of the failure a continuously increasing wind was blowing in the area of the reservoir. According to testimonies, the reservoir water rippled and undulated, but did not hit the walls of the dam. Following the direction of the wind, the waves travelled towards the corner which later broke away. In the 6-month period before the wall failure, excessive volumes of precipitation fell in this area. This heightened the ground water level, and a significant amount of rainwater penetrated the area within the curtain walls. Consequently, the water balance of the reservoir toppled in an unfavorable way. The water level, which was swollen near the curtain wall, and the exceptional volume of rainwater and seepage water collecting in the seepage ditches was pumped regularly into the reservoir. Such a big quantity of water could not be used by the technology, and therefore accumulated in the reservoir.

Further investigations were conducted concluding that the failure of this reservoir structure was due to the converging factors of poor siting, design and construction, as well as regulatory deficiencies and unfavorable environmental conditions.

5.4. Sinkhole – Phosphogypsum wet stack

A sinkhole event under a wet stack located on a previously mined area: water loss was noticed (215 million gallons of process water) before the sinkhole became visible.

Investigations were conducted using laser-based radar (LADAR) showing a 91m (300ft) deep hole, 7m (22ft) wide at the surface and up to 46m (152ft) wide in the middle. According to geological data, only the intermediate aquifer (shallow) was impacted but not the main aquifer (deeper). A monitoring well was installed 6.4km (4 miles) from the sinkhole. No contamination with acidic water was reportedly noticed.

The remediation plan included the construction of a batch concrete plant for installing a 150ft- wide work pad on the surface around the sinkhole as well as an access ramp (12m # 40ft high, 10% slope) for heavy vehicles and equipment. 40-50 holes were drilled up to the bottom of the sinkhole and concrete was injected to seal the potential conduit to the main aquifer. In the meantime, continuous pumping (954m^3/h # 500GPM) of water to be recycled in the process was maintained and testing was performed on 1,400 private wells in the region. This operation took several months, and the costs were around 50 million USD.

6. CURRENT TREND

The current most common solutions considered around the world for the storage of tailings consist of:

- Tailings Dams (also called "wet / slurry tailings dam" or "conventional tailings storage")
- Dry Stacks (also called "dry stacking", "dry stack storage" or "filtered tailings")

Further details are given below.

6.1. Tailings Dam Overview

Up until recently, the most common method and the cheapest way of managing tailings was stockpiling diluted or concentrated tailings slurries in ponds or impoundment dams.

The slurry is usually pumped from the ore processing plant to the tailings dam through a network of pipes.

Tailings ponds are constructed to permanently store the mining solid waste tailings forever. Some of the largest containment ponds constructed are over several miles in diameter and hundreds of feet deep. Tailings ponds may contain up to 60-80% of water.

Tailings dams are often built using the coarse fraction of tailings from mineral processing installations with steep slopes, thereby saving on costs.

See Section 2. for more details about the related hazards and assessment.

Due to several catastrophic large tailings pond failures causing loss of lives, destruction of large areas of land and pollution of waterways (canals, rivers or narrow sea channels), new technologies for improving the management of tailings have being considered and developed as, for example, the dry stack below.

6.2. Dry Stack Overview

The dry stack tailings method is not usually used in mines, where geotechnical conditions and the abundance of water tend to favor the use of tailings dams.

More common improved tailings management systems include thickening tailings (see paste tailings above) by mixing them with other materials such as cement, forming a paste.

To reduce the tailings volume further, dewatering technologies have been employed to remove additional water from thickened tailings slurries before placement in the containment pond.

Innovative modern dewatering technologies include press filters, vacuum belt filters, belt filter presses and centrifuges. The goal is to recover the maximum amount of water and generate a dry, stackable material (“dry cake”, “dry stack”).

Dewatered tailings can still contain 10- 20% moisture, but the material behaves more like a solid, making it possible to dry stack the tailings in containment areas located relatively far away from the process area, using trucks for transportation. Tailings are usually compacted into engineered mounds for stability.

II - FOCUS ON TAILINGS DAMS

1. STRUCTURE

Tailings are the materials left over after the process of separating the valuable fraction from the uneconomic fraction (gangue) of an ore in mining operations.

The tailings may be treated in order to neutralize acids and precipitate compounds such as heavy metals before pumping to the dam.

Tailings usually take the form of a liquid slurry made of fine mineral particles. Tailings may also be thickened.

Tailings dams are typically an earth-fill embankment dam.

Tailings dams remain wet during their entire operational life and normally only start drying out after decommissioning.

While water-retaining dams are designed and initially built to full height, then filled and operated, tailings storage facilities are usually built incrementally and operated during this incremental building phase.

Therefore, the construction of a tailings storage facility may take many decades until it reaches final design height, with a single tailings storage facility often being used for the entire life of the mine.

The design, construction and operation of tailings dams is a major consideration for most mining operations.

The disposal of tailings introduced may represent a significant fraction of production costs.

For economic reasons (i.e., transportation costs), tailings dams are usually located close to the mine.

However, the ground underlying the dam must be structurally sound and able to bear the weight of the impoundment. This should be the case at the time of the construction but also during the operating life of the tailings dam. Adequate monitoring should be provided, and investigations should be conducted in areas prone to phenomena that can impact the stability of the tailings dam (e.g., an area prone to sinkholes).

In some cases, when the ground properties near the mine are not suitable for such tailings storage, slurry may be pumped far away from the site to a suitable tailings' storage location. This will also add to operational costs.

For some ores, tailings storage may also be found at the process site where the valuable fraction is extracted through a chemical process and the residue is stored in a dedicated area (see Section 4: Focus on Some Specific Residues).

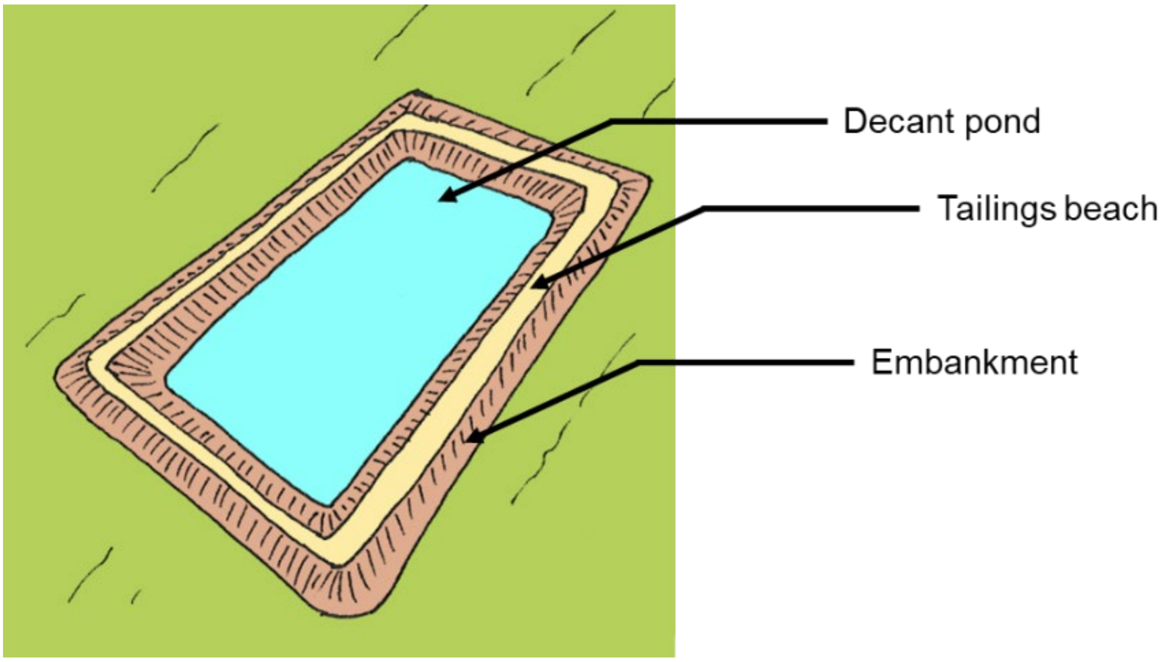
The type of tailings embankment is generally determined by the local seismic activity, ground condition, potential exposure, water clarification requirements and the need for recirculating the water to the process, tailings properties and stability, tailings size distribution, foundations, hydrological conditions, heavy rains, arid conditions, environmental factors and local regulations.

In order to ease the drainage of water, tailings dams may be built across river valleys or on the side of valleys with dam walls. "Lagoons" surrounded by multi-sided retention walls are built on relatively flat ground or ground provided with a gentle slope allowing for better drainage.

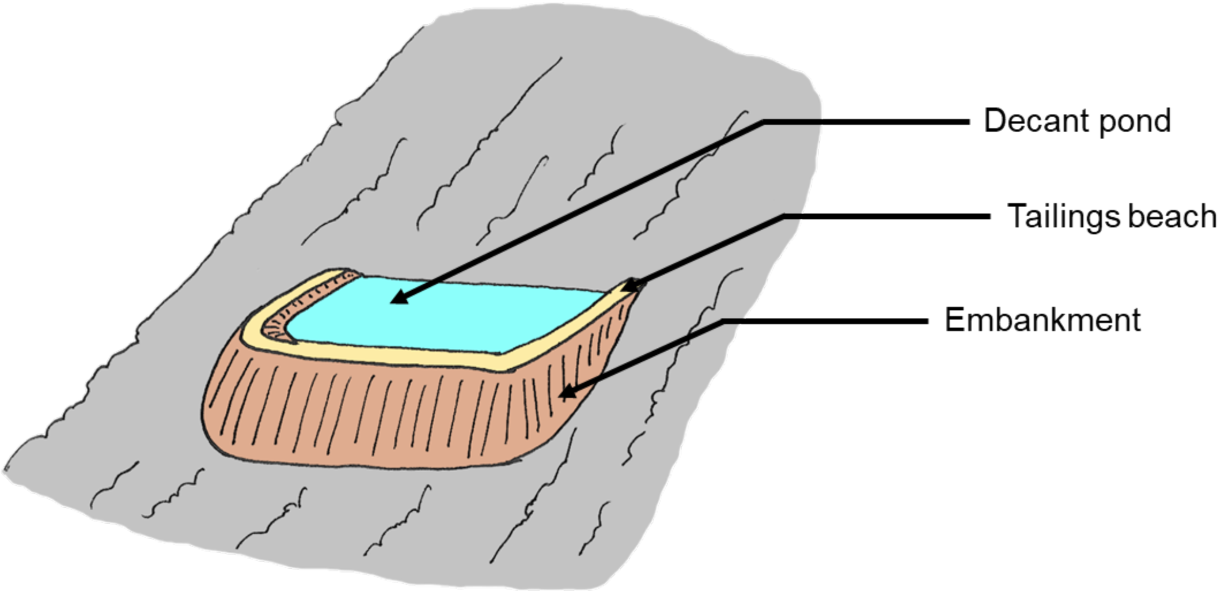
1. CONFIGURATIONS

Three configurations of tailings dams are used:

Paddock (or ring dyke): an enclosed dyke built above relatively level ground requiring 4 dam walls.

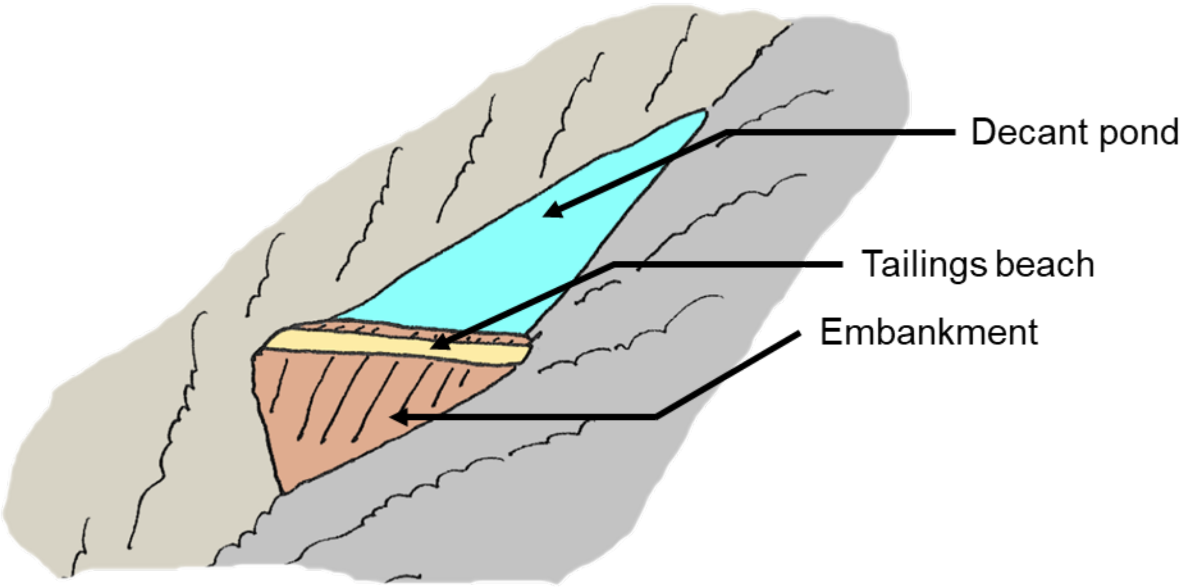


Hillside: the impoundment lies along the side of a slope or hill (3 dam walls needed), and does not cross a valley bottom



Example of a hillside-type tailings dam

Cross valley: the embankment crosses and blocks a valley - 1 or 2 dam walls needed.



Example of a cross valley-type tailings dam

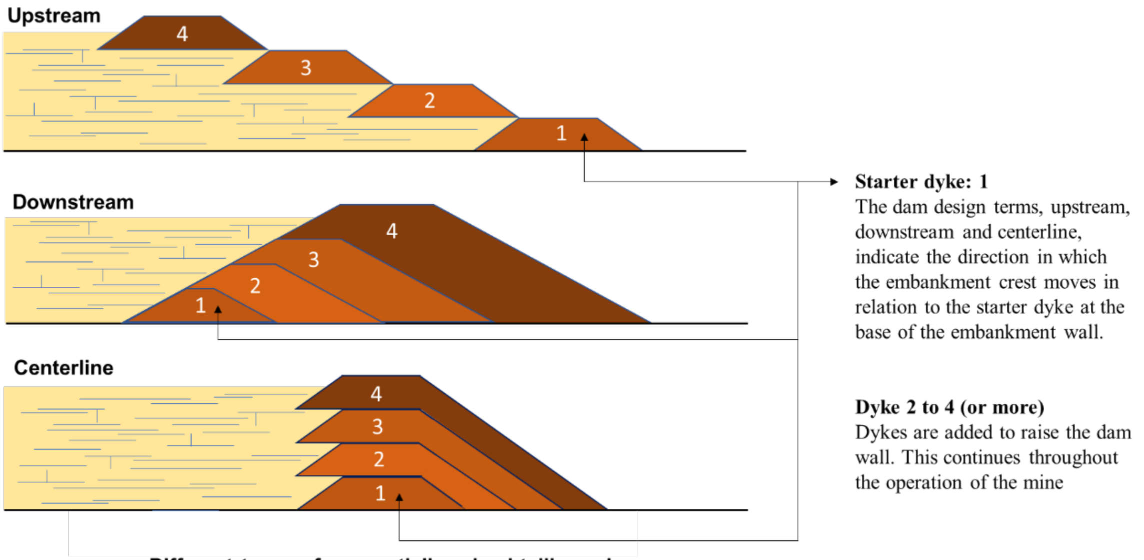
2. DIFFERENT TYPES OF SEQUENTIALLY RAISED TAILINGS DAMS

There are basically 3 different methods to raise tailings dams, as shown and described below:

1. **Upstream method** of tailings dam construction:
   This method is so named because the centerline of the dam moves upstream into the pond.
   In this method, a small starter dam is placed at the extreme downstream point (starter dyke) and the dam wall is progressively raised on the upstream side. The tailings are discharged by "spigoting" off the top of the starter dyke and, when the initial pond is nearly full, the dyke is raised and the cycle repeated.
   Material may be taken from the dried surface of the previously deposited tailings and the cycle repeated, or more commonly, the wall may be built from the coarse fraction of the tailings, separated out by cyclones or spigots, with the fines being directed into the pond.
   The disadvantage is that the dam wall is built on top of previously deposited unconsolidated slimes retained behind the wall.
   There is a limited height to which this type of dam can be built before failure occurs and the tailings flow out.
   Several major failures have involved tailings dams constructed with the upstream method.

2. **Downstream method** of tailings dam construction:
   This method produces safer dams both in terms of static and seismic loading.
   Downstream dam construction begins with an impervious starter dyke and normally includes an internal drainage system. The tailings are first deposited behind the dyke and the embankment is raised over time.
   As the dam wall is raised, the centerline shifts downstream, and the dam remains founded on coarse tailings. Most procedures involve the use of cyclones to produce sand for the dam construction.
   The major disadvantage of this technique is the large amount of sand required to raise the dam wall.

3. **Centerline method** of tailings dam construction:
   The centerline method is a variation of the downstream dam. The crest remains in the same horizontal position as the dam wall is raised.
   It has the advantage of requiring smaller volumes of sandfill to raise the crest to any given height. The dam can thus be raised more quickly and there is less trouble keeping it ahead of the tailings pond during the early stages of construction.
   Care, however, must be exercised in raising the upstream face of the dam to ensure that unstable slopes do not develop temporarily.



Different types of sequentially raised tailings dams

3. EROSION

Erosion of dams due to wind and rain can affect the stability and produce environmental problems. Many methods are used to combat this, such as vegetation of the dam banks and chemical stabilization to form an air and water-resistant crust.

A water-resistant crust may appear inside the tailings (i.e. internal erosion). This so-called secondary mineralization or natural cementation may suddenly break because of the internal load, releasing high pressure that can lead to “static liquefaction” and eventually to a rupture of the tailings dam.

4. MONITORING

In some countries, safety monitoring has been applied in geotechnical engineering for many years.

A number of technologies are employed by mining companies as a means to take tailings monitoring to the next level, but a clear picture of their advantages and disadvantages is needed going forward. They could include (but are not limited to):

Ground Penetrating Radar:

- Capable of monitoring and detecting movement within an embankment in real-time and triggering an alarm.
- This works by sending a radar pulse through the ground and measuring the time it takes to rebound, allowing an internal map of the ground to be drawn.
- This method has proven most effective when used on solid structures such as cliff faces or concrete retaining walls.
- This technology is, reportedly, not ideally suited to the dynamic structures of tailings dams that will ultimately move over time and potentially present new risks.

Terrestrial LiDAR:

- LiDAR uses a laser scanner to measure minute movements in the dam wall, building up a topographical model which can be compared to previous data or be programmed to scan continuously, triggering an alarm if movement is detected.
- The technology’s effectiveness varies depending on the nature of the dam. In the case of a downstream tailings dam, for instance, the constant expansion of the structure may reportedly cause false positives or create erroneous data which cannot be used.
- LiDAR is, reportedly, best suited to closed sites where the dam structure is intended to be final.

Seismic sensors:

- Designed to detect activity caused by earthquakes which could potentially result in a dam failure.
- There are also sensors using accelerometers and magnetometers to detect minute movements in the dam walls that can be set up to trigger alarms.
- Seismic sensors also reportedly have the downside of sometimes producing false positives, especially around active mines, where blasting is commonplace.
- These sensors could, reportedly, be connected and engineered to provide data in real time.

Various modern online monitoring systems are available such as (but not limited to):

Tailings dam displacement and saturation line online monitoring systems:

- Dam displacement GPS online monitoring system consisting of sensors deployed on the dam surface collecting data about the slope displacement and differential deformation of the tailings dam in real time
- Saturation line online monitoring that tracks the free water surface line of the seepage flow net, which is the lifeline for the safety of tailings dams, because the height of the saturation line directly relates to the stability and safety performance of the dam body. Vibrating wire-type sensors can be used for online monitoring of the tailings dam saturation line
- Data collection key factors: the monitoring indicators and monitoring point deployment plans should be selected scientifically and rationally according to the actual conditions of the tailings dam. The effectiveness of monitoring and early warning systems aims at reducing the cost of monitoring.
- Data display key factors: the tailings dam online monitoring system should provide true data indicating the production and operation status of a tailings pond, and should send out an early warning for any hidden safety hazard of the tailings dam, so that the mine operator is able to strengthen its hidden safety hazard remedial efforts accordingly, improving the safe operating conditions of the tailing ponds, ensuring long-term safe operations.

Subsidence and deformation monitoring through satellite imaging:

- This technic aims to perform ground deformation mapping and monitoring by satellite.
- This is done through East-West and Up-Down deformation rates produced by combining data stemming from ascending and descending orbits.
- Data are routinely collected using the Interferometric Wide Swath (IW) mode which is designed to be used for Interferometric Synthetic Aperture Radars (InSAR), a technique that allows the measurement of relative motion of the surface. Such motion includes movement of natural terrain caused by seismic strain, landslides and mining or landfill activities.
- SAR can provide a historical analysis of ground movement that can be used for infrastructure monitoring. Acquiring frequent (bi-monthly) infrastructure displacement measurements can serve as an early warning system for possible infrastructure malfunction or failure. This allows prioritization of vehicle and person-based inspections, thus reducing costs and increasing the efficiency of maintenance planning.
- SAR and GPS can often work in tandem, complementing an overall effort to keep public and private infrastructure closely monitored and stable:
    - GPS: 24-hour monitoring, defined area of interest, immediate need for information, requires a physical presence on the ground (receiver)
    - SAR: trends over time, large scale areas (up to 10,000 km2), long-term coverage of an area providing bi-monthly information, ability to monitor anything without a predefined location

5. GUIDELINES FOR ASSESSING A TAILINGS MANAGEMENT FACILITY (TMF)

Special thanks: The following handbook was compiled with the contribution of Chartered Mining Engineers.

Note – these notes are made for guidance only. They are not exhaustive and touch only on the key areas.

The following is meant to be a basis for eliciting a better understanding of the hazards associated with tailings dams and the preventative and corrective measures to be taken.

A questionnaire has been developed enclosing a preliminary list of questions for eliciting details about tailings dams that have a bearing on the quality of the facility **i.e. is it fit for purpose?**

5.1. Context

In terms of losses, scenarios concerning tailings dams are of an order of magnitude beyond most Loss Estimates incurring large Business Interruption (BI) losses grossing hundreds of millions in USD.

TMFs contain most of the waste material resulting from ore processing techniques where water is used as the media to transport crushed and ground material to allow for economic recovery of the target element or material. The residue that is formed can be fine (slimes) or larger coarser material and can include chemical effluents that pose an environmental issue for an operation should there be seepage into the local environment.

These paragraphs provide a summary view of the hazards, the causes and various 'look-outs' and rules of thumb that the author has established from his own work in assessing the risk quality of tailings dams. It would be pertinent to state that most risk engineering surveys are limited to a broad interpretation of the key articles (if at all) and the aim of the detail supplied herein is to help the 'interpreter' of this engineering detail to establish a reasonable rationale as to the quality of the TMF; and by the term quality, we mean 'fit for purpose'; is the TMF designed to achieve the requirements for the entire lifecycle of the dam (including closure)?

Some of the main exposures for TMFs are:

- Breach and subsequent inundation/destruction/pollution of downstream/zone of influence areas (PD/BI and penalties)
- Cessation of works by acts of authority (BI)

5.2. The problem

There is no doubt that legislative and regulatory penalties are great motivators for the design and operation of TMFs.

Most large mining entities have a long legacy of tailings dams which have gone through many changes in ownership and design; deviations (creep) from the original design and an increase in dam heights have typically resulted due to the ignorance of the mining company (at decision-making levels).

The cheapest solutions are (in descending order – cheapest first)

1- Upstream design
2- Centerline
3- Downstream

There are also variations and so-called hybrids and we see many examples where the original design was downstream before being subsequently changed to upstream but there is no paper trail with these decisions noted.

The cheapest and traditional TMF design has always been the upstream design with slurry (*). This is the cheapest and weakest method (water introduces adverse conditions) and the dam wall strength is dictated largely by the shear strength of the tailings (as the dam is raised onto the previously deposited tailings). Many dams have just been raised and raised, a decision perhaps driven by the lack of location for alternative dams (expansion) or more likely because it is the cheapest option (economics). These legacy dams (but not only) pose a large threat. Not all upstream designs are badly engineered though, but as a rule of thumb, dams higher than 40m in vertical height with an upstream design become riskier propositions. These dams should be particularly adequately managed i.e., strong water control (minimum water containment), adequate operating procedures, inspections and auditing programs, training of operators, ownership, leadership, etc.

(*) Slurry, paste and dry stacks are all used.

Dry Stack

Slurry

Slurry contains the most water, and paste can be anything over 60% solid. The reduction in water content has a huge bearing on the risk quality for a dam and where there is minimal water i.e., a dry-stack, this becomes the superior, but most expensive option.

Good regulation is one thing, but good monitoring is essential as long as it is adapted for the real exposure of a given dam (one size doesn't fit all) depending on the original design (upstream, centerline, downstream), design changes (if any), material, geology of foundations, hydrogeology, weather conditions, exposures, etc.

A combination of recent large TMF failures has created greater public awareness and many governments have pushed for tighter controls and better regulations which have established better guidance via various governing bodies e.g., (ICOLD).

5.3. Rules, Best Practices and Guidelines

Though a consistent assessment of the global inventory of tailings dams does not exist, sources such as the **International Commission on Large Dams**, an institution which maintains the World Register of Dams and which contains more than 58,000 entries, suggests there may be approximately 3,500 tailings dams worldwide.

Currently there is no set of universal rules defining exactly what a tailings dam is, how to build one and how to care for it after it is decommissioned.

There are also no prescriptive standards about mining as such but rather guidelines that a country may choose to adopt and interpret and that lead to a form of regulation. Penalties are becoming the way to ensure the enforcement of the resulting regulations.

Only three countries in the world – Chile and Peru (as they are seismic areas) and more recently Brazil - ban upstream dams.

There are many guidelines that can confuse the underwriter/engineer but in general the principal guidance is taken from the **International Commission on Large Dams (ICOLD),** (https://www.icold-cigb.org/). ICOLD is an international non-governmental organization dedicated to the sharing of professional information and knowledge of the design, construction, maintenance and impact of large dams. It was founded in 1928 and has its central office in Paris, France.

One of ICOLD's functions over the years has been to distill best international practices on all aspects of dams. This is done by 26 Technical Committees drawn from their membership of over 100 countries. These are then published in the form of Bulletins of which, to date, ICOLD has published more than 180.

There are various international members of ICOLD including ANCOLD (Australia), FINCOLD (Finland), INCOLD (India, etc.) amongst others; in fact, most countries subscribe to ICOLD.

However, ICOLD is not a regulatory body. They provide the baseline best-practice principles in accordance with which dams should be designed, constructed, operated and closed.

In 2001 the **International Council on Mining and Metals (ICMM)** was developed bringing together mining and metal company members and national, regional and commodities association members dedicated to a safe, fair and sustainable mining and metal industry.

Co-convened by the International Council on Mining and Metals (ICMM), the United Nations Environment Program (UNEP) and Principles for Responsible Investment (PRI), the Global Tailings Review has established a robust, fit-for-purpose international standard for the safer management of tailings storage facilities: Global Industry Standard On Tailings Management https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard_EN.pdf

The Global Industry Standard On Tailings Management basically aims at consolidating all the best practices and proposing a management plan.

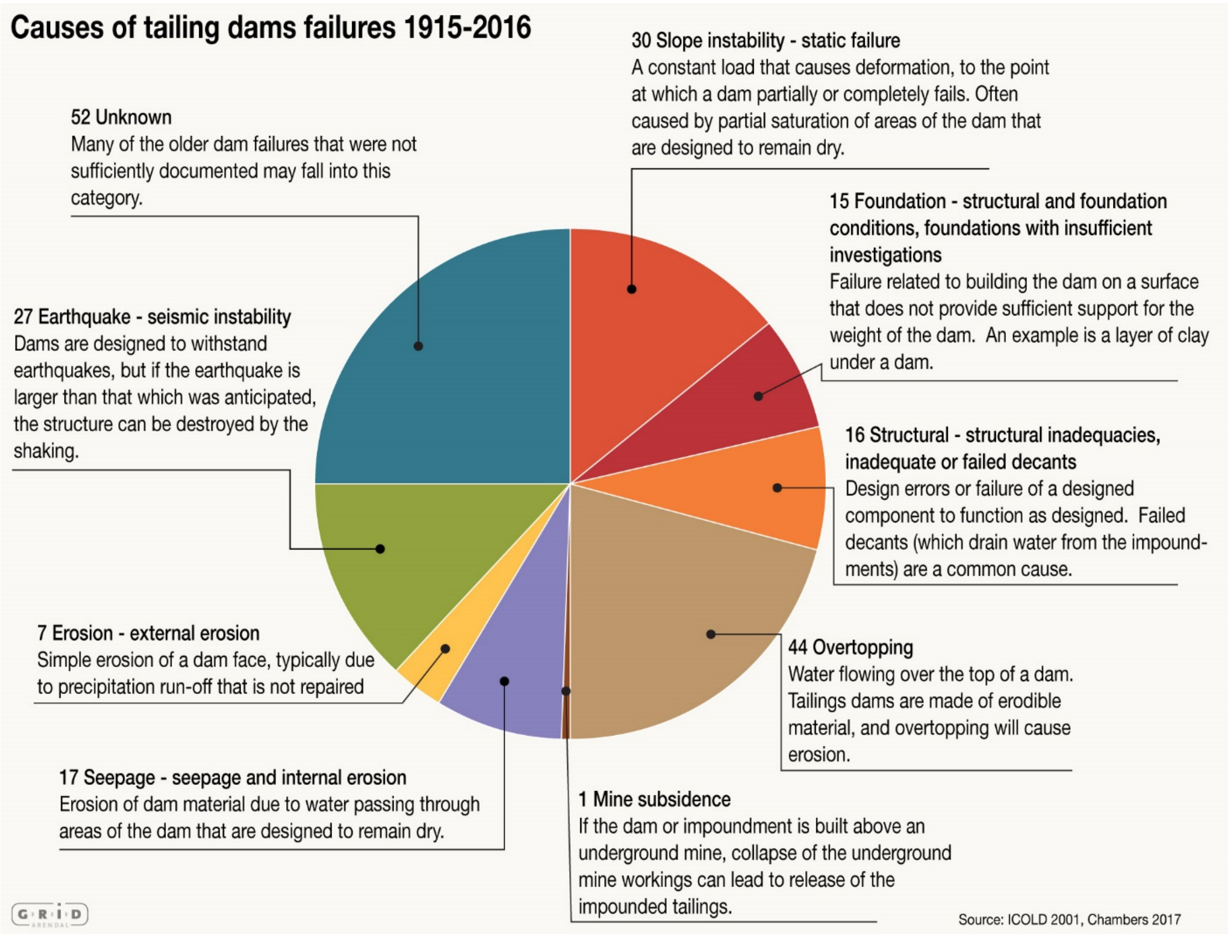
5.4. Why do failures occur?

Below are some typical examples:

- Liquefaction – when saturated tailings lose their strength (upstream and modified centerline dams only)
- Erosion – uncontrolled water
- Piping and internal erosion - incorrect design and/or construction
- Overtopping – insufficient freeboard/excess water. (One of the causes of overtopping can be slope instability further upstream and slope failure into the retained water can produce large waves that in turn overtop the dam)
- Seismic deformation
- Rotational sliding – construction materials/ geometry/pore pressures
- Seepage - incorrect design and/or construction
- Foundation failure - inadequate/incorrect geotechnical / geological / geophysical evaluations: (Foundation seepage as a cause of failure: one of the forms of failure - or at least of a need for significant remedial work - associated with foundations has been with limestone bedrock whereby the limestone has actually been damaged by water dissolving the material).
- A combination of the above

The most common theme here is water and it is without question the one parameter that contributes to a TMF failure. "Water is not our friend and less is best".

The following diagrams show reported causes of tailings dam failures from 1915 to 2016:



Courtesy of GRID-Arendal, Cartographer Kristina Thygesen https://grida.no/resources/11424

5.5. Preliminary questions – Global level

We have the following preliminary questions which may have to be completed with additional questions (see below) for better understanding a given TMF.

1) TMF management of change/configuration management:

a) **Are all technical documents available, from design stage up to present day?**

We are looking for indicators of good management and a precursor to this will be document management for all designs and changes going back to the geotechnical data. We want to see if the dam has been designed using appropriate engineering techniques. In some instances, there may be no indication of any MOC (Management of Changes) or configuration management or even an understanding of what geotechnical investigation was undertaken; this may be due to changes in ownership of the operation, or simply lost in time but it signifies a red flag.

b) **If the dam design has changed since the original design what were the drivers for this change and are these still relevant and on what/whose engineering authority?**

What we want to see is good regulation, supervision and governance.

c) **What was the original design life? What is it now? How was this change (if now beyond the original design life) managed and what are the changes (of Factors of Safety – FoS, etc.)? What are the future plans?**

We are looking for deviations from the original design requirements and established design. Sometimes we see changes completed by a consultant engineer and these may be appropriate or just cursory and maybe incorrect. It can be difficult to ascertain the position but only through questioning can we reveal any flaws.

2) What are the FoS for static failure?

In terms of static failure, we do not just want to see what the original design FoS was but what it is now and how this has been maintained over time or has there been a deviation? Note that the FoS can be reviewed and updated during inspections in terms of compliance with the regulatory body. The usual FoS – as per guidelines - for static loads is 1.5 with the exception of 1.3 during construction when remedial actions can be quickly implemented if a potentially unstable situation occurs. This lower FoS can only be used where there is no risk to life or release of tailings or water to the environment in the event of failure. The alternative fallback methods are defined in various tables in the ANCOLD Guidelines. The tables prescribe specific requirements for various aspects of dam design, including earthquake loading, freeboard requirements, spillway capacity and FoS.
Areas to consider are changes in width-to-height ratios. This will have a strong bearing on the FoS and generally we consider 2/2.5H: 1V (H: Horizontal. V: Vertical) as appropriate but this will be subject to the geotechnical requirements and the stability of the material/bedrock-basement interaction.

3) What are the design requirements for overtopping and seismic activity?

ICOLD exhibits these design requirements as an Annual Exceedance Probability (AEP).

- Flood - 1/1,000
- Earthquake - 1/10,000

ICOLD goes further, explaining that mining dams are often considered to remain in place in perpetuity i.e. a nominal life exceeding 1,000 years. In this instance, the design requirements should be:

- Flood – Probable Maximum Flood (PMF)
- Earthquake MCE – Maximum Considered Earthquake (MCE)

4) Is there a Breach Analysis? What is the impact and remedy for the scenarios (e.g. for Upstream Design TMF; CAPEX; time frame)? Collateral damage? Acts of authority (duration)?

What we are looking for is some indication of their readiness in the event of a failure. Breaches can sometimes be remedied, and it is only the absence of resources (people, equipment, training, etc.) that limits these possibilities. Such scenarios should include the associated BCP as this will be the highest risk to the operation.

5) Is there any potential for a local landslip into the dam itself?

In some parts of the world, landslips are a common feature and should the side of a TMF fail there could be overtopping of the dam and subsequent possible failure (if there is a landslip into the dam then that energy could lead to a catastrophic failure). We want to be sure that they have done their homework and this awareness has been considered in the design of the dam.

6) What is the closure plan and what hazards have been identified?

In essence, how will the dam be managed and maintained as safe? In Chile for example, basal drainage is required to be at an FoS of 10 which is enormous, but this compensates for any blockages of drains over time so that it will always be safe. Other considerations could be diversion channels and/or automated drainage wells in the dam itself to ensure that water levels do not become critical, leading to potential hydraulic uplift and potential failure.

7) Have there been any leaks in the dam, any seepage? Has there been any rat-holing or slumping in the tailings themselves?

Seepage is an issue as it can signify serious problems relating to internal erosion which is one of the main causes of failure. The Brumadinho TMF failed as a consequence of this, although seepage was noted well in advance of the failure, but little was done about it.

8) Is there a tailings management plan?

We want to see good governance. How are procedures documented and how are they reinforced i.e., management/supervision?

9) TMF audits

What is the process and frequency? What are the main steps, focus points, do they include studies of original design documentation, changes and reviews of management programs – i.e., monitoring / supervision / dewatering procedures? Are there lists and names of the experts and reports available for our review? In terms of policies/procedures and design changes, these should be audited based on the frequency of change. Many organizations look at 2-yearly periods or less, subject to need. What we want to see is that they undertake audits and that these are bespoke, corresponding to the nature of the changes of that particular TMF.

5.6. Additional questions – Tailings Management Facility (TMF) level

The following questions may help to complete the preliminary questions above for a given TMF when needed.

10) Date of commissioning?

A TMF is generally at its most robust at the beginning and becomes increasingly riskier over time as the height increases. For upstream dams, any facility over 40m should be considered very risky.

11) What was the original basis of the design?

Is it a valley fill or impoundment or something else? There are many designs, the safest being an old exhausted open pit facility. Valley fill offers other risks that may require diverting the local hydrology, etc. The aim is always to keep water away from the TMF wherever possible.

12) How was the dam wall built? And what from? What is the starter dam made from? What was the QA/QC?

We want to see a well-engineered starter dam as this is where the load bearing takes place. We also want to be satisfied that not only was it designed appropriately but that it was built to plan.

13) What is the foundation of the dams? Can it degrade over time and weaken the structure? Describe the geological/geophysical/geotechnical work that was undertaken. How many drill holes and trenches? What was the dam preparation – was there much removal of soils/colluvium and what dictated this removal? Is the dam wall tied into solid rock?

All of these factors relate to the stability of the dam. What we want is a dam tied into a competent bedrock - what we sometimes get is a dam built on loose materials or faulty bedrock that is prone to degrading which can then compromise the dam.

14) Is the dam lined or unlined?

A lined dam is best as far as we are concerned, as we negate any issues with seepage (if integrity is maintained) which can lead to failure.

15) What freeboard is there?

Freeboard will be designed to accommodate a flood event and in general we would like to see >1000-year return periods for this. The cost of doing this tends to be prohibitive for many operations and they attempt opting for a cheaper solution whereby you will see 50-year return periods with rainfall over 24 hrs., etc. The idea of freeboard is that this provides a buffer for containing any water that emerges into the dam. The safety feature here is usually an overspill but not always, as the area of the TMF can be very large so that overtopping is practically negated.

16) Are there any spillways? Are these kept clean?

Spillways are important as a preventative feature. If these are blocked by rock or foliage then this would compromise the dam itself.

17) How is water managed in the dam itself – how is freeboard maintained? Pumps: how many/redundancy/power?

Freeboard is maintained by controlling the water levels through pumping.

18) Are there any monitors and where are they? How is dam wall movement monitored: is it real time/nr real time or another frequency i.e., online or dedicated Survey Department?

One of the key indicators of an impending dam failure can be movement. Newcrest's Cadia Mine failure in 2019 is an example of this whereby a back analysis revealed that movement was identified at least 6 months before the event itself.

19) Is there any water underneath the dam? What about hydrostatic uplift potential; seasonal variations? Are there any sinkholes or old workings in the local geology?

Positioning a dam is very difficult, and the local topology is often a strategic constraint i.e., you are where you are. This means that sometimes TMFs have to be situated above old water courses or perennial stream beds, and diversion techniques are used. Sometimes the ambient phreatic levels (water table) can rise and in such an instance can cause a hydraulic uplift simply because water is not compressible (non-Newtonian fluid) and can uplift up the dam simply by being underneath it. Sinkholes and old workings are another feature that should be revealed during geological/geophysical/geotechnical investigations but, if this is not thorough, anomalies can be missed. This is what occurred at the Hemerden tungsten mine in the UK where old tin streaming workings were not initially identified; had they not eventually been picked up, this would have been troublesome and potentially catastrophic.

20) Are there any roadways or buildings or structures on the dam wall?

A dam is built to fulfil a certain utility. This utility won't include roadways, haulage routes, telegraph/electrical poles/pylons, housing or offices, etc. Nor do we want to see heavy flora such as trees or even wildlife such as burrowing animals.

III - FOCUS ON DRY STACKS

Filtered tailings can be a viable disposal alternative to slurry, thickened or paste tailings at many mine and ore processing sites.

1. DEWATERING TECHNICS

The filtration process basically accelerates the consolidation process that would naturally occur in other tailings deposits (slurry, thickened or paste). The resulting filtered product is an unsaturated (often between 50 to 75 % saturated) material that is firm with a low compressibility and low hydraulic conductivity. In this state, the filtered tailings are often termed "dry stacked" tailings, since the materials resemble a moist sand that can be stacked and compacted into a stable landform.

Dewatering or tailings filtration can be accomplished through the following main techniques:

- **Gravity Belt Thickener**: reduces the sludge volume of solids, waste-activated sludge and slurries and produces a pumpable concentrate for further dewatering, treatment or transport. A Gravity Belt Thickener is a highly effective tool for dewatering. It operates quietly at a minimal cost, consuming low volumes of wash water. Sludge may be flocculated using polymers, introduced on the belt, and the released water is drained through the gravity belt.
- **Filter press**: also called a Plate & Frame Press or "membrane filter plate". It consists of two basic components, including a skeleton frame and a plate stack. Filtration is achieved by clamping the plates together and pumping slurry under pressure into the cavities formed between the closed plates. Filter media line the chambers and capture solids while permitting clarified liquid to pass through. Filtration proceeds until the cavity is filled with cake or a preset pressure is reached. By unclamping and shifting the plates, the cake drops from the cavities and the filter is ready to repeat the operation. The filtration rate is dependent on feed pressure, thickness of the cake, slurry temperature and viscosity, nature of the cake solids, and filter media.
- **Belt filter press**: a belt press separates water from solids by using a series of belts and rollers that process, transfer and compress the solids in various ways to separate them from the water. Belt presses have 4 main zones consisting of a preconditioning zone, gravity drainage zone, linear compression (low-pressure) zone and roller compression (high-pressure) zone. Preconditioned slurry, which is flocculated and/or coagulated depending on the feed and process, is thickened in the gravity drainage zone. The gravity drainage zone is a flat or inclined belt where gravity drainage of free water occurs. The gravity drainage area is sized according to solid feed concentrations. Depending on the required conditions of the cake, belt filters can have added washing stages and infrared, hot gas or even microwave drying stages. Belt presses are an effective and efficient way to clean all types of process water, wastewater, industrial and agricultural water, and more. Once the solids are separated out using the belts and rollers, they are typically augered into a container or truck for easy disposal.
- **Screw Press**: a screw press separates liquids from solids by continuous gravitational drainage. Screw presses are often used for materials that are difficult to press, for example those that tend to pack together. The screw press squeezes the material against a screen or filter and the liquid is collected through the screen for collection and use.
- **Vacuum belt filter**: the sludge is delivered to the filter fabric by the feeding system. The filter cloth is driven by a rubber belt with horizontal notches and holes on it, and this enables the filtrate to be sucked into the vacuum box. The sludge forms a dewatered filter cake after passing through the forming zone, washing zone and drying zone before being discharged at the end of the filter belt and then transferred to the destination by the conveyor.
- **Centrifuge**: a centrifuge separates the water from the solids by high revolution. The sludge is pumped into the centrifuge where the screw and the bowl are operating at a high revolution creating pressure and separating the water. Centrifuges usually operate with a horizontal, rotating, perforated (screen mesh) basket. Feed slurry enters the centrifuge and is distributed to the basket surface. The basket's rotational g-forces push the slurry against the surface of the basket, where

the solids are held in place. The water is able to filter through the thin bed of solids and exit the centrifuge through the holes in the basket surface, to then be discharged. Vibration motors produce a highly controlled, rapid vibration stroke in the basket, which moves the solids a small distance down the basket with each stroke, until they finally discharge as a dry product. The water is discharged into a centrate pan and the dewatered solids are augered into a container or truck for transfer to a landfill or a field site for disposal.

1. DRY STACK ADVANTAGES

Compared to a (wet) Tailings Dam, Dry Stack (Tailings) present the following advantages:

- The structural stability of the material storage is greatly improved. This is especially advantageous in seismic, populated and environmentally sensitive areas (i.e., it reduces dam failure probability and limits groundwater contamination).
- Recycled water diminishes the need for water, sourcing the process.
- Residual process chemicals can also be recovered from the recycled water.
- The complexity of tailings management is minimized (i.e., basically no dewatering system inside the retention).
- The above points prevent pipe freezes and frosting problems in cold climates.
- Minimized land area is needed for storing tailings (lower volume, higher rise rates can be achieved).
- The above points can extend the life span of a tailings storage area.
- In the future, tailings could be progressively reclaimed (closing and rehabilitation) thus reducing the footprint of conventional wet tailings storage.

2. DRY STACK DISADVANTAGES

Dry stack tailings also have some disadvantages such as:

- Modern filtration technology comes with high capital and operating costs (filtration plant, haulage and compaction equipment).
- Up until recently they were mostly suitable for low-throughput operations (the dewatering plant is a bottleneck). While there are several Dry Stacked Tailings (DST) systems operating around the world, the throughput tonnage of these plants is relatively small, so DST may not be economically feasible for larger mines. But with a breakthrough in filtration technology, some manufacturers have shown that a full DST solution is technologically feasible at a large scale and that even for high tonnages, recovering 90-95% of the water can be economically competitive (e.g., compared to desalination for producing fresh water in some areas).
- Dry stack installations in a high-rainfall environment can create day-to-day management problems (see photo below) for trafficability of haulage and compaction equipment. Seasonal fluctuations are an important consideration in the design of a dry stack facility.

Alumina refinery "red mud" dry stacking.

- Dust generation, especially in arid climates, can occur relatively quickly after tailings disposal due to the low moisture content of the placed material.
- Oxidation of sulfides for some ore types (many important metal ores are sulfides such as iron, copper, zinc, lead, nickel, silver) in the tailings can create high concentrations (but low volumes) of seepage water. Dissolved free sulfides (H_2S, HS^- and S^{2-}) are very aggressive species causing corrosion of many metals such as steel, stainless steel, and copper. Sulfides present in an aqueous solution are responsible for stress corrosion cracking (SCC) of steel which is also known as sulfide stress cracking. Corrosion is a major concern in many industrial installations.

3. DRY STACK DESIGN CONSIDERATIONS

Refer to Dry Stack Tailings – Design Considerations, J. Lupo &, J. Hall, AMEC Earth and Environmental, Englewood, CO, USA, as highlighted below:

- In the design of dry stack tailings facilities, it is important to consider the material characteristics that are unique to dry stack tailings as well as operational and material handling considerations of filtered tailings.
- Characteristics include particle size, shear strength, hydraulic conductivity and compressibility.
- The design of a dry stack tailings facility is a balance between the handling and construction of the materials and the geotechnical properties of the tailings. From a material handling standpoint, the facility needs to be designed to support the method of transport and deposition of the tailings to the facility.
- Handling methods and methods of transport may include trucks and/or conveyors depending on the distance and topography between the tailings storage and the dewatering plant. Access roads and cross-country corridors need to be included in the design.
- The tailings property may include a wide range of products (different particle sizes, moisture content) depending on the ore processing and dewatering plant conditions. This leads to a wide range of tailings material (more or less saturated).

The following parameters need to be closely investigated:

- Stacking height, generally based on slope stability (foundations, presence of groundwater under the surface, porous ground, soil layers allowing for lateral movement, clay soil layers “healing” as lateral movement occurs, seismic load).
- Stacking rate (placement and compaction) depending on ground surface available and mining / ore processing output and development. Highly compressible tailings, if stacked too quickly, may generate excess pore pressures, which could compromise the stability of the dry stack.
- Infiltration and Surface Water Management (rainwater). Tailings placed in an unsaturated state result in relatively low hydraulic conductivity. This limits infiltration through the dry stack. However, proper surface water management is needed to control infiltration.

4. DRY STACK MINIMUM REQUIREMENTS

Prior to construction the following basic criteria should be met:

- Soil/underground/basement analysis performed
- No exposure reported from and to plant facilities (i.e., third party, river, lake, sewer network, etc.)

A dry stack should be provided with minimum requirements:

- Upstream diversion systems preventing flooding of the dry stack area
- Surface contour management for preventing surface water accumulation (i.e., rainwater, especially in heavy rainfall regions) ponding and erosion
- A network of haul roads and drains to facilitate transport of residue, collection of leachates (if any) and management of runoff
- A stockpile area for unloading and intermediate stockpiling of residue and waste delivered to the site by road trucks prior to placement in the cells. The residue and waste can then be reloaded onto trucks for transport and placement into the cells where it is spread by bulldozers and compacted. The stockpile area should have a similar lining system as in the cells below.

- Cells for residue storage: storage cell floors should be designed to promote drainage of leachate to sumps. Cells are usually constructed with a lining system designed to resist the high pH conditions expected within the cells (this depends on tailings material type). This lining system may be comprised of (from the bottom up – given by way of example):
  - Prepared subgrade
  - Geosynthetic clay liner
  - HDPE geomembrane
  - Sand protection layer with a network of leachate collection pipes

- The cells should also feature the following:
  - A small perimeter embankment: a cell floor shaped to promote drainage of leachate to sumps (at least 2 per cell to ensure redundancy)
  - Two-way access ramps (1 or more per cell depending on the size) over the perimeter embankment to enable vehicles hauling waste to access the cells
  - Stormwater management drains to channel stormwater to the Runoff Pond
  - Benches on the outer slope to enable progressive capping and rehabilitation of waste slopes

- A pond with one or more compartments for storage of run-off and leachate. The Leachate and Runoff Pond should have similar lining systems as the cells above
- A system to monitor leachate levels in the sumps alerting operators when leachate needs to be extracted from the sumps
- A network of ponds for management of liquids proposed for use as dust suppressants (i.e., Neutralized Waste Slurry - NWS-sedimentation ponds and or Dust Suppression Water Ponds). Usual arrangements include the following (this example is given for an Alumina Refinery processing bauxite ore and producing red mud as a by-product and tailings): The Dust Suppression Pond is used for storage of (sea)water trucked to the site for dust suppression in the ore storage cells. The water is extracted from the pond by water trucks. Neutralized Water Slurry is brought from the Refinery to the dry stack area (BRSA, see below) by tankers and discharged into the sedimentation ponds. Solids in the NWS are retained in the ponds and the liquid is decanted into the Clarified Liquid Pond.

5. DRY STACK OPERATIONS

A comprehensive Operations Manual should be developed by the designers of the Dry Stack detailing the management strategies for the residue storage and ponds, as well as inspection, monitoring and testing methods.

Operational procedures should be in place for movement of residue into the cells to ensure that trucks only travel on already placed and compacted residue.

This Operation Manual should be strictly followed by the Dry Stack operational team.

IV - FOCUS ON SOME SPECIFIC RESIDUES

This Section focusses on material (called residue) produced during the processing of ore.

1. BAUXITE RESIDUE (RED MUD) CASE

The alumina industry produces bauxite residue (red mud) as a by-product of the refining process.

Red mud is a thick red-brown paste consisting of silicon, iron oxide, titanium oxide and other compounds.

Red mud is disposed of in special isolated areas (Tailings Dam or Dry Stack), which are designed to prevent the seepage of alkali contained in the mud into the ground water, as summarized below.

See also the Handbook Aluminum Industry / Alumina Refinery Focus / Tailings for details.

1.1. Red Mud Tailings Dam

Red Mud Tailings Dams (may also be called "Mud Disposal Areas" – MDA - or red mud storage facilities) are often referred to as Dry Stack facilities, even though the tailings are commonly discharged into the facility by pipeline deposition.

In reality, this is a "conventional tailings storage" (high rate thickened or paste but similar to a wet tailings dam), but the term 'dry stacking' refers to the final product based on the methods used to promote sedimentation and release of water within the facility, thus drying and gaining in strength.

Due to the fine nature of the tailings properties, flocculation addition and mechanical disturbance are commonly-used techniques which increase overall operational costs.

Red mud is a material that does not reconsolidate very quickly and so does not usually form its own containment. An impoundment is therefore needed.

See Section 2 "Focus on Tailings Dams" for more details. See Section 1.5.3. Tailings Dam Failure – Red Mud.

1.2. Red Mud Dry Stack

Some low throughput alumina operations filter their tailings to produce a wet cake and thus 'dry stack' the tailings.

This is the common definition of dry stack tailings or filtered tailings placement.

The filtered cake containing approximately 70% solids is usually transported by truck to the Dry Stack area. This area may also be called the Bauxite Residue Storage Area (BRSA).

The residue (filtered cake) is dumped, dozed and compacted to conform to the residue configuration plan in a dry stacking methodology.

See section 3 "Focus on Dry Stacks" for more details.

2. PHOSPHOGYPSUM CASE

Phosphogypsum refers to the calcium sulfate hydrate formed as a by-product of the production of fertilizer from phosphate rock. It is mainly composed of gypsum ($CaSO_4 \cdot 2H_2O$) and impurities carried through the phosphoric acid manufacturing from the source phosphate rock.

There are two types of phosphate processing: wet processing and dry thermal processing. Wet processing, done with sulfuric acid, is the most used method for more than 90% of the phosphate fertilizer production. The reaction of calcium phosphate with sulfuric acid leads to different products depending on the relative amount of sulfuric acid added to the phosphate ore. Phosphogypsum is a by-product of wet processing. Generally, 4-5 tons (Imperial) of phosphogypsum are produced per ton of phosphoric acid (P_2O_5).

As the manufacturing of phosphoric acid is not a mining operation, phosphogypsum is therefore not a mine tailings material. Phosphogypsum is a waste residue from the phosphoric acid production within the fertilizer process.

Phosphogypsum may be:

- disposed as Riverine Tailings Disposal (RTD) or Submarine Tailings Disposal (STD) or Deep-Sea Tailings Disposal (DSTD). See Section 1.1 above.
  or
- vacuum-washed on a filter at the plant in conjunction with either wet or dry stacking operations. Filtration is an important step in P_2O_5 recovery (i.e. the lower the water content of the gypsum filter cake, the better the recovery). From the filter, a chute directs the filter cake to:
  - a conveyor belt in the case of a dry stack. Dewatering technologies are then used to recover the maximum amount of water and generate a dry, stackable material (“dry cake”, “dry stack”). (See below). Note that the actual moisture content of gypsum after filtration and dewatering is typically between 20 and 25% (i.e. 75-80% solids in weight).

  or
  - the gypsum cake is jetted into a slurry tank for hydraulic pumping in the case of a wet stack (see below). The gypsum slurry contains 15 to 30 % solids in weight.

2.1. “Dry” Vs “Wet” Stacking

Although gypsum is a widely used material in the construction industry, phosphogypsum is usually not used, but is stored indefinitely because of its weak radioactivity. Long-range storage is controversial.

The storage of phosphogypsum is highly regulated (e.g., U.S. Environmental Protection Agency) because of the toxicity (*) of these stacks which are classified as tailings or residue management facilities.

(*) acidic water / spill that may contaminate underground drinking water resources, rivers and biota, causing environmental issues.

In terms of the selection of dry vs wet stacking, climate seems to be the overpowering factor and in wet areas such as the USA, wet stacking is almost exclusively used. In most instances, wet stacking is preferred over dry stacking because of economic and maintenance considerations. The key differentiator with phosphate and phosphogypsum waste or residue is that wet gypsum is preferred over very dry gypsum as wet gypsum solidifies into a suitable material after placement, whereas powdery dyke material that is too dry will have to be wetted and moisture conditioned prior to compaction.

With wet transport, the gypsum slurry is transported hydraulically by pumping through pipelines at 15 to 30% solids. Wet hydraulic transportation (which is more conventional than dry transportation) involves pulping the gypsum cake, using fresh water or re-circulated process water, to form a slurry that is pumped through a pipeline from the plant to the disposal site. As such, the costs of pumping material through a pipeline vs conveyor/trucking and filtering material suggests that wet stacking is by far the most economical solution. In areas where water is a limitation this may not be the best solution.

Other factors may be considered:

- Hydrogeology: a synthetic liner or a layer of clay may be needed to control seepage.
- P2O5 recovery: a wet stack allows an operator to recover P2O5 through recirculation of the process water, thus increasing the efficiency of the plant (up to 3%). Return water is typically picked up from the pond or return ditch by vertical pumps for recirculation to the plant to wash the filters and re-slurry the gypsum cake. Soluble P2O5 is recovered from water entrained in the gypsum cake, from unreacted rock and from plant spills diverted to the cooling/surge pond. This can improve plant efficiency by up to 3%.
- Dust control: dry stacks may generate a lot of dust posing a very significant environmental problem.

Details on “Dry Stacking” and “Wet Stacking” are given below.

2.2. “Dry Stacking”

Dry transportation can be achieved by one or a combination of belt conveyors, trucks (these two are most widely used) and even rail cars. This will depend on the distance of the plant to the Dry Stack.

Fig 7 (a) Dry transport by conveyor belts *(b) Dry transport by trucks*

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The corrosive nature of phosphogypsum requires particularly high maintenance of the belt conveyor system. In addition, dusting may have an adverse effect on roller bearings and/or grease in bearings, thus adversely affecting conveyor equipment operations.

“Dry Stacking” may be implemented:

- **With trucks and dozers**: for relatively small volumes on flat areas or on the side of a mountain.
- **In valleys**: a fixed belt conveyor transfers the gypsum cake from the chemical plant to a ridge where a hopper feeds a fixed extendable belt conveyor running along the crest of the gypsum pile. The conveyor in turn feeds a single radial stacker on rails which automatically rotates up to 180º as it senses the buildup of gypsum. Grasshoppers on both sides of the stacker allow for a broader spread of gypsum across the valley.

- **On level ground**: at relatively flat disposal sites the fixed belt conveyer from the plant feeds a series of movable belt conveyors with hoppers (grasshoppers) that are staggered and that feed a stacker dumping the gypsum down the face of the advancing dry stack slope. A front loader is often used for distributing the gypsum cake uniformly across the wide disposal site area. T
- **On liner systems with movable conveyors**: movable conveyors (self-propelled or not) are set in series, one feeding the other, and finally a radial stacker runs perpendicularly to the slope of the stack spreading the gypsum.

Fig 11. Self-contained movable spreader/stacker

Notes:

- Wet Transport and Dry Stacking: on very rare plants the filtered gypsum cake may be slurried and pumped from the plant in high pressure lines to the disposal site where a second filter is used to wash the gypsum with fresh water to a neutral PH. The wash water is returned to the plant for re-use and P_2O_5 recovery. The “dry” cake is then conveyed by belt or truck to the stack area.

Hazards, Prevention, Protection:

- Dry Stacking in valleys: the side slopes of a dry stack advancing by avalanches are barely stable, and the gypsum creeps with time, causing the stack to develop large and wide longitudinal cracks that pose a safety hazard to operational personnel. Heavy rainfall events may fill open cracks and then cause a massive sliding failure of the stack slope. Therefore, such cracks should be properly backfilled as soon as they are detected.

Fig 8 (a) Dry transport to a stack in a valley

(b) Settlement cracks in a dry stack in a valley

- Dry Stacking on level ground: the gypsum slopes formed by the stacker on flat ground will also be positioned at the angle of repose for loose gypsum (a safety factor against failure should be observed). As with a dry stack in a valley, the stack on flat ground advances via avalanches and develops significant cracks.

Fig 9 (a) Cracks in dry stack on level ground

(b) Dry stacking using grass hoppers

(c) Advancing face to dry stack

- The lower portion of a dry stack will be saturated, even in arid climates, due to gypsum self-weight consolidation and settlement. Hence, even without rain infiltration, the lower portions of dry stacks may become saturated with time. As a result, significant seepage can be expected at the base of a dry stack. A synthetic liner or a layer of clay and some containment around the dry stack is therefore required to control seepage of entrained process water from the stack.

Fig 10. Seepage from the base of a dry stack

- For a dry stack advancing via avalanches (see stacking on level ground or in valleys above), it is reportedly almost impossible to install a liner or underdrains because they would be destroyed by the sloughing gypsum slopes.
- See Section 3. Focus on Dry Stacks.

Dry Stack - White Mountain - large open air phosphogypsum waste storage near Voskresensk, Moscow oblast, Russia

Dry Stack

Dry Stack

2.3. “Wet Stacking”

Wet transportation may be achieved through slurry pipelines (hydraulic transport). This involves pulping the gypsum cake after filtration, using fresh water or re-circulated process water, to form a slurry that is pumped through a pipeline from the plant to the disposal area.

Fig 1 (a) High pressure gypsum slurry pipeline

(b) HDPE slurry line to stack top

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HDPE / metal pipes (lined with either rubber or HDPE) underground (protected from mechanical stress, vandalism) or aboveground may be used.

Aboveground black HDPEs may be painted white for controlling contraction and expansion due to heating from exposure to the sun (thus limiting the lateral movement and “snaking” of the line). There are usually at least two gypsum slurry lines (one in duty and one as backup).

High pressure pipes may be used for pumping high pressures over long distances or to great heights with or without the need for booster pumps.

It is good practice to include flanges in the slurry line at a low point for flushing and cleaning the line. Gypsum sediment may settle in the line and accumulate (e.g. after a power failure and shutdown of the slurry pumps).

“Wet Stacking” may be implemented through:

- **Single-point discharge**: at the disposal site, the slurry flows into one of the settling compartments on top of the stack. A single-point slurry discharge in one of two alternating adjacent compartments may be considered. One compartment is used for slurry deposition. The other compartment enables dewatering and dry-out and is prepared by digging gypsum and raising the perimeter dykes. Such arrangements are reportedly not efficient. The water tends to accumulate at the low end where the gypsum fines are very wet and difficult to handle. Moreover, the dyke at the low end is subject to overtopping during heavy storm events.
- **Elevated Rim Ditches**: the use of elevated rim ditches is reportedly more efficient than a single-point discharge above. The slurry is discharged at a single point into the perimeter rim ditch and routed around the stack at the natural angle of deposition of the gypsum slurry. The rim ditch is maintained at a higher level than the ponded inner compartment. The material in the rim ditch is, therefore, always available allowing for dyke construction (no need for moisture conditioning). Once the rim ditch is filled with gypsum, the inner rim ditch dyke is manually breached allowing the slurry to be directed to the inner compartment. This enables the forming of gypsum “beaches” in the vicinity of the rim ditch (all around the compartment). This is achieved by sequentially breaching the inner dyke at progressively more distant locations. In such a sedimentary-type deposit, beaches are developed with either very deep ponds (e.g., up to 10 meters of water depth) or shallow ponds. This reportedly allows for an optimized water inventory management on top of the stack without the need for a high dyke. Gypsum excavated (using an excavator or even a dragline and dozers)

from the rim ditch (above the water level) is used to raise the perimeter dyke using the upstream method of construction. Construction may reportedly take place even while the inner compartment is full of water.

Fig 2 (a) Wet stack with single location discharge

(b) Gypsum slurry discharge to rim ditch

Fig 3 (a) Elevated sloping rim ditch

(b) Beaches formed from rim ditch cuts

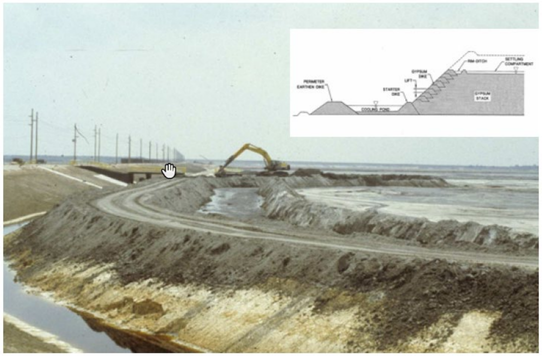


Fig 4 (a) Upstream method of construction

(b) Equipment accessible on inner & outer dykes

- **Spigoting**: this is an alternative to a rim ditch. A slurry pipeline is placed on the crest of the perimeter gypsum dyke with branches through spigots (T's and discharge line branches connected to the main slurry pipe). These spigots feed the inner compartment at regular intervals. This method requires moving the pipeline network upslope as the stack is being raised. A lot of manpower is therefore required. This method is reportedly particularly suitable when the gypsum stack is located in a valley as it allows for the raising of only one wall. The other sides abut the mountain.

Fig 5. Gypsum slurry deposition using spigots

Notes:

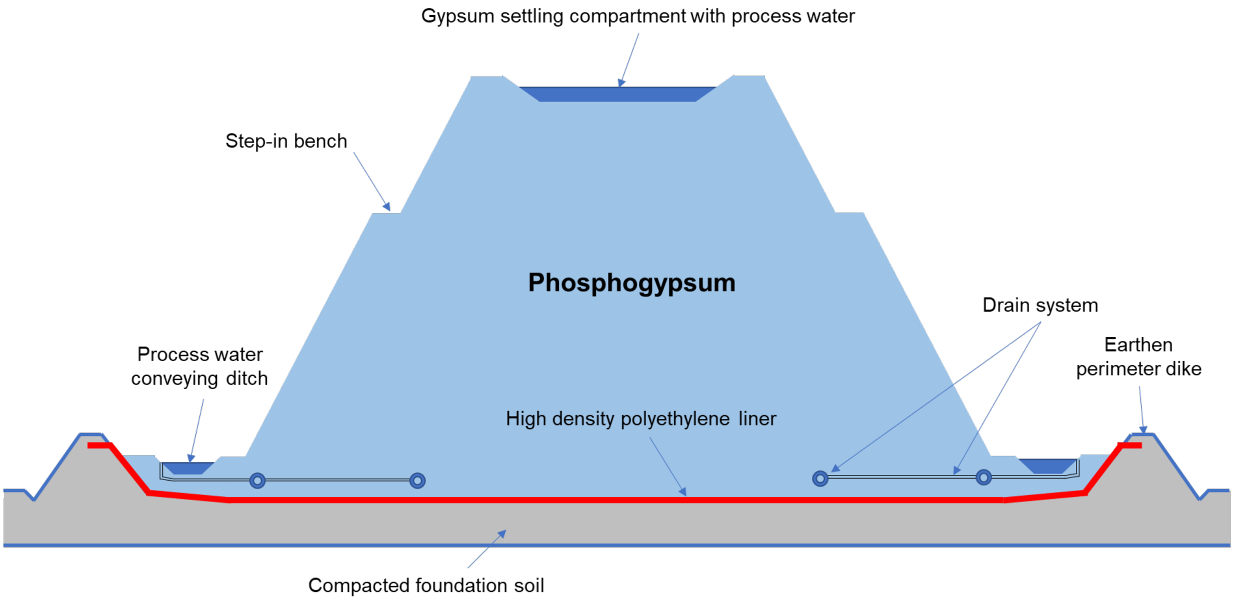
- Dry Transport and Wet Stacking: in some plants (relatively rare) the phosphogypsum is transported in a so-called "dry" form by conveyor belt from the plant to a mixing tank at the disposal site where the gypsum is then slurried and pumped as a slurry via a pipeline for disposal on a wet stack. This method is exclusively used because of some issues regarding the hydraulic transport of gypsum. This, therefore, results in relatively high maintenance costs.
- Based on the above, the method for raising the wet stack is therefore upstream (see Section 2.3). It is so-named because the centerline of the stack wall moves upstream into the pond.
- The slurry is pumped into the pond to allow the sedimentation (physical separation) of solids from the water.
- The settling compartment on top of the stack must be large enough to provide for adequate settling and sedimentation (decantation) of the fine gypsum particles and to allow sufficient time for clarification prior to decanting and recirculation of the process water to the plant for re-use.
- Prior to recirculation to the plant for re-use, clarified water is stored in cooling ponds, surge ponds and the cooling ponds need to be adequately sized to provide adequate cooling of the re-circulated process water and sufficient surge storage capacity based on water balance analyses during extreme storm events.
- Process water return systems: the process water typically flows back towards the plant in an open return ditch. Narrow channels around the stack are useful for containing accidental spills and are very effective in promoting plug flow cooling (the velocity of the fluid is assumed to be constant across any cross-section of the process water return network).

Hazards, Prevention, Protection:

Stacking material up to a certain height is common practice. Adequate drainage systems underneath the stack are required as a receptor for water travelling vertically through gravity; basal drainage captures this water and transfers it to a containment pond for subsequent use or water treatment. This is called water percolation, referring to the movement and filtering of fluids through porous materials.

Note that the cementation of the material limits water percolation. That means that the first control is to manage the water on top of the dam and keep it as a closed system. Any rainfall and run-off will be caught in the 'bathtub' below and either reintroduced to the system or treated and released subject to water quality issues. As far as permeability is concerned, it will be of a low order. The liner at the bottom of the 'bathtub' is for environmental reasons, to ensure there is no seepage into local water course/aquifers and ensuing general contamination.

In case of impairment of the drainage system underneath the stack, the risk of a hydraulic uplift caused by water which is a non-Newtonian fluid (not compressible) is present. In fact, should water travel laterally for some reason, this could also weaken the dam wall structures through the same hydraulic mechanism, and is, therefore, a consideration for all dams with unconsolidated matter. Phosphogypsum stacks, however, are essentially solid structures but dam wall slumps can and do happen either through an inherent weakness or via water action. The impact of rainfall should also be carefully considered when designing such drainage systems, as overtopping remains a hazard.



Major components of a gypsum stack

Phosphogypsum Wet Stack

Water issued from the wet-stack will be acidic (pH of 1.4 to 1.8) or may contain some contaminants posing an environmental issue. Adequate supervision, including water flow control and leak detection, should therefore be provided. Also, radioactive contaminants may be present, giving rise to concerns for airborne particles as well as contamination caused by the effects of leaching.

Discharge through spigots or through a purpose-built rim around the dam is critical to reduce the potential of a wetter area which could prove problematic. Older stacks fit this bill where there are a number of compartments or cells with a single discharge point i.e., a cell is filled one at a time while the others are raised – as such, water can accumulate at one end where gypsum fines are very wet and could cause additional problems in a heavy storm event through overtopping.

The failure of a stack containing saturated material or unconsolidated material may lead to a catastrophic failure allowing a large amount of material to move away – very similar to a large amount of slurry being suddenly released or a “mud flow” (i.e., tailings dam failure). However, the amount of ‘mud’ would be limited to the top portion of the stack which is not too deep, but the volumes may be enough to cause an environmental issue which would necessitate acts of authority interventions and cleanups which could cause a cessation of operations of potentially up to 6-months and may involve closure of other operations in the area subject to clarification of failure mechanisms and environmental damage. In terms of Physical Damage, the location and direction of the breach and flow are key, as the topography for this type of occupancy is generally flat or undulating. The zone of influence could be contained by the embankments within the containment bunds (like a bathtub) but could likely overflow them, (depending on their design) and flow into any near water course feature (stream) or depression. It is, however, unlikely the breach would reach capital-intensive fixed assets such as the plant. The flow reach is limited to the volume of the material that has breached the dam, which for wet-stacking is generally limited, and water is controlled via pumping systems that create a closed circuit for use in the plant as process media.

The failure of a stack containing unsaturated material or consolidated material is expected to lead to more limited consequences such as a failure on one side releasing relatively solid material over a relatively confined area. The sudden release of a large amount of water if the pond is located at the top of the stack may also lead to the flooding of the nearest processing facility.

Stack failure basically results from the geometry of the stack being disturbed, or through a weakening of the structure. This can happen with sinkholes or via subsidence disturbance or where the stack itself has not been designed to an appropriate technical parameter e.g., an unstable factor of safety. Carbonate environments such as Karst (*) geologies are prone to sinkholes and subterranean geological variations in rock mass characteristics; however, sinkholes remain the prime candidate for instability although there are geophysical techniques such as Ground Penetration Radar or gravimetric measurements that can pick up anomalies.

(*) Karst is a topography formed from the dissolution of soluble rocks such as limestone, dolomite and gypsum. It is characterized by underground drainage systems with sinkholes and caves.

The risk of phosphogypsum stack failure should be mitigated by the design, ongoing monitoring of operations and annual inspections, as summarized below (but not limited to):

- The maximum height should be determined by geotechnical conditions beneath the site. (e.g., an average of 15 feet of pondwater in each of the ponds with the remaining 140 feet consisting of solid, stable phosphogypsum. The design should incorporate the following (not limited to):
    - A minimum safety factor for slope stability failure.
    - Dykes at the top of a certain width with external and internal slope design.
    - An external bench (offset) to maintain the overall design slope from the toe ditch.
    - Use a method for automatically adjusting dyke slopes to compensate for pond settlement.
    - Prefer a series of ponds rather than one single pond so that a failure would result in the limited release of pond water.
    - The gypsum stack containment system should be designed to exceed the requirements to withstand a 24-hour record rainfall (return period to be defined in accordance with local data).

- Clarified water from the pond on top of the stack is drained out using either a moveable riser and exposed outlet pipe laid on the slope of the stack or floating siphon lines that can be relocated to allow for siphoning from more than one location. Fixed vertical riser structures with an outlet pipe at the base of the stack were commonly used in the past but were subject to settlement in response to settlement of the surrounding gypsum.
  Another decanting method consists of a cut made in the gypsum perimeter dyke allowing process water to flow down the slope of the stack. Such a decant method is reportedly feasible with gypsum-saturated water high in fluorosilicates that precipitates on the slope of the stack forming an erosion-resistant hard crust that resists erosion in spite of the turbulent flow. Such a decant method is reportedly not feasible for use with earthen materials which would be highly susceptible to erosion. Special precautions should be taken when properly filling the cut made through the gypsum dyke.

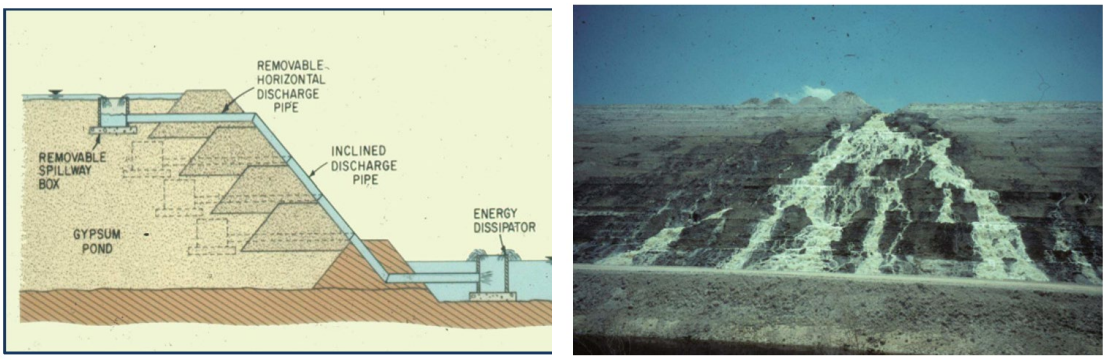


Fig 6 (a) Movable decant system *(b) Process water decantation though cut*

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- Process water return systems: where chutes are present between differently elevated return water ditch sections, scaling and crystal formation may occur. The return flow is reportedly not usually impeded as a result of crystal growth in such open ditch situations. However, in the case of HDPE pipelines used for process water return, scale formation and crystal growth may severely impede flow, causing major problems to the plant process. Scale formation and crystal growth is dependent on a number of factors such as the distance from the pond to the plant, the temperature, the flow and the chemical composition of the water. When scaling and crystal growth is an issue, return water lines must be cleaned regularly to prevent the formation of large crystals in the line (frequency to be established in accordance with the key factors influencing the phenomena to be defined). Suitable additives may also be used for preventing scaling.
- The gypsum stacks and ponds should be monitored 24/7 by site operations and inspected annually by a recognized 3rd party expert.
- The stability of the gypsum management system should be assessed and monitored using suitable electronic instrumentation when possible, as well as routine measurements of water levels, and by completing routine inspections.
- It should be ensured that there are no changes to the management of phosphogypsum. (i.e. the phosphogypsum stacks should be constructed from solid, stable phosphogypsum in order to prevent any “mud flow” in the event of a catastrophic failure).

V - GLOSSARY OF TERMS

Courtesy of Global Industry Standard on Tailings Management August 2020:

- **Adaptive Management**: A structured, iterative process of robust decision-making with the aim of reducing uncertainty over time via system monitoring. It includes the implementation of mitigation and management measures that are responsive to changing conditions, including those related to climate change, and the results of monitoring throughout the tailings facility lifecycle. The approach supports alignment on decisions about the tailings facility with the changing social, environmental and economic context and enhances opportunities to develop resilience to climate change in the short and long term.
- **Alternatives Analysis**: An analysis that should objectively and rigorously consider all available options and sites for mine waste disposal. It should assess all aspects of each mine waste disposal alternative throughout the project life cycle (i.e. from construction through operation, closure and ultimately long-term monitoring and maintenance). The alternatives analysis should also include all aspects of the project that may contribute to the impacts associated with each potential alternative. The assessment should address environmental, technical and socio-economic aspects for each alternative throughout the project life cycle.
- **As Low As Reasonably Practicable (ALARP)**: ALARP requires that all reasonable measures be taken with respect to 'tolerable' or acceptable risks to reduce them even further until the cost and other impacts of additional risk reduction are grossly disproportionate to the benefit.
- **Best Practices**: A procedure that has been shown by research and experience to produce optimal results and that is established or proposed as a standard suitable for widespread adoption.
- **Breach Analysis**: A study that assumes a failure of the tailings facility and estimates its impact. Breach Analyses must be based on credible failure modes. The results should determine the physical area impacted by a potential failure, flow arrival times, depth and velocities, duration of flooding, and depth of material deposition. The Breach Analysis is based on scenarios which are not connected to probability of occurrence. It is primarily used to inform emergency preparedness and response planning and the consequence of failure classification. The classification is then used to inform the external loading component of the design criteria.
- **Catastrophic Failure**: A tailings facility failure that results in material disruption to social, environmental and local economic systems. Such failures are a function of the interaction between hazard exposure, vulnerability, and the capacity of people and systems to respond. Catastrophic events typically involve numerous adverse impacts, at different scales and over different timeframes, including loss of life, damage to physical infrastructure or natural assets, and disruption to lives, livelihoods, and social order. Operators may be affected by damage to assets, disruption to operations, financial loss, or negative impact to reputation. Catastrophic failures exceed the capacity of affected people to cope using their own resources, triggering the need for outside assistance in emergency response, restoration and recovery efforts.
- **Change Management System**: Changes in projects are inevitable during design construction and operation and must be managed to reduce negative impacts to quality and integrity of the tailings facility. The impact and consequences of changes vary according to the type and nature of changes, but most importantly according to how they are managed. Managing changes effectively is crucial to the success of a project. A change management system has the objective of disciplining and coordinating the process, and should include an evaluation of the change, a review and formal approval of the change followed by detailed documentation including drawings and, where required, changes to equipment, processes, actions, flow, information, cost, schedule or personnel.
- **Construction versus Design Intent Verification (CDIV)**: Intended to ensure the design intent is implemented and still being met if the site conditions vary from the design assumptions. The CDIV identifies any discrepancies between the field conditions and the design assumptions, such that the design can be adjusted to account for the actual field conditions.

- **Construction Records Report (CRR)**: Describes all aspects of the 'as-built' product, including all geometrical information, materials, laboratory and field test results, construction activities, schedule, equipment and procedures, Quality Control and Quality Assurance data, CDIV results, changes to design or any aspect of construction, nonconformances and their resolution, construction photographs, construction shift reports, and any other relevant information. Instruments and their installation details, calibration records and readings must be included in the CRR. Roles, responsibilities and personnel, including independent reviews should be documented. Detailed construction record drawings are fundamental.
- **Corporate Governance**: Refers to the organizational structures and processes that a company puts in place to ensure effective management, oversight and accountability.
- **Credible Failure Modes / Scenarios**: Refers to technically feasible failure mechanisms given the materials present in the structure and its foundation, the properties of these materials, the configuration of the structure, drainage conditions and surface water control at the facility, throughout its lifecycle. Credible failure modes can and do typically vary during the lifecycle of the facility as the conditions vary. A facility that is appropriately designed and operated considers all of these credible failure modes and includes sufficient resilience against each. Different failure modes will result in different failure scenarios. Credible catastrophic failure modes do not exist for all tailings facilities. The term 'credible failure mode' is not associated with a probability of this event occurring and having credible failure modes is not a reflection of facility safety.
- **Dam Safety Review (DSR)**: A periodic and systematic process carried out by an independent qualified review engineer to assess and evaluate the safety of a dam or system of dams (or in this case a tailings facility) against failure modes, in order to make a statement on the safety of the facility. A safe tailings facility is one that performs its intended function under both normal and unusual conditions; does not impose an unacceptable risk to people, property or environment; and meets applicable safety criteria.
- **Design Basis Report (DBR)**: Provides the basis for the design, operation, construction, monitoring and risk management of a tailings facility.
- **Designer of Record (DOR)**: A qualified professional engineer designated by the Engineer of Record to design the tailings facility in the case where the Engineer of Record is an internal professional.
- **Deviance Accountability Report (DAR)**: Provides an assessment of the cumulative impact of changes to the tailings facility on the risk level of the achieved product and defines the potential requirement for updates to the design, DBR, OMS or the monitoring program.
- **Emergency Preparedness and Response Plan (EPRP)**: A site-specific plan developed to identify hazards, assess capacity and prepare for an emergency based on tailings facility credible flow failure scenarios, and to respond if it occurs. This may be part of operation-wide emergency response planning and includes the identification of response capacity and any necessary coordination with off-site emergency responders, local communities and public sector agencies. The development of the EPRP includes a community-focused planning process to support the co-development and implementation of emergency response measures by those vulnerable to a tailings facility failure.
- **Engineer of Record (EOR)**: The qualified engineering firm responsible for confirming that the tailings facility is designed, constructed, and decommissioned with appropriate concern for integrity of the facility, and that it aligns with and meets applicable regulations, statutes, guidelines, codes, and standards. The Engineer of Record may delegate responsibility but not accountability. In some highly regulated jurisdictions, notably Japan, the role of the EOR is undertaken by the responsible regulatory authorities.
- **Environmental and Social Management System (ESMS)**: A methodological approach which draws on the elements of the established process of 'Plan, Do, Check, Act', and is used to manage environmental and social risks and impacts in a structured way in the short and longer term. An effective ESMS, appropriate to the nature and scale of the operation, promotes sound and

sustainable environmental and social performance, and can also lead to improved financial outcomes. The ESMS helps companies integrate the procedures and objectives for the management of social, environmental (and, local economic) impacts into core business operations, through a set of clearly defined, repeatable processes. An ESMS is a dynamic and continuous process initiated and supported by management, and involves engagement between the Operator, its employees and contractors, project-affected people and, where appropriate, other stakeholders. The interaction of the ESMS with the TMS facilitates alignment of decisions about the tailings facility with the changing social, environmental and local economic context and reflects the fact that a tailings facility is situated within a complex and dynamic local and global environment.

- **Free Prior and Informed Consent (FPIC)**: A mechanism that safeguards the individual and collective rights of indigenous and tribal peoples, including their land and resource rights and their right to self-determination. The minimum conditions that are required to secure consent include that it is ‘free’ from all forms of coercion, undue influence or pressure, provided ‘prior’ to a decision or action being taken that affects individual and collective human rights, and offered on the basis that affected peoples are ‘informed’ of their rights and the impacts of decisions or actions on those rights. FPIC is considered to be an ongoing process of negotiation, subject to an initial consent. To obtain FPIC, ‘consent’ must be secured through an agreed process of good faith consultation and cooperation with indigenous and tribal peoples through their own representative institutions. The process should be grounded in the recognition that the indigenous or tribal peoples are customary landowners. FPIC is not only a question of process, but also of outcome, and is obtained when terms are fully respectful of land, resource and other implicated rights.
- **Impact Assessment (IA)**: A decision-making and management support instrument for identifying, predicting, measuring and evaluating the impact of development proposals, both prior to major decisions being made, and throughout the lifecycle of a project. While impact assessments typically focus on a single project, assessments can be scoped at the landscape level, and consider strategic implications of a change. Depending on the context, the circumstances, and the issues at hand, impact assessments may be discipline-specific, or conducted as part of an integrated set of studies. Assessments can be conducted in advance of impacts, or retrospectively. In this context, impacts are consequences to people, built infrastructure or the natural environment caused by a tailings facility or its failure, including impacts to the human rights of workers, communities, or other rights holders and including sensitive ecological receptors and ecosystem services. Impacts can be positive or adverse, tangible or intangible, direct or indirect, acute, chronic or cumulative, and measurable quantitatively or qualitatively.
- **Independent Tailings Review Board (ITRB)**: A board that provides an independent technical review of the design, construction, operation, closure and management of tailings facilities. The independent reviewers are third parties who are not and have not been directly involved with the design or operation of the particular tailings facility. The expertise of the ITRB members shall reflect the range of issues relevant to the facility and its context and the complexity of these issues. In some highly regulated jurisdictions, notably Japan, the role of ITRB is undertaken by the responsible regulatory authorities.
- **Involuntary Resettlement**: Resettlement can be either voluntary or involuntary and may involve either physical or economic displacement. Involuntary resettlement occurs when project-affected people do not have the right to refuse resettlement. This includes cases where a company has the legal right to expropriate land. Voluntary resettlement occurs when resettled households have a genuine choice to move. When the voluntary nature of resettlement cannot be confirmed, resettlement should be treated as involuntary.
- **Mitigation Hierarchy**: Identifies a series of essential, sequential steps that Operators must follow through the project lifecycle in order to limit negative impacts and to enhance opportunities for positive outcomes. It describes a process to anticipate and avoid adverse impacts on workers, communities and the environment from a proposed action. Where avoidance is not possible, actions must be taken to minimize, and where residual impacts remain, to compensate fairly or offset for the risks and impacts.

- **Observational Method**: A continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction, as appropriate. All of these aspects must be demonstrably robust. The key element of the Observational Method is the proactive assessment at the design stage of every possible unfavorable situation that might be disclosed by the monitoring program and the development of an action plan or mitigative measure to reduce risk in case the unfavorable situation is observed. This element forms the basis of a performance-based risk management approach. The objective is to achieve greater overall safety. See Peck, R.B. (1969) "Advantages and Limitations of the Observational Method in Applied Soil Mechanics" Geotechnique 19, No2., pp.171-187.
- **Operations, Maintenance and Surveillance Manual (OMSM)**: Describes the performance indicators and criteria for risk controls and critical controls, and the ranges of performance linked to specific pre-defined management actions. An OMS manual also describes the procedures for collecting, analyzing and reporting surveillance results in a manner consistent with the risk controls and critical controls and that supports effective, timely decision-making.
- **Preliminary Design**: For the purpose of Requirement 4.2 of the Standard, preliminary design is a design performed to a level of detail sufficient to determine the differences between viable designs that adopt different external loading design criteria in terms of required footprints, volumes and drainage requirements.
- **Project-affected People**: People who may experience impacts from a tailings facility. People affected by a tailings facility may include, for example, people who live nearby; people who hear, smell or see the facility; or people who might own, reside on, or use the land on which the facility is to be located or may potentially inundate.
- **Reclamation**: The process of restoring the mine site to a natural or economically useable state as provided in a reclamation plan. Reclamation results in productive and sustainable landscapes to meet a range of conditions that might allow for biodiversity conservation, recreational or agriculture uses, or various forms of economic development.
- **Responsible Tailings Facility Engineer (RTFE)**: An engineer appointed by the Operator to be responsible for the tailings facility. The RTFE must be available at all times during construction, operations and closure. The RTFE has clearly defined and delegated responsibility for management of the tailings facility and has appropriate qualifications and experience compatible with the level of complexity of the tailings facility. The RTFE is responsible for the scope of work and budget requirements for the tailings facility, including risk management. The RTFE may delegate specific tasks and responsibilities for aspects of tailings management to qualified personnel but not accountability.
- **Restoration**: The process of assisting recovery of the social, environmental and local economic systems that have been degraded, damaged or destroyed.
- **Safe closure**: A closed tailings facility that does not pose ongoing material risks to people or the environment which has been confirmed by an ITRB or senior independent technical reviewer and signed off by the Accountable Executive.
- **Senior Independent Technical Reviewer**: An independent professional with in-depth knowledge and at least 15 years' experience in the specific area of the review requirements, e.g., tailings design, operations and closure, environmental and social aspects or any other specific topic of concern. The independent reviewer is a third-party who is not and has not been directly involved with the design or operation of the particular tailings facility.

- **Senior Technical Reviewer**: A professional who is either an in-house employee or an external party with in-depth knowledge and at least 15 years' experience in the specific area of the review requirements, e.g., tailings design, operations and closure, environmental and social aspects or any other specific topic of concern.

- **Tailings Facility Lifecycle (TFL)**: The phases in the life of a facility, which may occur in linear or cyclical succession, consisting of:
  1. Project conception, planning and design
  2. Initial construction
  3. Operation and ongoing construction (may include progressive reclamation)
  4. Interim closure (including care and maintenance)
  5. Closure (regrading, demolition and reclamation)
  6. Post-closure (including relinquishment, reprocessing, relocation, removal)
- **Tailings Governance Framework (TGF)**: A framework that focusses on the key elements of management and governance necessary to maintain the integrity of TSFs and minimize the risk of catastrophic failures. The six key elements of this TSF governance framework are:
  1. Accountability, Responsibility and Competency
  2. Planning and Resourcing
  3. Risk Management
  4. Change Management
  5. Emergency Preparedness and Response
  6. Review and Assurance
- **Tailings Management System (TMS)**: The site-specific TMS comprises the key components for management and design of the tailings facility and is often referred to as the 'framework' that manages these components. The TMS sits at the core of the Standard and is focused on the safe operation and management of the tailings facility throughout its lifecycle (see above). The TMS follows the well-established Plan-Do-Check-Act cycle. Each Operator develops a TMS that best suits their organization and tailings facilities. A TMS includes elements such as: establishing policies, planning, designing and establishing performance objectives, managing change, identifying and securing adequate resources (experienced and/or qualified personnel, equipment, scheduling, data, documentation and financial resources), conducting performance evaluations and risk assessments, establishing and implementing controls for risk management, auditing and reviewing for continual improvement, implementing a management system with clear accountabilities and responsibilities, preparing and implementing the OMS and EPRP. The TMS and its various elements, must interact with other systems, such as the environmental and social management system (ESMS), the operation-wide management system, and the regulatory system. This system's interaction is fundamental to the effective implementation of the Standard.
- **Triggered Action Response Plan (TARP)**: A TARP is a tool to manage risk controls, including critical controls. TARPs provide pre-defined trigger levels for performance criteria that are based on the risk controls and critical controls of the tailings facility. The trigger levels are developed based on the performance objectives and risk management plan for the tailings facility. TARPs describe actions to be taken if trigger levels are exceeded (performance is outside the normal range), to prevent a loss of control. A range of actions is pre-defined, based on the magnitude of the exceedance of the trigger level.

VI - TECHNICAL REFERENCES

The following documents were consulted for this study:

- Tailing dam – an overview (https://www.sciencedirect.com/topics/engineering/tailing-dam)
- International Commission on Large Dams, (https://www.icold-cigb.org/)
- Dry Stack Tailings – Design Considerations. J. Lupo &, J. Hall. AMEC Earth and Environmental, Englewood, CO, USA
- The Pros & Cons of Wet Versus Dry Stacking, Dr. Nadim F. Fuleihan, Sc.D., P.E, Procedia Engineering 46 (2012) 195 – 205
- Barry A. Wills, James A. Finch FRSC, FCIM, P.Eng., in Wills' Mineral Processing Technology (Eighth Edition), 2016
- NuTrien, Mine Tailing Disclosure Table 2020-02

This list is not exhaustive.

Other publications in this series:

- RISK CONTROL PRACTICE: CONSTRUCTION MATERIAL
  Wall Assembly Classification Handbook
- RISK CONTROL PRACTICE: EXPOSURE
  Falling Aircraft Handbook
- RISK CONTROL PRACTICE: SPECIAL HAZARDS
  - Embankment Dams Handbook
- RISK CONTROL PRACTICE: OCCUPANCY
  - Renewable Energy Handbook
  - Aluminium Handbook
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