MINING TAILINGS AND MANAGEMENTS

By

Aya Rafat Abd El-Salam

(4th year Special Geology)

Supervised by

Prof. Dr. Hassan Zakaria Harraz

Geology Department

Faculty of Science

Tanta University

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Abstract

Tailings consist of ground rock and process effluents that are generated in a mine processing plant. Mechanical and chemical processes are used to extract the desired product from the run of the mine ore and produce a waste stream known as tailings.

The process of beneficiation of run of the mine ores and subsequent disposal to surface containment facilities exposes elements to accelerated weathering and consequently increases mobilization rates. The addition of reagents used in mineral processing may also change the chemical characteristics of the processed minerals and therefore the properties of the tailings and waste rock

Tailings characteristics can vary greatly and are dependent on the ore mineralogy together with the physical and chemical processes used to extract the economic product.

There are many deposition methods of tailings. For conventional storage the tailings are generally discharged from spigots/outfalls located along the embankment(s) of the facility. For surface thickened and paste storage the tailings are generally discharged from a central location either through risers or from point sources that are raised over the life of the facility. Dry stacking of tailings is normally carried out by a radial conveyor stacker or by truck.

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CHAPTER ONE:

INTRODUCTION

What Are Tailings? - Their nature and production

Tailings consist of ground rock and process effluents that are generated in a mine processing plant. Mechanical and chemical processes are used to extract the desired product from the run of the mine ore and produce a waste stream known as tailings. This process of product extraction is never 100% efficient, nor is it possible to reclaim all reusable and expended processing reagents and chemicals. The unrecoverable and uneconomic metals, minerals, chemicals, organics and process water are discharged, normally as slurry, to a final storage area commonly known as a Tailings Management Facility (TMF) or Tailings Storage Facility (TSF). Not surprisingly the physical and chemical characteristics of tailings and their ability to mobilise metal constituents are of great and growing concern (ICOLD and UNEP 2001).

Tailings are generally stored on the surface in retaining structures but can also be stored underground in mined out voids by a process commonly referred to as backfill. Backfilling can provide ground and wall support, improve ventilation, provide an alternative to surface tailings storage and prevent subsidence (EC 2004). Backfilling is discussed in the relevent section which can be accessed here.

The challenges associated with tailings storage are ever increasing. Advances in technology allow lower grade ores to be exploited, generating higher volumes of waste that require safe storage. Environmental regulations are also advancing, placing more stringent requirements on the mining industry, particularly with regard to tailings storage practices. This ultimately places added pressure on the operators of a tailings facility who carry out the day to day roles of tailings discharge and water management. The majority of historical tailings related incidents have been influenced by poor day to day management, which has resulted in the strengthening of regulations controlling tailings storage today. The research carried out in the PhD thesis submitted at the University of Leeds in 2006 has targeted the management roles to improve day to day operations and reduce the risks associated with surface tailings storage. The parameters that influence the stability, operation and management have been identified and presented together with their methods of control, intervention and mitigation. This is supported by a novel online database called TailPro (www.tailpro.com) that has been developed to ensure the tailings personnel can implement a tailings management system efficiently and effectively.

Tailings are a waste product that has no financial gain to a mineral operator at that particular point in time. Not surprisingly it is usually stored in the most cost effective way possible to meet regulations and site specific factors. Dams, embankments and other types of surface impoundments are by far the most common storage methods used today and remain of primary importance in tailings disposal planning (Vick 1990). The particular design of these retaining structures is unique to a particular environment and mining operation.

When considering the design of a tailings storage facility there are many parameters which impact on the optimum site selected and the storage and tailings discharge methods used (Ritcey 1989). The environment is the most crucial parameter constraining tailings storage which ultimately affects the way a facility is designed, built, operated and closed. For this reason a range of alternate methods of tailings storage and discharge techniques need to be considered when designing a facility for a particular location.

This briefly highlights the generation and nature of tailings. The various tailings storage and discharge methods used, the water management requirements for conventional tailings storage are discussed in the relevent sections of this website. The water management considerations discussed are only specific to conventional storage and should highlight why this method is so problematic compared to other storage techniques.

Nature of tailings

The process of beneficiation of run of the mine ores and subsequent disposal to surface containment facilities exposes elements to accelerated weathering and consequently increases mobilization rates. The addition of reagents used in mineral processing may also change the chemical characteristics of the processed minerals and therefore the properties of the tailings and waste rock (EC 2004). Problems arise when this accelerated weathering process generates toxic levels that create short and long term tailings management challenges. The processing of hard rock sulphidic bearing ores is just one example of the potential problems associated with accelerated weathering. In this case the sulphide minerals more readily oxidize in the tailings facility as a result of the size reduction from milling increasing the surface area and thus exposure of the tailings to air and water. Acid generation and metal mobilization occur that eventually find their way into the surrounding environment through runoff or seepage. This phenomenon is a well known problem affecting the mining industry and is commonly known as Acid Mine Drainage (AMD) or Acid Rock Drainage (ARD) (Garcia, Ballester et al. 2005; Ritcey 2005).

Production of tailings

The disposal of tailings is commonly identified as the single most important source of environmental impact for many mining operations (Vick 1990). This is not surprising when considering that the volume of tailings requiring storage can often exceed the in-situ total volume of the ore being mined and processed. Over the last century the volumes of tailings being generated has grown dramatically as the demand for minerals and metals has increased and lower and lower grades of ore are being mined. In the 1960's 10's of thousand of tons of tailings were produced each day and by 2000 this figure has increased to 100's of thousands (Jakubick, McKenna et al. 2003). Understanding the mineral processing techniques can help to determine how tailings are produced and the challenges associated with their storage.

Run of the mine ore is physically reduced by crushing and grinding methods (figure 1). The optimum degree of grinding is determined by the extraction methods used to remove the economic product. A simple mineralogical examination can hold the key to identifying the most advantageous extraction methods to use. The examination can also determine other minerals of economic interest, the type and quantities of reagents required to separate the concentrate from the gangue materials and the necessary storage methods for the tailings (Ritcey 1989). Pilot plant tests can also be useful to determine optimum particle size, processing reagents required and the final tailings characteristics. However, such pilot tests may not be an exact representative of the tailings that will be produced from the full scale plant. This means that the final design of any tailings facility is always provisional and must be confirmed once tailings production is underway (Blight 1998).

Concentration is the process of extracting the economic product from the crushed and ground ore, the waste from this process is the tailings. Froth flotation (figure 1) is the most widely used concentration method and is normally the first step in the mineral processing sequence where chemical reagents are introduced (Vick 1990). Gravity and magnetic separation techniques are also used to win the economic product from the ground ore. Gravity separation is used in gold processing to recover the coarser particles, the finer being recovered by leaching (EC 2004).

Figure 1: Grinding circuit (left) and froth flotation cells (right) at Highland Valley Copper, BC, Canada

The five basic types of reagent used in froth flotation recovery include:- ***collectors, frothers, depressants, activators and modifiers***. When designing the processing plant the types and quantities of reagents used should be considered together with any depressing requirements to lessen environmental impacts in the tailings streams (Ritcey 1989). Reagents dosed in small quantities are either consumed, retained in the process or are discharged with the tailings.

The design of a tailings storage facility should therefore be optimized to prevent weathering and the mobilization of contaminants, whilst also increase the degradation rates of reagents stored in the tailings facility. It may be more economical to hold water for longer periods of time to allow natural degradation of reagents rather than promoting rapid degradation through dosing.

Tailings characteristics

Tailings characteristics can vary greatly and are dependent on the ore mineralogy together with the physical and chemical processes used to extract the economic product. The tailings characteristics have to be determined to establish the long term behaviour of the tailings and the potential short and long term liabilities and environmental impacts. Once the likely characteristics of the tailings are determined from mineralogical examinations and pilot plant tests, the necessary design requirements can be identified to mitigate liability and impact. A certain type of tailings storage method may be preferred or certain design considerations may need to be adapted to a more realistic or suitable storage method.

To help determine the design requirements of a tailings storage facility the following characteristics of the tailings will need to be established (EC 2004):

- Chemical composition (including changes to chemistry through mineral processing)
- Physical composition and stability
- Leaching behaviour
- Behaviour under pressure
- Erosion stability
- Settling behaviour
- Hard pan behaviour (e.g. crust formation on top of the tailings)

The engineering characteristics of tailings are in most instances influenced by the method of deposition. It is therefore essential that while investigating the properties of tailings that the physical characteristics, phenomenon and material parameters (e.g. beach slope angles, particle size segregation) that can occur as a result of varied deposition techniques be identified (SANS 1998).

Once the potential environmental impacts and behaviour of the tailings are identified the process of deciding a suitable storage method can begin.

Tailing Forms

Tailings are:

- finely ground rock from the mill
- particles ≤ 0.1 mm in diameter (sand and silt)

1). Waste Rock (Dump)

While it is not a pretty aspect of mining, waste rock is always produced at an open pit mine and rarely, if ever, produced at an underground mine.

Dumping must be managed because uncontrolled dumping can be dangerous. Water flowing through a dump must also be controlled to maintain stability and prevent contaminating surface water or groundwater.

The operation and management of a waste dump are affected by the mine plan*, i.e., the geometrical relationship between waste and ore in the mine and the strip ratio*.

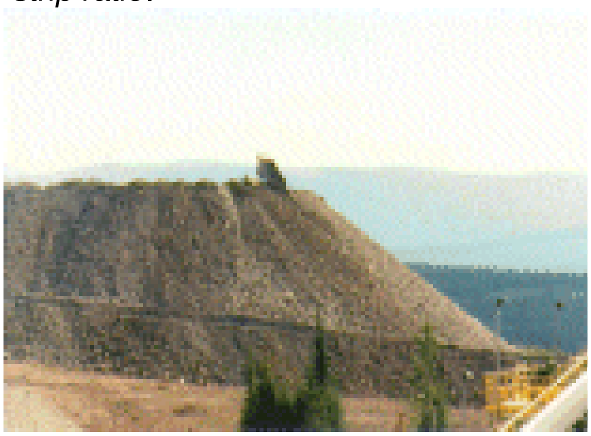
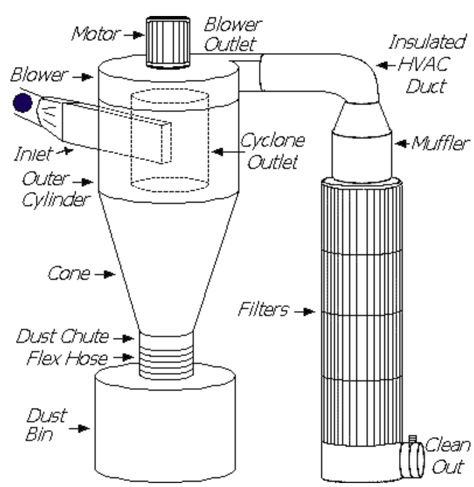
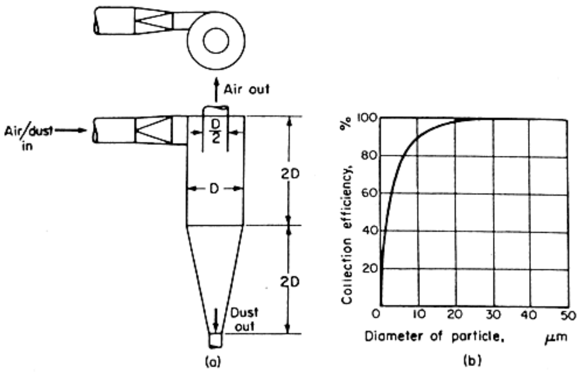



Figure : 2 : Waste Rock

A cyclone is like a large washing machine. The cyclone separator separates sand from silt in tailings (coarse-grained from fine-grained). This is also called ***classification***. It is done to provide material for tailings dam construction or to assist with deposition of tailings.

Low pressure is created in the center of the cyclone as in a tornado. Fine-grained particles float to the top, to the overflow; and coarse-grained particles drop to the bottom, to the underflow.





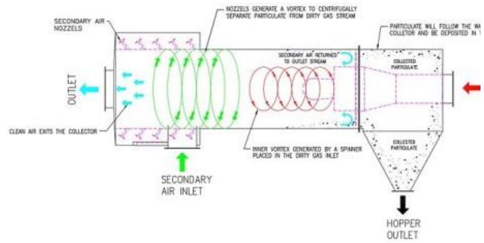


Figure 3 : Airflow diagram for Aerodyne cyclone in horizontal position, an alternate design. Secondary air flow is injected to reduce wall abrasion, and to help move collected particulates to hopper for extraction.

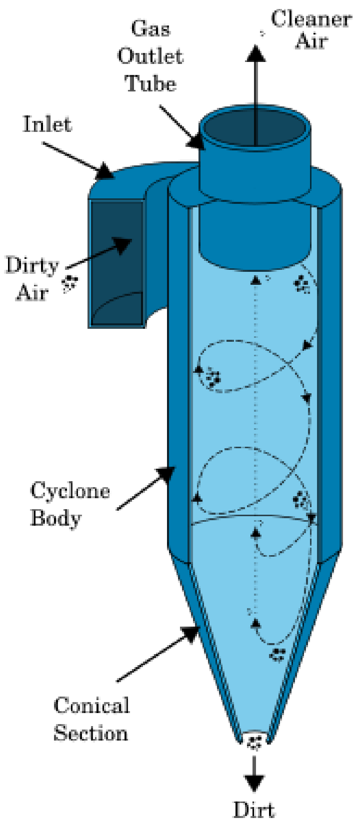


Figure 4: A simple cyclone separator

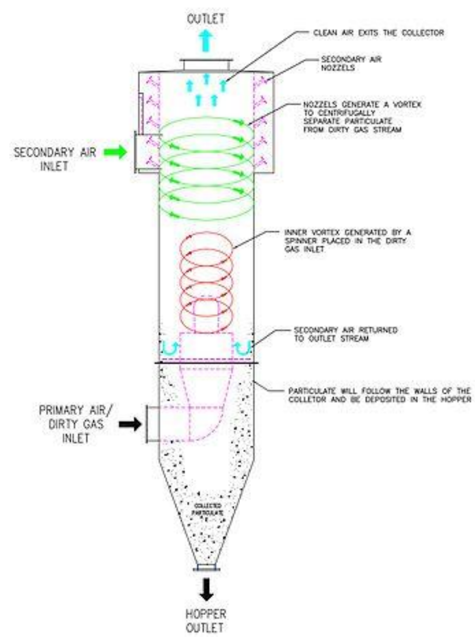


Figure 5 : Airflow diagram for Aerodyne cyclone in standard vertical position. Secondary air flow is injected to reduce wall abrasion.

2) Waste Water

Waste water *consist*s of liquid wastes from processing:

- flotation reagents, SX/EW solvents
- acids or cyanide used in leaching
- water

Waste water *from* a mine may contain:

- ammonia from explosives
- contaminated groundwater

Something has to be done about waste water. The best strategy is to minimize the production of waste water but this usually leads to higher costs. It could be contained, as in behind a dam, but this is difficult and risky. ***Usually it is treated and reused or discharged to the environment***.

Wet Tailings Deposition : A "starter dam" is built according to standard earth-fill dam design principles (Figure 1). Tailings are piped to the top of the dam and deposited upstream (i.e., opposite to the direction of water flows into the pond area from streams). Coarse-grained material (sand) deposits near the dam and fine-grained material (slimes) flow out into the pond. Ideally water covers the tailings.

As the tailings rise up, the dam is raised to increase the pond's capacity. This is called "centerline construction" because the dam rises straight up from the center of its base. Upstream construction of the dam could also be done, but then the foundation of the dam would be weak tailings, which is not good in general and especially bad if earthquakes occur in the area.

The entire tailings disposal operation must be closely monitored because if things go very wrong, production has to stop.

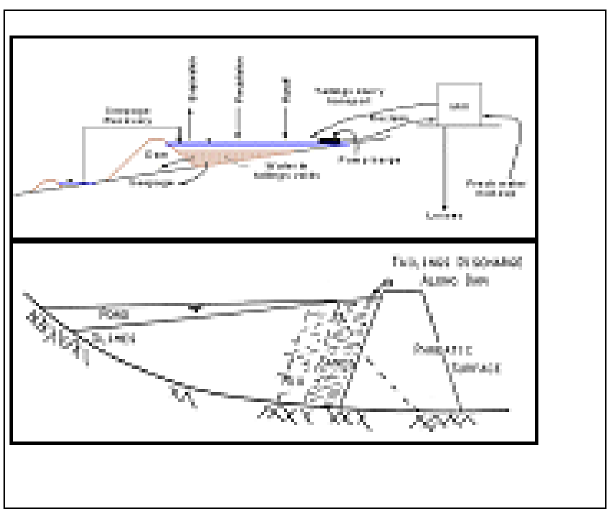


Figure 6 : tailings disposal operation

There are two forms of disposal:

- ***wet tailings in the form of slurry***
- ***dewatered tailing***s (i.e., ***Dewatering*** is expensive but avoids problems in tailings management. Dewatering may be essential in a dry environment to conserve water, e.g. in Chile).

3) Acid Rock Drainage (ARD)

Acid is produced by exposing sulfide minerals to air and water, producing more oxidation.

$$\textit{pyrite} + \textit{oxygen} + \textit{water} \rightarrow \textit{sulfuric acid} + \textit{iron hydroxide}$$

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 8H_2SO_4 + \underset{\text{"Yellow boy"}}{4Fe(OH)_3}$$

ARD can be treated with lime but that's expensive. ***It can be prevented by flooding acid-generating materials, which keeps oxygen out***.

ARD is a significant and costly water treatment problem at most mines. ***For example***: if a mine site has a perimeter 2 km by 2 km or 4,000,000 m^2 and rainfall of 0.5 m/year (20 in/year), and water chemistry is unacceptable (acidic), then 4,000,000 m^2 x 0.5 m/yr = 2,000,000 m^3 must be handled and treated each year.

This is 2,000,000,000 (2 billion) liters of water at a treatment cost of US$0.001/liter -- **$2,000,000 per year**.

This is a conservative estimate and assumes that all rainfall ends up as acidic discharge that can be collected and treated, however only a small portion of water remains in the soil.

Waste rock dumps are common sources of ARD, tailings less common sources. *Examples of collect and treat facilities include*:

- Canada
  - BC: Equity Silver, Britannia Beach, Island Falls
  - Ontario: Kidd Creek, Inco, Falconbridge
- USA
  - PA: Rausch Creek
  - CA: Leviathan Mine Site

Examples of costs:

- capital cost of treatment facilities is $2-10M
- operating costs are > $100,000/year
- operating life may be > 50 years (???)

Figures 7 through 10 show some examples of ARD

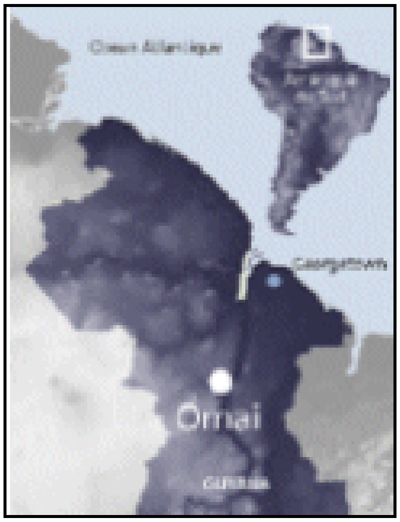
Tailings Incidents

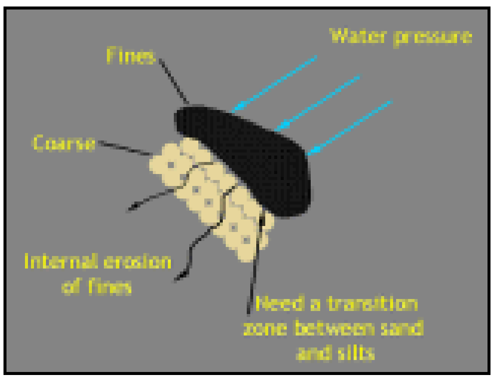
- Stava, Italy (July 1985)
- Merriespruit, South Africa (February 1994)
- Omai, Guyana (August 1995)
- Marcopper, Philippines (March 1996)
- Los Frailes, Spain (April 1998)

Omai, Marcopper and Los Frailes will be described in this session.

Omai, Guyana

This incident is an example of internal erosion, which caused the crest of the tailings dam to drop over 1 m and cyanide-laced tailings water was released into the Omai river. Figure 2 shows the crest slump at Omai. Never let this happen!



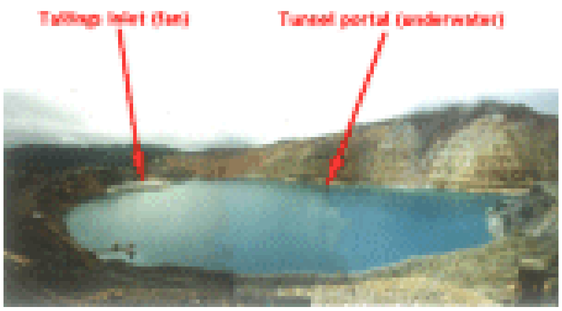
Fige 11 throw 14 : show omai.guyana

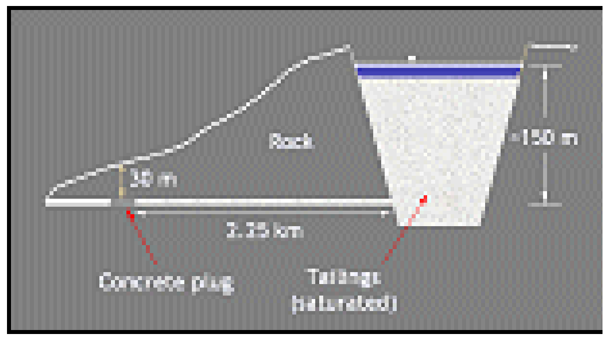
The story is that suitable material to continue building the dam became unavailable, but production continued. So the cyanide-laced tailings kept coming with no dam to contain them. Mine personnel used what was available -- crushed waste rock. This was too coarse-grained and the sandy material used to build the dam filtered through it (Figures 3 and 4).

Marcopper, Philippines

The Tapian pit is a 300 m deep copper mine on Marinduque island in the Philippines. Rainfall is heavy, 20-25 in/day, so the pit was often flooded. During the 1970s a 2.2 km long drainage tunnel was constructed to drain the pit into the ocean. More ore was then found under the tailings pond (the San Antonio pit shown on the map).

- 1980s - tailings pond dredged and tailings were pumped into the ocean (Figure 6)
- ~1990 - ocean disposal stopped
- 1992 - drainage tunnel plugged with concrete
- 1992 to 1996 - tailings pumped into the Tapian pit





How much water pressure was on the rock around the plug (15) in the Tapian Pit? That is easily computed:

$$P = \text{density of water} \times \text{acceleration due to gravity} \times \text{height of water}$$

$$= 1000\ kg/m^3 \times 9.8\ m/sec^2 \times 150\ m$$

$$= 1{,}470{,}000 \text{ Pascals}$$

That's about 213 pounds per square inch (psi). (By way of comparison, your car tire pressure is 30 psi.) But what was the pressure in the ground where the rupture occurred? That is also easily computed. The depth of rock over the rupture was about 30 meters. The density of most rock is between 2000 and 2500 kg/m^3. Let's estimate a range of rock pressure:

$$P = \text{density of rock} \times \text{acceleration due to gravity} \times \text{depth of rock}$$

$$= (2000 \text{ to } 2500)\ kg/m^3 \times 9.8\ m/sec^2 \times 30\ m$$

$$= 588{,}000 \text{ to } 735{,}000 \text{ Pascals}$$

That's a range of 85 psi to 107 psi. So there is 213 psi of water pressure up against 85 to 107 psi of rock pressure. What do you think will win? (Hint: The concrete plug would likely not crack -- way too strong.)

March 24, 1996 -- the physics worked. Rock around the plug fractured, which caused leaks. 1.6 million m^3 of tailings were released into the 26 km long Boac river .

Fige 16 : tailing long boac river

Los Frailes, Spain

The mine had been operating for decades before the failure in 1998. The new owners (Boliden) decided to build the tailings facility on top of older tailings. The foundation couldn't take the load and failed. The results were:

- deep failure in the foundation caused the dam to rupture
- acidic tailings were released into Rio Agrio

In Figure 17 the dam in the impoundment separated tailings containing pyrite on the left from tailings with no metallic mineralization on the right. Thousands of hectares of farmland were affected.

CHAPTER TWO:

DEPOSITION METHODS OF TAILINGS

Introduction

For conventional storage the tailings are generally discharged from spigots/outfalls located along the embankment(s) of the facility. For surface thickened and paste storage the tailings are generally discharged from a central location either through risers or from point sources that are raised over the life of the facility. Dry stacking of tailings is normally carried out by a radial conveyor stacker or by truck (Davies and Rice 2001).

Deposition Techniques

Tailings can be discharged using subaqueous (below water) or subaerial techniques (above the water line, on the ground or on the tailings beach) (DPI 2003). The choice between these methods can dramatically effect how the tailings deposit and settle within the impoundment. The tailings characteristics themselves can also influence the behaviour of the tailings after they are discharged. Generally as the tailings deposit they flow away from an outfall and natural segregation occurs. The degree of this segregation essentially depends on the particle size range of the tailings and the pulp density of the slurry (Vick 1990). Robinsky (2000) reported that as the degree of thickening of tailings increases there is less slurry to carry the coarse fraction and the tailings begin to stack closer to the discharge point. Further thickening eventually results in a non-segregated slurry due to the high pulp density of the depositing tailings. When this stage is reached the voids in the coarse fraction of the slurry are filled with the fines resulting in a homogeneous mixture.

For low pulp densities the coarse fraction of the tailings settle closest to the discharge point with the finer material (slimes) being carried furthest away. For subaerial deposition this results in a beach sloping downwards from the spigot towards the supernatant pond. Vick (1990) notes that for most tailings types the expected beach slope grade is 0.5 – 2.0% within the first several hundred feet and that the higher the pulp density and/or the coarser the gradation of the tailings the steeper the beach slope.

Multiple outfall deposition is by far the most common method used to fill a surface storage facility. For conventional storage facilities, multiple spigots help to control the geometry and location of the supernatant pond within the facility. This helps to prevent the pond encroaching the embankment and reduces the risk of loss of freeboard. Static single point discharge is normally only used when the ponded water is pushed to a required zone of the tailings facility or where subaqueous deposition is practiced.

1) Subaerial

Subaerial deposition is more common than subaqueous as it can form a Beach Above Water (BAW) sloping gently towards the supernatant pond (figure 1). As the tailings discharge onto this beach they form shallow low velocity braided streams that allow the tailings to settle and segregate (DME 1999). Subaerial deposition is generally practiced at tailings facilities that have multiple discharge points. This allows the deposition of tailings to be rotated between different locations around the facility to allow newly deposited tailings to bleed, dry and consolidate while tailings can continue to be discharged to other zones of the facility. The frequency of discharge point rotation and the number of deposition zones is dependent on the climate, tailings production rate, tailings drying characteristics and the tailings facility shape (Gipson 1998).

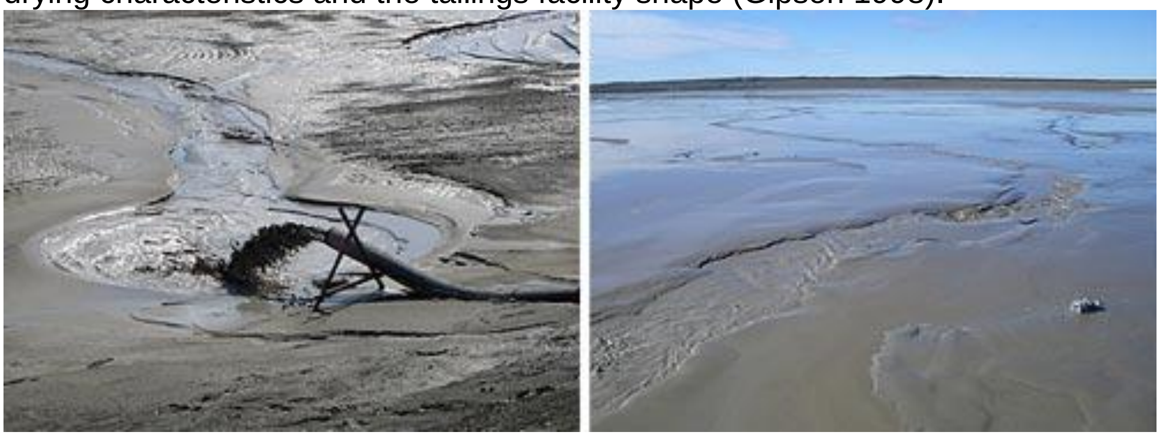


Figure 18: Subaerial tailings discharge (left) and shallow low velocity braided streams on a tailings beach (right)

The general process of multiple subaerial deposition is as follows (modified from (Ulrich, East et al. 2000)):

- Tailings are discharged onto a portion of the gently sloping beach creating braided flows towards the supernatant pond.
- Upon completion of this layer the discharge point is moved to another section of the beach leaving the newly deposited layer to drain, bleed and dry. Desiccation and shrinkage can occur as water expels and can become completely unsaturated if allowed to dry for a sufficient amount of time.
- Under drainage systems intercept seepage and convey it out of the facility promoting faster drying.
- A new layer of tailings are then placed over the dried area at a time corresponding to the facility's discharge zoning plan.

Subaerial deposition exposes the beached tailings to oxygen and water allowing oxidation of infused sulphides and the production of acids (Newman, White et al. 2001).However, the exposure of tailings can maximize evaporation and can help to degrade cyanide compounds if they have been used in the ore extraction process (DPI 2003).

2) Subaqueous

Subaqueous deposition is particularly suited to tailings that contain sulphides that are likely to oxidize, mobilize metals and produce acid (Tremblay 1998). Restricting oxygen to the tailings by permanently placing them underwater will prevent oxidation and minimize the environmental problems associated with AMD (figure 2). With this in mind, the offshore disposal of tailings to natural water bodies is appealing but the actual overall environmental consequences of this technique are not fully understood. However, subaqueous deposition can be practiced in conventional impoundments.

Figure 19: Subaqueous deposition within a conventional tailings impoundment (Courtesy Anglo American)

The Lisheen mine in Ireland is one such site that uses this technique to control AMD. Part of their license to operate requires them to deposit all their tailings subaqueously with a minimum water depth of 1.3 m above the tailings in June and 1 m in October (EPA 2000). As a result the TMF stores a considerable volume of water right up to the upstream faces of the embankments. The tailings are discharged from a mechanised floating head that is controlled by two railway track mounted trucks on either side of the impoundment. The TMF is fully lined on the upstream embankment face with a composite linear low density polyethylene (LLDPE) liner and a geosynthetic clay liner (GCL). The basin area is lined with LLDPE and the compressed peat underneath acts as a second lining (Dillon, White et al. 2004).

Discharging of tailings below water can create significantly steeper slopes than that of subaerial deposition (Robertson and Wels 1999). Dillon et al. (2004) report that for Lisheen the underwater tailings slope could be in excess of 10%. This means that if the distribution head or spigot is not regularly moved then differential settlement, slumping and squeezing can occur. This can damage synthetic liners particularly if the underlying material is likely to compress. It is essential for a lined impoundment using subaqueous deposition that the tailings are evenly distributed and that depth measurements are recorded at regular time intervals to establish dramatic elevation changes.

3) Spigots

Spigot disposal (normally subaerial) is used where the tailings are discharged generally around the perimeter of the tailings facility to create a beach between the embankment and the supernatant pond (Ritcey 1989). This generally means the pond is completely surrounded by beached tailings (figure 20). The spigots are changed over as set out by the deposition plan to promote bleeding and drying prior to further layering and raising. It is essential that a deposition plan be established during the design stage and implemented and managed throughout the operational stage.

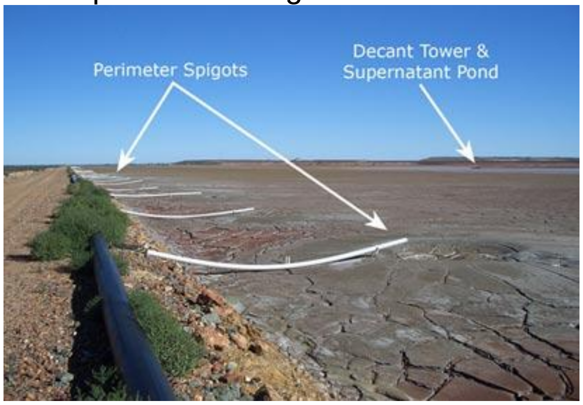


Figure 20 : Multiple spigot discharge at the Jundee Gold Mine, NT, Australia

The ideal spigot spacing can be determined by deposition trials to establish likely beach slope angles and widths. Incorrect spacing can lead to undulating beaches between spigots that can ultimately reduce the efficiency of tailings deposition.

Multiple sighting creates pipework management challenges as blockages and ruptures can occur (DPI 2003). Monitoring and maintenance schedules are also intensified to ensure that tailings are being delivered to the correct areas, for the correct time period and in the intended quantities. Normally multiple spigots are small diameter pipes that feed off ring main configurations (sometimes known as distribution lines) that then feed off the larger diameter main delivery lines from the plant. The pipeline size reduction ratios and incorrect flow velocities can lead to sanding and plugging of lines (WMC 1998). Valve stations and flushing lines are also required for multiple spigots to allow lines to be flushed to prevent sanding after they have been shutdown.

Multiple spigotting helps to reduce the discharge velocity of the tailings being pumped to the storage facility compared to single point deposition. This helps to promote laminar rather than turbulent flow allowing the coarser particles to settle nearer the spigot creating a greater drainage potential. This will also promote a slightly steeper angled beach that will aid the removal of fluids from tailings deposited near the spigot (Ulrich, East et al. 2000).

4) Single point

Single point discharge requires irregular movement of the discharge lines. Vick (1990) reports that deltas are normally formed or a single beach deposit of tailings within the impoundment (figure 21). This normally means the supernatant pond is restrained to a certain area of the impoundment which may be against one of the embankment walls resulting in high and low ends of the impoundment. The lower end of the impoundment will collect the slimes increasing the possibility of seepage erosion (Ritcey 1989). This type of deposition is not suitable where the pond and/or the slimes must be kept away from an embankment (EPA 1994).

Figure 21 : Single point discharge at Glebe Mines, Derbyshire, England

Single point deposition can place the tailings in fairly thick layers causing the tailings to remain saturated for years if not dried before new layers are deposited (Norman 1998). This method of deposition is suited to valley type impoundments (downstream and some centreline embankment designs) where the supernatant pond can be forced to reside against a valley face (i.e. against the hillside away from the retaining embankments).

CHAPTER THREE:

WET TAILINGS MANAGEMENT (ENGINEERED WASTE)

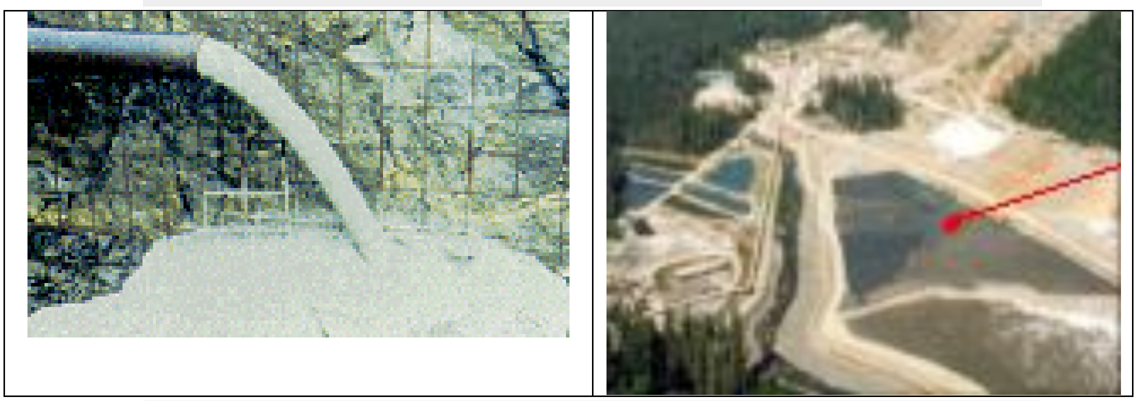
What Can Be Done

1 Backfilling of tailings into operating underground mines

In underground mines tailings are often used as backfill material to provide geotechnical support or to facilitate ore extraction. Increased safety and ore recoveries can thereby be obtained. As the porosity of tailings is approximately double that of the original ore forming rock it is normally not possible to backfill all the generated tailings. In base metal mines approximately 40 % of the generated tailings can be backfilled (EU, 2004). Backfilling is normally done using hydraulic backfill or paste backfill prepared on the surface and pumped into the filling areas in the mine. The backfill may or may not need an addition of binders, such as cement.

Paste Backfill. The steps in creating paste backfill are:

- separate coarse and fine grained particles of tailings (cyclone and/or thickener)
- allow water to drain from coarse material
- filter fines to release water
- recombine with cement
- pump the paste underground into stopes



The benefits are:

- minimizing surface disposal of tailings
- using engineered backfill material

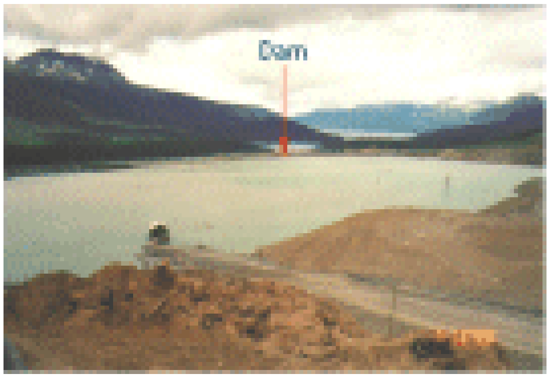
Fige 22 :past back fill

Myra Falls, British Columbia is an underground mine producing Cu, Zn, Pb with Au and Ag. The mine is situated in Strathcona Provincial Park. As for the tailings pond, this is it (Figure 3). There's no more room for coarse tailings. The mine must use paste backfill.

2. Tailings ponds

There is a wide variety of tailings dam designs and disposal schemes. A design must adapt to local conditions, use readily available materials, be inexpensive to operate, and be simple to rehabilitate when the mine closes. The design of these facilities is highly specialized work carried out by 10-20 consulting engineering organizations worldwide.

Tailings pond operation and management are affected by production from the mill.



In Figure 23 at the Huckleberry mine, BC, the dam is in the background. The little shack on the pond houses the reclaim pump which returns water to the mill -- it is not an ice fishing shack.

In Figure 24 at the Rio Paracatu Mineracao (RPM) gold mine, Rio Tinto Brazil, the pond has a capacity of 126 million tonnes of tailings and four million tonnes of free water.

Tailings that is not used for backfilling operating underground mines are normally managed on the surface in ponds or heaps, backfilled into old excavation voids or, in rare occasions in Europe deposited into the sea (e.g., Cleveland Potash, England). Salt brine can in some cases be re-injected into the ground in deep wells (EU, 2004). Of the above mentioned methods, disposal of tailings as a slurry into engineered ponds or old excavation voids is the most common method where wet processing methods are applied and disposal in heaps or into old excavation voids when dry processing methods are used.

There are numerous ways to deposit the slurry tailings into the facility where the most common method is sub-aerial (Cambridge, 2003) single point or multiple point discharge (spigotting). Subaqueous discharge is practiced at a few sites to minimize sulphide oxidation (e.g., Neves Corvo Mine, Portugal). There are also many ways to construct the embankments containing the facility. The facility may or may not be lined (synthetic liner, clay liner, natural liner or a combination) depending on the tailings to be deposited into the facility and the specific hydro-geological setting. Lining can, if it is used, be covering the interior of the entire facility (e.g., Aguablanca Mine, Spain, Figure 23) or just in relation to the embankments (e.g., El Valle Mine, Spain).

Figure 25. Disposal of thickened tailings into the fully lined tailing pond at the Aguablanca mine in Southern Spain.

A conventional tailings pond is a facility designed to store both the solid part of the tailings and the water. Depending on how the pond is located the pond type is called; valley facility (embankment built across a valley); hill side or off-valley facility (embankment built to contain the tailings towards a hill side); or paddock (built on flat land with an embankment surrounding the facility). Some common location types are illustrated in Figure 26. The primary function is to allow for the settlement of the solids in the pond. Secondary functions can be to allow for recovery of process water and some times for storage of water. The tailings pond can be a single structure from which the water is either recycled to the processing plant or discharged to the recipient (e.g., Neves Corvo, Portugal) or it can be a combined structure of two or more ponds where the solids settle in the first pond and the water is clarified (polished) and if required stored in the following pond (clarification pond or polishing pond) before it is either recycled to the processing plant or discharged to the recipient (e.g., Aitik Mine, Sweden). If water treatment, in addition to clarification, is necessary it is either done at the processing plant before pumping the tailings to the tailings pond (e.g., Svartliden Gold mine, Sweden), between the tailings pond and the clarification pond or in a separate water treatment facility before discharge. There are often additional processes that take place in tailings ponds (e.g., natural degradation of trace concentrations of cyanide and oxidation of thiosalts) apart from settling of solids and therefore the pond can form an important part of the water treatment scheme at the site.

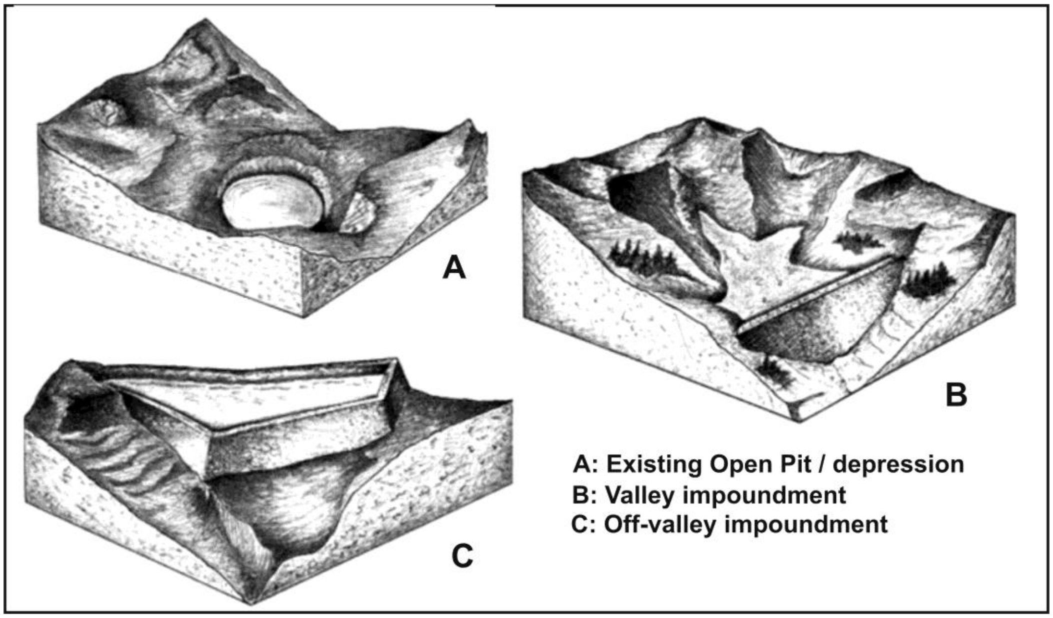


Figure 26. Illustration of common location alternatives for tailings facilities. (From EU, 2004).

Downstream construction

upstream construction using tailings

Tailings ponds are often raised and built higher at the same rate as the tailings are generated, so called staged construction or sequentially raised construction. There are many ways to design and raise a tailings pond embankment over time and it is not uncommon to change dam construction method over time. The embankment can either be built as a conventional dam, a staged conventional dam (where borrow materials are used in the construction of the embankment) or by using tailings as the main construction material for the embankment (Figure 4). The common methods are listed below and described in detail in UNEP/ICOLD, 1996 and in EU, 2004 and a compilation can be found at www.tailingsinfo.com:

- ***Upstream***: the embankment is raised inwards on top of the deposited tailings using mainly the coarse fraction of the tailings. The design relies on maintaining a wide beach, i.e., a large distance from the dam crest to the free water stored in the pond, and the draining properties of the coarse tailings. The closer the free water is to the dam crest, the higher the phreatic surface of the embankment and thus the greater the risk of failure. The filter under-drain system of the embankments is a key component in reducing the phreatic surface of an upstream designed embankment (tailingsinfo.com).

- ***Downstream***: the embankment is raised expanding downstream (away from the previously deposited tailings).
- ***Centerline dams***: the embankment is raised vertically, which is a middle ground between the upstream and the downstream methods.

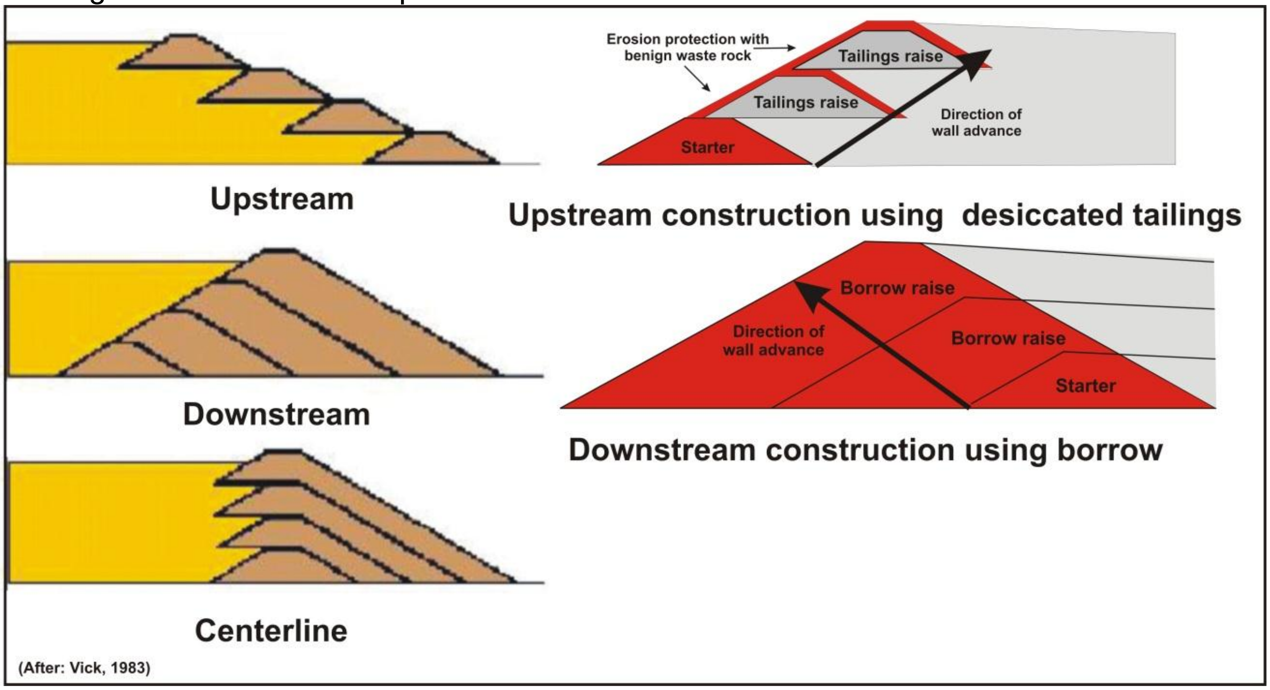


Figure 27 Types of sequentially raised dams with tailings in the structural zone (From EU, 2004)

For the three construction methods either tailings or borrow material can be used. The BAT-document (EU, 2004) gives a summary of different dam construction techniques and when they are suitable, table 1. The International Commission on Large Dams Bulletin 121 (UNEP/ICOLD, 2001) provided a comprehensive report of lessons learnt from past accidents, drawing from the global experience from a range of tailings storage facility failures and incidents. The main causes of failures and incidents identified were (as summarized by Australian Government, 2007):

- lack of control of the water balance
- lack of control of construction
- a general lack of understanding of the features that control safe operations.

Table 1 Different dam construction techniques and when they are suitable (from EU, 2004).

Dam Type	Applicability	Discharge suitability	Water storage suitability	Raising rate restrictions	Construction material	Seismic resistance	Dam Coast
Conventional	Suitable for	Any	Good	Not	Natural soil	Good	High

dam or water retention type	any type of tailings	discharge procedure suitable		dependent on tailings material properties	borrow		
Upstream	If tailings are used at least 40-60% sand (0.075-4 mm) in whole tailings*****. Low pulp density desirable to produce grain size segregation	Peripheral discharge and well controlled beach necessary, center discharge for thickened tailings	Suitable under certain conditions	Less than 5 m/yr most desirable, to avoid insufficient consolidation and pore pressure build-up	Natural soil sand tailings or waste-rock or sand tailings in combination with natural soil or waste-rock	Poor in high seismic area	Low
Downstream	Suitable for any type of tailings	Varies according to design details	Good	None	Sand tailings or mine wastes if production rates are sufficient otherwise natural soil	Good	High
Centerline	Sands or low plasticity fines	Peripheral discharge necessary	Not recommended for permanent storage. Temporary flood storage acceptable with proper design details	Height restrictions for individual raises may apply	Sand tailings or waste rock if production rates are sufficient, otherwise natural soil	Acceptable	Medium
***** does not apply to thickened tailings							

Tailings embankment failures were (in order of prevalence):

- slope instability
- earthquake loading
- overtopping
- inadequate foundations
- seepage.

Tailings incidents appeared to be more common where upstream construction was employed, compared with downstream construction. UNEP/ICOLD Bulletin 121 (2001) also concluded that successful planning and management of tailings storage facilities could benefit greatly from:

- the involvement of stakeholders
- thorough investigations and risk assessments
- comprehensive documentation

- tailings management integrated into mine planning, operations and closure.

From the above compilation of the UNEP/ICOLD (2001) findings it can be concluded that poor water management is one of the main reasons for embankment failures. The water stored in the facility may constitute a significant risk to the downstream area if released and it may mobilize and transport significant amounts of tailings out of the facility (e.g., Eriksson and Adamek, 1999).

2.1. In-pit tailings storage

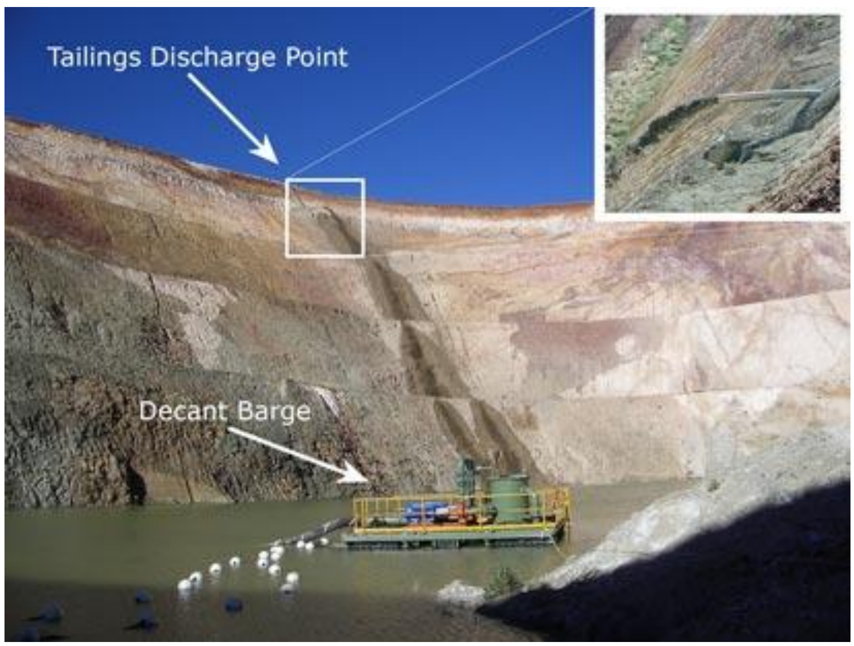


Figure 28: Typical in-pit tailings storage

In-pit tailings storage, as the name suggests, is simply the process of backfilling abandoned open pit surface mines with tailings (figure 28). This method is very attractive to a mine operator as worked out voids can be filled at a fraction of the costs associated with designing, constructing and operating a conventional, thickened, paste or dry stack facility. Another advantage to in-pit storage is that the tailings do not require retaining walls, thus the risks associated with embankment instability are eliminated (EPA 1994).

The main disadvantage to in-pit storage of tailings is that the potential for groundwater contamination below and around the void can be very significant (DME 1999). Other disadvantages to in-pit storage are:

- Rapid rates of rise occur particularly in the early stages of deposition when the pit is at its deepest and the exposed surface area the smallest. This reduces the solar drying and desiccation potential of the tailings resulting in low strength and poor consolidation properties (DPI 2003).

- The stability of underground mines in the vicinity to an in-pit tailings facility may be jeopardized. Liquefied tailings may rush into underground voids resulting in catastrophic consequences or the increasing weight of the overlaying tailings may cause convergence in underground roadways. The Mufulira disaster of 1970 claimed the lives of 89 miners when a tailings inrush flooded the underground workings (DME 1999).
- Poor consolidation can result in long durations of surface deformation after a pit has been filled. This is mainly due to the low solids content of the tailings and the depth of the stored material. Pits will have to be continuously topped up with tailings until the consolidation rates are minimal and a rehabilitation cover can be implemented and contoured successfully (DME 1999).
- Groundwater bores will have to be installed around the pit to monitor the seepage plumes. In some cases it may be necessary to monitor these long after a pit has been filled and to even pump out the seepage by wells to prevent groundwater contamination (DME 1999).
- As a consequence where environmental laws exist the backfilling of pits is either forbidden or controlled to prevent excess groundwater contamination.
- Sterilization of reserves as modern block cave or cut and fill underground mining methods would be too hazardous to contemplate. Remote mining operations in Australia have used in-pit storage for decades where the groundwater is saline or non-potable. Also, the aboriginal stakeholders prefer voids to be filled after mining has ceased and grant permission to backfill suitably located pits.

3. Tailings disposal into old voids

Tailings disposal into old voids or in-pit tailings disposal (Figure 29), is simply the process of backfilling abandoned open pit surface mines with tailings. The main advantage to in-pit disposal is that the tailings do not require retaining walls, thus the risks associated with embankment instability are eliminated.

However, in pit disposal may also result in serious accidents if a proper risk assessment is not conducted also considering underground workings (e.g., Marcopper accident in the Philippines 1996 when 1.6 million m3 of tailings was lost from storage pit through old drainage tunnel). In pit disposal may appear attractive as worked out voids can be filled at a fraction of the costs associated with designing, constructing and operating a conventional, thickened, paste or dry stack facility. However, water management costs may be significant and the potential for groundwater contamination below and around the void has to be considered.

Figure 29. In pit disposal of slurry tailings. (From EU, 2004).

4. Co-disposal of tailings and waste-rock

Tailings and waste-rock co-disposal is worldwide viewed as a novel concept for the containment and disposal of tailings within waste-rock heaps. However, it has been used for some time in Europe, e.g., in Austrian iron mine and German coal heaps. The method utilizes the void space in mine waste rock for the disposal of the fine grained tailings. Because waste rock is commonly a coarse, run-of-mine product created from blasting of hard rock, there are large voids created when the waste is placed in a waste dump. When applied to competent waste, these large void spaces make a good place for the placement of tailings. Clayey and sandy wastes may not be suitable for this technology, depending on the gradation, ratio of waste-to-tailings and, ultimately, the available void ratio (Leduc and Smith, 2007).

Co-disposal is the mixing of fine and coarse mine waste to produce a single waste stream (Martin, Davies et al. 2002). Mixing the fine and coarse waste reduces the empty void space primarily associated with coarse waste streams whilst simultaneously increasing the strength of the fines. The strength and rapid stabilization of the co-disposal waste allows early access onto the tailings for rehabilitation and reduces the risk and consequences of static and dynamic loading (DPI 2003).

Co-disposal storage, like dry stack, does not require retention embankments which thus eliminates the risk of embankment breach and transportation of tailings outside the storage zone (Smith and Leduc 2003). Another advantage is that co-disposal can significantly reduce the generation of acid associated with sulphide bearing coarse mine waste. The fine waste stream (tailings) are much less pervious to water and atmospheric oxygen than coarse mine waste. Combining the two waste streams increases the physical stability (high shear strength) and the chemical stability thus reducing oxidation and the potential for AMD (Martin, Davies et al. 2002).

The major disadvantage of co-disposal is controlling the deposition strategy to optimize the blending of the coarse and fine waste feeds. This is only really economic where the two feeds can be pumped together or blended for in-pit storage (DPI 2003).

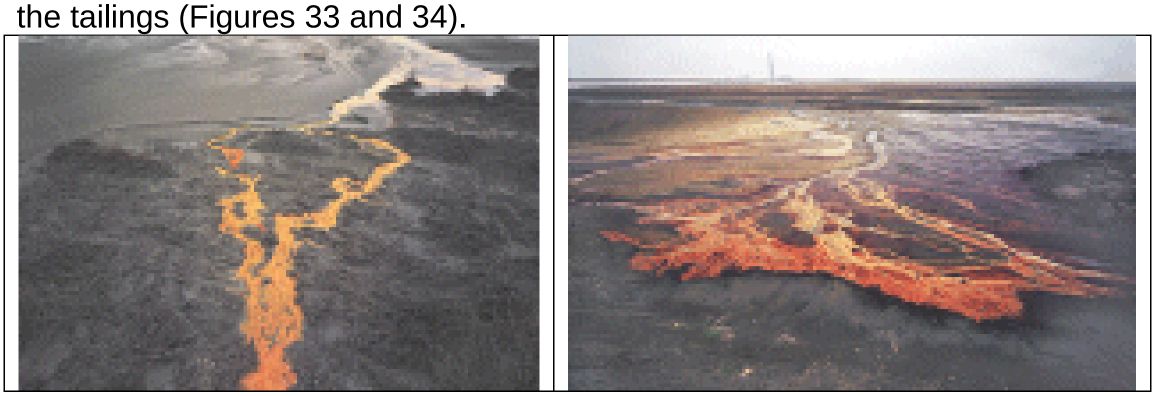
Waste rock is mixed with layers of compacted tailings (Figures 30, 31, and 32). Waste rock gives the mixture strength and fine-grained tailings prevent or minimize the flow of water.

The co-disposal process requires more material handling, but co-mingling should delay the onset of acid mine drainage and reduce the magnitude of ARD produced in waste rock or tailings.

Co-disposal is currently the subject of a major research project at UBC under the direction of Dr Ward Wilson (Wilson et al (2000))

(Figures 30, 31, and 32)

Tailings as art - The red color is not molten rock. It is due to iron oxide in the tailings (Figures 33 and 34).



(Figures 33 and 34).

5. Dewatered Tailings

5.1. Thickened and Paste tailings and Dry stacking of tailings

Thickeners can be used to decrease water content. One advantage is that the waste disposal scheme has a smaller "footprint".

Thickening tailings reduces the quantity of water delivered to the tailings storage facility. This in turn reduces the risks of overtopping, and reduces seepage and evaporation losses. Thicker tailings discharge also enables better control of the decant pond and return water system. Where tailings are discharged into surface storage facilities, depositional beach angles will steepen as the tailings are discharged at a thicker consistency, and the reduced water content will, in turn, reduce the containment requirements (Australian Government, 2007).

Past limitations to successful thickened tailings disposal were either cost or the lack of suitable thickener technology. Today, thickener technology has developed well beyond the conventional thickener to produce high underflow densities, close to the filtration limit, and costs have reduced. These thickeners range from deep bed thickeners (typically used for red mud) through to paste or deep tank thickeners developed for the production of cemented paste tailings backfill for underground application (Potvin et al. 2005). At the recently constructed Aguablanca Mine in southern Spain thickened tailings disposal into a drained and lined pond is practiced. The experience is after almost 2 years of operation very positive with a high degree of consolidation of the deposited tailings and a high degree of water recovery (Castro, 2007).

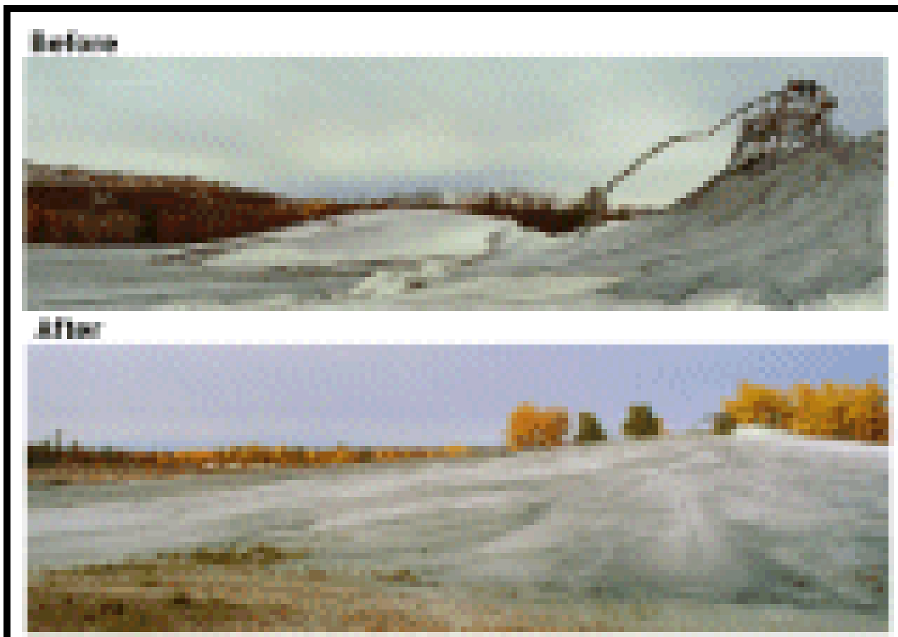


Figure 35 shows tailings disposal at Unimin Canada Ltd.'s Blue Mountain operation before and after converting to thickened tailings

5.2. Thickened Tailings Storage

Figure 36: Thickened discharge at Kidd Creek, ON, Canada (left) and at Mt Keith, Western Australia (right)

Thickened tailings, as the name suggests, involves the mechanical process of dewatering low solids concentrated slurry (Fourie 2003). This is normally achieved by using compression thickeners or a combination of thickeners and filter presses (DPI 2003). Thickened tailings are defined as tailings that have been significantly dewatered to a point where they will form a homogeneous non-segregated mass when deposited from the end of a pipe (Welch 2003). When placed layer by layer the thickened tailings will dry to near its shrinkage limit and become dilative under dynamic shaking, thus preventing the possibility of liquefaction (ICOLD and UNEP 2001).

The idea of Thickened Tailings Disposal (TTD) is to stack the pulp to form a self supporting conical pile thus reducing the height and retention forces of the containing perimeter embankments. The tailings are generally discharged from topographical high points within the tailings storage facility or by riser towers or central ramps (ICOLD and UNEP 2001). Water remaining after deposition and any surface runoff is collected in a pond at the toe of the pile. Typical slope angles of 1 – 3.5 degrees can be achieved to form a self draining easy reclaimable shape (ICOLD and UNEP 2001).

In 1973 the Falconbridge owned Kidd Creek Metallurgy Plant in the town of Timmins, Ontario, Canada was the first site to utilise surface thickened disposal of tailings (Engels and Dixon-Hardy 2004). The conventional storage facility was converted to TTD to eliminate further raising of the traditional retaining embankments that were situated on very soft and sensitive clay foundations (ICOLD and UNEP 2001). The tailings are discharged from spigots on a central ramp that is currently 20m high . At the base of this ramp is the 32 m diameter high compression thickener that produces a slurry density of 60 – 65% solids (Golder 2005).

Operating costs are higher for thickened disposal due to the associated dewatering costs. However, there are significant advantages to thickening tailings. Perhaps the most important is that water is conserved and evaporation is minimised in arid climates. Sustainable water use in the mining industry is becoming increasingly more important (Welch 2003). The potential for recovering high volumes of water at the plant (by the thickeners) eliminates the losses associated with the transport and storage of water either at the tailings facility or in holding ponds (Fourie 2003). Environmental problems such as seepage, spillage of process water and the potential for water to act as a transporter for tailings flows (e.g. embankment breach) is significantly reduced. Some other main advantages to thickening tailings are:

- No large starter dam is required which significantly reduces capital cost.
- Reclamation costs are significantly lower than impoundments that store tailings and water. This is particularly true when considering a thickened tailings facility can be progressive restored, thus reducing closure costs.
- Concerns of the instability of high retaining embankments associated with conventional storage are potentially addressed (Fourie 2003).
- Little or no ponded water to manage which not only reduces seepage but reduces water pumping costs to and from the processing plant.
- Little or no solid/liquid separation results in less oxygen ingress which will reduce oxidation and thus the generation of acid from sulphur bearing tailings (Welch 2003).
- Modification of the tailings properties by adding binders to increase the static and dynamic stability, reduce the likelihood of erosion and prevent seepage (e.g. bentonite addition) (DPI 2003).

Besides the costs associated with thickening the tailings, many mine operators are reluctant to switch from conventional to thickened storage even though wet deposition is more problematic. The argument could also lead to the fact that thickened tailings is relatively unproven and requires larger areas of land compared to conventional storage. This in itself can immediately rule out thickening if space is a constraint.

In the future, the benefits of thickened tailings storage will be more prominent, particularly as environmental regulations tighten and increased pressure is placed on the mining industry to become more sustainable (Welch 2003).

5.3. Thickener and Filter Press.

Thickeners and presses are used if:

- it is necessary to dewater tailings in order to obtain water for mineral processing
- more stable solid tailings are desired

Thickeners are large diameter cones which accelerate settling of solids and dewatering of tailings. As tailings enter the thickener in the feed well the solids start to settle immediately. Settling is aided by rotating rakes which force the solids down to the bottom of the cone. Flocculants are also added to coagulate the solid particles.

The thickened tailings usually contain ~30 - 35% solids. They are pumped from the bottom of the cone as an underflow to either a lagoon or a conditioning tank for further dewatering, e.g., in a filter press. The overflow is clear water which is piped to a storage tank and reused in mineral processing.

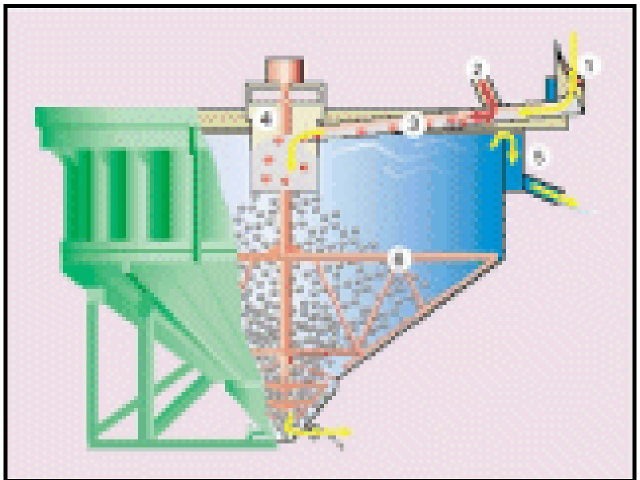


Figure 37 shows the major components of a thickener

Fige 38 : *Thickener and Filter Press.*

A belt press filter sandwiches the underflow between two tensioned conveyor belts which are passed through a sequence of rolls. The pressure on the rolls gradually increases to squeeze water out of the solids.

In dry climates there is a need to conserve water for processing ore so tailings are dewatered and deposited dry (Figure 39).

Fig.39: shows conserve water for processing ore so tailings are dewatered and deposited dry in dry climates.

6. Monitoring of tailings management facilities

Normal environmental monitoring practice applies to tailings management facilities. Surface- and groundwater monitoring up-streams and down-streams the facility is normally performed. Monitoring of dust emissions is done at many sites.

Figure 40. Collection and monitoring of drainage flow rate from the toe of the Enemossen tailings pond.

Of special interest is the monitoring of parameters that might give an early warning of any kind of problems with the facility, such as the drainage flow rate, Figure 40. A list of parameters, monitoring instrumentation and frequency is given in table 3 for such parameters.

Table 2 Typical measurements and their frequency and instrumentation for tailings dams monitoring (from EU (2004)).

Measurement	Instrumentation	Frequency
Water level in pond	Level scale, doppler	Weekly, daily or online
Seepage discharge through: ▪ the dam itself ▪ the foundation ▪ the abutments	▪ weirs or containers ▪ pore water pressure gauges ▪ groundwater wells	Weekly, daily or online
Seepage samples	Taking of samples and measurement of turbidity	Monthly or weekly
Position of phreatic surface	Piezometer (typically open standpipe)	Monthly or weekly
Pore pressure	Piezometer or bourdon tube pressure gauge	Monthly or weekly
Movement of dam crest and tailings	Geodetic datum points on beach (completed dam) and crest of the dam, aerial photography, GPS	Yearly or half-yearly
Seismicity	Strong motion accelerographs	Events (not done on site)
Dynamic pore pressure and liquefaction	Vibrating wire piezometers	Yearly
Soil mechanics	Penetrometers for density and shear strength	Yearly (only during design phase)
Tailings placement procedures	Shear strength, compressibility, consolidation, grain size and density samples, width of the non-submerged beach as indication of phreatic surface via aerial or satellite photography	Yearly (only during design phase)

The tailings management facility is normally submitted to periodical audits The BAT-document suggest auditing of tailings management facilities are done according to the schedule presented in table 3.

Table 3 Tailings dam assessment regime during operation and in the after-care phase (from EU, 2004).

Assessment Type	Frequency		Personnel
	Operational Phase	After-care Phase	
Visual Inspection	Daily	Half-yearly	Dam operators, after the closure possibility follow-up staff
Annual Review	Yearly	Yearly	Engineer
Independent Audit	Bi-annually	15-20 years	Independent Expect
Safety evaluation of Existing Dams (SEED)	15-20 years	15-20 years	Team of Independent Experts

7. Seepage flow to surface water and groundwater

Seepage to surface water and groundwater may lead to surface water and groundwater contamination in the short- medium- and long-term. The facility needs to be adequately located and designed and the relevant seepage control measures need to be in place according to the characteristics of the managed tailings in order to minimize contamination of surface and groundwater. Figure 41 illustrates schematic seepage flow scenarios for different types of tailings facilities.

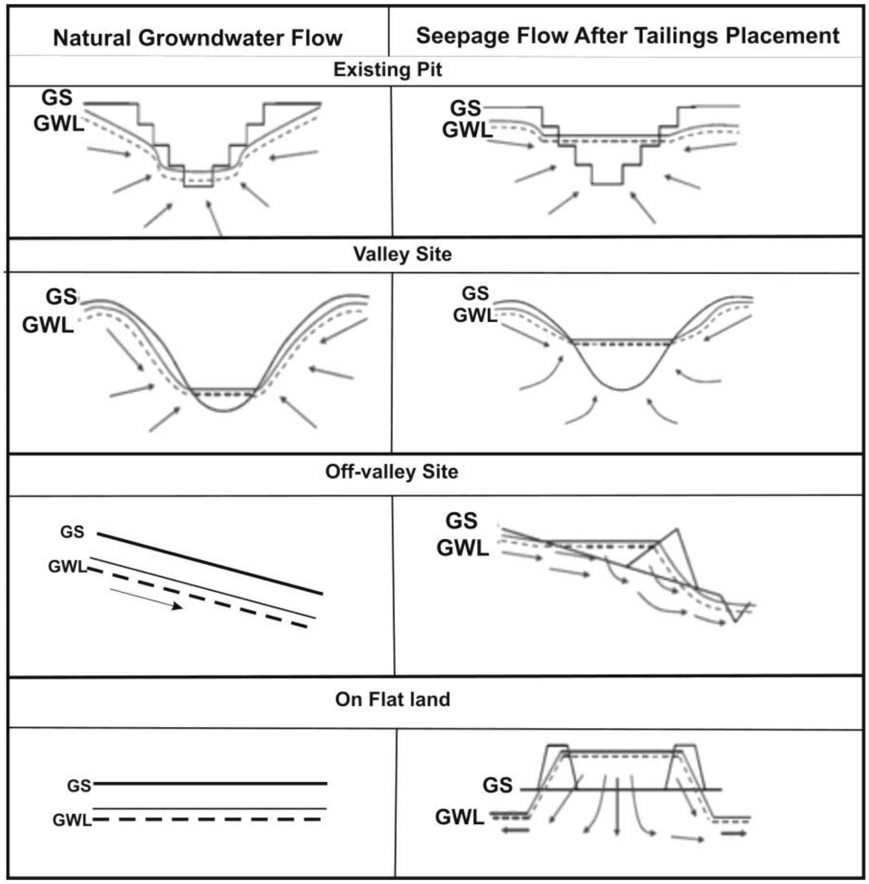


Figure 41. Schematic seepage scenarios for different types of tailings pond (from EU, 2004).

8. Closure of tailings management facilities

Typically closure of tailings ponds involve assuring safety, landscape integration and assuring physical and chemical stability of the facility. A significant risk reduction is normally obtained after closure when the pond is drained. Specific cover requirements may be required depending on the ARD characteristics and leaching characteristics of the waste. For tailings ponds containing potentially ARD generating waste various methods have been developed to minimize oxygen flux to the deposited tailings, including qualified covers and flooding (EU, 2004). Figure 8 illustrates shows the Aznalcóllar tailings pond after failure in 1998, during closure 1998-2000 and after closure was completed in year 2000. Figure 43 is a view of the closed Aznalcóllar tailings pond in 2000, 3 years after the failure occurred.

Figure 42. The160 ha Aznalcóllar tailings pond after failure, during closure and after closure

Figure 43. View of the160 ha Aznalcóllar tailings pond after closure had been completed in year 2000, 3 years after the failure occurred

CHAPTER FOUR:

WATER MANAGEMENT CONSIDERATIONS FOR CONVENTIONAL STORAGE

Introduction

Water has been the underlying source of virtually all failures of tailings storage facilities between 1980 and 1996 (Fourie 2003). All these failures have occurred at facilities that store their tailings by conventional impoundment methods. The liquefaction phenomenon, internal and external erosion, seepage and overtopping are some of the main water induced failure modes of tailings facilities (ICOLD and UNEP 2001). Increasing the pulp density of the tailings is the most obvious step to reduce water handling and subsequent storage requirements. Fourie (2003) also notes that the presence of large quantities of stored water is the primary factor contributing to most of the recent tailings storage failures. The risk of physical instability for a conventional tailings facility can be reduced by having good drainage and little (if any) ponded water. Simply put, ‘no water, no problem’.

Water management of a tailings facility not only involves the superficial water flows but the interception, collection and treatment of seepage. Control measures may be required to prevent levels exceeding regulatory licenses and tailings guideline documents (Ritcey 1989). This section reviews these key water management considerations for conventional tailings storage as well as the infrastructure required to control ponded water. The intention of this section is to highlight how problematic conventional storage can be to both design and manage.

This water management page is not relevant to thickened, paste and dry stack facilities as little or no water is stored with the tailings. This strengthens the argument that these methods of surface tailings storage have a lower risk of failure as water management is virtually eliminated. However, reclaim ponds may be used to capture surface runoff or any bleed water as the tailings deposit within the facility.

1. Water balance and release

This is analogous to balancing cash flow between balance sheet, income statement, and cash flow statement. Just as a cash imbalance indicates something is wrong (e.g., missing accounts, over or under-valuation, or maybe even fraud), a water imbalance indicates an inflow or outflow has not been correctly estimated or (horrors) there may be a leak.

Establishing a stable water balance for a TMF during the design stage is one of the most important considerations to prevent water management problems occurring during operation and closure. Water plays a key role in the day to day responsibilities of a tailings operator and it is essential that a facility is designed to handle and control the required inflows and outflows as well as any unpredictable fluctuations (e.g. storms). Poor design of water management infrastructure and control methods can increase the risk of problematic situations occurring during the operating and closure stages (e.g. upstream inrushes, pipe bursts, low freeboard, seepage). During operation the plant will also demand a certain, and sometimes variable, flow of water that the surge capacity of the decant systems and reclaim/holding ponds have to cater for. Any water balance survey for a proposed tailings facility should take into account that higher volumes of water may require storage during the dry season to maintain plant production. Ice and snow melt, upstream inundation (valley impoundment) and severe storm reoccurrences (e.g. 1 in 100 year) should be considered when designing a TMF to prevent any loss of minimum freeboard levels.

When determining the water balance the various inputs and outputs of the proposed TMF will need to be considered. Wels et al. (2003) noted that determining the water balance of a tailings storage facility can be a difficult task if all the physical processes of water movements are to be considered. During the design stage a conceptual water balance of all inflows and outflows should be determined for a particular location and include all the worst case combination of risk factors (e.g. decant failure, storm, upstream snow/ice melt) (DPI 2003). A simple and accurate method to determine water balance of a TMF is to determine average annual water inflows and outflows as well as estimating seepage and evaporation rates. A more complex method is to use hydrogeological modelling methods (WMC 1998). Estimating the phreatic surface will help to determine seepage plumes and groundwater movement. Figure 44 shows the various water gains and losses for a typical conventional TMF. The seepage and evaporation losses will be predictions and should be included in any design proposal.

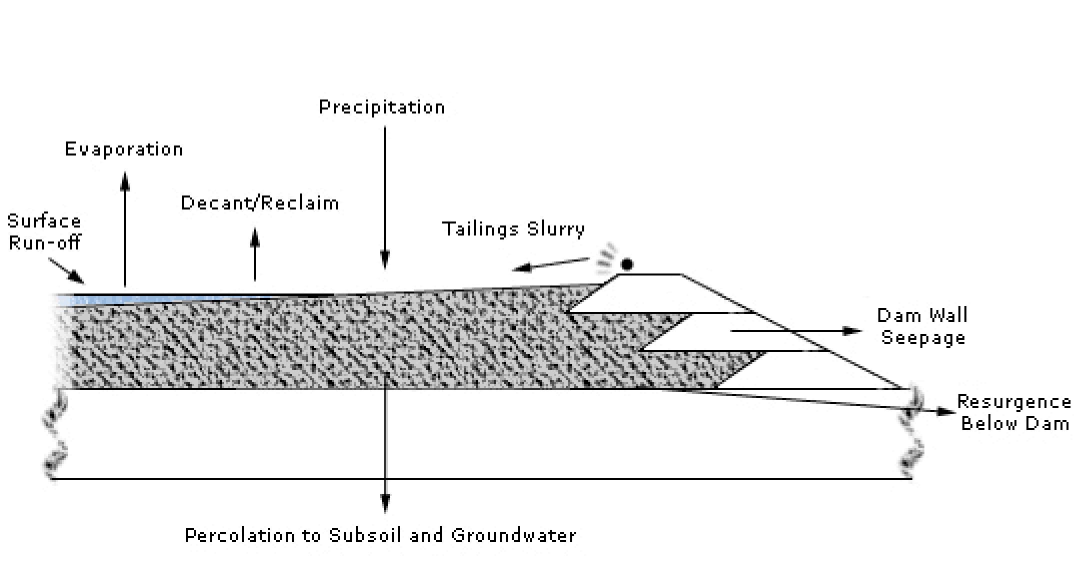


Figure 44: Water balance of a typical conventional tailings storage facility (Adapted from (Vick 1990))

Water stored in a tailings facility is either decanted to reclaim ponds or sent directly to the processing plant. If the plant requires none or only a small volume of the stored water then the remainder will need to be either sent to evaporation ponds or treated and discharged to the environment.

2. Supernatant pond

The control of the supernatant pond is probably one of the most important procedures in managing a TMF. Inadequate pond control can result in overtopping, increase in pore pressures, reduction of freeboard, high seepage rates and embankment settlement (Engels, Dixon-Hardy et al.). These few consequences can lead to instability and high risks of problematic situations occurring. For a conventional impoundment (particularly upstream and centerline designed) it is essential that the ponded water be kept to a minimum volume and the freeboard be sufficiently high all along the tailings embankment(s). Suitable monitoring and management of the supernatant pond is required to operate a TMF safely.

3. Decant systems

The decant system(s) of a TMF should be designed to cope with the day to day management of the supernatant pond as well as storm condition surges. The design of the decant should allow for a high surge capacity of storm water to compensate for near future storm events. If the pond cannot drain fast enough (decant system or reclaim/evaporation pond ingress restriction), then the freeboard of the TMF may be lost if a near future storm reoccurs. As a guide the decant system should be able to remove storm water in 2 – 4 weeks, but this is highly dependent on climate conditions (WMC 1998).

The two most common methods of water control within a tailings storage facility are a decant barge and a decant tower. A decant barge consists of a floating platform that houses the pumps used to reclaim water from the supernatant pond back to the processing plant or holding ponds. A decant tower is an intake structure consisting of a vertical hollow tower (riser) that is connected to a horizontal conduit or pipe that normally travels beneath the impoundment and through/under an embankment. The vertical riser is extended as the level of tailings in the impoundment rises. The decant tower skims off the clear water from the surface of the supernatant pond and carries it away by gravity through the underlying conduit (EC 2004).

4. Decant tower

Decant towers can be very effective at removing ponded water from a tailings facility but can be very problematic. Decant tower systems come under increasing stress as more tailings are disposed of in an impoundment. The ever increasing weight of the tailings can crack and damage a decant conduit that flows underneath and through an impoundment facility (Engels and Dixon-Hardy

2004). Failures of decant conduits and towers can lead to water management problems that have caused impoundment failures in the past (ICOLD and UNEP 2001). It will not be immediately apparent to an operator that a decant system has failed until the decant outfall is showing signs of low flow or the presence of sediment (tailings). Water levels in the impoundment can rise rapidly and overtopping can occur if contingency plans are not implemented. The Stava disaster in Italy in 1985 was a good example of a decant conduit failure that created a rise in the phreatic surface of the embankment (Penman 2001). A rotational slip occurred causing tailings from the upper impoundment to inundate the lower impoundment which eventually overtopped and failed (Davies 2001). Tailings escaped down the hillside engulfing the town of Stava claiming the lives of 269 people. Stava remains as one of the world's worst tailings disasters in terms of loss of human life.

Figure 45: Decant tower with walkway (left), view inside the tower showing riser pipe and submerged decant collars (right)

One major disadvantage to a decant tower is that the water has to be continuously positioned around the tower as unlike a decant barge a tower cannot be relocated. If a decant tower becomes inoperative (beached tailings moving the pond away from the tower) then emergency pumping or spillways will need to be implemented. Any tailings facility operating plan should have precise contingency plans documented in case a decant tower becomes inoperative either by isolation, blockage or failure.

Cracking of a decant conduit can cause internal erosion which will eventually lead to impoundment instability. Ice thrusts can also generate movement in the riser that can crack the joints between the riser and horizontal conduit (ICOLD and UNEP 2001). Repairing the buried conduit is a near impossible task and far too expensive to carry out. The Aitik tailings dam failure in Sweden was triggered by a damaged concrete decant conduit. Cracks developed causing settled tailings to pipe through creating a sink hole (EC 2004). Figure 3 shows the extent of the breach and the cracks in the washed away conduit.

Figure 46 : Aerial view of the embankment failure at Aitik (left) and the cracks in the decant conduit (right)

5. Decant barge

Unlike decant towers that are gravity fed, a decant barge requires power to operate the pumps that decant the water from the supernatant pond. This increases operating costs as a constant and reliable power source is required to ensure the pumps operate. If a power failure occurs then no water can be decanted. It is good practice to have standby pumps and diesel generators to use in emergency or when a decant barge cannot cope with rapid ingress (e.g. storm conditions or when process water is required in vaster quantities). Before power or equipment failures occur there should be emergency procedures and response plans to rapidly mitigate any decant problems that can be implemented in both normal and storm conditions.

Figure 47: Fixed decant barge (left) and a mobile barge (right)

The capacity of the barge(s) should be adequate enough to remove day to day decant demands as well as storm water accumulation. The barge should also be situated in an easily accessible location for maintenance and inspection purposes. Ideally this should be against the side of a valley wall (for a valley impoundment), or against the side of a jetty wall (either floatable walkway or purpose built) in an area of the impoundment where the ponded water is at it's deepest. The water depth below the barge can influence the clarity of the decant water and prevents tailings being sucked up by the barge.

A decant barge or submersible pump can be moved as the decant pond location changes and/or the tailings volume increases. For valley impoundments or in-pit disposal the decant barge or pump is generally retracted to keep the equipment close to the valley or pit walls. This makes it easier to access and prevents the use of heavy anchoring to control varied movement which can be expected the further away the equipment is from surface anchoring points. Each time a barge is moved to other cells the plant water demand should be calculated to ensure the barge is capable of meeting the demand from the water in the new cell.

6. Reclaim pond(s)

The reclaim pond(s) (or return pond(s)) store the water that is being decanted from the TMF. Reclaim ponds are sometimes referred to as decant ponds which in most parts of the world is another name for the supernatant pond. A reclaim pond is situated outside the confining walls of the tailings storage area a short distance away (figure 48). The water in the reclaim pond is either sent to treatment/polishing ponds for discharge to the environment or pumped back to the plant for use in the processing operation. Some reclaim water can be sent to evaporation ponds or sprays if the climate is suitable.

Figure 48: Reclaim ponds at Kalgoorlie, Western Australia

The reclaim ponds should be suitably sized to balance the water inflows from the TMF's supernatant pond with the normally variable outflows to the plant. For this reason the reclaim ponds can vary in volume and so an adequate depth is required to prevent overtopping and ensure the return pumps have sufficient head. The surge capacity should also be adequate to remove storm water flow rates from the TMF. This should be similar to the TMF's (2 – 4 weeks depending on climate conditions) to allow for reoccurring storms (WMC 1998). This should be checked against the plant volume requirement and overspill/evaporation pond volumes.

The degree of design specification will be determined by the quality and quantity of the return water. The ponds will need to be suitably lined to prevent groundwater contamination (e.g. clay or normally HDPE/LLDPE lined). Prior to installation, the liner system should be checked to determine if the decant liquor will cause any chemical degradation. This is particularly true for HDPE where even UV radiation can degrade the liner (SANS 1998).

Reclaim ponds are particularly useful for tailings facilities that utilise the subaerial deposition technique as the supernatant pond can be drained into reclaim ponds increasing the beach exposure. This aids the drying and consolidating rates of the tailings in the TMF (DPI 2003).

7. Freeboard

Normally the minimum freeboard is determined by national/local legislation and/or company policies. It is essential in the design stage that water balance calculations take into account average and extreme conditions to prevent loss of freeboard during operation.

Freeboard is used to establish the elevation of the lowest point of the embankment crest relative to the normal or maximum operating levels of the supernatant pond (SANS 1998). Freeboard management is a critical factor used to control water of a conventional tailings storage impoundment (DME 1998). To promote good drainage of the embankments, the supernatant pond has to be as far away from the embankments as possible (maintain a high freeboard and wide beach). Ideally the pond should be of a small area, to reduce seepage, and be at a maximum depth at the decant facility to improve reclaim water clarity.

Figure 49: Loss of freeboard (left) and high freeboard (right). (Right picture courtesy of Anglo American)

The definition of freeboard varies in tailings guidance and legislation documents around the world. Confusion can arise where the freeboard is interpreted as the vertical height between the pond and the top of the beach OR the top of the embankment crest. This is further confused where the embankment crest is measured as the external rather than the internal height. The correct definitions of freeboard are (DME 1999):

Total Freeboard (freeboard): The vertical height between the waterline and the top of the embankment crest (internal). Total freeboard (freeboard) = beach freeboard + operational freeboard 56

Beach Freeboard: The vertical height between the waterline and the beached tailings against the embankment crest.

Operational Freeboard: The vertical height between the beached tailings against the embankment crest and the crest itself.

The following are diagrams explaining freeboard:

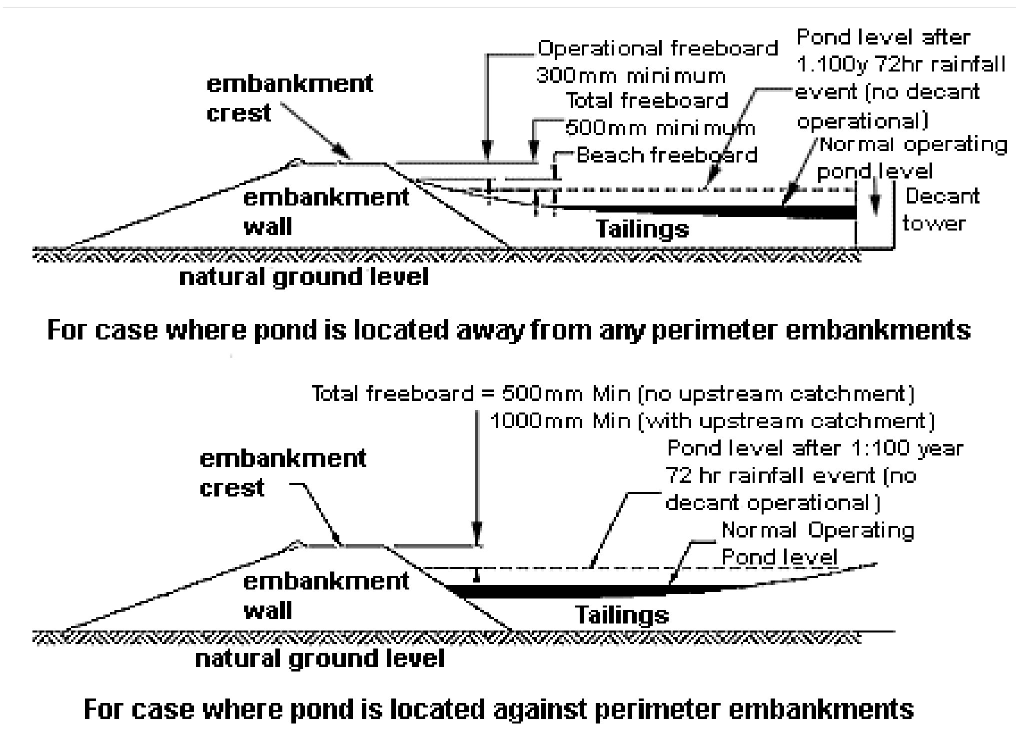


Figure 50: Freeboard of a tailings facility explained (Adapted from (DME 1999))

The freeboard limit for a TMF depends on the type of embankment raising, the method of deposition, geographical location, beach angles (if any beaching occurs), regulations, and the climate.

The use of wing walls around a decant tower can help to prevent the movement of a supernatant pond away from a tower and give more control over its location. This lowers the risk of a pond encroaching an embankment and subsequently lowering the freeboard. Wing walls are particularly suited to arid climates and TMF's that experience minimal water balance changes (e.g. no high inflow fluctuations).

8. Storm considerations

The design of a TMF has to cater for storm events both during and after operation. The storm conditions vary depending on the climate, but as a guide the TMF's minimum freeboard should not be met even after a 1 in 100 year, 72 hour duration storm (DME 1998). Suitable storm condition mitigation measures should be in place if the minimum freeboard will be lost during a storm event. Typical mitigation measures are emergency spillways, overflow/storage ponds and emergency decant facilities (e.g. floating pumps).

The impacts of a storm on a TMF are not just specific to the impoundment area but also the surrounding environment. Suitable mitigation techniques will need to be in place to prevent storm water eroding and inundating a TMF. For a valley impoundment this is more difficult compared to the ring dyke facility. In this case, spillways and diversion channels will be required to prevent inundation and the risk of overtopping.

9. Seepage control

Seepage flow through the tailings stored in a surface impoundment is inevitable. Vick (1990) notes that zero discharge of seepage from a tailings facility remains an elusive goal even with complex liner systems. For this reason the control of seepage is an important water management requirement both during the operational and post-operational phases of a TMF (DME 1998). The design stage of a tailings storage facility should take into account seepage control methods to ensure the facility remains perpetually stable and that environmental regulations are not compromised.

Seepage can be controlled by using either barrier or collection systems. Barrier systems retain or resist the flow of seepage outside the impoundment area whereas collection systems intercept and safely focus the seepage as it leaves the tailings storage facility (EPA 1994). Barrier control methods consist of liners and embankment barriers to prevent or hinder seepage passing through the tailings containment area and into the surrounding environment.Collection methods create pathways for the seepage to accumulate then flow to controlled locations such as embankment and toe drains. Other types of collection systems intercept the seepage as it migrates into the environment by using extraction wells and ditch systems.

The monitoring of seepage is an essential part of any tailings management strategy to understanding how the facility is performing within. Visual inspections of a tailings facility can determine the superficial operations (e.g. pond control, discharge management, pipework integrity) but the internal performance of a TMF can only be identified by monitoring changes and anomalies of the seepage effluents. Understanding seepage can determine the consolidation of the tailings, high seepage pathways (e.g. caused by liner damage or internal erosion), and groundwater contamination and movements (e.g. plumes).

Lowering the water content of the delivery tailings can help to reduce seepage as the water handling and storage volumes of the TMF are reduced.

One of the reasons for utilising thickened, paste and dry stack tailings storage is to reduce and even eliminate the water management requirements associated with conventional impoundment storage. Fourie (2003) notes that this lowers seepage losses and groundwater contamination as there is less moisture present in the deposited tailings and no supernatant pond.

10. Phreatic surface

The phreatic surface is essentially the water table in the tailings and is defined as the position between the zone of saturation and the zone of aeration (EC 2004). The exact level at where the phreatic surface resides is the point where the water rises have pressure equal to that of atmosphere (Anglo 2004).

The stability of a tailings embankment under static and seismic loads is influenced by the position of the phreatic surface. For long term stability, tailings embankments rely on the drawdown of the phreatic surface and therefore adequate internal and under drainage systems should exist (Jakubick, McKenna et al. 2003). Essentially, the phreatic surface can be successfully controlled by using materials of differing permeability within the embankment. Drainage zones and low permeable cores are common methods of controlling material saturation. Vick (1990) reports that the objective of prime importance is to keep the phreatic surface as low as possible in the vicinity of the embankment face. It is important that the properties of the materials used in the embankment zones are adequate and that low permeable cores will not crack and allow seepage through, and that drainage zones will not clog and become inoperative (ICOLD and UNEP 2001).

11. Internal embankment zones

Blanket and chimney drains are the most common types of drainage zoning to use in tailings embankments. A chimney drain is a vertical or inclined zone that captures lateral seepage flows, and a blanket drain runs along the base of the embankment (WSDE 1993). Chimney drains are usually connected to the blanket drains to aid the flow of seepage migration. Finger drains are similar to blanket drains but are not continuous. They can be used in areas of high seepage (e.g. where water is designed to be against the upstream face).

Internal filters are required to prevent fines washing through into drainage zones and creating internal erosion. The Omai tailings impoundment failure of 1995 occurred as a result of inadequate internal filters (Martin and Davies 2000). Synthetic materials such as geotextiles may be used if suitable filter material is not available locally or is too expensive to import. It is important to realise that the filter material should be adequate to prevent piping as well as drain the embankment, thus lowering the phreatic surface. If an unsuitable filter is chosen the filter may become clogged rendering the drain useless.

All drainage zones installed during tailings embankment construction need to be suited to the particular effluent and tailings characteristics. If for example seepage effluent has suspended particles then the drains may become blocked over time and render them useless. If coarse limestone is used for the drains and effluent of a low pH were to pass through, then erosion of the drains can cause instability of the dam wall, thus increasing the risk of catastrophic failure (Ritcey 1989).

For downstream and centreline embankment design the use of low permeable cores can help to reduce the phreatic surface of the embankment. It is essential that the ratio of permeability be such that the embankment can drain easily compared to the seepage entering from the lowpermeable cores. Vick (1990) reports that cores are essential for embankments that are designed to have water against the upstream face.

12. Barrier systems

There are several barrier systems available to impede migration of seepage out of a tailings facility. Barrier systems are particularly useful where toxic liquors are stored in the TMF and where environmental regulations restrain groundwater contamination.

Grout curtains, cut-off trenches, and slurry walls are all types of embankment barriers that are installed below the impoundment. They are only suitable for downstream and centreline dams as upstream structures generally rely on a pervious foundation to keep the phreatic surface to a minimum, and thus increasing impoundment stability (Vick 1990). For downstream and centreline structures the embankment barrier should be installed underneath the starter dyke towards the internal structure of the impoundment.

Embankment barriers are only useful where porous material is underlain by a continuous impervious material that prevents vertical movement of impoundment seepage. It is essential that a tight seal should be made between the impervious and porous impoundment foundation material to prevent any seepage migration.

Liner systems are becoming more attractive to TMF designers to reduce seepage into the environment. The major disadvantage is the high cost of installation particularly if the entire impoundment requires lining. The two major types of liners used to control seepage flows are synthetic materials, which are very expensive, and constructed liners made of local clays or other readily available materials (EPA 1994). Low permeable tailings slimes can also be used as a liner.

13. Collection systems

The two main methods used to collect seepage from a tailings impoundment are a collection ditch or a collection well (figure 51). Ditches are the most common and cheapest method of entrapping seepage with the idea of eventually pumping the seepage back into the dam. A collection ditch is usually dug around the perimeter of a ring dyke impoundment, or at the toe of an embankment wall allowing the seepage to flow through the pervious strata material underneath the impoundment to the ditch (Vick 1990). The return system to the impoundment can simply be a submersible pump that steadily removes the seepage, and thus allowing more to import through the pervious layer into the ditch.

Figure 51: Seepage collection ditch (left) and a seepage well (right)

A collection well is basically the same as a dewatering system for a mine, in that a cone of depression is created when pumping starts. Several wells can be installed around the impoundment in the same vicinity as a collection ditch. The effectiveness of the well depends on the permeability of the soil, and the depth of extraction. Such wells are expensive to install and each well has to be pumped dry and so a ditch is preferred. Collection wells can be installed at the toe of a tailings embankment to reduce the phreatic surface. The well creates a drawdown through the dam wall and can help increase the strength of the embankment. This can be used as a remedial measure for an embankment with drainage problems, and/or where there is a risk of a liquefaction event occurring.

CHAPTER FIVE:

REGULATORY CONTEXT

The primary responsibility for tailings and tailings storage facilities regulation in Australia rests with state and territory Governments. While the regulatory requirements vary between jurisdictions, common principles apply. In all jurisdictions:

- responsibility for tailings deposition and management (including rehabilitation and closure) regulation rests with the mining department or environmental protection agency
- responsibility for pollution control and tailings storage facility water discharge regulation rests with the environmental protection agency
- the focus of the regulation is on ensuring that tailings management methods, including tailings storage facilities, are safe, stable and non-polluting.

Life-of-Mine Risk-Based Approach

- Tailings storage facilities must be designed, operated, closed and rehabilitated to ensure negligible operator and public health and safety risks, and acceptably low community and environmental impacts.
- A risk-based design approach provides a framework for managing the uncertainty and change associated with tailings storage facilities.
- The risk-based approach applied to tailings management must have sufficient flexibility to allow changing circumstances to be managed.
- Alternative tailings management, storage and closure strategies can usually be accurately coasted, for incorporation into a cost-effectiveness analysis to reduce identified risks.

Concept of acceptably low risk

Tailings storage facilities must meet operator and public health and safety, community, and environmental protection objectives. These objectives can only be met if tailings storage facilities are designed, operated, closed and rehabilitated to a level of risk that is acceptable to stakeholders for the full operating life of the facility and beyond.

A systematic approach to effective tailings management is therefore advocated. Management strategies need to be risk-based and account for the viewpoints and expectations of the communities in which companies operate. The principal tailings-related risks to people and the environment can be characterized for the operational and closure phases.

1. Operational risks

The principal objective of a tailings storage facility is for tailings solids and any stored water to remain contained. Failure modes and risks to public health and safety, the community, and the environment during operation of a tailings storage facility could include:

- rupture of the tailings slurry delivery pipeline or decant water return pipeline n rainfall-induced erosion or piping of the outer tailings face (image 52)


image 52

- geotechnical failure or excessive deformation of the containment wall (image 53)
- overfilling of the tailings storage facility with tailings, leading to overtopping of the containment wall by water


image 53

- seepage through the containment wall, potentially leading to tree deaths (image 54)
- contaminated seepage into the foundation impacting on the groundwater


image 54

- particulate (dust) or gaseous emissions (for example, radon, hydrogen cyanide (see Environment Australia, 1998) and proposed Cyanide Handbook in this series, sulfur dioxide and hydrogen sulfide) (image 55)


image 55

- exposure of birds, wildlife or livestock to potentially contaminated decant water that

ponds on the surface of the tailings storage facility
- exposure of wildlife or livestock to soft tailings in which they may become trapped.

2. Closure risks

Failure modes and risks after closure of a tailings storage facility could include most of the operational failure modes and risks, apart from failure of the tailings delivery or return water pipelines. Additional post-closure failure modes and risks could include:

- rainfall-induced erosion of the outer face of the containment wall, which may expose and mobilize tailings (see image)
- failure of the spillway, (if provided)
- overtopping by rainfall runoff, causing erosion of the containment wall
- failure of the cover system placed over the tailings surface.

Fige 56 : Closure risks

3. Risk analysis methods

There are many definitions of risk. Best Practice Environmental Management in Mining (1999) defines hazard as a potential cause of harm, describes risk as having two dimensions — likelihood and consequence, and defines risk as the likelihood of actual harm.

Risk analysis allows quantification of the options, and of the likelihood, consequences and costs of failure. The ’risk rating is obtained by the product of the likelihood and the consequence.

AS/NZS 4360:2004 recommends the following risk assessment process:

- establish the context: geographically, socially and environmentally, and decide on the design criteria
- identify the hazards: what can happen, where and when, and how and why

- analyze the risks: identify existing controls, determine the likelihoods and consequences, and hence the level of risk
- evaluate the risks: compare them against the design criteria, carry out sensitivity analyses to highlight both the key and unimportant risks, set priorities, and decide whether the risks need to be addressed
- address the selected risks: identify and assess options, prepare and implement treatment plans, and analyze and evaluate the residual risk.

Overarching this process is the need to communicate and consult with stakeholders, and to monitor and review.

A variety of risk analysis methods is used by different mining companies, depending on the scale of the mining development and company approaches adopted. The main types of risk analysis methods are: n qualitative risk charts — including hazard identification, its likelihood, its consequence, the risk ranking, and remedial action

- semi-quantitative and quantitative methods: lending themselves to well-defined and quantifiable hazards
- computer analysis: requiring large amounts of data that need to be collected for design of major industrial facilities.

The quantitative method relies on assigning numerical values to likelihoods and consequences. The most commonly used quantitative method is the probabilistically-based fault/event tree method, which is set up as a series of connected boxes, typically in a spreadsheet. In applying the method, the key event or outcome must first be identified, such as failure of the tailings storage facility. This forms the top of the event tree. The causes or failure modes that might lead to this key event are then identified. These form the tops of the branches of the fault tree. Each of these causes has a variety of contributing sub-causes, some of which contribute to more than one cause.

SUMMARY

Any tailings management systems should including the following points:

- Tailings storage facilities should be designed, operated, closed and rehabilitated to ensure performance that meets or exceeds the criteria agreed to through consultation with key stakeholders.
- Each stage in the life of a tailings storage facility, from concept design to rehabilitation and aftercare, needs to be fully considered and documented in a series of reports within a tailings management plan, which is a ‘living' document.
- The scale of the tailings management plan should match the scale of the project.
- Early and ongoing consultation, information sharing and dialogue with stakeholders is an integral part in the ongoing development of the tailings management plan.

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