



**TAILSAFE**

**Sustainable Improvement in Safety of Tailings Facilities**  
**TAILSAFE**

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**Report**

**Risk Reduction Actions**  
**for Substandard or Impaired Tailings Facilities**

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# **Risk Reduction Actions for Substandard or Impaired Tailings Facilities**

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## **Other reports of the TAILSAFE project:**

Witt, K.J. & Schönhardt, M. (Eds., 2004): Tailings Management Facilities – Risks and Reliability. Report of the European RTD project TAILSAFE, <http://www.tailSAFE.com/>, 176 p.

Engels, J. (Ed., 2004): Tailings Management Facilities – Intervention Actions for Risk Reduction. Report of the European RTD project TAILSAFE, <http://www.tailSAFE.com/>, 150 p.

Witt, K.J. & Wudtke, R.-B. (Eds., 2004): Tailings Management Facilities – Implementation and Improvement of Design and Authorisation Procedures for Proposed Tailings Facilities. Report of the European RTD project TAILSAFE, <http://www.tailSAFE.com/>, 24 p.

Xenidis, A. (Ed., 2004): Tailings Management Facilities – Implementation and Improvement of Closure and Restoration Plans for Disused Tailings Facilities. Report of the European RTD project TAILSAFE, <http://www.tailSAFE.com/>, 54 p.

Engels, J. (2004): Risk Reduction Actions for Substandard or Impaired Tailings Facilities. Report of the European RTD project TAILSAFE, <http://www.tailSAFE.com/>, 29 p.

Kreft-Burman, K., Saarela, J. & Anderson, R. (2005): Tailings Management Facilities – Legislation, Authorisation, Management, Monitoring and Inspection Practices. Report of the European RTD project TAILSAFE, <http://www.tailSAFE.com/>, 66 p.

Niederleithinger, E., Kruschwitz, S. & Martin, T. (2005): Non-Destructive and Minimally Intrusive Methods for the Investigation and Monitoring of Tailings Impoundments. Report of the European RTD project TAILSAFE, <http://www.tailSAFE.com/>, 51 p.

List of reports will be updated according to availability

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## **1.0 Prepared procedures**

### 1.1 Introduction

Tailings impoundments should be designed to be permanent structures with resistance to both human and natural actions. The storage facility will need to retain its structural integrity long after a mining operation has ceased. Following of basic guidance and legislative documents on tailings storage will ensure an extensive life and a low risk structure. The key parameter influencing the life and stability of a tailings impoundment is water.

Basic criteria need to be met for unpredictable natural events which have caused stability issues with impoundments in the past, both active and abandoned. Designing a tailings impoundment for a 1 in 100 year flood and maximum credible earthquake (MCE) resistance is crucial in lowering the risk of failure of tailings facilities.

Human actions also play an important role in the operation of a tailings facility. Inadequate management and operating procedures can help to cause instability issues if a problem occurs during the operation of a tailings impoundment. For example if a decant system fails suitable mitigation techniques and emergency actions will need to be implemented quickly to prevent the free ponded water rising and subsequently overtop the embankment(s). The majority of embankment failures could have been avoided if suitable contingency plans and monitoring procedures were in place. Most large mining companies have a global reputation to adhere to and they have the experience and capital available to produce stringent operating policies and procedures for their tailings facilities. The smaller mining companies primarily turn to the consultants for the expertise to aid with the design and operation of their tailings facilities, which can be very expensive. Most of the impoundment failures world wide have occurred at mines owned by small companies that have only one or a few operations. Management systems, guidance documents and operating procedures are becoming more widely accessible to these companies, primarily due to the advancement in communications technologies.

This chapter looks at the most common problems associated with tailings facilities and suggests emergency and remedial techniques to prevent and lessen environmental impacts. Before any impoundment is built, hazard ratings and design and operating requirements have to be assessed during the design stage to determine preparedness procedures. The tables on the following page are taken from ANCOLD (1999).

**Table 1: Hazard Rating – Mine tailings storages – ANCOLD (1999)**

Type of effect	Hazard Category		
	HIGH	SIGNIFICANT	LOW
<b><i>Uncontrolled release of seepage</i></b>			
Potential loss of human life	Contamination of a water supply likely to be consumed by humans is probable	Contamination of a water supply likely to be consumed by humans is possible but not probable	Contamination of water supply likely to be consumed by humans is not expected
Potential loss of stock	Contamination of a water supply likely to be consumed by stock is probable	Contamination of a water supply likely to be consumed by stock is possible but not probable	Contamination of water supply likely to be consumed by stock consumption is not expected
Environmental damage	Damage to an environment feature of significant value is probable	The significance of the environmental feature is less or damage is possible but not expected	No environmental feature of significance or no damage expected
<b><i>Embankment failure</i></b>			
Loss of human life	Loss of life expected because of community or other significant developments	No loss of life expected, but the possibility recognised. No urban development and no more than a small number of habitable structure downstream	No loss of life expected
Direct economic loss	Excessive economic loss as serious damage to communities, industrial, commercial or agricultural facilities, important utilities, mine infrastructure, the storage itself or other storage downstream	Appreciable economic loss, such as damage to secondary roads, minor railways, relatively important public utilities, mine infrastructure, the storage itself or other storages downstream	No significant economic loss, such as limited damage to agricultural land, minor roads, mine infrastructure, etc.
Ongoing economic loss	Storage essential for services and repairs not practicable	Repairs to storage practicable without major interruption to services	Repair to storage practicable. Losses of service not significant.

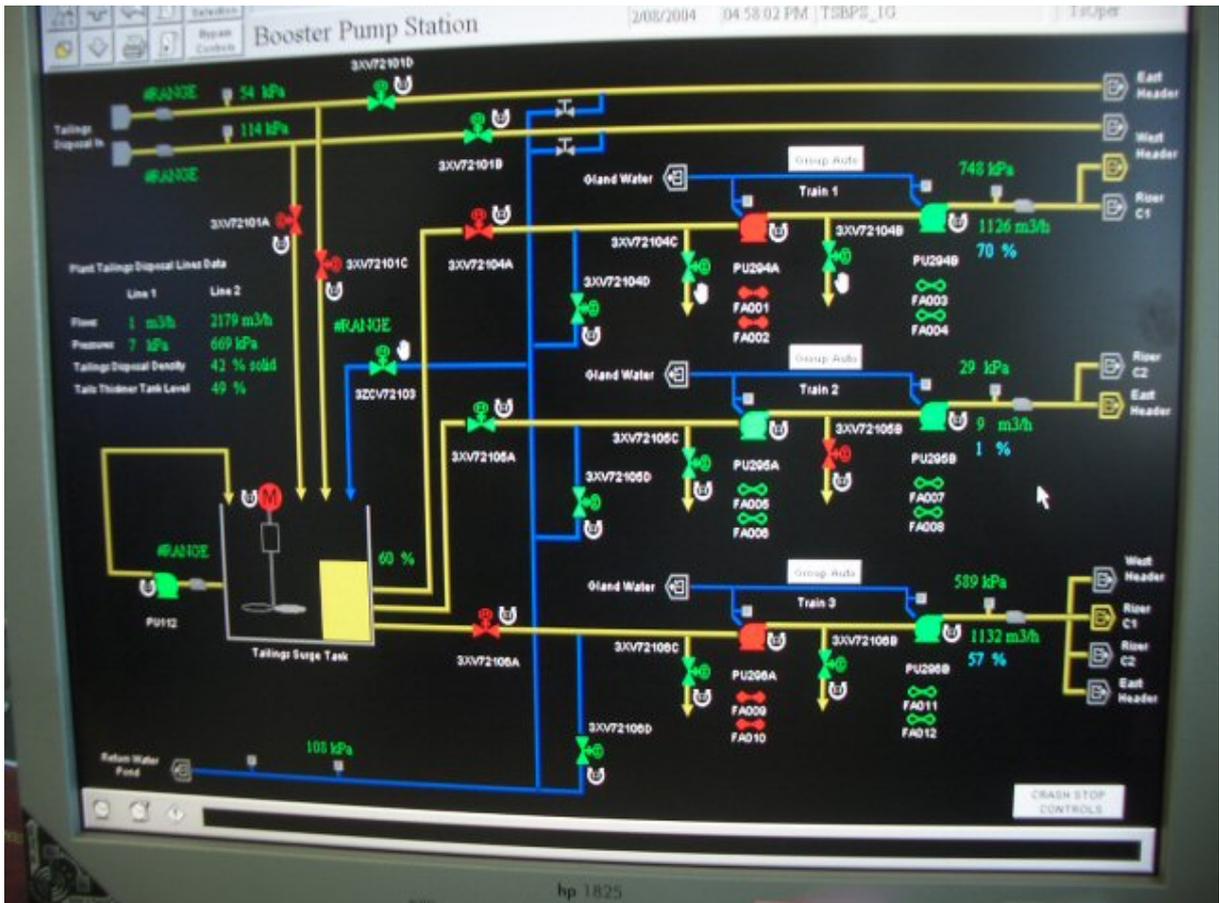
**Table 2: Design and operating requirements – Mine tailings storages – ANCOLD (1999)**

	<b>HIGH HAZARD</b>	<b>SIGNIFICANT HAZARD</b>	<b>LOW HAZARD</b>
Completion of tailings storage data sheet	Yes	Yes	Yes
Check aftercare requirements	Probably state government	Probably state or local government	Probably landowner
Design	Report prepared in detail by Geotechnical/Engineering specialist. Operations manual required	Report prepared by Geotechnical/Engineering specialist. Operations manual required.	Notice of intent of works approval required including operating criteria
Construction	Supervised by Geotechnical/Engineering specialist. Detailed construction report with as-built drawings	Supervised by suitably qualified engineer. Brief construction report with as-built drawings.	Constructed by a suitably experienced contractor.
During operations	Annual inspection and audit by Geotechnical/Engineering. Operation manual reviewed.	Inspection and audit every 2 years by Geotechnical/Engineering specialist. Operation manual reviewed.	Inspection and audit every 3 years by Geotechnical/Engineering specialist. Operating criteria reviewed.
Risk assessment	Yes	Preferred	Possible
Provision of emergency inspection by site personnel	Yes, based on a dam break analysis	Yes	Yes
Routine daily inspection by site personnel	Yes	Yes	Yes
Rehabilitation phase	Inspection and decommissioning report by Geotechnical/Engineering and other specialists depending on rehabilitation required. Formal handover to aftercare agency.	Inspection and decommissioning report by Geotechnical/Engineering and other specialists.	Inspection and decommissioning report by Geotechnical/Engineering specialist.

## 1.2 Emergency actions

Tailings operating manuals should have emergency procedures in case of problems that may arise during the operating life of a tailings impoundment. Water balance is the key and if the processing plant shuts down, heavy rain occurs or snow melt, the free ponded water stored in a conventional impoundment can fluctuate rapidly. These may be rare events but still need to be properly assessed and researched to calculate the consequences of rapid freeboard reduction. In the design manuals a specific level of ponded water controlled by decant systems will be maintained to allow for extra volumes of water ingress in times of unpredictable events. Operating a tailings impoundment with negligence of a 1 in 100 year flood can be catastrophic and has been the cause of many impoundment failures around the world.

Modern tailings impoundments in countries with guidelines and legislation have sophisticated monitoring equipment to assess the operation of the tailings facility, pipelines, return water, and treatment. Commonly these online monitoring systems (see Figure 1) are connected to the processing plants online systems to assess the entire water cycle of the mining operation. This allows a mill manager or senior engineer up to date information on the available water stored in the tailings facility, decant ponds, open pits etc... This sophisticated system can also act as a money saving feature to allow shut downs of remote borefield pumps which can be more costly (depending on distance pumped) than returning free water from a tailings pond.



**Figure 1: Online computer monitoring system for a tailings impoundment**

### 1.2.1 Key personnel

In an emergency situation it is critical to identify and communicate with the appropriate person(s). Contact person(s) and numbers should be displayed around the tailings facility to enable third parties to respond if problems occur. In the case of a failure or where a failure is likely then the police and civil defence should be notified to help evacuate or warn occupants (if any) downstream of the facility.

The key personnel responsible for the day to day operations and management of the tailings facility should be trained to deal with a range of emergency situations. Some of these include overtopping, decant failure, pipe bursts, embankment failure (minor and major), storm events, and excessive dust pollution. Each emergency situation will have different responses, all of which should be practiced to make the most of the little time that may be available, or to mitigate the problem quickly.

### 1.2.2 Dam break analysis

If a tailings storage facility is located upstream of human inhabitants a dam break analysis should be carried out to determine the likely impact and potential loss of life. By assessing different failure scenarios the likely extent of damage can be determined and appropriate emergency actions assigned to mitigate events. A mud flow analysis will help to determine the flow path of the tailings and the environmental damage a failure may cause (Blight, 97).

### 1.2.3 Containment

The design of a tailings storage facility is the key phase in helping to reduce environmental impacts occurring from unusual operating procedures. Installation of cut-off trenches, bunding of pipelines (tailings and return water) and pumping stations, burying of pipelines, will help to control and contain escaped tailings or decant water should a pipe burst occur.

For a conventional surface paddock facility the storage of storm water from a 1 in 100 year flood will be required. This water needs to be decanted and sent to the processing circuit or treated before release to the environment.

The online monitoring systems can tell an operator in real time when, and with some systems where, a pipe burst or pump failure has occurred. Simple magnetic flow meters determine the flow in the tails pipe at the plant and along the various lines to the impoundment. Any difference in flow indicates a burst pipe (or broken spigot) which alerts the operator to take action.

#### 1.2.3.1 Thickened and paste disposal

For impoundments using thickened tailings or paste disposal the conical piles will cause runoff as the design of the facility prevents storage of free water. In this case sufficient storage of the runoff from a 1 in 100 year flood would be required as tailings sediment collection and contamination by chemicals will occur.

Thickened or paste disposal is normally utilised in arid areas, poor soil conditions for high embankment building or where ground water conditions are poor (e.g. saline). This type of disposal can help to remove the free water contained in the tailings and thus recycling directly

back to the plant. Free water stored with the tailings in a conventional impoundment can be lost through evaporation and seepage. If a storm occurs over a paste or thickened site the collected ponded water is normally held for long period of times to provide the processing plant with water, reducing borehole pumping and/or groundwater treatment costs (see Figure 2).



**Figure 2: Containment zone for surface runoff and tailings water.**

#### 1.2.4 Power failure

Power failures can lead to water imbalances in an impoundment. For example, if decant barges are used to remove the free water in an impoundment, then a power failure prevents the pumps from decanting the water resulting in a constant reduction in the freeboard. If a storm occurs before power is resumed then rapid rates of rise of the ponded water can occur.

The pumps used to pipe the tailings to the impoundment may stop and blockages/clogging may occur. This is usually a case when power has been lost at the plant and so an automatic flushing system may be implemented if power is available at the tailings storage facility. If booster pumps fail preventing the ring spigots of a conventional impoundment to operate, then a system should be in place to allow the tailings to dispose freely in a set area of the impoundment.

For total power failure of a mine site, manual opening of dumper valves at the tailings facility will be required to ease pressure on the tailings lines and prevent clogging. This is particularly true for thickened or paste discharge where risers are used. Long durations of static paste tailings can cause complete blockages of the tails line which can render the pipe useless.

#### 1.2.5 Erosion and sloughing of earthworks

Visual observations of the tailings embankments may highlight weaknesses and instabilities of earthfill structures. Emergency actions will need to be undertaken to prevent further erosion and assess the short and long term risks of the sloughing. If a high risk is identified then a short term remedial measure should be implemented to prevent further erosion or sloughing. Once full remedial action has been conducted and the sloughing/eroded section is fully repaired, long term monitoring will be required.

## **2.0 Implementation and improvement – Remedial actions**

### 2.1 Introduction

Once a tailings impoundment has been identified as a hazard with a risk of instability, there are several options available to mitigate and reduce such risks. Intervention actions have been discussed in WP3 of the TAILSAFE project outlining strengthening, treatment and evacuation techniques for a range of varied tailings storage facilities. The following remedial actions are emergency actions and methods of temporarily reducing the risk of a more catastrophic failure occurring. Table 3 is taken from the ANCOLD 99 guidance document to help introduce the typical methods of failure of a tailings embankment before more detailed remedial measures are given later in this chapter under the relevant sections.

Remedial works are generally carried out on impoundments that have not met good engineering principals, management and operating procedures. Even impoundments that meet stringent operating procedures and management strategies are susceptible to dilemmas, generally after unsuspecting natural events or human errors.

Impoundments at abandoned mining operations are particularly at risk, as little or no monitoring of the current state of the embankment(s) and free pond (if any) occurs. Stability issues of abandoned impoundments generally occur after heavy rainfall or snow and ice melt, leading to embankment erosion and internal erosion by seepage.

Consolidation of tailings continues long after an impoundment has been decommissioned (depending on the tailings characteristics) which can alter the surface contours of the impoundment. This can lead to water management issues if spillways and decant systems are not removing the required amount of free water.

**Table 3: Types and causes of defect and possibility of detection of potential failure by inspection and/or monitoring - ICOLD Bulletin 106.**

Type of defect	Cause	Possibility of detection by inspection and/or monitoring
Overtopping	Inadequate hydrological or hydraulic design.	Inspection may reveal potential problem.
	Loss of freeboard due to crest settlement	Detectable by survey and inspection
Slope instability	Overstressing of foundation soil and dam fill.	Precise line and level survey, inclinometer monitoring and inspection may reveal potential problem.
	Inadequate control of water pressure	May be possible to detect by piezometer and seepage monitoring.
Internal erosion by seepage	Inadequate control of seepage.  Bad filter and drain design.  Poor design or construction control resulting in cracking or leakage paths. E.g. against conduits	May be possible to detect by piezometer monitoring. Difficult to detect in early stages, but seepage flow monitoring may reveal potential problem; inspection will sooner or later reveal problem, but possibly too late for effective remedial measures to be taken. Extreme alertness required if seepage increases unrelated to supernatant water level.
External erosion	Inadequate slope and toe protection	Detectable by inspection
Earthquake damage	Inadequate geometry e.g. slopes too steep.	This is a design matter. However, inspection after non-catastrophic earthquake event may indicate need for design modifications.
	Liquefaction of tailings, embankment, foundation soils.	This is a design matter. However, piezometer monitoring during and after a non-catastrophic earthquake event may indicate potential of liquefaction.
Groundwater pollution	Seepage of leachate into aquifers due to lack of or deterioration of liners	Detectable by monitoring observation wells
Damage to decant systems	Excessive settlement.	Possibly detectable by inspection.
	Chemical attack on concrete/steel	Possibly detectable by inspection.

## 2.2 Overtopping

Overtopping occurs when the free water in an impoundment rises above the crest of the embankment(s) and flows down the downstream face. Erosion of the face can occur increasing the risk of embankment failure. Overtopping may occur due to one or a combination of the following:

1. A miscalculation of the free water that can be stored in the impoundment. For example preparation for a 1 in 100 year storm water ingress.
2. Decant failure or insufficient decanting outflow which causes a rise in the free water. For example, total power failure rendering a decant barge useless.
3. Inadequate spigoting which moves the ponded water closer to an embankment and could render a decant tower useless.
4. An embankment crest spigot is not monitored correctly and the tailings (rather than the free water) overtop causing erosion.
5. A reduction in the freeboard as a result of subsidence of the dam crest, which can be caused by the following methods:
  - Foundation compression
  - Piping failure resulting in partial or complete collapse/sloughing of an embankment
  - Self weight settlement of the embankment material (consolidation)
  - Internal erosion resulting in a loss of embankment material
  - Collapse of underground voids (old mine workings)
  - Seismic shaking causing consolidation or sloughing

### 2.2.1 Overtopping remedial works

Providing a complete failure hasn't occurred, remedial works can be carried out if an embankment has been damaged by overtopping. The basic idea is to import material lost on the crest and/or downstream slope as a result of erosion. A suitable material must be selected to have the ideal properties (density, permeability, durability, strength etc..) to increase the strength of the embankment.

Care must be taken when using mechanical equipment to import material (depending on the scale of erosion or sloughing) as the phreatic surface of the embankment will have risen. A static or dynamic liquefaction event may occur due to equipment operating at the toe or crest of the embankment.

Apart from the import of material to repair overtopping consequences, swifter action maybe required to prevent hazards and further erosion or sloughing of the embankment. In this case gabions, mine pit waste or surrounding borrow material maybe quickly imported to aid the

strength of the embankment. Although dangerous, if a major failure is inevitable, rockfill can be placed at the toe of the embankment if saturation of soils is not too high to allow mobile equipment access.

The best way to mitigate any problem is to concentrate on the source (in this case the overtopping) rather than the pathway (dam erosion) or target (downstream destruction). Emergency pumps, removal of decant collars, and/or spillways should be opened if the embankment continues to overtop. If the freeboard has lowered but not extensively then pumping and decant should continue. The embankment will need to dry out and subsequently lower its phreatic surface.

A risk assessment will need to be carried out before works can continue. However, if time is of the essence then emergency contingency plans should be implemented. An assessment to determine the cause of the overtopping is essential to prevent a recurrence. Operating methods, additional freeboard, crest raising, decant capacities and rapid water ingress will need to be looked at to achieve a more appropriate water management strategy.

### 2.3 Slope instability

Slope instability occurs due to three main reasons:

1. Overstress of foundation materials
2. Overstressing of embankment materials
3. Pore pressure problems:
  - Seepage pressures
  - Rapid uniform loading (particularly upstream embankments being raised quicker than the ability to dissipate pore pressures by consolidation processes)
  - Shearing pressures



**Figure 3: High phreatic surface causing sloughing of a tailings embankment.**

Stability issues can normally be determined by an operator, prior to mass movement, by piezometer and embankment movement markers. Visual observations of tension cracks on the crest or upper part of the embankment (generally on the downstream face), bulging at the toe, ground heaving in front of the toe, and creep movements that don't reduce with time. Movement markers and piezometer readings will determine small movements and increases in the phreatic surface of the embankments.

Figure 3 shows a tailings embankment saturated at the toe and sloughing as a result of the phreatic surface and steep embankment angle.

### 2.3.1 Remedial actions

The cause of the instability should be determined prior to any remedial works. The cause may not always be obvious, and so a detailed investigation should be carried out to help with the design of the remedial measures.

If emergency works need to be carried out to prevent further instability or release of tailings there will be no time to carry out risk assessments and/or a detailed investigation of the cause of failure.

The various types of remedial actions are discussed below:

1. Soil reinforcement and strengthening measures (methods discussed in Tailsafe WP3)
2. Modification to the dam profile
3. Control measures for the phreatic surface by installing a drainage trench at the toe of the downstream face and/or horizontal bore drains. Filters need to be incorporated to prevent dam fill material transferring into the drain. Incorrect filtering can lead to further instability problems, mainly by internal erosion

The following table (Table 4) has been taken from the ICOLD Bulletin 106, which details possible works for slope stability problems

Care has to be taken that mechanical equipment doesn't induce high static or dynamic loads on the dam whilst repairing slope stability issues. Increase in dam pore pressures could result, increasing the risk of instability.

**Table 4: Possible remedial measures for slope instability problems – ICOLD Bulliten 106**

<b>Types of slope instability</b>	<b>Possible remedial measures</b>
Potential deep seated failure	Modify dam profile <ul style="list-style-type: none"> <li>- Flatten downstream slope</li> <li>- Add toe berm</li> <li>- Reduce crest height</li> </ul> Install deep drainage <ul style="list-style-type: none"> <li>- Sub horizontal bored drains</li> <li>- Pressure relief wells at the toe</li> <li>- Well points</li> </ul> Construction retaining structure <ul style="list-style-type: none"> <li>- Anchored toe walls</li> </ul>
Shallow instability	Lower phreatic surface  Flatten slope  Construct trench drains on slope  Reinforce and/or strengthen the soil <ul style="list-style-type: none"> <li>- Nailing</li> <li>- Grouting</li> <li>- Counterforts</li> </ul> Remove and replace weak or disturbed material  Plant appropriate vegetation

## 2.4 External erosion

Wind and water can erode the dry impounded tailings or more importantly erode the embankment(s) of a tailings facility (see Figure 4). Over time channelling from water runoff can cut into the embankment and wind can pick up loose material from the down and upstream faces.

Water erosion is not specific to rain waters eroding the embankment, but also the water that can flow down a face from overtopping (see Figure 7). Internal erosion is also a problem particularly where seepage exits through the downstream face (commonly from piping failures - see Figures 5 and 6) and erodes the embankment.



**Figure 4: Wind and water erosion on the downstream face of a tailings embankment.**

External erosion from water can also affect a tailings facility if a river or storm drainage channel runs close to an embankment toe. The failure of tailings pond No5 at the Placer Bay Mine in the Philippines was due to toe erosion from a small river rising which caused 12 deaths and a 100m breach in the embankment. The tailings and cyanide washed into the sea.

Some tailings facilities have to store their tailings under water (license restrictions) to prevent acid generation if the tailings are sulphide bearing. Abandoned tailings facilities are a huge environmental problem from the Acid Mine Drainage (AMD) that forms when the sulphide tailings react with water and air. A water cover can form a barrier to prevent the air coming into contact with the tailings and forming AMD. In this case the free water will generally be in contact with the upstream face of the embankment walls. Wave actions may erode the face if suitable mitigation measures are not taken (e.g. lining, car tyres to dissipate the energy, or reed beds).



**Figure 5: Piping failure and subsequent erosion on a downstream face.**



**Figure 6: Multiple piping on a downstream face with mine waste rock strengthening.**



**Figure 7: Extensive water erosion (channelling) on a downstream face of a tailings embankment.**

#### 2.4.1 External erosion – Remedial measures

The best method to prevent wind and water erosion of an embankment is to use a barrier. Simple grassing of the downstream face can significantly reduce surface runoff channelling and wind picking up fine dust. Vegetation such as small trees and shrubs can further help to improve eroding effects, however this can introduce wildlife like burrowing animals which can cause other forms of erosion.

For high rates of erosion a coarse material can be placed on the downstream embankment face and can be a relatively cheap option if locally available (e.g. crushed mine waste).

Geotextiles and geogrids have been used on embankment faces with great success. This however can be very expensive if a large area needs to be covered. Geotextiles can help with planting in arid areas as water can be absorbed into the textiles.

Berms can be constructed on the downstream face to lessen the erosion of water by dissipating the energy. Fast running water can lead to rapid channelling as has been seen in many overtopping failures cutting into the embankment face causing slope instability (see Figure 7).

Toe erosion can be mitigated by placing rockfill such as mine pit waste adjacent to the toe. This helps to dissipate energy from the flood waters of any local rising river that might encroach the toe of a tailings embankment. Gabions and rip rap can also be used but are generally more expensive mitigation techniques if suitable material is available locally.

## 2.5 Internal erosion

Internal erosion generally occurs from dam fill material washing through chimney and blanket drains, or from seepage washing fill through settlement cracking. It can be very difficult to assess internal erosion. Piezometers can determine if a drainage zone of an embankment is adequate by monitoring the water pressures. If historical data is collected a steady rise over time for piezometers in a particular area of the impoundment (assuming the water management remains the same) can be an indication of clogged drainage zones.

Visual observation of the seepage coming from the drainage zones can be a good indication of internal erosion. If the seepage effluent is discoloured and contains sediment (or an increase in sediment) this usually means fine material is washing through into the coarser material of the drainage zone. Increases in seepage volumes discharging from a toe without changes in the water content and management of the impoundment can also be a sign of internal erosion. The installation of weirs can measure seepage rates very easily and effectively.

### 2.5.1 Internal erosion - Remedial measures

If internal erosion appears to be a problem the first mitigation measure should be to increase the freeboard of the dam thus pushing the free water away from the embankment(s). Placement of drainage material on the downstream toe of the embankment will act as an inverted filter and thereby control the exit gradient of the seepage and reduce the risk of headward erosion (ICOLD)

Long term measures for correcting and controlling the internal erosion need to be carried out.

Some of the techniques available are:

1. Raising using downstream method of construction utilising a drainage blanket
2. Installation of horizontal bores to relieve pressure
3. Installation of deep trenches in front of the downstream face
4. Toe drainage
5. Installation of a bentonite-slurry wall in the embankment or diaphragm wall
6. Finger drains can be installed to ease pressure

When installing new drains in an embankment (or repairing clogged drains) it is important to include filters like geotextile to prevent fines washing through into the coarse fraction of the drains. This causes the clogging, thus rendering drains inefficient or useless.

## 2.6 Earthquake induced problems

Earthquakes have been the cause of many tailings failures over the years. The liquefaction phenomenon of tailings was discovered in the 1960's and is still to this day unpredictable and misunderstood.

Earthquakes impose cyclic loading, generally of short duration in the horizontal and vertical directions. Some of the earthquake effects on embankment dams are (Fell, 1992):

1. Settlement and cracking of the embankment, particularly at the crest
2. Reduction of the freeboard due to settlement which can cause overtopping to occur
3. Instability of the upstream and downstream slopes
4. Differential movement between the embankment, abutments and spillway structures increasing the likelihood of leakage and piping failure
5. Liquefaction events due to increases in pore pressures
6. Movement of faults below the impoundment
7. Waves overtopping the embankments due to large volumes of material land-sliding into the impoundment (valley design)
8. Damage to outlet works passing through the embankment leading to leakage and potential erosion of the embankment

Drainage works of an embankment can become damaged after an earthquake and the effects of which may not be known for some time after the event. Seepage rates and piezometers should be monitored to determine changes in the water flow behaviour of the embankment.

### 2.6.1 Liquefaction

Earthquakes can induce dynamic loading across the entire impoundment. Tailings facilities located in seismic areas have to be built to withstand both horizontal and vertical accelerations. With dynamic loading the shaking increases pore pressures, particularly where drainage is restricted or impeded. Shear stresses build up in the embankment and when the pore water pressure equals the external load the soil begins to act like a fluid. When this occurs, normally under extreme seismic conditions, liquefaction has occurred.

If very strong shaking occurs then high consolidated soil and clays are subjected to liquefaction events. Failures can occur along fracture planes, fissures or along variations in the properties of a soil mass. The risks of liquefaction events occurring can be reduced by understanding the contributing parameters of a soil mass. Further information and behaviour of liquefaction events is mentioned in WP2 of the TAILSAFE project.

### 2.6.2 Earthquake induced problems - Remedial actions

If an embankment sloughs material will need to be imported to raise the freeboard. If overtopping occurs then more careful techniques should be used (see section 2.2).

Lateral cracking may occur on the embankment crest which can be filled with a suitable material. Regular monitoring will be required to see if this material hasn't eroded or dropped through into internal erosion zones that may develop over time, particularly where a drainage zone has been damaged from a seismic event.

### 2.7 Decant systems

Decant tower systems come under increasing stresses 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. Failures of decant conduits and towers can lead to water management problems in an impoundment. It won't be immediate to an operator that a decant system has failed until the decant collection pond is showing signs of low ingress from the impoundment. 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 decant conduit failure, which caused an overtopping of the embankment and subsequent release of tailings. 269 people lost their lives and this tailings disaster remains as one of the world's worst for human fatalities.

If a decant tower is designed to be raised to a height of 30m and the management wants to continue to raise the impoundment then stability issues of the decant system are put into jeopardy. A tower should always be designed to higher levels than intended if storage and consolidation rates don't fall under textbook conditions. In this case a new decant system can be installed prior to a raise and the old tower sealed under the rising tailings.

Conduit failures can cause internal erosion as the collapse can cause the tailings to fill the conduit thus causing subsidence of the tailings. Repairing the horizontal underlaying conduit is a near impossible task and far too expensive to carry out.

### 2.7.1 Decant systems - Remedial measures

If a decant tower fails and becomes useless (beached tailings moving the pond away from the tower) then emergency pumping or spillways will need to be implemented. Digging around the tower, if the tailings are not too saturated, can help to move the ponded water back towards the tower.

If there is too much water in the impoundment collars can be removed from the tower to increase the outflow of the conduit (see Figure 8). Heavy lifting equipment may be needed if the collars are encased in tailings or have become lodged in position. Care should be taken not to impose stress on the pipe joints below the tower where the conduit travels towards the outside wall.



**Figure 8: Decant tower and submerged collars in concrete housing.**

Complete failure of a decant conduit can be very difficult to repair and can lead to internal erosion of the impoundment and embankment. A decant barge maybe introduced as a future method of decanting the water.

## 2.8 Groundwater pollution

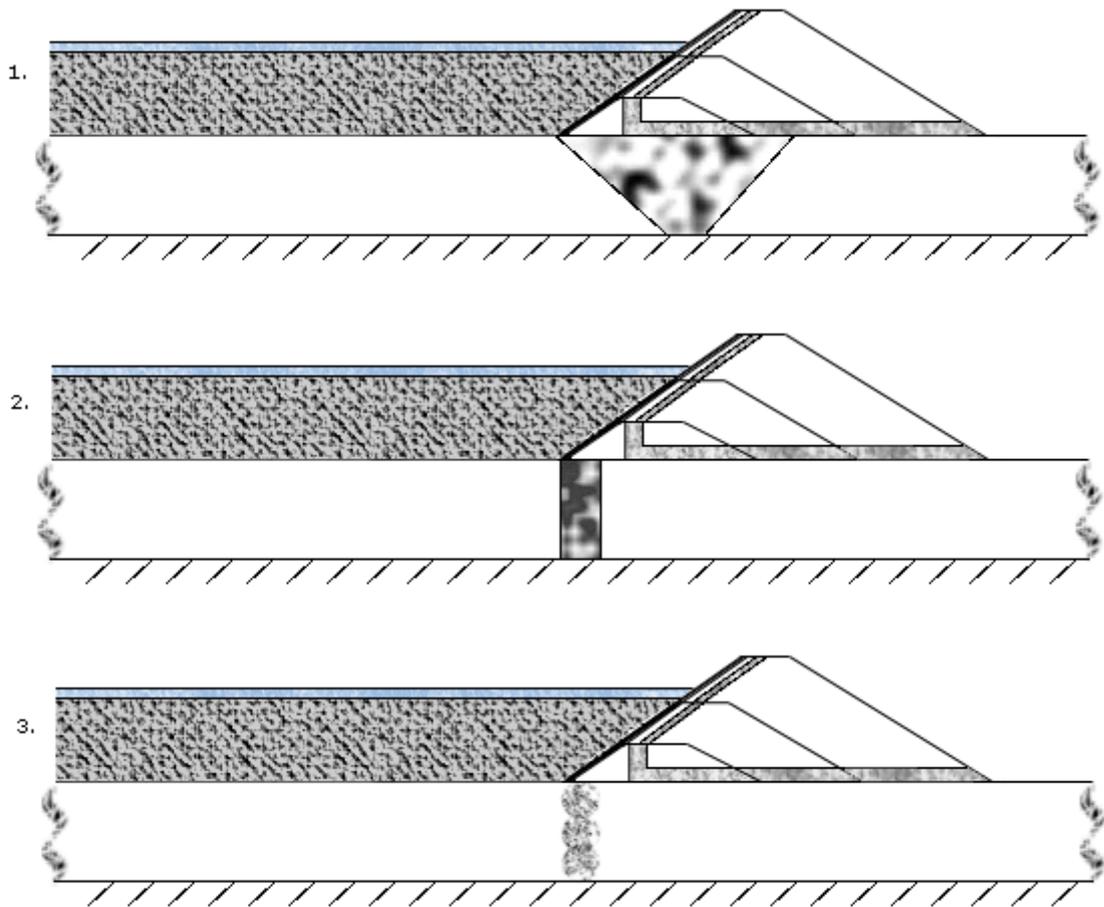
Today legislation is the key component in preventing environmental damage from tailings facilities. For remote areas tailings facilities won't have such stringent regulations compared to mines located in the vicinity of a community or valuable and/or stakeholder land. Mining companies will meet these guidelines and won't spend extra capital to prevent groundwater seepage if their license to operate doesn't require them too. Where groundwater is naturally poor (e.g. hyper saline) the tailings seepage may be an advantage to vegetation in the area.

Impoundments located at abandoned mine sites pose a particular problem as monitoring of the dam is limited or non-existent. Observation wells can determine groundwater flow and the contaminants of the tailings seepage. Historical data can be compared to assess if seepage rates are increasing over time. If this is true then the liner systems of the impoundment are damaged or have failed. Over time the seepage rates should converge to a lower constant annual level as the tailings reach their maximum consolidation. Synthetic liners can degrade over time if stored effluents chemically attack the liners. UV radiation levels in arid climates can also degrade exposed synthetic liners.

### 2.8.1 Groundwater pollution – Remedial measures

If groundwater contamination is increasing due to a liner failure, or where more stringent legislation is issued remedial measures need to be implemented. Before any works are carried out a detailed hydrogeological survey will need to be conducted. Monitoring wells can determine seepage directions and piezometers can measure pressures heads of the groundwater. Once areas of high seepage are determined mitigation options and costs can be calculated.

There are two main methods used to control groundwater seepage from a tailings impoundment. These are return and barrier systems. Seepage barriers prevent the mobilisation of seepage through the base of the embankment and are generally installed from the ground surface down to a less permeable or impermeable material or rock. The seepage is thus contained below the impoundment forcing future seepage back through the tailings to the free pond. Typical seepage barriers are cut-off trenches, grout curtains and slurry walls. More details of these barriers are mentioned in TAILSAFE WP1 and are shown in Figure 9.



**Figure 9: Embankment barriers, (1) – Cut-off trench, (2) – Slurry Wall, (3) – Grout curtain.**

Return systems are much cheaper to install than seepage barriers. A return system collects seepage rather than resisting its flow. A trench round the base of the downstream embankment toe is a common return system allowing seepage to be drawn into the trench and subsequently pumped back to the impoundment. Seepage wells can also be installed to collect seepage further below ground level that a seepage ditch can't collect.

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