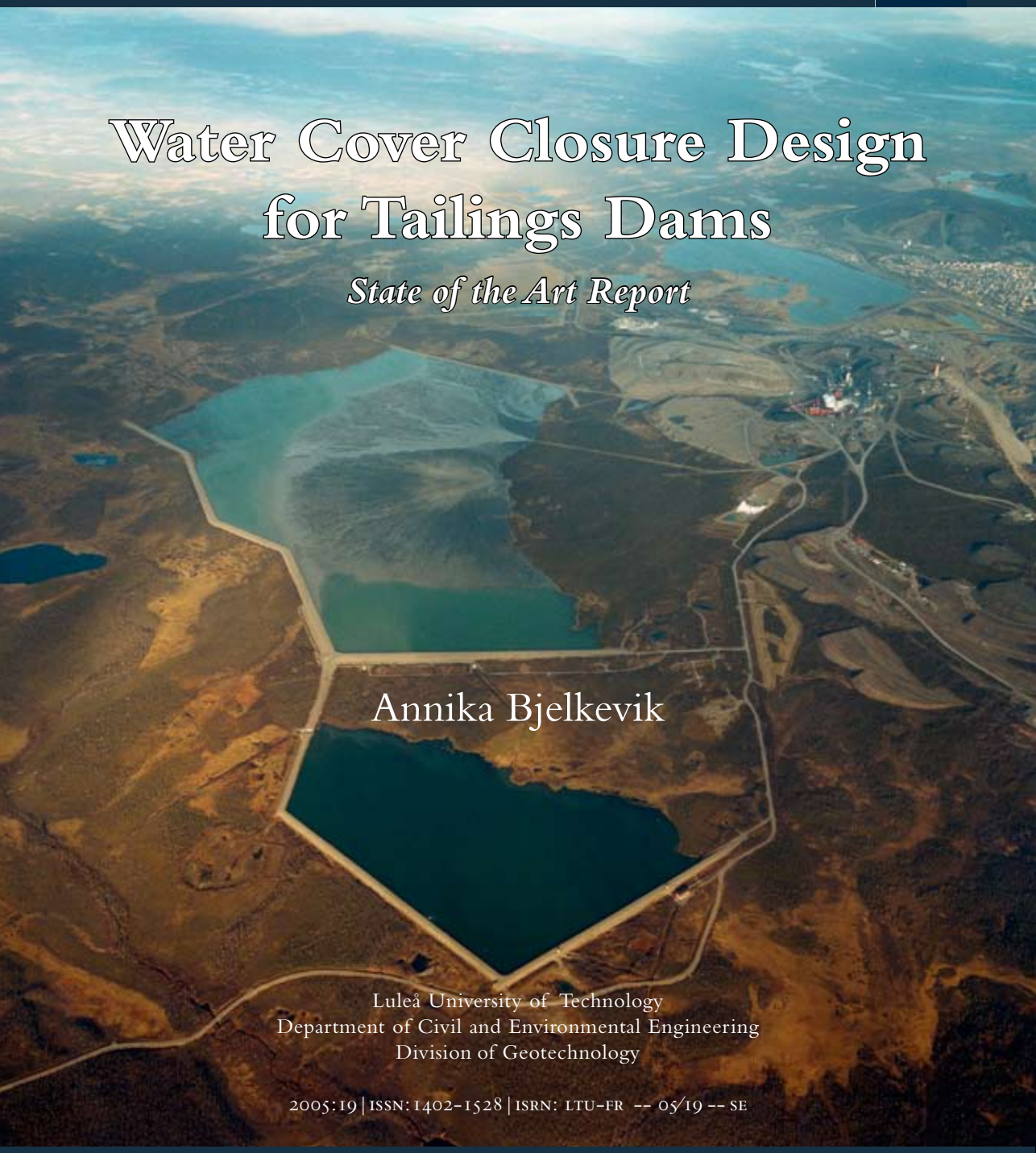
2005:19

FORSKNINGSRAPPORT

Water Cover Closure Design for Tailings Dams

State of the Art Report



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Foreword

This report constitutes the main part of the research project "Tailings Dams – design and construction for operation and long term effective performance", which was initiated by SveMin[1] in 1998 due to the increased focus on tailings dams and the long term complex of problems. A steering group representing financers and Swedish mining companies has directed the project and especially the work on this State of the Art report.

The project has been carried out as an industrial research project at the Div. for Geotechnology at Luleå University of Technology, even though the researcher has been located in Stockholm at the Sweco office.

I want to thank all people within the steering group for valid input and comments on this report, as well as all financers for making this project, and especially this report, possible. Financers are Georange[2] (50%), SweMin (25%), Sweco VBB AB[3] (25%) and MiMi[4] (2%).

Annika Bjelkevik
November 2005

[1] Swedish Association of Mines, Mineral and Metal Producers. The Association is a member of the Confederation of Swedish Enterprise. http://www.mining.se/

[2] Swedish co-financed EU project, which aims to successfully contribute to a structural development of the mineral and mining sector in the northern part of the Norrland region. http://www.georange.nu/

[3] Belong to the Sweco group, which is the largest Swedish consultant company, working in the fields of Hydropower and Dams, Public transportation, Roads and railways, Nuclear Energy, Road charges, Bridge engineering and civil structures, Rock engineering, Geotechnical engineering, Soil engineering and landscape architecture and Measurement technology. http://www.sweco.se/

[4] Mitigation of the environmental impact from mining waste. www.mimi.kiruna.se or www.mistra.org/mimi

Abstract

When a mine comes to an end and the operation closes down the whole site will be abandoned. Thus there is a need for remediation of the tailings storage facility (TSF), where the fine (crushed and milled) waste material, i.e. tailings, from the process plant is stored. The composition of the tailings vary, i.e. content of chemicals, minerals etc., between different mine sites. Unwanted processes may take place in the tailings and an example of this is acid mine drainage (AMD), which result in acidic leachate and leaching of metals from the tailings. Processes of this type will be harmful for the environment and must therefore be prevented or reduced. There is a need to have them controlled.

This state of the art report starts with a review of terms related to tailings dams and remediation of tailings dams. Definitions and/or explanations of different terms in the context of the report are given. For example *long term* is the time period for which tailings dams should be designed for at remediation. This term is explained and discussed. Long term is here thousands of years or more, or in a philosophical sense to the next glacial period, after which we do not expect man made structures above ground to be standing.

The most common construction methods for tailings dams are presented, as well as the construction methods used for Swedish tailings dams in operation. Several differences and similarities occur in comparison with water retention dams (WRDs), which are highlighted. In order to find out the performance of Swedish tailings dams, failures and incidents have been investigated and analyzed during the last 60 year period. Even though the data is incomplete, the conclusion drawn is that tailings dams are not safe enough today, to be regarded as long term stable without measures taken.

In order to prevent unwanted processes, such as AMD, in a long term perspective, different cover methods for the tailings have been developed. In this report the focus has been on the water cover method, where the tailings is covered with water. For a successful water cover design the most important conditions to be fulfilled are the long term water balance and physical stability of surrounding dams. The key factor is the long term stability of dams, which is discussed in the report.

Processes affecting the stability of the tailings dams are presented, such as slope stability, hydraulic gradients and its relation to internal erosion and slow deterioration processes (weathering, erosion, frost and ice, vegetation and animal intrusion etc.). One factor affecting the dam safety quite considerably is the climate change. This is briefly discussed and references are given to ongoing work.

In order to find out how long term stable dam structures should be designed to be stable during long periods of time, natural analogies and ancient mounds can be studied. Some examples of both types are described and discussed in the report.

The aim of this report has been to document the existing knowledge on long term tailings dam stability. The intention has also been to analyse areas requiring extended knowledge in order to reach the goal with design and construction of long term stable tailings dams. Areas needing more research are identified. The document thus provides a platform for further research and is aimed to be a strategic document in the communication between the industry, authorities and organisations in the public sector.

The final conclusion from this study is that criteria for long term stable tailings dams can hardly be defined today. More research is needed and more experience must be gained before specific design criteria can be given. Considering the limited knowledge of long term stability of tailings dams there is a demand for more studies. Some of the important processes identified here in this aspect are:

- Internal erosion
- Long term changes in material properties
- The effect of the hydraulic gradient on slope stability
- Interaction between deposited tailings and sealing elements/foundation within the tailings dam
- External erosion on slopes
- Seepage points

Sammanfattning

När en gruva är utbruten och verksamheten upphör kommer hela gruvområdet att överges. Det finns då ett behov av att efterbehandla gruvdammsanläggningen, i vilken den fina (krossade och malda) restprodukten, eller den s.k. anrikningssanden, från anrikningsverket har deponerats. Anrikningssandens sammansättning, d.v.s. innehåll av kemikalier, mineraler etc., varierar mellan olika gruvor. Oönskade processer kan uppkomma och pågå i anrikningssanden och ett exempel på en sådan ärden urlakning av metaller som orakas av en miljö med lågt pH. Denna är mera känd som ”acid mine drainage” (AMD). Processen resulterar i surt lakvatten och urlakning av metaller från anrikningssanden. Processer av denna typ är skadliga för miljön och måste därför förhindras eller reduceras. Det finns också ett behov av att kontrollera dessa.

Rapporten inleds med en genomgång av termer relaterade till gruvdammar och efterbehandling av gruvdammar. Definitioner och/eller förklaringar av termer beskrivs. Ett exempel är *långtidsfas* som är den tidsperiod för vilken gruvdammars efterbehandling ska designas för. Denna term förklaras och diskuteras. Långtidsfasen är i detta sammanhang tusen år eller mer, eller i ett mer filosofiskt perspektiv till nästa istid. Efter detta förväntar vi oss inte att konstruktioner som människan uppfört ska kunna finnas kvar.

De vanligaste konstruktionsmetoderna för gruvdammar beskrivs, liksom de konstruktionsmetoder som används för svenska gruvdammar i drift. Det finns flera skillnader och likheter med vattenregleringsdammar och dessa belyses. För att se hur väl svenska gruvdammar fungerar har haverier och incidenter under de senaste 60 åren undersökts och analyserats. Även om uppgifterna inte är kompletta så kan slutsatsen dras att gruvdammar inte är tillräckligt säkra idag för att betraktas som långtidsstabila utan att åtgärder först måste vidtas.

För att förhindra oönskade processer, så som AMD, i ett långtidsperspektiv har olika typer av efterbehandlingsmetoder utvecklats. I den här rapporten har fokus varit på vattentäckning, vilket innebär att anrikningssanden täcks med vatten. För att denna metod ska fungera måste två förutsättningar vara uppfyllda, nämligen långtidsstabil vattenbalans och långtidsstabila dammar. Den viktigaste är att dammarna som omger magasinet är stabila, vilket diskuteras i rapporten.

Processer som påverkar stabiliteten hos dammarna presenteras och diskuteras, så som släntstabilitet, hydrauliska gradienter och deras relation till inre erosion och långsamma nedbrytnings processer (vittring, erosion, frost och is krafter, intrång av vegetation och djur etc.). En faktor som avsevärt påverkar dammsäkerheten är klimatförändringar. Detta diskuteras kortfattat och referenser ges till pågående arbeten.

För att komma fram till hur långtidsstabila dammar ska designas för att vara stabila under mycket lång tid har naturliga analogier och forntida

jordanläggningar studerats. Några exempel på dessa typer av formationer beskrivs och diskuteras i rapporten.

Målsättningen med rapporten har varit att dokumentera den befintliga kunskapen på området gruvdammars långtidsstabilitet. Intentionen har också varit att se vilka områden som erfordrar ytterligare kunskap för att man ska kunna designa och konstruera långtidsstabila gruvdammar. Områden som kräver mer forskning identifieras. Dokumentet utgör därmed en plattform för fortsatt forskning, liksom att det också utgör ett strategiskt dokument i kommunikationen mellan industri, myndigheter och samhället i övrigt.

Slutsatsen av denna studie är att det idag inte finns några kriterier för design och konstruktion av långtidsstabila dammar. Mer forskning krävs, liksom att mer erfarenhet måste uppnås innan specifika kriterier kan tas fram. Det finns ett behov av mer studier med hänsyn till den begränsade kunskap vi har om långtidsstabila gruvdammar. Några, i detta avseende, viktiga processer har här identifierats:

- Inre erosion
- Förändringar av materialparametrar i ett långtidsperspektiv
- Den hydrauliska gradientens påverkan på släntstabiliteten
- Samverkan mellan deponerad anrikningssand och dammens tätande element respektive dess grundläggning
- Yttre erosion på slänter
- Källsprång

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1 Introduction

This report is part of the research project "Tailings Dams – design and construction for operation and long term effective performance". The main issue is to review the state of the art for remediation of tailings storage facilities using water or wetland cover methods. Focus will be on the geotechnical long term stability of the dams impounding the deposited tailings to create a safe and sustainable impoundment after remediation. Additionally, this report covers terminology used, tailings dam design and the current tailings dam designs used in Sweden and abroad.

Other, important issues, like dry cover design, environmental aspects, acid mine drainage (AMD), planning, landscaping, revegetation, monitoring etc. have been addressed by others, for example in the Swedish MiMi[5] project. These fields will only be commented on when justified.

The objective of this report is to analyse areas where extended knowledge is required and consequently what future research may focus on. It therefore, provides a platform for further research and is aimed to be a strategic document in communication with the industry, authorities and organisations in the public sector.

2 Terminology

Technical language is used in the field of tailings dams and their remediation. The most relevant terms will be discussed here and some will be illustrated as well. In Appendix B all terms will be listed and full references given. No definitions are quoted directly from one reference, but reworked from several references and/or influenced by the author. Figure 1 shows the terms concerning the basic components of a tailings management facility (TMF).

Tailings, by ICOLD's definition (ICOLD, 1996c), include all waste material (or "tail" products) from any activity. In this report tailings are, however, defined as mill tailings from mining activities. The ore is in the process ground-up to a size less than 0.01-0.1 mm, i.e. silt fraction. The metal content is removed and the remains are waste materials deposited in slurry form (Vick, 1990), i.e. the tailings.

Tailings dam (tailings embankment or tailings disposal dam) is a structure designed to settle and store tailings and process water. Solids settle in the pond and the process water is usually recycled (European Commission, 2004). There is a wide range of different tailings dam designs. The designs can, however, be divided into three general methodologies described in 4.3 "Design Methods" and in ICOLD (1996c). Depending on the design, the boundary between the tailings dam and the impoundment may not

[5] MiMi, Mitigation of the environmental impact from mining waste (http://www.mimi.kiruna.se), is a Swedish research programme within MISTRA (http://www.mistra.org).

always be clear. In general, the dam is normally the part, which is physically constructed in a controlled manner. Here the boundary is defined for the two main cases:

1. For conventional earth fill and downstream constructed tailings dams the boundary is defined by the limit between construction material placed in a controlled way and the deposited tailings. This boundary will be constant over time even though the dam is built in stages, as the dam moves outwards when raised, see Figure 2b.

2. For other methods (upstream, centreline and paddock) the deposited tailings constitute the dam structure, or part of it. In those cases, there are no clear boundary between the dam and the impoundment. The boundary of the dam is therefore defined to encompass the part of the embankment influencing the total stability of the dam or where the construction material has been placed in a controlled manner, including for example cycloned or mechanically compacted tailings. This area will be affected by the position of the pond as the location of the pond directly affects the hydraulic gradient, which in turn affects the stability. The boundary of the dam will in these cases change over time due to design and method of construction, see Figure 2a.

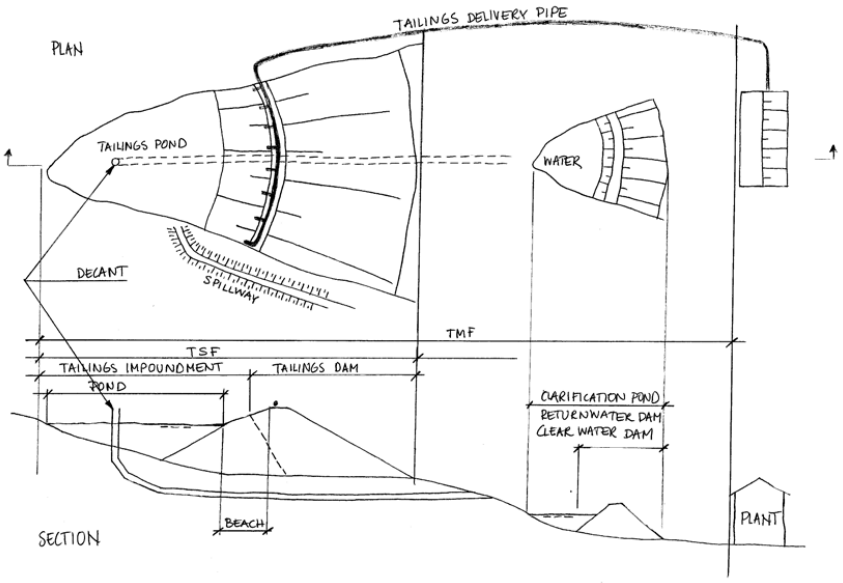


Figure 1 *The sketch shows the basic components used to describe a tailings management facility (TMF).*

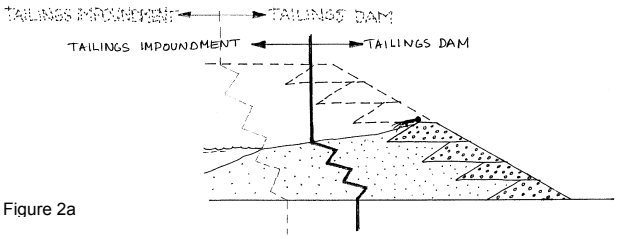


Figure 2a

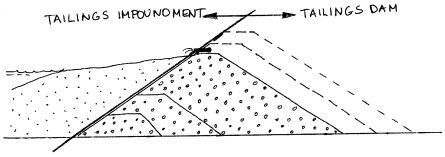


Figure 2b

Figure 2a and 2b *Examples of the definition of the boundary between tailings dam and tailings impoundment for upstream as well as downstream construction.*

Tailings impoundment is the storage space/volume created by the tailings dams where the tailings are deposited and stored, see Figure 1. In many cases the boundary between the impoundment and the dam is not very clear. An attempt to clarify the boundary has been made in Figure 2 and a more detailed discussion is given under "tailings dam".

Tailings pond or supernatant pond is the water stored in the tailings impoundment, see Figure 1.

Tailings storage facility (TSF) comprises the tailings dam, impoundment, pond as well as decant structures or spillways, see Figure 1. A TSF does not have to be a structure where tailings dams are used, but can also be open pits, dry stacking, lakes or under ground storages.

Tailings management facility (TMF) comprises the whole set of structures needed for the handling of tailings. TMF starts at the point where the tailings leave the plant and end at the point where it is finally deposited. This includes tailings dams, impoundments, decants, clearwater dams, pipes, pumps etc., see Figure 1. TMF can be one or several of mined out open pits, lakes, the sea, heap leach dumps, tailings ponds (including clear water pond if there is one), underground backfill or recycling.

Closure is the phase when mining activities ceases and the transition of the mining area into a long term stable area takes place. Closure, in turn, encompasses different phases, see Table 1 and descriptions below. The philosophy of closure is to minimize the release of contaminants to an environmentally acceptable level, normally not to a zero discharge level, but to a level manageable by the environment. This means that the philosophy is to spread the total discharge over a time span long enough to enable the natural environmental processes to accommodate it. Mine closure is a continuous series of activities starting at pre-planning and ending with the achievement of a long term site stability and the establishment of a self-sustaining ecosystem (WMI, 1994)

Table 1 Phases of a tailings management facility.

	Phase	**Detailed phase**
Time ↓	Planning	Environmental Assessment Preliminary Design Hazard Rating
	Design	Applying and Receiving Permits Detail Design
	Construction	Initial Construction
	Operation	Operation & ongoing Construction
	Closure	Decommissioning Remediation After Care
	Long term	

Decommission is here defined as the close down of operations and removal of unwanted structures like infrastructure, buildings, pipelines, services etc., which will not be needed or used in the future.

Remediation is the measure required to secure the long term stability and environmental safety of structures like tailings dams and impoundments left at the site. This often includes measures to encapsulate the tailings and stabilise dam structures in order to decrease releases of toxic or contaminant particles to levels approaching the natural background or otherwise environmentally acceptable levels in a long term perspective. Remediation includes rehabilitation and reclamation, see Appendix B.

After care is the time period required to verify that measures taken perform according to design. This includes analysis of data, inspections and other necessary measures. When the performance and durability of the measures taken can be verified, the long term phase starts and the mining company should be able to leave the site.

Long term phase is the time period for which closure is designed. In a philosophical sense, this means to the next glacial period in regions where a future glacial period is expected. Man made on land structures lasting over a glacial period is not expected. The lifetime of measures taken at remediation must therefore be long enough, i.e. thousands of years.

3 Tailings

The volumes of mining wastes are significantly larger than those of both domestic and industrial waste (ICOLD, 2001). Resulting in tailings probably being the, by volume, most handled material in the world (ICOLD, 1996c). Satellite imagery has led us to the realisation that tailings storage facilities probably are some of the largest man-made structures on earth (ICOLD 2001).

Sweden, as a small mining nation internationally, produces about 25 Mt ferrous ore per year and 22 Mt non ferrous ore per year (SGU, 2004). This corresponds to 1.5% of the world production of ferrous ore and about 0.7% of the non ferrous. However, a similar comparison in Europe shows, that the Swedish production of copper, lead, zinc, iron, gold and silver stands for about 40% of the total production in Europe.

In addition to tailings, Swedish mines produce approximately 35 Mt of waste rock. This is mostly produced in order to access the ore (SGU, 2004). Handling of waste rock will not be treated here.

The properties of tailings vary depending on their source and degree of compaction, but generally tailings have (ICOLD, 1996c):

- a high water content
- low to moderate hydraulic conductivity[6]
- low plasticity
- low to moderate shear strength
- high to moderate compressibility

Additionally it can be mentioned, that the general properties normally are of (Eurenius, 2005 and others):

- particle size less than 0,01-0,1 mm
- high porosity
- moderate to high shear strength in relation to particle size and porosity of the tailings material in comparison to natural geological materials

[6] Hydraulic conductivity is the proportionality factor in Darcy's law. This factor is sometime referred to as permeability. Hydraulic conductivity takes the viscosity into account and is measured in [m/s]. Permeability, however, is a material constant measured in [m^2]. Permeability, which do not incorporate the effects of the fluid, can be converted into hydraulic conductivity.

Material properties of tailings at Swedish tailings storage facilities, TSFs, have been summarised and analysed by Bjelkevik and Knutsson (2005b). The samples were collected in 2002 and analysed in 2003. Table 2 shows some of the data. It can be seen, that the average dry density for ferrous tailings is 1.8 t/m^3 compared to 1.6 t/m^3 for non ferrous and for bulk density the corresponding relationships are 2.2 t/m^3 to 1.9 t/m^3. The compact density is about 3 t/m^3 for both tailings types, with 2.88 t/m^3 as the lowest value for ferrous tailings and 4.07 t/m^3 as the highest for non ferrous tailings. If samples had been taken of tailings from the pond area, densities would have been lower as the material becomes even finer in this region and due to the experience of unpublished sampling of Swedish tailings. (Eurenius, 2005).

Hydraulic conductivity differs as ferrous tailings are about twice as permeable as non ferrous. However, the hydraulic conductivity may differ with the same order of magnitude within each facility as this parameter varies both horizontally and vertically together with the void ratio and degree of compaction. Any solid conclusion of the hydraulic conductivity is difficult to make as there are only a few surface samples taken at each site.

The conclusions from the analysis in Bjelkevik and Knutsson (2005b) are:

- the typical grain size of tailings corresponds to silt or silty sand
- the grain size decreases with increasing distance from the outlet
- the void ratio increases with increasing distance from the outlet
- tailings at Kiruna and Malmberget can be compacted to void ratios of about 0,45, whereas the others varied between 0.55-0.70
- the porosity varies between 38-57%
- the degree of compaction varies between 71-96%
- the hydraulic conductivity can not be calculated very well by the empirical equations studied (i.e. Hazen, Chapuis etc.).

What still needs to be investigated is sampling methods, in-situ testing and evaluation routines. Are the standard methods used for natural material valid for tailings? Do in-situ testing methods need to be calibrated for tailings?

Due to the grinding of the ore, to a fraction of silty sand, the specific particle surface area is relatively large, which may facilitate an increased release of trace elements from the ore, which in turn, can have a negative effect on the environment. To avoid contaminants to spread into the environment the tailings have to be handled in a safe way. TSFs are designed for this purpose. The most common way to store tailings is by using tailings dams to create an impoundment for settling and storage of tailings.

Experience from the tests of the shear strength of tailings in Sweden is, that the friction angle normally is relatively high (up to 45°) compared to natural materials with the same high porosity. This is probably due to the angularity of the particles (Eurenius, 2005 and others).

Table 2 Summary of some material properties determined from samples collected at Swedish TSF during 2002. All values are average values for each impoundment. (Bjelkevik and Knutsson, 2005)

Name of facility	Type of ore	Dry density [t/m^3]	Bulk density [t/m^3]	Compact density [t/m^3]	Poro-sity [%]	Hydraulic conductivity; [10^{-6}m/s]
Kiruna	Fe (magnetite)	1,74	2,11	2,88	40	12,7
Svappavaara	Fe (magnetite)	1,75	2,16	3,42	48	5,9
Malmberget	Fe (magnetite, hematite)	2,01	2,35	3,31	40	17,5
Aitik	Cu, Au, Ag	1,49	1,92	2,82	47	1,7
Boliden	Zn, Cu, Pb, Au, Ag	1,86	2,12	4,07	54	2,7
Garpenberg	Zn, Ag, Pb, Cu, Au	1,46	1,91	2,99	51	2,2
Zinkgruvan	Zn, Pb, Ag	1,54	1,86	2,80	45	11,7

** crude ore*

4 Tailings Dams

Professionals within the civil engineering industry are, in general, familiar with conventional water retention dams (WRDs), but not with tailings dams, which normally just are known by the mining industry and experts in the field. This section will therefore briefly describe tailings dams in general, Swedish tailings dams in particular and compare these to WRDs.

Tailings impoundments are geotechnical structures in the way that they consist of ground-up soil and rock, mostly placed on a soil foundation and retained by engineered soil and rock containment dikes or embankments, i.e. tailings dams, (Caldwell and Robertson, 1986). To facilitate the purpose and the function of the TSF the tailings dams need to be designed for earth and water loads and to be long term stable as they mostly cannot be removed after closure. WRDs on the other hand are designed for water loads only and can, at least theoretically, be removed when no longer adequate for use.

4.1 General

Most mining processes are wet and the tailings leave the treatment plant as a slurry, i.e. tailings mixed with process water. This makes it convenient to pump it from the plant to a place for sedimentation and storage. The use of tailings dams to create an impoundment for storage is the most common way of handling tailings. When the tailings have settled within the impoundment, the water will either be recovered for use in the treatment plant, released after proper treatment into a tributary river or stream or, in arid climates, evaporate. As the tailings fill the impoundment, the surrounding dams are continuously raised. (ICOLD, 1996c)

4.2 Historically

To facilitate the understanding of the safety issues of tailings dams, both in a short and long term perspective, a brief historical review of how the tailings dam technology has developed will be given here. Facts are derived from (Vick, 1999).

Tailings dam technology has evolved from changes in the mining process and in the public's response to its effects. During the 19th century the mining technology was rather primitive and it was only profitable to mine rich ores, resulting in comparatively coarse waste and correspondingly small volumes. The waste was normally dumped in the most convenient place, like the nearest lake or stream, to be washed away.

Lower graded ore could be mined shortly after the turn of the century as the "froth flotation" was developed. This process required the ore to be crushed to a finer particle size in a wet process, requiring water. As a result, the tailings became finer, larger by volume due to the low grade ore and left the process as a slurry. The growing volumes and the decreasing particle size contributed to spread the tailings in the environment over greater distances, particularly in streams.

The new technique contributed to the development of minor communities around the mines including agricultural developments. Conflicts soon arose as the dumped tailings started to block irrigations channels and contaminate croplands, which gradually lead uncontrolled dumping of tailings to an end. The purpose of the first dams, often constructed across the stream where the tailings used to be dumped, was pollution control.

Construction of conventional earth fill dams without earth moving equipment was economically impossible for any mining operation at this time. As a result, miners by trial and error developed a method where the deposited tailings constituted part of the dam and only small volumes of fill material were required to be put in place. Today, this method is called the "upstream method", see 4.3 "Design Methods". Due to the lack of proper spillways etc. some of these first dams did not survive for long and failures started to take place. The first documented tailings dam failure was in 1917.

After the seismic failure of the Barahona tailings dam in Chile in 1928, the upstream method was replaced by the downstream, see 4.3.2 "Downstream construction". This method resembles the design of the conventional WRD. By using cyclones, that separate the fine fractions from the coarse, it is possible to create zones within the dam with different functions. The coarser fraction is used for the downstream part of the dam and the fines settle along the beach to create a progressively finer, and therefore less permeable, zone. During the 1940's when earth moving equipment and mechanical shovels became available it was possible to construct tailings dams like conventional water retention dams by the use of earth fill material.

The development of tailings dam technology this far was empirical as it was learned by trial and error, passed on by word of mouth, understood and applied. Soil mechanics, hydrology and other disciplines adopted and refined these principles

during the 1960's and 1970's. The seismic failures of several tailings dams in Chile 1965 received attention and were the start for major research in seismic liquefaction of tailings material. About two decades later the environmental aspect came into focus again. It was the effect on groundwater by contaminants in the seepage water from the tailings dams, i.e. acid mine drainage (AMD), that became an important factor. Both aspects, liquefaction and AMD, are still important topics for the fields of tailings dams.

4.3 Design Methods

Design methods for tailings dams differ somewhat from WRDs, which will be discussed in 4.4 "Comparison with Water Retention Dams (WRD)". Here the methods and principles of tailings dam construction will be discussed.

The fundamental dam engineering principles for tailings dam design are:

- locating the dam to minimize the catchment area
- maintaining a wide beach to control internal seepage from the free water pond
- enhancing internal drainage by constructing pervious initial starter dikes
- exploiting pervious foundation conditions

The beach is the area between the crest of the dam and the free water pond where the coarser particles from the tailings settle during deposition. Starter dike is the initial dam stage from which the subsequent raises of the dam are constructed.

The fundamental principles described above were understood during the beginning of the 20th century. From that time three, for tailings dams, typical construction methods have developed (Vick, 1999). The methods are, upstream, downstream and centreline constructions, which all are described in detail in ICOLD (1996c).

4.3.1 Upstream construction

The following is described according to Vick (1990).

The upstream construction method is shown in Figure 3. Initially a starter dam/dike is constructed, normally of borrow material as no tailings is produced yet. Tailings are then discharged from the crest of the dam along it's periphery to create a tailings beach where the tailings can settle as the slurry run towards the pond, see Figure 3a. When the impoundment is full, or rather before that, the second dike is constructed on the settled and consolidated tailings beach. This process continues as the tailings dam increases in height, see Figure 3b-d.

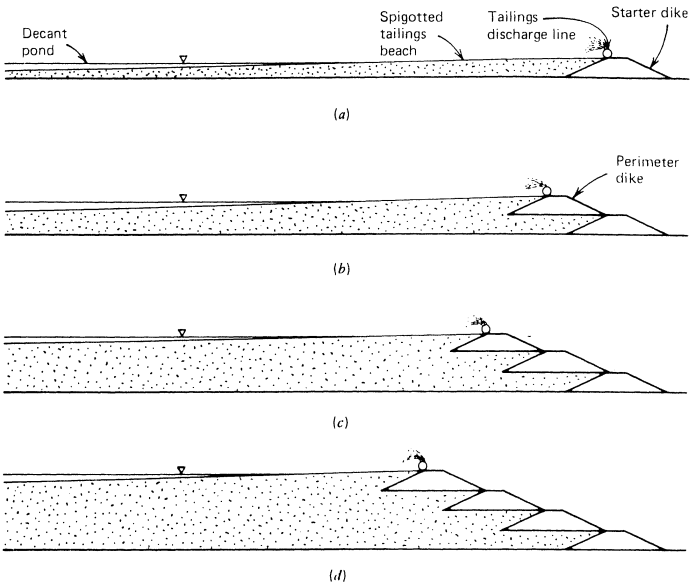


Figure 3 Sequential raising, upstream embankment, (Vick, 1990).

Advantages of the upstream construction are:

- Low cost and simplicity.
- The man made dikes may be constructed of sand from the tailings beach and this process is simple and ongoing.
- The method results in a low hydraulic gradient due to the required long beach and the, from the free water pond to the downstream slope, gradually coarser fraction of the tailings. A low hydraulic gradient is good for long term conditions as well.
- The outer slope can be remediated during operation as the crest moves inwards.

A general rule for upstream construction is that 40-60% of the total tailings fraction needs to be sand, i.e. in the fraction of 0,07-5,0 mm according to Vick (1990) and the U.S. standard. (According to the Swedish standard, SS 02 71 06 (1990), sand is in the fraction of 0,06-2,0 mm.)

Disadvantages or factors that are a constraint to the application of the upstream construction include:

- control of the hydraulic gradient
- water storage capacity
- susceptibility to seismic liquefaction
- rate of raise
- dust control at high winds

The location of the hydraulic gradient is important in order to control dam stability. Its location is basically influenced by three parameters, (see Figure 4 as well):

- the hydraulic conductivity of the foundation relative to the tailings (both in the dam and the impoundment)
- the degree of grain size segregation and lateral hydraulic conductivity variations within the tailings (both in the dam and the impoundment)
- the location of the pond water relative to the dam crest

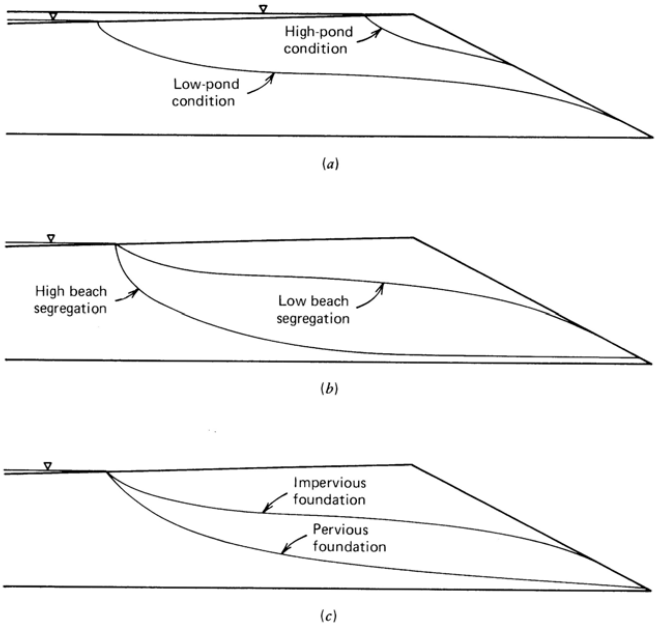


Figure 4 Factors influencing the location of the hydraulic gradient for upstream embankments. (a) Effect of pond water location. (b) Effect of beach grain-size segregation. (c) Effect of the hydraulic gradient in the foundation. (Vick, 1990).

Design measures like underdrains and cyclones can be used to control the hydraulic gradient. Underdrains have the effect of increasing the hydraulic gradient in the foundation. Cyclones promote the grain size segregation, i.e. separates the coarse and fine fraction of the tailings more effectively. The coarse fraction is used for dam construction and the fine is deposited within the impoundment. During operation the location of the pond water is the only tool to control or change the hydraulic gradient.

As the tailings beach is flat, a slightly increased pond level often results in a large horizontal movement of the pond water towards the crest. This result in most upstream constructed tailings dams, depending on the design, not being suitable for storage of large volumes of water or where the water level may change a lot.

Upstream construction often results in a low relative density and generally high degree of water saturation. This dam design is therefore not recommended in seismic areas.

Rate of raise is limited for the upstream dam construction. Rapid rate of raise results in excess pore water pressures within the tailings and lower effective stresses, which then results in reduced shear strength. (ICOLD, 1996c). According to Eurenius (2005) a rate of raise less than 2-3 m/year will, according to experience, be sufficient for safe upstream construction of tailings dams.

The required long and flat beach may cause dust problems when exposed to high winds. Preventative measures are limited due to the normally ongoing deposition on the beach.

4.3.2 Downstream construction

The following is described according to Vick (1990).

The downstream construction method is shown in Figure 5. Initially a starter dam is constructed, normally of borrow material as no tailings are produced at this time. Tailings are then discharged behind the starter dam. When the impoundment is full, or rather before that, the next raise is placed on the downstream slope of the existing dam, see Figure 5b-d. This enables the incorporation of internal zoning for control of the hydraulic gradient within the dam, resembles conventional water dams, see 4.4.1 “General”. Significant volumes of water can therefore be stored along with the tailings.

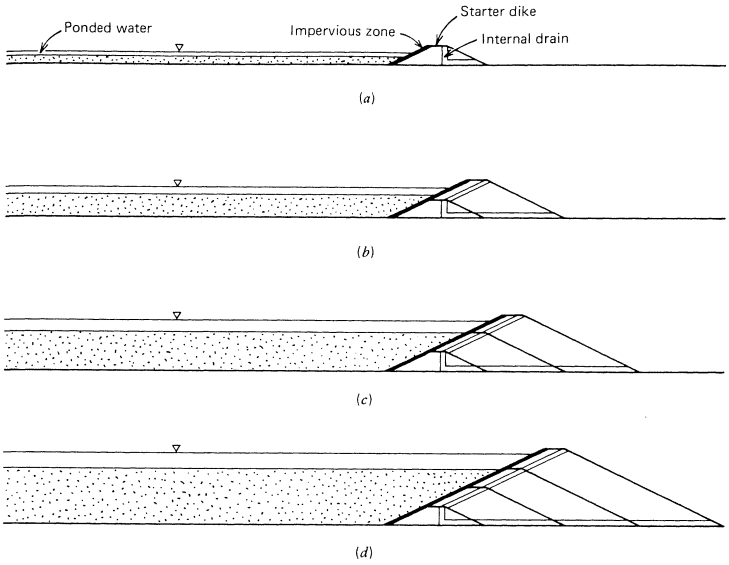


Figure 5 Sequential raising, downstream embankment, (Vick, 1990).

Advantages of the downstream construction method are:

- suitable for any type of tailings
- more resistant to liquefaction than other methods

Disadvantages of the downstream construction method are the requirement of advanced planning due to:

- progress of the toe moving outwards at each raise
- large volumes of fill material, which results in high costs
- the volume of fill material needed for a raise increases with each raise. The material available when tailings is used for construction is produced at a constant rate and therefore often resulting in a lack of construction material as the dam height increases
- remediation can not take place before the final height of the dam has been reached

4.3.3 Centreline construction

The following is described according to Vick (1990).

The centreline construction method is shown in Figure 6. Initially a starter dam is constructed, normally of borrow material as no tailings are produced at this stage. Tailings are then discharged peripherally from the crest to form a beach, see Figure 6a. When the impoundment is full, or rather before that, the next raise is placed on the beach and on the downstream slope of the existing dam, see Figure 6b-d. This enables the incorporation of structural measures for control of the hydraulic gradient within the dam, similar to the downstream construction. Storing of significant volumes of water along with the tailings are not recommended due to the need of an adequate beach, even though this beach does not need to be as wide as for the upstream construction (see section 4.3.1 “Upstream construction”).

The centreline construction method is a compromise between the upstream and downstream methods in many aspects, it shares the advantages of both methods and mitigate the disadvantages. The volume of fill material needed is intermediate between upstream and downstream methods as well as the cost. The seismic resistance is generally acceptable as the main part of the fill material can be compacted. The rate of raise is normally not restricted by pore pressure dissipation for centreline construction. This is due to the height of a raise normally being less than technically allowed, due to the maximum height allowed being higher than for upstream construction, i.e. more then 2-3 m/year. The reason for this is that the section of the dam being raised on deposited tailings is smaller than for upstream construction.

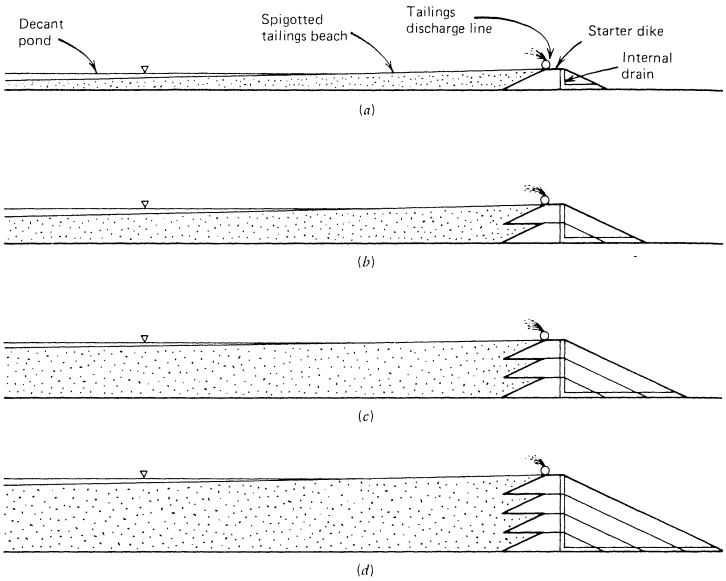


Figure 6 Sequential raising, centreline embankment, (Vick, 1990).

4.3.4 Other methods

There are other methods for depositing tailings in addition to tailings dams and the three fundamental methods described above. For example, refill of mines (often paste fill), paste and thickened tailings disposal, co-disposal of tailings and waste rock, and seepage dams. The latter is a new method, which the Swedish mining company LKAB is investigating. Åkerlund (2005) has carried out research studies on this type of draining dams. The dams are constructed in a way that they create relatively small cells into which tailings can be deposited. The dams enclose the tailings but drain the water. When one cell is filled it is left to dry, while the next cell is filled and so on. In this way dry tailings deposits can created where the cells can designed and placed in order to fit in to the landscape.

4.3.5 Comparison of construction methods

When comparing different construction methods the cost is often of particular interest, which to a large degree is proportional to the total fill volume. A rough estimate is, that the three methods described, for a certain height require the following relative volumes (Vick, 1990):

upstream construction	fill volume V
centreline construction	fill volume 2V
downstream construction	fill volume 3V

Differences in fill volume will increase even more if the height increases, as will the costs. As the contribution of the costs of the dam fill material to the total cost may vary

widely, the comparison of cost with respect to fill volume only may be misleading. In some cases other costs may outweigh the cost for dam construction, for example costs for:

- impoundment area top soil stripping (i.e. stripping the top soil of the area for the dams and impoundment)
- impoundment lining (i.e. when the tailings is highly toxic (for example containing cyanide) lining may be required between the natural foundation and the dam and impoundment)
- closure (see Table 1)

Selection of construction method has in many cases been by combinations of historic precedent, empirical observation, and regulatory requirements rather than by strictly rational evaluation of each alternative (Vick, 1990). Tailings dam technology has developed by trial and error and therefore different methods have turned out to be the best in different areas. "For example, upstream embankments are widely used in copper mining regions in the south-western United States and in South African gold mining districts. The arid climate put water at a premium, which results in the pond water being kept low due to mill recycling and therefore few problems with water accumulation. Low seismicity in these areas has also contributed to the generally successful use of upstream methods. In other areas, for example, the lead-zinc-silver districts in northern Idaho the same method were chosen for a completely different reason, namely the permeable alluvium foundation in the valley bottoms which is normally used as tailings dam sites. In other places, like Missouri and British Columbia, which have extensive rainfalls, steep topography and seismic activities, the centreline construction method using cycloned tailings and borrow material has developed. This combination results in a more seismic resistant and controlled dam construction, where the borrow material can be chosen to be more permeable than the tailings. The role of precedent in choosing construction method should not be ignored, but thorough planning and analysis should always dominate the choice", Vick (1990).

In Sweden ferrous mines normally have a good supply of material from the mining process, which can be used as fill material due to its good environmental properties. This has resulted in most tailings dams at ferrous mines are being constructed by the downstream or centreline method, Eurenius (2005). The use of seepage dams, instead of conventional tailings dams, are under development by Swedish iron ore mines, see Åkerlund (2005). Processed materials at non ferrous mines normally are too rich of sulphide to be used as fill material, resulting in the upstream method often being regarded as more advantageous, Eurenius (2005).

According to the author, the above described methods are equivalent with regard to safety as long as the conditions, principles, behaviour and particular setting for each site and method are properly evaluated.

4.4 Comparison with Water Retention Dams (WRD)

Earth fill water retention dams (WRD) are normally constructed for hydropower or water supply (for example irrigation) purposes, whereas tailings dams are constructed to mainly store tailing (i.e. sand/silt). To fulfil the purpose of tailings dams, less expensive designs, where the tailings itself can be used as construction material, are often possible and necessary to find. It can, however, sometimes be necessary to use designs similar to WRD for tailings storage if, for example, storage of large volumes of water is required, which can be due to either extensive rainfalls in the area, requirements of the plant/process or if the tailings need to be disposed under water due to environmental reasons. Never the less, a comparison between the two types of dams is of interest, as there are similarities as well as differences between the two.

4.4.1 General

The first WRD dams were built thousands of years ago. Dams with a height over 10 m were built more then 2000 years ago. Many of these ancient dams have disappeared, but some are still operational 500 or 1000 years after being built. Most of these dams were constructed of clay, or similar locally available material, especially for those up to about 20 m height (homogenous earth fill dams). Two modifications of the design that increased the safety was the flattening of the slopes (from about 1930) and the use and/or improvement of filters and drains (from about 1960). The latter reduced failures from internal erosion remarkably, (ICOLD, 1997). Today the criteria for design of filter and drains are even more sophisticated, due to gained experiences.

The design of a typical earth fill WRD may look like that depicted in Figure 7, with zones of erosion protection (riprap), impervious core, filter, drains and upstream and downstream support fill.

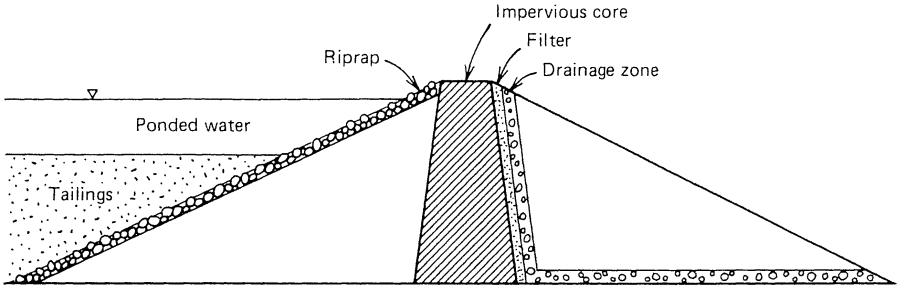


Figure 7 Water-retention type dam for tailings storage, (Vick, 1990).

4.4.2 Comparison

Due to the increasing need of metals and minerals, new mining operations are likely to develop and new tailings dams to accompany them. Rich ores being mined out and the development of ore processing technology, results in low graded ore being profitable to mine. This gives more waste, and more tailings. As a result, the relative importance

of tailings dams to the dam safety community will grow in proportion (Vick, 1999). In industrial countries most of the possible potential hydropower schemes are already developed, whereas tailings dams still are being raised and/or new constructed.

4.4.2.1 Main differences

The construction procedure differs in the sense that a WRD is constructed to the final height at once, while tailings dam construction is an ongoing process where the dams are raised in stages or more or less continuously. The size and capacity of a tailings impoundment must increase with the mine production of tailings. Construction and design conditions will therefore change over time, as will the responsible staff. This will result in a tailings dam requiring considerably more planning and attention over a much longer time period compared to WRD. Positively for staged construction is the cost distribution over time and that all fill material need not to be available at the start of the construction, which gives more flexibility regarding the fill material, (Vick, 1990). Negatively for staged construction, are the change of staff and the associated risk of loosing the over all purpose or intention of a specific design.

The main purpose of tailings dams is to store tailings and water required for clarification purposes and sometimes for process needs as well. This result in several differences compared to WRD, namely:

- The TSF (see 2 “Terminology”) can, theoretically or practically, not be removed due to the large amount of stored tailings. The purpose is to store the tailings in a safe way for a long period of time (in principle thousands of years). To achieve a long term stable structure, good closure plans are needed from the start. The long term aspect has during the last decade raised the question of closure to become one of the main tasks with regard to tailings dam design.
  Not many WRDs have been removed. However, theoretically they, and the stored water, can be removed if they are no longer adequate for use.
- Loading conditions: In TSF the deposited tailings often result in considerably less water depth within the impoundment compared to WRD. Therefore upstream slopes of tailings dams do not experience rapid drawdown and as a result the slope can often be steeper than those of conventional WRD counterparts, Vick (1990). The deposited tailings can also support the upstream slope of the dam depending on deposition technique and tailings properties. This may, as well, allow for a steeper upstream slope compared to a similar WRD. On the other hand, the load on the dam may increase if the fine graded and loosely deposited tailings liquefy. Liquefied tailings can have a density more than two to three times that of water (Bjelkevik and Knutsson, 2005b).
- Tailings often include different kind of metals from the ore and chemicals from the process. These can sometimes be toxic and if released into the environment in too high concentrations cause damage. The tailings dams, therefore, need to minimize the risk of such leakage of toxic substances during both operation and the long term phase. The TSF also need to minimize the risk of weathering in both a short and a long term perspective as weathering results in more toxic particles that have a potential to be released into the environment.

- WRD are normally founded on rock and grouting is often required, whereas tailings dams normally are founded on soil and do not require grouting. This is because the deposited tailings constitute an extensive and effective source of fine material for self sealing of cracks etc., Eurenius (2005).

4.4.2.2 Other differences

Conventional WRDs have a long history (thousands of years) compared to tailings dams (just over hundred years). The tailings dams were normally constructed and built by the mining companies, who did not always benefit from existing civil engineering knowledge, (Vick, 1999). Familiarity and knowledge about dam design has normally been better within the organisation operating a WRD than a tailings dam. For Swedish tailings dams, the responsibility of dams lies on the operator of the processing plant, whose main focus is on the processing of ore. In contrast, the responsibility for WRDs normally lies with the dam operator, whose main focus is on energy production and operation of the dam.

In cases when the tailings constitute the dam, or part of the dam, the characteristics of the tailings become important. However, it is not always easy to take samples for testing of the material properties, i.e. strength parameters, like friction angle etc.. Tailings are often relatively loose and water saturated and thus having low bearing capacity. This is because the tailing often is hydraulically deposited and not placed and compacted in the same manner as construction material for WRDs. The knowledge about tailings as a construction material is not as good as for natural materials, which often are used in WRDs. All these factors result in difficulties when it comes to how samples should be tested in order to give results that correspond to in-situ conditions. In-situ testing is also difficult to perform on tailings due to the limited knowledge about tailings as a material. All standard equipments for in-situ testing are calibrated for natural geological materials.

There are differences regarding the operation of WRD's and tailings dams considering the staff on site. A tailings dam is normally located close to the mine, which is manned at all times during operation and so are the tailings dams. This provides good conditions for regular and frequent visual inspections, assuming the staff has required skills and qualification. At some Swedish tailings dams visual inspections are carried out each shift, i.e. 3 times each 24-hour period. WRD, and especially hydropower dams in Sweden, are normally operated from a remote control centre hundred of kilometres away from the dam site, and a very small number of staff members often operate several dams from the same control room. Visual inspections normally take place once a week according to RIDAS (2002).

4.4.2.3 Other Similarities

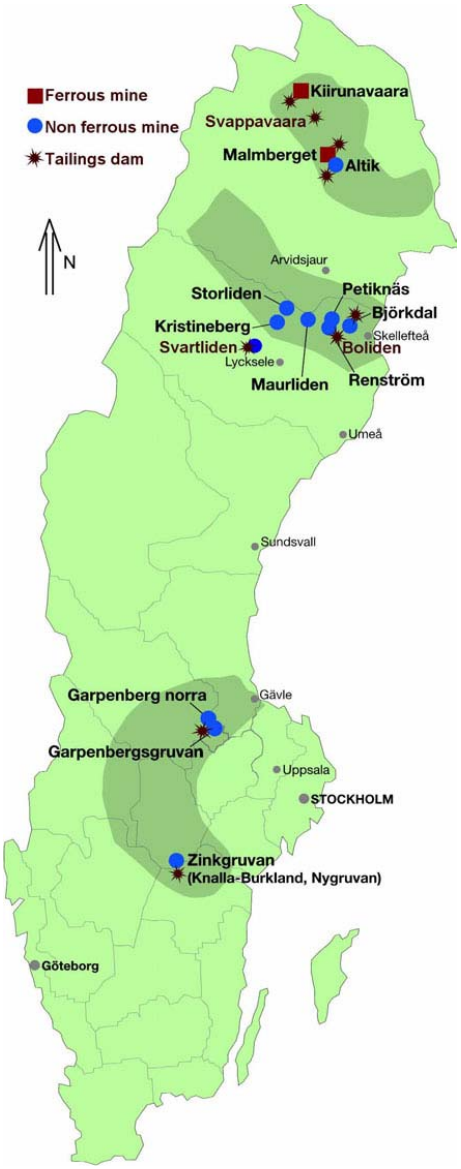
Tailings dams designed for wetland or water cover closure will be exposed to the same processes as WRDs. The hydraulic gradients within a tailings dam will in most cases, due to design and construction method be lower and some processes, such as internal erosion, may therefore take longer time than in a dam with a high hydraulic gradient.

However, the knowledge from WRD about, for example, internal erosion will be valuable for tailings dams as well.

Sedimentation and siltation of today's reservoirs (hydropower and water supply) will in the future produce dam safety issues having much in common with tailings dams, as they successively become permanent repositories for solid materials (Vick, 1999).

4.5 Swedish Tailings Dams

In 2005 nine tailings dams were in operation in Sweden, se Figure 8 and Table 3.



Mining activities date back to as early as the Viking era or the early Middle Ages in Sweden. Well known examples of old mining activities are the Falu copper mine, Sala silver mine and the Bersbo mine, all situated in the south mining district shown in Figure 8 (MiMi, 2004). Today the predominant Swedish mining activities are located to the two northern districts, with only three active mines in the south district.

Figure 8 Mines and tailings dams in operation in Sweden 2005. Figure modified from MiMi (2004).

Table 3 Some general data about Swedish tailings dams and tailings storage facilities 2005.

Name of TSF	Type of ore	Ore production [Mt/y]	Foot-print area [km^2]	Dam height* [m]
Kiruna	Fe (magnetite)	App. 22**	2.6	14
Svappavaara	Fe (magnetite)	(0,004 from Kiruna)	1.2	15
Malmberget	Fe (magnetite, hematite)	13.5**	1.8	35
Aitik	Cu, Au, Ag	18	12.0	50
Boliden	Zn, Cu, Pb, Au, Ag	1.6	2.5	13
Garpenberg	Zn, Ag, Pb, Cu, Au	Just above 1.0	0.5	19
Zinkgruvan	Zn, Pb, Ag	0.8-0.85	0.6	27
Björkdal	Au	1.2	1.5	25
Svartliden	Au, Ag	0.3	0.3	14

** Largest dam height at the tailings storage facility.*
*** Crude ore.*

4.5.1 Design

In Sweden the development of construction methods for tailings dams have developed from the basic knowledge of WRD. During the 1960's to the 1980's most of Sweden's WRDs were constructed and the knowledge and experience gained from this time period were used for tailings dams as well. This has resulted in tailings dams primarily being constructed as staged earth fill dams with designs similar to WRDs, i.e. downstream, or centreline, tailings dams with a core (of moraine), filter and support fill. The choice of construction material was probably influenced by the fact that there was good access to suitable moraine at all tailings dam sites.

Around 1990 international experience changed some designs, from zoned earth fill dams to upstream constructions using moraine only for the dikes and tailings for the rest of the dam construction (VBB, 1992 and TR, 1992). The importance of controlling the hydraulic gradient, and hence the seepage, have not always been completely understood, but experience and improved knowledge have improved design and operation. Examples of cross sections from Swedish tailings dams are shown in Figure 9-11.

Figure 9 shows a cross section where the first four raises were according to the downstream method and construction material (both core and support fill) was moraine. This was due to this part of the impoundment originally being used as water storage with water up against the face of the dam. Thereafter the method was changed to the upstream method, using moraine for raising the dykes five times and cycloned tailings placed upstream the dyke. When this change in method was carried out a new clarification pond was constructed downstream the dam. During this phase buttress support of waste rock were placed downstream the dam in several stages, finally covering the whole downstream section of the dam. The last three raises were carried out by bringing tailings by trucks from the upstream part of the impoundment, where the tailings had the same particle distribution curve as the cycloned tailings, and put it

in place using earth moving equipment. From there on tailings is spigotted along the whole crest of the dam and raises are carried out by moving tailings up from the beach.

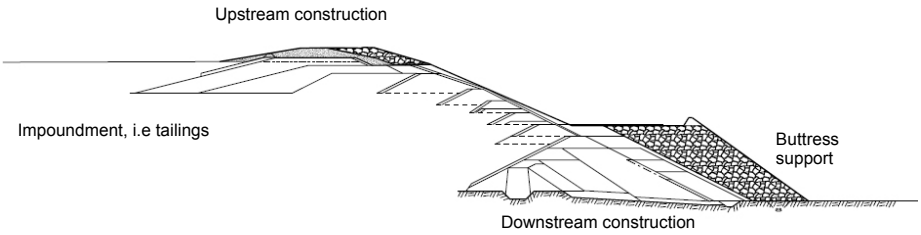


Figure 9 Cross section of dam G-H at Aitik tailings dam in Gällivare from 2004.

Figure 10 shows a cross section of a staged moraine dam, where raises have been carried out according to the upstream method. This dam has had a relatively long beach until 2001 when the water level rose and as a result a high hydraulic gradient developed. As a consequence the dam was raised according to the downstream method including three layers of filters and drainage and necessary support fill.

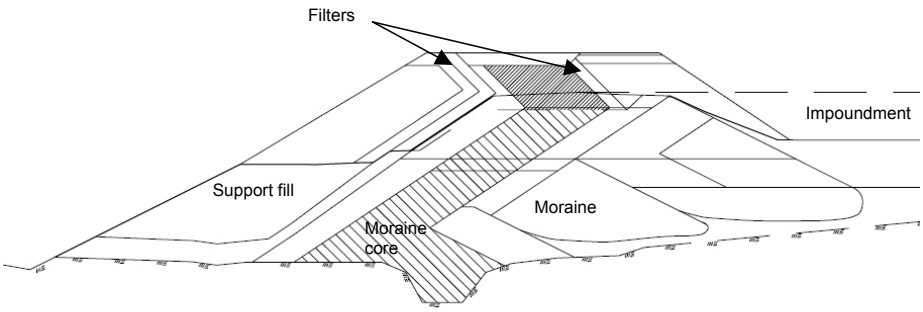


Figure 10 Cross section of dam A-C at Svappavaara tailings dam south of Kiruna from 2004. (Impoundment at the right side of the dam)

Figure 11 shows a cross section of a tailings dam with a moraine core and support fill of waste rock. Tailings deposition is carried out more or less under water moving the delivery pipe around in the impoundment on temporary waste rock dykes. Initially the dam was a downstream construction, but to save material the method was changed to centreline construction with a vertical moraine core. Thereafter three raises have been carried out using the upstream method. To get support for the inclined core waste rock was placed on the tailings upstream the core, which reduced the benefit of having tailings upstream and maximise the load on the core section. Due to dust problems on the beach, the water level has at several occasions been raised, resulting in sinkholes in the dam. To get around the problem, a dyke of waste rock has been constructed 30 m

upstream of the crest of the dam. The area in-between is then filled up with tailings, which will relatively quickly drain and then dust preventative actions can be taken here, while the tailings is deposited within the impoundment. In this way there will always be a beach at least 30 m wide.

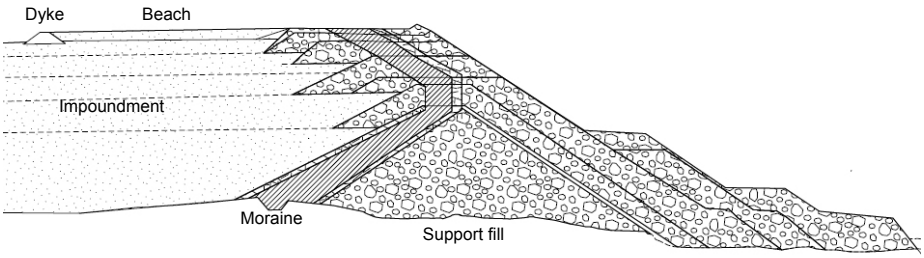


Figure 11 Cross section of dam X-Y at Enemossen tailings dam in Zinkgruvan from 2004.

4.5.2 Incidents and Failures

Events like failures, incidents and event driven maintenance occurring at Swedish tailings dams have been presented by Bjelkevik (2005a and 2005c). Definitions of these terms are from Bjelkevik (2005c):

- *Tailings dam failure* is an event resulting in the tailings dam structure failing to retain what it is designed and constructed to retain, causing an emergency situation due to the spill of tailings and/or water.
  Consequences can be human, environmental, economical or cultural.
- *Incident* is an unexpected event that happens to a tailings dam that poses a threat to the overall dam safety and needs response quickly to avoid a likely dam failure.
- *Event driven maintenance* is an event that could have been expected, but is not included in the normal operation of the tailings dam and requires measures to be taken in order to prevent further development of the event and/or to lower the risk associated with the event.

In total 60 events were found from 1944 to 2004. The data is believed to be more or less complete covering the period from 1998, when all Swedish mining companies initiated dam safety programmes. Before that, several events are believed to be missing. However, the conclusions from Bjelkevik (2005a and 2005c) are, that Swedish mining companies have come to realise the value of documentation and accessibility of data to improve dam safety knowledge. As a result, the number of events (including failures, incidents and event driven maintenance) has decreased during the last 5-year period. The main causes of events at Swedish tailings dams are structural (malfunction, faults and/or deficiencies in design or construction) and internal erosion resulting in consequences like; slope instability, spill and leakage. About 55% of Swedish tailings dams are of the type staged conventional embankments

and the events at this dam type are related to structural aspects, internal erosion or ice and frost (cold climate), which represent about 20% each.

4.5.3 International Comparison

The design used for tailings dams in Sweden, similar to WRDs, has not only been used here, but also in other countries, like Canada and the U.S., in which there also are an easy access to suitable borrow materials like moraine. However, the general trend for tailings dam design internationally is the use of tailings as dam construction material. But as Vick (1990) points out, the regulatory requirements sometimes direct the design towards other methods, like the WRD, as the experience and familiarity lies with this type of embankments. The experience is less extensive for other embankment types (i.e. where tailings is used) even though they are equally well suited for tailings disposal.

The level of documentation and reporting of events in Sweden has improved a lot, in comparison to international statistics, see Bjelkevik (2005a) Figure 12 and 13. A reason for this can be that Sweden is a relatively small country with respect to mining. It takes more effort to collect data from a larger number of mines than the eight tailings dams in operation within Sweden, which are all included in Bjelkevik (2005a and 2005c).

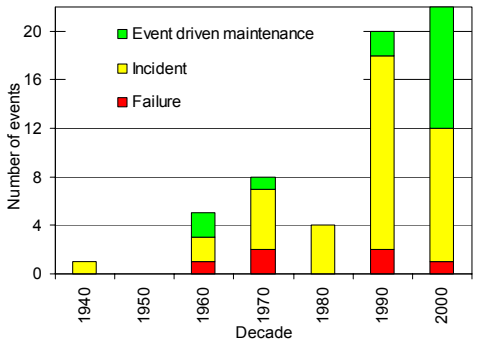


Figure 12 Number of failures, incidents and event driven maintenance per decade in Sweden. (Bjelkevik, 2005a).

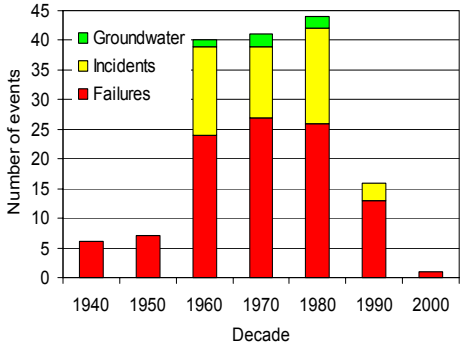


Figure 13 Number of failures, incidents and event driven maintenance per decade internationally. (ICOLD, 2001).

International statistics of failures and incidents have been compiled and analysed by ICOLD (2001). In total 221 cases are included, but none of the Swedish events. The conclusions from ICOLD's study are:

- that many factors influence the behaviour of tailings storage facilities
- accidents and other incidents are often the result of inadequate site investigation, design, construction, operation or monitoring of the facility
- a combination of the above two factors

Although our understanding of the behaviour of tailings dams has improved to the extent that they can be designed to perform adequately indicating that specific design features can be applied, tailings dams continue to fail. The ICOLD Tailings Committee makes the statement; "*technical knowledge exists to allow tailings dams to be designed, built and operated at low risk, but that accidents occur frequently because of lapses in the consistent application of expertise over the full life of a facility and because of lack of attention to details"*.

5 Risk and Safety

Risk is a combined measure of probability and severity of an adverse event, and is often the product of probability and consequence of an event. The main purpose of risk management is to provide support in decision-making. Society demands now, more than ever before, transparency in decision-making regarding safety issues and risk levels associated with dam safety. Hartford and Baecher (2004) define the corner stones of good dam safety practice as surveillance, periodic dam safety reviews, tested operation procedures, regular maintenance and emergency preparedness.

Two methods of risk analysis prevail; the qualitative and quantitative method. Qualitative analysis can be valuable although it stops short of quantitative risk estimation. Quantitative analysis have until now (2003), not been extensively used in dam safety practice, mainly because the profession has not known how to get meaningful and reliable estimates of the probability of an event occurring. For more details about risk assessment, see for example; Hartford and Baecher (2004) and ICOLD (2005).

The term *safety,* when applied to a remediated TSF, usually means public safety by governments, in particular with the objective of minimising the possibility of a post-operational dam failure. This may result in release of contaminants into the environment and potential loss of life. (Jewell et. al., 2002).

Vick (2001) discusses the term *portfolio risk* in relation to the choice of cover method. Portfolio risk is the risk that accrues collectively over some inventory of individual risks. It depends on their magnitudes, the size of the inventory and the duration of exposure period. The dry and water cover method differ markedly in these characteristics, which gives rise to substantial differences in their respective portfolio failure risks. Dry cover closure results in a dry deposit where the "exposure" period for dam failure is limited to the time of operation, resulting in a probability of large scale flow failure becoming relatively low as time of operation is short compared to time of closure. Whereas, the water cover closure result in an unlimited exposure period as the water cover remains in perpetuity giving a high portfolio risk. However, the physical stability need to be balanced against the chemical stability and in this respect the water cover method is more effective, which should offset its physical risks somewhat. The nature of this tradeoff depends on the conditions at hand.

6 Remediation by water cover

Remediation is defined in 2 “Terminology” as one part of the closure process of a TSF. The other parts included in closure are “decommission” and “after care”. All three are described below:

- *Decommission* constitutes the close down of operations and removal of unwanted infrastructure, buildings, pipelines, services etc.
- *Remediation* comprises the measures required to secure the long term stability and environmental safety of structures like tailings dams and impoundments left at site.
- *After care* is the time period required to verify that measures taken are according to design and expectations.

According to Worldbank/IFC (2002), a large number of mine closures are expected over the next decade, particularly in developing countries. A number of factors are contributing to this trend. First, following a surge in mining investments and privatisation in the 1960s, 1970s and 1980s, many of the large modern mines established during this period are now moving toward the end of their economic life time. Second, increased pressures on the commodity markets will leave room only for the most cost-effective producers, thereby leading to closure of less attractive operations. At the same time, fiscal pressures in poor countries are reducing direct and indirect subsidies to mining operations.

Experience of long term behaviour of tailings exists as several tailings storages from early mining activities can be found around the world. One example is the Falu copper mine in Sweden, the largest copper mine in the world during the 17th and 18th century (Kopparberget, 2005). The remains of tailings and waste from early operations still produces significant amount (i.e. amounts harmful for the environment) of acid mine drainage (AMD). Some of the dumps in the Falun area are even declared as historical monuments. Never the less, the remains from old mining activities emphasise the importance of remediation of today’s tailings dams and waste dumps in order to prevent negative environmental impact on the surrounding area after closure.

A fundamental goal of long term closure of tailings dams is to achieve “walk away” conditions that assure both physical and chemical stability without the need for long term monitoring, maintenance or repair, Vick (2001). Methods for remediation of tailings dams can, in general, be divided into two main categories, i.e. dry and wet covers, compare 6.3 “Methods for tailings dam remediation”. The latter method, wet covers, is normally divided into water covers and wetlands, of which both will be discussed in this report. Remediation of tailings dams requires a departure from conventional engineering thinking according to Caldwell (in Vick, 2001): *“From an engineering perspective, the design and construction of waste disposal facilities demands a philosophical mindset that is different from anything else in engineering. We design with nature, to avoid the effects of nature, for as long periods of time into the future as possible”*.

Water covers are generally regarded as one of the most cost effective methods for the mitigation of potentially acid-generating mine tailings. Among the benefits are low cost, low maintenance, no dust problems etc.. A major draw back involves the construction of dams and especially the long term stability of dams (MiMi, 2004).

Experience regarding the long term behaviour of dams surrounding the tailings is more limited. Relatively few tailings dams are older than 100 years, as the first documented tailings dams were taken in use around the beginning of the 1900s (see 4.2 "Historically"). Few remediated tailings dams are older than a few decades, i.e. most are still in the phase of after care. Our knowledge of the importance, the demand and the techniques of remediation and closure have successively increased. The experience of the long term (i.e. 1000 year, see 2 "Terminology") stability of tailings dams after closure is, however, still limited, as there is only a few decades since the first tailings dams were remediated. Developments in the field of remediation and closure are increasingly important and must continue. Therefore, closure and remediation will remain an important topic for many decades to come, as they are necessary if we don't want to leave environmental problems to future generations.

6.1 Environmental Impact

A broad definition of adverse environmental impact as it arises from TSF is: *"any negative impacts on man, animals, plants and their habitat caused by the disposal and dissemination of mine or industrial waste"*, (ICOLD, 1996a).

To achieve environmentally acceptable solutions for closure of TSFs, environmental aspects have to be considered and negative impacts minimised. The goal of closure is to:

- mitigation of risks to human health and safety, without limiting access to the remediated area
- protect the long term conditions of the environment
- protect the quality of natural ecosystems in a long term perspective.

The Swedish research programme MiMi (2004) defines some fundamental demands needed to be fulfilled for feasible remediation of tailings dams, irrespective of remediation method:

- Very long functional life-time
- Passive methods must be applied, i.e. methods not requiring maintenance
- Only robust and stable constructions in the long term perspective
- The longevity needs to be demonstrated beforehand in a robust scientific way
- The relevant time-scale is hundreds to thousands of years
- Ecological integration is necessary, including lessons from nature

Comments on the demands described above include that it is not obvious:

a) how to demonstrate the longevity in a robust scientific way
b) how to integrate remediation with the ecology of the surrounding environment, as we do not know what the environment will look like in 1000 years from now. What plant species and animals will be present? Two examples may be given here; i.e. that the mink and muskrat did not exist in Sweden 1000 years ago.

On the workshop "Long-term Stability of Remediation Measures" in Freiberg in Germany in 2002 (Freiberg, 2002) some general aspects of closure and remediation were emphasised as well. Firstly, the magnitude of the "problem" was found to depend of the volume of tailings to a large extent,. This will affect decisions like:

- relocate or not
- amount of required funding
- risk reduction options

Secondly, several steps that need to be considered during the closure process were identified and some of them are listed below:

1. Defining the terms related to closure and *communicate* these to regulators and stakeholders to minimise misunderstandings.
2. Comprehensive site *characterisation* of the geological, hydrogeological, hydrological and climatological environment is important. As well as to include possible extreme climatic events.
3. The concept of *risk-based* design should be introduced more widely.
4. *Monitoring* during the long term phase seems difficult, however, modern society seems to continuously "monitor" the surrounding environment and take remedial actions when needed.
5. The *reliability of records* beyond a few hundreds or thousands of years may be questionable. Survival of archives is often accidental.
6. As we do not know the *requirements of future generations* it may be difficult to establish long term management strategies. Public acceptability of risk also changes over time.
7. Study of *natural analogues* can assist in designing for long term disposal stability.

The author believes that most mining companies, authorities and jurisdictions will agree on the seven items above. All are steps to be considered as "requirements" in accordance with general aims regarding most phases of not just tailings dams and mining operations, but almost all activities affecting its surroundings in some way or another. Therefore the items above, except number, can be accepted without further discussion. The exclusion is, item number 4, regarding long term monitoring cannot, in the opinion of the author, be accepted long term monitoring must not be requirement. We cannot rely on society taking a long term responsibility for taking readings or carrying out maintenance, as we do not know what the society will look like in the future. Closure also has to allow for people to use the remediated area, as fences or similar structures, will not last in the long term perspective. On the other hand no remediation will allow people to do just anything on a remediated site. For example

improper land use like excavation of remediated dams or cover structures must be prohibited. In that sense, the use of remediated land has to be restricted, requiring some kind of society long term responsibility. This is a contradiction to "we cannot rely on society taking long term responsibility", which shows how complex this question is. A final solution to this "problem" will not be found or presented in this report.

Finally, to achieve an environmentally accepted closure of a TSF there should, if possible, be redundancy in the closure system to increase "warning time" of potential hazards as well.

6.2 Long term Containment of Tailings

The meaning of long term containment of tailings is that the tailings dam should be designed and constructed to prevent the release of harmful or toxic material into the environment. Water seeping from the TSF, which may have a harmful effect on the environment, is of major concern. This applies particularly when the tailings contain toxic elements of a certain concentration. Examples of toxic elements are:

- arsenic
- heavy metals
- acid generating elements (causing AMD)
- cyanide from the process
- radioactivity (i.e. from uranium tailings)

All these have a potential of leaching into the environment, and especially the groundwater systems, if not properly dealt with.

Chemical pollution associated with tailings is an extensive subject, that have been investigated by MiMi (2004) and others, which will not be discussed in detail here. However, four basic approaches can be taken to reduce the environmental impact to an acceptable level at the remediation of a TSF. These are to (MEND Manual, 2001 and Parker and Robertson, 1999):

- eliminate or reduce the oxygen flux through the tailings when sulphide minerals are present,
- prevent or reduce the amount of water passing through the structure which can act as a transport or leaching medium,
- eliminate the transport of tailings into the environment by wind and water erosion, and
- treat liquid seeping out of the structure to remove pollutants before the water is released into the surrounding environment, for example by active barriers or wetlands

Active treatment of seepage emanating from the TSF is normally only undertaken during a transition phase or when more passive techniques have been unsuccessful in reducing pollution to acceptable levels. Many environmental regulators, in for example Sweden, would not consider a TSF requiring active treatment to be closed. Therefore,

they will not be described any further in this report. However, in Appendix A, some references on both active barriers and wetlands are given.

6.2.1 Control of Acid Mine Drainage (AMD)

Oxidation of sulphides in tailings impoundments and seepage of acidic water, metals and heavy metals into the environment is one of the main issues to deal with both during operation and remediation. Mine deposits from the Romans are still producing AMD, which shows the potential magnitude of the problem, Vick (1999). The problem could be expected to increase dramatically with the increase in mining activity unless remedial procedures are implemented.

The development and control of acid mine drainage has been extensively investigated by the Mine Environmental Neutral Drainage Program, MEND, through a partnership between the Canadian mining industry and the Government of Canada and several Canadian Provincial Governments. The MEND Manual (2001) is an excellent source of information about AMD.

Other sources are the main report (MiMi, 2004) and separate reports (for example Berglund et.al., 2003) produced within the Swedish research programme "Mitigation of the environmental impact from mining waste" (MiMi). This programme has studied the processes in deposits of mine tailings containing sulphide to understand the chemical and transport processes. The aim has been to understand the chemical and transport processes sufficiently well to design methods that will hinder unacceptable releases of acidity, toxic metals and other substances to the environment. Soil and water cover design have been studied with focus on the performance of the cover itself. It should be stressed that no studies of the surrounding dam structures have been undertaken.

6.2.2 Control of Cyanide

Cyanide is very toxic, but normally in a relatively short term perspective due to its chemical instability. However, it can form long term stable compounds, e.g. copper cyanate. This can be a long term ongoing problem. Evaluation of the long term effects is therefore required, but this will not be considered in this report.

Guidelines and restrictions for handling cyanide exist, e.g. Environment Australia (1998), ICME (1999) and ICMI (2002).

6.2.3 Control of Radioactivity

Radioactivity is harmful to the environment. Its long half-life of thousands of years, depending on the radioactive material, makes it important to deal with. Radioactivity may be spread by erosion of tailings particles, seepage of dissolved radioactive material in water and by release of radon gas. This is a special and extensive field of research, which will not be covered by this report.

6.2.4 Other safety concerns

Other safety concerns include the possibility of improper land use in the future. On one hand, people must have full access to remediated land as it is difficult to prohibit intrusion as fences or similar structures will not last in a long term perspective. On the other hand, no remediation will allow people to do just anything, like excavation of remediated dams or cover structures. This results in a contradiction where we cannot rely on society taking a long term responsibility, but we need restrictions regarding improper land use in a long term perspective. A final solution to this "problem" will not be found within the scope of this report.

6.3 Methods for tailings dam remediation

TSFs are site specific and there is a high degree of variability between dams and even within different areas in one TSF. These differences are caused by variations in ore types and geochemistry, the process used for ore extraction, the quality of process water, reagents used in the process, the disposal technique and the environment in which the TSF is situated. A wide range of closure methods is available for TSFs.

The first stage in selecting type of remediation method is to consider site-specific aspects such as number of people in the nearby area, topography, climate, geochemistry and the wanted end land use. Other factors such as the chemistry of the tailings and reagents deposited in the tailings impoundment will also influence the type of remediation method selected for closure.

There are two main categories of covers; dry and wet covers. These can be divided into five generic types of cover, see Table 4, each of which has its own advantages and disadvantages (Wels and O'Kane, 2002, Wels et. al., 2001 and MMSD, 2002b).

Table 4 Different types of cover methods for TSF.

Dry Covers	Wet Covers
Low hydraulic conductivity cover	Water cover
Capillary barrier cover	Wetland cover
Store and release cover	

A slightly different grouping and classification is made by MiMi (2004) in Table 5.

Table 5 Cover types and their primary function (MiMi, 2004).

Cover type	Example of cover material	Primary function
1. Oxygen diffusion barriers (soil covers)	Soil, till	To limit the transport of oxygen by acting as a barrier against the diffusion of oxygen to the waste.
2. Capillary barriers	Gravel	To prevent the transport of water into a deposit.
3. Oxygen consuming barriers	Sludge, peat	To limit the transport of oxygen by consumption of oxygen which penetrates into the cover.
4. Low permeability barriers	Clay	To limit the transport of oxygen and the formation of leachate by acting as a barrier against the diffusion of oxygen, as well as against the infiltration of precipitation.
5. Reaction inhibiting barriers	Phosphate, bactericides	To provide a favourable environment to limit reactions rates and metal release.
6. Water covers	Water	To limit the transport of oxygen by acting as a barrier against the diffusion of oxygen to the waste. Oxygen concentration in waste is limited by its solubility in water.

The conditions for new and existing TSF differ with respect to the level of closure planning, that existed during design and construction. It may therefore not be technical and/or economical feasible to achieve the same final result for an existing TSF compared to a new at closure. To make sure serious problems are not imposed on future generations, the approach for tailings dam remediation must, however for all TSFs, be to use and apply the best method applicable for each site at each time in order to create a long term stable solution. A closure plan will most probably change with time for a new TSF as well, due to improved and gained knowledge.

The document, European Commission (2004), section 4.2.4, covers the "Closure and after-care phase". The author does not, however, agree to all aspects presented in this document. There are four main points for disagreement and they are listed and discussed below:

- Under the heading *"Long term stable slopes of dams designed to permanently retain water"* (page 333), filters and seepage are discussed giving the impression that *"vertical filters" "between the low permeable core and the support fill"* are allowed in a long term stable dam. The opinion of the author is that the performance of filters in a long term perspective is questionable due to the risk of filters getting blocked.

- Under the heading *"Overtopping"* (page 333), it is said *"the discharge capacity is usually 2.5 times the highest flow measured at any point"*. Without any criteria for the time span required for determination of the *"highest flow measured"*. This does not agree with the criteria used for operation in Sweden. The discharge capacity for a high risk dam must correspond to the one in a hundred year flood (i.e. the maximum flood that will occur in a 100 year period) and the facility, or the freeboard, need to be able to manage the flood of a return period of one in approximately 10 000 year. To say *"2.5 times the highest flow measured"* seems, by the author, be too simple for designing long term capacity.
- Under the heading *"Instabilities"* (page 334), it is said *"a safety factor of 1.5 is often considered to give sufficiently low long term probability for instabilities in the underground, the foundation and within the dam"*. In Sweden a factor of safety (FS) of 1.5 is required for total stability against slip surfaces during operation (RIDAS, 2002). This will therefore result in no difference in requirements between the operational and long term phase in Sweden. The author believes that it is too simple to prescribe just a FS for the long term stability. Calculated stability, and long term stability, depends on loading condition, geometry, insecurity in material properties, groundwater location and calculation method. The factor of safety should therefore be chosen with respect to all these factors.
- Under the heading *"Slow deterioration actions"* (page 334), it is said "*it is possible to avoid/prevent inner erosion if the inclination of the hydraulic gradient is as low as in natural soil formations that are stable against groundwater flow. Generally, a soil slope is stable against internal erosion if the inclination of the hydraulic gradient is less than half of the friction angle of the soil material."* This discussion assumes that the tailings dam is constructed of natural materials, like fore example moraine. It also assumes a FS equal to one and that the slope of the dam is of infinite length and parallel to the hydraulic gradient, i.e. that the slope is 100% saturated. However, most tailings dams, and especially in an international perspective, are constructed of tailings, which is a crushed material, and therefore not directly comparable with natural analogies. It is also questionable if a FS of one is sufficient, which is assumed if the inclination of the hydraulic gradient is less than half the friction angle of the soil and the assumptions are fulfilled (i.e. infinite length and parallel to the hydraulic gradient). These assumptions are normally not fulfilled for tailings dams, and the FS equal to one is a contradiction to the point above as well.

Due to the examples described above the author find this document (European Commission, 2004) being too simple in many important aspects and should therefore not be paid too much attention to. Other references have therefore been used when possible.

6.3.1 Water Cover

Water covers are generally regarded as being one of the most cost effective methods for the mitigation of potentially acid-generating mine tailings, (MiMi, 2004). On the

other hand it is difficult to assess the long term safety and stability of the surrounding dams and the durability of the water cover. This is, above all, due to the limited knowledge about climate conditions and internal processes within the dam affecting the over all performance in a long term perspective. The most important factor is to maintain the water (i.e. the cover) at all times, even during extreme periods such as droughts (or winters) and floods. The cover must not dry or spill out. This requires a catchment area large enough to provide adequate inflow to maintain water balance and long term stable tailings dams to prevent the water from spilling out. At the same time the impoundment needs to be able to cope with storm events.

The most critical structural part in maintaining the cover, when using the water cover method, is the long term stability of the surrounding dams, see section 6.4 “Physical stability”. Pore pressures and the hydraulic gradient affect both the slope stability and the stability against internal erosion. It is therefore important to understand the development of pore pressures over time and the change of the hydraulic gradient within the dam, see section 6.4.1.1 “Hydraulic gradient and pore water pressure”.

Other aspects important for the longevity of the cover are wave actions and ice. Wave actions may create turbulence and thereby increase the oxygen concentration in the water or lead to resuspension of particles, which brings the particles up to the surface where they can oxidise. In this case the tailings surface have to be covered by a protection cover (SNV, 1993, SNV, 2002 and Peinerud, 2003). The water cover must not freeze at the bottom either, which can cause resuspension in the same way as for waves. This has to be considered for each specific case. Knutsson (1989) investigated this for the water cover remediation of Stekenjokk in Sweden. Due to these factors the water cover therefore needs to have a certain minimum depth.

If the tailings already have started to oxidise the water cover method might not be suitable, as the acid products and metals might be dissolved in the water and give unacceptable levels of metals in the water (SNV, 1993). The seepage water may then transport the harmful products and metals into the surrounding environment. In these situations other methods of remediation is necessary, for example dry covers.

The conditions for water cover closure in Sweden are generally good. Geology (hardly any seismic activity), topography (average, not too steep and not too flat landscape), climate (no typical dry or wet seasons), long term stable materials (moraine and crystalline rock) etc. result in favourable conditions for remediation by water cover, especially out of the mountain regions, Eurenius (2005). Experiences of the in general cold climate are problems with discharge facilities due to icing, but mostly that negative, or all, processes are delayed during the cold periods.

6.3.1.1 Water Balance

Natural geohydrological formations have in some areas of cold climate, been stable for a long time, i.e. thousands of years. In Sweden, for example, are there natural lakes dammed by natural formations created during the last glacial period. Long term stable man made structures are fewer, even though there are some (see 7.1 “Ancient

structures"). The design of water cover remediation should therefore aim at reproducing conditions of natural lakes, with a natural inflow of water and a natural outlet. The sustainability of the water cover is going to depend on adequate external catchment area. Both the minimum runoff and the maximum flood in a long term perspective must be taken into account. A situation, sometimes overlooked, is the condition of minimum flows during winter in cold climates where ice often accumulates in the outlet, resulting in increased risk for overtopping.

Important for water cover design is the outlet, which need to function at all times in a long term perspective. Outlets should therefore be located in natural ground and preferable in rock, which will reduce the risk of erosion damage. Only long term stable materials like crystalline rock should be used for construction. This excludes material like concrete, as this material has a design life of about 100-200 years, which is not enough in a long term perspective.

Small, shallow lakes have a tendency to silt up and fill up with plants and trees in a long term perspective. This process can be positive if the water cover is in place long enough to facilitate the development of a natural "sediment cover" on the tailings surface. The remediation by the water cover method will then naturally turn into a wetland cover and finally into a dry cover. This has to be considered in the design.

6.3.2 Examples of water cover

Some examples of water cover remediation are briefly described in this section. In Peinerud (2003), nine other examples are given where water cover has been used to reduce oxidation. AMD is for those examples described on an environmental basis rather than on the basis of long term dam stability.

6.3.2.1 Stekenjokk

Stekenjokk is the first Swedish TSF where water cover has been used as remediation method.

Stekenjokk mine is situated in the northern part of Sweden close to the Norwegian border in Västerbotten county, see Figure 14. Boliden AB mined zinc and copper from 1976 to 1988 and about 4.4 Mton pyrite tailings were deposited. The remediation was carried out during 1990-1991 and consisted of a 2.2 m deep water cover on top of the tailings. Within the impoundment a system of wave breakers were designed to prevent waves from causing resuspension of the tailings. (SNV, 2002).

In general, the remediation measures have been effective. The quantity of zinc in drainage water has been reduced by 90% com-pared to the situation during operation and a char population, see Figure 15, has moved into the impoundment. Char is a freshwater fish normally living in lakes in mountain regions. The Artic char is extremely sensitive to pollution of the water. Uncertainties about dam stability resulted in an inspection in 1998, which led to measures taken to stabilise the dam.

The long term dam stability is, however, still not verified. Authorities are therefore requiring external inspections at regular intervals. (SNV, 2002).

The measures taken after the 1998 inspection, consisted of placing filters and support fill on the downstream slope of the dams at strategic sections. A second outlet was constructed as well, to improve discharge capacity as there had been problems with icing in the existing outlet.

A comprehensive dam safety assessment of the dams was performed in 2003 (Sweco, 2005), which among other things concluded that there still are sections of the dams requiring filters and extended support fill before they can be considered to be stable.

Figure 14 Stekenjokk's location in Sweden.

The author is, however, not convince-ed that the remediation measures that are, and will be, taken at the dams will be enough for long term stability. The reason is manly due to the use of filters, as it is questionable if remediation should involve filters and/or drains at all, see section 6.4.3.3 "Internal erosion". As the Stekenjokk TSF still is in the after care phase, monitoring and evaluation of dam performance will continuously be carried out for approximately some decades.

Figure 15 Arctic char, Salvelinus alpinus in Latin. (http://www.jjphoto.dk/index.html)

6.3.2.2 Enåsen

At Enåsen, part of the TSF has been remediated by the water cover method. Data are collected from Boliden (2003) and Boliden (1999a).

Enåsen is situated in the middle of Sweden in Gävleborg county, less than 1 km from the border of Västernorrland county, see Figure 16. Boliden AB mined gold from 1984 to 1991 and about 1.1 Mm^3 tailings were deposited in the tailings dam. The remediation was carried out 1994 and consisted of a 2 m water cover on top of the tailings impoundment. In the north, i.e. the upper, part of the impoundment the dry cover method using moraine was used. The lower part, being approximately 60 000 m^2, which was used as clarification pond during operation, was covered with water, with a depth of approximately 2 m (or 100 000 m^3).

The clarification pond was a natural lake, Norra Grundvattssjön, with a natural water level at +398,0 masl[7] before deposition of tailings started. After remediation the water level was raised with 0.5 m. The dams surrounding the impoundment are low, between 3.7 to 4.2 m high. The outlet is situated at the abutment of one of the dams and excess water is diverted to Norrbäcken, which is a tributary to Enån. The required water depth is >1.5 m and is assumed to be preserved during normal as well as extreme years (drought or flood). During 2001, 2002 and 2003 lime have been added to the water covering the tailings to increase the pH-value.

Inspections are still carried out according to the OSM-manual (operation, supervision and maintenance manual), Boliden (2003).

Figure 16 Enåsens location in Sweden.

6.3.2.3 Kristineberg

At Kristineberg two parts of the TMF are about to be remediated by water cover. Data are collected from Boliden (1999b).

Kristineberg is situated in the northern part of Sweden in Västerbotten county at the border of Malå och Lycksele municipality, see Figure 17. Boliden AB has mined copper in the area since1940. In 1991 the plant was closed down and since then ore is transported to Boliden by truck. Four different TSF have been in use in Kristineberg. They are all situated in the same valley, with the first (No. 1) at the top of the valley and the others subsequently located after each other. Most of the tailings are remediated by using dry moraine covers. Two areas will, however, be remediated by the water cover method, resulting in two dams (dam 2 and 4). These have to be long term stable. Remediation work is ongoing.

Figure 17 Kristinebergs location in Sweden.

Dam No. 4 is the largest dam of the two dams. It also holds the largest water volume. The construction of the dam started in 1952 and is today about 20 m high. During operation stability problems were noticed. The documentation of the foundation of the dam is missing. However, at remediation the downstream face of the dam will be flatten out to a slope of 1V:3H and proper filters and drains will be put in place under the new support fill. The river, Vormbäcken, will be re-diverted into the impoundment of dam 4 to maintain the water level.

The author is not convinced that remediation measures at the dams are sufficient for long term stability due to the use of, and trust in, filters and/or drains. Readings from instruments and evaluations will continuously be carried out for approximately some decades.

[7] masl=meter above sea level

Kristineberg was selected as the common study site for the MiMi programme and more information and data can be found in MiMi (2004).

6.3.2.4 Falconbridge

The remediation of the "new" tailings area at Falconbridge is described by Hall (1999) and Beckett and Wilkinson (2000). Falconbridge is situated near Sudbury in the very south of Northern Ontario, Canada, see Figure 18. (Ontario is divided into 4 regions; Northern Ontario (green area), East & Central Ontario, Golden Horseshoe and South & West Ontario.)

Mining of nickel and copper at Falconbridge began in 1928 and continued until 1988. The "new" tailings area was built in a low-lying area and four dams surrounded the deposited tailings. 3.2 Mt was rich sulphide tailings, deposited between 1978 and 1984, and 1.1 Mt was low sulphide tailings, deposited between 1985 and 1988. Closure work commenced in 1996 with the construction of new dams and dredging to facilitate flooding of spring water. The spring water flows into the Upper Terrace and Lower Terrace, which occupy areas of approximately 560 000 m^2 and 300 000 m^2 respectively.

Tests showed that it was possible to establish wetland plants on the tailings and that the plants developed an organic layer which improved the effectiveness of the water cover (Beckett and Wilkinson, 2000). The conclusion by Hall (1999) is that the facility appears to be heading toward a walk-away closure scenario.

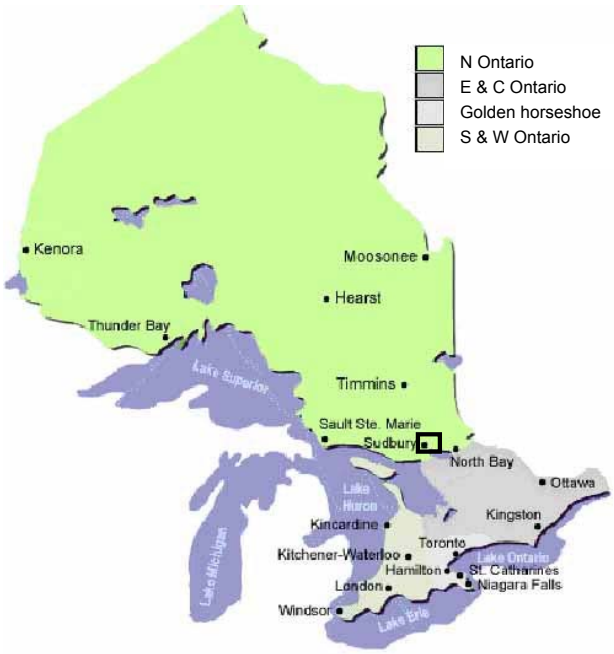


Figure 18 The location of Sudbury and the four regions of Ontario.

The hydrological design in a 200-year perspective can, according to the author, be questionable to use in order to calculate minimum water level at extreme drought. For flood calculations the probable maximum precipitation (PMP[8]) has, however, been used. Probable maximum flood (PMF) calculated from PMP, which is determined in a way similar to the determination of the Swedish "class 1 flow", which in turn corresponds to a return period of approximately 1 in 1000 or 1 in 10000 years.

6.3.3 Examples of lakes dammed by natural dams (i.e. soil formations)

There is little experience of ageing of dam structures when it comes to thousands of years. A comparison of natural analogies from the latest glacial period can then be useful in choosing the best closure design. Geological Survey of Sweden (SGU) has, in 2002, investigated natural lakes formed by soil formations and compared them to constructed dams (SGU, 2002). The main interest was focused on the mean hydraulic gradients in the formations creating the natural lakes. The examples presented below are selected from SGU (2002).

6.3.3.1 Ragundasjön

Ragundasjön was a 25 km long lake at Indalsälvens valley, see Figure 19. The depth in the lake varied between 6-10 m and the level was regulated at the Storforsen waterfall. The lake was formed about 6500 B.C. and had a mean water level at 139 masl.. In 1796 the lake was emptied due to an accidental break through of the natural dam. This was due to the construction of a channel through the damming soil layers in order to drive timber past the Storforsen waterfall, which otherwise broke the timber. The initiator, "Vildhussen", came up with the idea to let the water, by erosion, create the channel, which resulted in an uncontrolled course of events. In a few hours the lake was emptied and the final breach was 1 000 m wide and 60 m deep. The soil formations where the breach developed, consisted of sand mixed with silt and clay layers. After the failure the river came to follow the original routing from the time before the ice age. The natural dam between the lake and the downstream water level covered a distance of 1000 m horizontally and 40 m vertically, left from the ice age, had a hydraulic gradient of 4% (1V:25H). It was standing for over 8 000 years. If the construction of the channel in 1796 had not taken place, it would most certainly still have existed.

Figure 19 Ragundasjöns location in Sweden.

6.3.3.2 Skuttungesjön

Skuttungesjön was a lake in the Uppsala region, see Figure 20, with an area of 10 km^2 and just a few meters water depth. It existed from 1500 B.C. to 500 B.C.. Researchers believe that it was the climate changes at the end of the Bronze Age that raised the water level and caused the overtopping of the "dam", i.e the esker, at the south end of the lake. In this area the lake was dammed by a 10 m high and approximately 200 m wide natural dam formation. At the highest water level the gradient was about 5% (1V:20H).

6.3.3.3 Hennan

Hennan is a lake upstream lake Storsjön in the Ljusdal area in Gävleborgs county, see Figure 21. The difference in water level between the two lakes is approximately 22 m and the minimal horizontal distance about one kilometre (1 000 m). This results in a mean hydraulic gradient of 2% (1V:50H). From investigations, i.e. drilled holes, four

kilometres from this place 47 m of soil layers were found on top of the bedrock. The ridge between the two lakes probably developed by sedimentation of glacial soils against a sill of moraine and hard compacted glacial soils from an earlier glacial period. This has resulted in the ridge being similar to a moraine dam covered by glacial soil.

6.3.3.4 Styggtjärn

The lake Styggtjärn in Funäsdalen in Jämtlands county, see Figure 22, with an elevation of 779.6 masl is dammed against lake Käringsjön, elevation 777.5 masl, i.e. a difference in height of 2.1 m. The natural dam is formed by a moraine plateau, 100 wide at the most narrow section. This result in a mean hydraulic gradient of 2% (1V:50H).

Figure 20 Skuttungesjöns location in Sweden.

Figure 21 Hennans location in Sweden.

Figure 22 Styggtjärns location in Sweden.

6.3.3.5 Summary

These four examples, summarised in Table 6 below, show that natural formations have dammed water for, in some cases, several thousands of years. To be able to use this data in a specific remediation design, the examples need to be more thoroughly investigated with regard to the true hydraulic gradient variation. They also have to be investigated with regard to "dam design", i.e. how the natural formations are formed and what material they consist of. Due to natural variations in properties, the gradient may vary within the formation, resulting in local values of the gradient probably being steeper than the mean, which is presented in this study. Also, material properties of the natural soils/materials within the formation need to be clarified. In order to find criteria for long term stability, the material properties have to be put in comparison with the acting hydraulic gradients in the structures. Normally materials in natural formations are not structured in the same way as the material in a tailings dam, especially if the tailings dam is a zoned dam with a core, filters, drainage and support fill of different materials. Therefore are investigations and studies of these natural formations necessary before they can be related to tailings dam long term stability.

Table 6 Summary of mean hydraulic gradients for natural dams.

Object	Difference in height, Δh [m]	Length, l [m]	Mean gradient, (V:H)
Ragundasjön	40	1000	1:25
Skuttungesjön	10	200	1:20
Hennan	22	1000	1:50
Styggtjärn	2,1	100	1:50

What is said above, leads the author to the hypothesis, that it should be possible to design and construct long term stable dams that can be left unattended. The "real", or "true", geotechnical and hydrological behaviour of natural formations just need to be copied for the remediation of tailings dams surrounding a water covered impoundment.

6.3.4 Wetland method

Creating a wetland on the tailings impoundment is a relatively new method to prevent oxidation and AMD. The opinion exists that the effectiveness of the water cover method can be improved through the establishment of wetland vegetation on the flooded tailings, see e.g. MiMi (2004) and Wilkinson et.al. (1999). The vegetation will control tailings resuspension, remove metals from the water column and develop an organic layer to consume oxygen and support sulphate reducing bacteria (Wilkinson et.al., 1999). Some more references in the field of wetland covers are found in Appendix A. It should be emphasized that dam stability is not dealt with in these references.

Jacob and Otte (2004) have investigated a tailings pond, which has been abandoned for about 90 years. Wetland plants have naturally colonized the flooded Pb-Zn tailings pond at Glendalough, Ireland. The pond could be divided into four zones with varying conditions regarding flooding, vegetation and organic matter. This allowed for comparison of the effects resulting from the differences. It was expected that either water cover or high organic matter would result in enhanced reducing conditions and thus lower metal mobility. However, living plants would increase metal mobility due to root radial oxygen loss. The conclusions were that (1) the mobility of As and Fe decreased in the shallow/intermittently flooded zone, (2) accumulation of organic matter caused retention of Zn but not Fe and As and (3) the presence of living roots reversed these reducing conditions in the root zone enough to either limit the formation or reverse the accumulation of organic matter. Jacob and Otte (2004) emphasize that the conditions seen are not in a steady state condition and they could relatively easily be altered due to changes in climate, for example drought or changed water levels, temperature etc..

Regarding the long term stability of the dams surrounding the flooded impoundment the principles are the same as for water cover. However, as the volume of free water is

limited, the consequences if the dam fails are greatly reduced as there is no water to cause a flood. The risk from having the dams overtopped is reduced as well, as the impoundment does not require the same amount of water coming in, a smaller catchment area is required, which makes the impoundment less sensitive to a storm event. Except for that, the surrounding dams are still exposed to a hydraulic gradient and a water pressure similar to that from a volume of free water and therefore the long term stability needs to be verified in the same way as for dams surrounding a water covered impoundment.

The wetland method requires an outlet in the same way as the water cover method. However, for the wetland method the design flow will be much smaller and discharge will not occur continuously.

One potential drawback is the fact that water-growing plants actually transport oxygen to their roots. However, if the organic decay exceeds the rate of transport to the roots the establishment of a wetland cover might be beneficial to the remediation performance (MiMi, 2004). With time, the organic layer will increase in thickness and in that way improve the protection against oxygen intrusion.

Wetlands are also created downstream of TSFs to retain metals and neutralize acid mine drainage (AMD) draining from a facility. This will, however, not be discussed any further here as this application does not involve the TSF itself, but the downstream area.

6.4 Physical stability

To achieve an environmental safe remediation of a TSF, where the tailings material will be contained safely, the requirements for physical dam stability need to be fulfilled in a long term perspective. The conditions for physical stability include stability against:

- slope failure, including settlements etc.
- extreme events (seismic and climatic)
- slow deterioration processes

6.4.1 Slope stability

According to Blight and Amponsah-Da Costa (1999) it is becoming common, in some countries, to require that the remediation of a tailings dam be designed to be maintenance-free for 1000 years. This may, in many areas, seem to be unrealistic, as climatic factors have changed the landscape dramatically in just the last 100 years. For example in areas sensitive to wind erosion (sand dunes) and water erosion (thunderstorm and monsoon areas) erosion may change the landscape fast. On the other hand, there are ancient man-made mounds in many parts of the world with slopes that have resisted 1000 or more years of erosion and still exist in good condition (Blight and Amponsah-Da Costa, 1999), see section 7.1 “Ancient structures”. It is

therefore, in the opinion of the author, possible to design a slope being stable in a 1000-year perspective.

Slope instability, or failure, is caused by one of, or a combination of:

- slip surfaces
- external erosion causing progressing slip surfaces
- internal erosion causing sinkholes or collapse of the dam

The erosion processes will be covered under section 6.4.3 “Slow deterioration processes”.

Factors influencing the slope stability with regard to slip surfaces are:

- the geometry of the dam (e.g. slope angle and beach, i.e. length of drainage path, see Figure 23)
- dam construction performance
- the pore water pressures (hydraulic gradient)
- material properties (hydraulic conductivity, friction angle, cohesion and density etc.)
- stress conditions
- rapid changes in water levels (more important for WRD)

These factors affect each other, and it is therefore important to understand the relationship between each of them. For example, if the beach width is reduced, i.e. the geometry is changed, it will affect the pore pressures and the hydraulic gradient, which in turn change the stress conditions and the conditions for internal erosion respectively. Another example is if the real hydraulic conductivity does not correspond with the design value, a different hydraulic gradient compared to the assumed will then be present, which may demand different geometry, for example a flatter downstream slope.

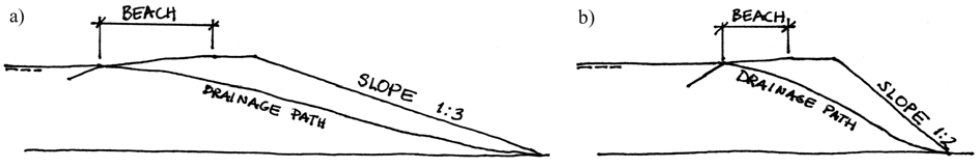


Figure 23 Drainage paths for a dam with a) flat slope and long beach and b) steep slope and short beach.

Tailings dams and their foundations need to be stable, i.e. they must not fail. Often stability is determined in form of a factor of safety (FS). This FS is defined as the relationship between the mean shear strength along a proposed slip surface and the corresponding mobilised shear stress. Theoretically a dam is stable if the FS>1, and dam is expected to fail if the FS<1. There will be a statistical spread of the results as there are uncertainties in calculations and in determination of input data. This means that there still is a probability that a dam may fail even though the FS>1. Therefore,

satisfactory stability actually means a probability against failure low enough, compare *Figure 24*. It is then understandable that improved investigations, reliable loading conditions and suitable calculation methods can improve the reliability of the result and the required FS can therefore be lower, compare curve B in Figure 25, without increasing the probability against failure. (Commission on slope stability, 1995 and 1996).

Stability of dams during operation is well known and described in literature, see Lamb and Whitman (1979), Vick (1990) and others. A FS of 1.5 is often determined to be enough for normal conditions during operation according to documents like RIDAS (2002) and other guidelines. The criteria for long term stability are, however, difficult to determine as the uncertainty of material properties, loading conditions etc. increase. Today there are no known, or formulated, criteria for long term stability of remediated tailings dams, except for in European Commission (2004). This document presents a criterion where a FS of 1.5 is said to be sufficient considering "long term probability for instabilities in the underground, the foundation and within the dam". With respect to what has been said and shown above (*Figure 24* and Figure 25) this criterion seems to be questionable and too simple without defining criteria for loading conditions, security in determination of long term material properties, choice of calculation method, acceptable simplification etc..

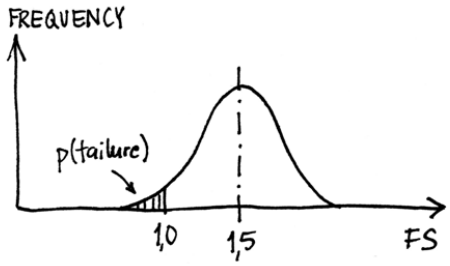


Figure 24 *Statistical spread for an example with a factor of safety of 1.5 and the corresponding probability of failure. Derived from Commission on slope stability (1996).*

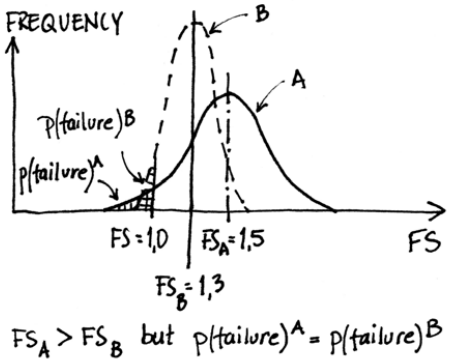


Figure 25 *Statistical spread for two examples with a factor of safety (FS) of 1.5 and 1.3 respectively, but with the same probability for failure. The lower FS is associated with more thorough investigations, which gives a more accurate result that allows for a lower FS. Derived from Commission on slope stability (1996).*

In Sweden Equation 1 has been used in order to determine the long term stability of slopes of remediated tailing dams. This equation is presented in the literature, for example by Tell W. et. al. (1961), Lamb and Whitman (1979) and others. The equation takes the effect of pore water pressures and seepage into account and is valid for homogenous, infinite slopes of friction material with a ground water flow parallel to the slope surface. These conditions may be reached in the lower portions of natural slopes, as shown in Figure 26. For tailings dams, all requirements for this equation are normally not fulfilled. The slope is not of infinite length and the seepage flow (i.e. the hydraulic gradient) is not parallel to the slope surface. How these differences affect the result is, however, not analysed in this report or elsewhere. This may make the equation questionable to use.

However, the conditions for tailings dams are normally on the "safe side". The dam construction material is nearly homogenous as long as the dam is constructed of tailings. The material may, however, become coarser in the downstream direction due to the segregation of fine and coarse particles during sedimentation. The slope is not of infinite length, but tailings dams normally have dam crests hundreds of meters long. The length of the slope (S in Figure 26) is however normally short due to the fact that tailings dams normally do not have any seepage points. The reason there are no seepage points are that the ground water flow (or hydraulic gradient) normally is lower then parallel to the slope surface, which is on the "safe side". Equation 1 is therefore believed to be the best design tool we have today, even though we do not know how much on the "safe side" we are.

$$FS = \frac{\gamma'}{1+\gamma'} \cdot \frac{\tan\phi'}{\tan\beta} \qquad \textit{Equation 1}$$

Where: FS=factor of safety
ϕ'=friction angle of material
β=slope angle
$\gamma' = \gamma_{sat} - \gamma_w$ = saturated unit weight - unit weight of water

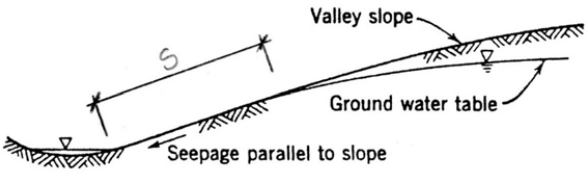


Figure 26 Seepage in a natural slope. (Lamb and Whitman, 1979)

Two examples are given below in order to exemplify the use of eq 1. The slope angles for a typical moraine and typical tailings material has been used together with both the FS=1.5 and FS=1.0.

1. material (tailings) with a friction angle (ϕ') of 25º,
   saturated unit weight (γ_{sat}) of approximate 2.1 t/m^3,
   unit weight of water (γ_w) of 1.0 t/m^3 and
   no cover (i.e. erosion protection etc.)
   In order to achieve a FS=1.5 the outer slope need to have a slope angle of in maximum 9º (1V:6H), and
   in order to achieve a FS=1 the outer slope need to have a slope angle of in maximum 13º (1V:4H).
2. a material (moraine) with a friction angle (ϕ') of 35º and
   the same saturated unit weight and FS as above
   will need an outer slope of about 13º (1V:4H) to achieve a FS=1.5, and
   20º (1V: 3H) to achieve a FS=1.

The choice of the required FS, probability of failure, calculation method etc. for long term design has to be analysed for each case and each loading condition. The author believes that one of the most difficult parts in designing a long term stable slope will be to cover all possible long term situations (loading conditions), including climate changes.

Another factor to consider is the risk of seepage points. Aronsson and Björk (2004) showed that the critical point for the risk of external erosion on a slope, is not the seepage point itself, but the face and the toe of the slope below the seepage point. This is because the total accumulated flow of seepage water and additionally precipitation may cause erosion, starting at the toe of the dam. The maximum water flow a tailings material at a specific slope angle can take, i.e. the capacity against external water erosion, is therefore interesting as well as proper erosion protection on the face of slopes.

More research and experience with regard to the validity of using Equation 1 will be required before this can become an official design criterion.

6.4.1.1 Hydraulic gradient and pore water pressure

Within a dam, or tailings dam, a hydraulic gradient develops when there is a difference in water level upstream and downstream the dam. For a dam with given geometry and of a material with a specific hydraulic conductivity the velocity (or flow) of the seepage water will increase with increased difference in water level, i.e. with increasing hydraulic gradient, according to Darcy's law (Vick, 1990):

$$Q = K \cdot i \cdot A \quad \text{or} \quad v = K \cdot i \qquad \textit{Equation 2}$$

Where: Q=flow of liquid (m^3/s)
K=hydraulic conductivity (m/s)
i=hydraulic gradient
v=velocity (m/s)
A=sectional seepage area (m^2)

Positive pore water pressures develop as soon as a material becomes saturated. If there is a difference in water level, as normally is the case for a dam, a hydraulic gradient develops as well, and gives rise to seepage flow trough the dam. Seepage is water (or fluid) flowing through the dam material. At a flow rate high enough, the force on the material will start to move fine particles. When particles start to move the process of internal erosion is initiated, see section 6.4.3.3 “Internal erosion”. Pore water pressures (u) affect the stress (σ) condition within the dam as the effective stress is ($\sigma'=\sigma-u$). The pore water pressure therefore has a direct effect on the stability of the dam, see section 6.4.1 “Slope stability”. The maximum hydraulic gradient a material or a slope can resist without internal erosion or slope failure, depend mainly on the properties of the material and the inclination of the slope.

Remediation becomes important already at the planning stage, as the choice of dam design affects the conditions for the hydraulic gradient. For example, a tailings dam designed as a conventional embankment with a low permeable core, raised in stages according to the downstream method (common in Sweden), will have a high hydraulic gradient over the core during operation. This design therefore demands filters and drainage downstream the core to prevent internal erosion. To lower the hydraulic gradient in order to achieve a lower stress on the material in the long term phase, measures to allow the dam to function without filters and drainage will be needed during remediation. An example of measure is to extend the beach to increase the distance between the free water and the downstream toe in order to achieve a longer seepage distance. A second example of dam construction is a tailings dam constructed of tailings material according to the upstream method. This dam type will, on the other hand, have a lower hydraulic gradient due to the higher hydraulic conductivity of the construction material and due to the beach required upstream. It will for this dam type be easier to lower the hydraulic gradient during remediation, which can be achieved by, for example, lowering the water level or extending the beach with. Even though tailings dams normally have a shallow water depth, a small decrease in water level will result in a large increase in beach width, as the inclination of the beach is very flat.

6.4.1.2 Material properties

Material properties are related to the origin of the material and how it is formed, for example by crushing. For tailings the properties are a function of:

- mineral content
- mode of formation (affect how the material act during for example crushing)
- handling of the rock (i.e. crushing, milling etc.)
- process chemicals
- deposition method
- water chemistry
- sulphide content

Factors, like weathering and frost, influence the properties of tailings, change over time, which have to be considered. For the long term design, it is difficult to predict how time affect the properties of materials used in a tailings dam. Critical design

measures like the function of filters and drainage often has to be more or less neglected in the long term, due to lack of knowledge about the effect of time, i.e. how time affect the material. By not taking the function of filters and drainage into account the design will be on “the safe side”.

Material properties affecting the slope stability are primarily friction angle, cohesion, density and hydraulic conductivity, the latter as it directly affects the hydraulic gradient. The long term effect of chemical and biological processes affecting the properties of the foundation or dam materials need to be taken into account. There are, however, no existing criteria today for how to incorporate these processes.

As we lack long term experience of the performance of man made structures. We therefore use natural land formations, that have been stable for long times, in order to try and see if we can resemble the properties that have made these natural formations long term stable. Knowledge from natural analogies has to be used in combination with the specific characteristics of tailings in order to design long term stable tailings dams.

6.4.2 Extreme events

Extreme events such as floods, droughts, earthquakes, land- and rockslides and high winds will occur in any long term perspective. With regard to ongoing climate changes it is difficult to predict the long term extreme events. The state of knowledge is a function of the knowledge at the time they are derived. Therefore the original design estimates will change over time, but they will always increase in magnitude and never reduce as future extreme events only can increase in magnitude compared to the events already known, Vick (2001). Robertson and Skermer (1988) said already in 1988, that future extreme events may well exceed those presently recorded. Design events for post-closure must be based on long-term conditions taking this into account.

Scientists are more and more united regarding the fact that the increase of the global average temperature during the last 100 years is unique in a 1000-year perspective. According to KVA, 2003, the temperature increase during the last 25 years cannot be explained unless the increasing level of carbon dioxide in the atmosphere is taken into account. This supports the fact that man affects the climate on our globe. The models used are still not complete and predictions of extreme weather situations are uncertain. (KVA, 2003). There are other explanations as well, but climate change will, however, not be covered in detail in this report. Here it will only be emphasised that design parameters used must be chosen according to local conditions, experience and according to the most recent knowledge about climate changes.

Other factors, which have to be considered to be extreme events, are; sabotage, terrorism and artisanal miners, of which all are difficult to predict. Such possible scenarios must be evaluated and incorporated in the design. This will, however, not be discussed any further here.

6.4.2.1 Swedish research on climate

Impacts of climate change in Sweden have recently been published (Andréasson et.al., 2004 and to some extent in Elforsk, 2005). Conclusions are, that there is a considerable range in the results originating from differences in; geographical location, emission scenarios, global climate models, versions of the regional climate model, time periods used and how the hydrological models are interfaced to the regional climate model results. The common features from the study of Swedish climate in the future, by Andréasson et.al. (2004), can be distinguished as follows:

- Decreased spring flood peaks
- Decreased summer runoff in southern Sweden
- Increased autumn and winter runoff
- Predominantly decreased annual runoff volumes in south-eastern Sweden
- Increased annual runoff volumes in northern Sweden
- Decreased frequency of high flow events during spring
- Increased frequency of high flow events during autumn

6.4.3 Slow deterioration processes

All tailings dams are affected to some degree by slow deterioration, or progressive, processes that degrade dam stability over time. Processes discussed are:

- weathering of fill materials
- water and wind erosion (divided in external and internal erosion)
- frost and ice forces
- intrusion by vegetation and animals

Weathering of fill materials is here defined as mechanical, chemical or biological weathering of material particles in their original place/location, whereas the latter three include a movement of the material particles from one place to another. In other contexts they all might be seen as just weathering.

The processes above can normally, during the operating phase, be controlled. During the long term phase they must, however, be incorporated in the remediation design as their (combined) effect over time can lead to overall failure of the tailings dam.

Robertson and Skermer (1988), Vick (2001), ICOLD (1996a) and others describe these mechanisms as well in accordance to the text below.

6.4.3.1 Weathering

Weathering is defined as the chemical alteration and mechanical and biological breakdown of rock forming minerals during exposure to air, moisture and organic materials. In nature this alteration is often gradual. This can be noticed in engineering excavations such as highway cuts or in large open pits, where lowest levels may be fresh. It is important to understand that this alteration process can, in some cases, be accelerated quite considerably when fresh rock from the deep levels is brought to the

surface and physically and chemically exposed. This will then result in release of minerals (Jones, 2004).

For tailings, in temperate areas of the world, the weathering due to biological activities (biological weathering) is the dominant process, whereas the chemical weathering is more important in other areas. Physical weathering plays a minor role in affecting tailings originating from crystalline rock, but a greater role for tailings originating from sedimentary rock. In the long term phase all processes must be considered as the time factor becomes dominant.

The chemical weathering of rocks, particularly the chemical weathering of sulphides, can also have an impact on the physical stability of tailings dams as the chemical weathering process may be accompanied by volume changes which in turn can affect the overall stability of the structure. It therefore becomes important, that the weathering potential of materials placed in critical sections of the tailings dam are fully understood, so that volume changes can be accommodated in the design.

Materials used for remediation must be selected by long term durability criteria. Gravel, stones and moraine from crystalline rock are examples of materials that are stable against weathering during operation and maybe in the long term. Other materials, for example materials from sedimentary rock, are more susceptible to weathering. The only reliable reference in this aspect is the long term durability of existing natural material. In the areas with cold climate, for example Scandinavia, some natural material deposited during the last glacial period (app. 10 000 years ago) are still stable and therefore interesting to use for comparison of remediated tailings dams. (Eurenius, 2005)

6.4.3.2 External erosion

Splash erosion commonly initiates water erosion and occurs when raindrops fall onto a bare soil or tailings surface. The impact of raindrops breaks up the surface aggregates and splashes particles into the air in form of water drops of water/particles. The particles will then be redistributed from their original position as the drops fall down. On a sloping surface most of the particles will fall downhill. For example wind may, however, change this. Some of the soil particles may fall into the voids between the surface aggregates, thereby reducing the infiltration and increasing the runoff. (FAO, 2005).

Water running over a surface may pick up particles released by splash erosion and can also detach particles from the soil surface. This results in sheet erosion where particles are removed from the whole surface on a fairly uniform basis. Where runoff becomes concentrated into deeper channels, rill and gully erosion may result. Rill erosion represents the intermediate process between sheet and gully erosion. Rills are normally channels up to 0.3 m deep and gullies up to several meters deep and wide. (FAO, 2005 and DPIWE, 2005).

Generally speaking, water erosion poses great problems in wet areas and wind erosion in all types of climate, but especially in arid areas. Depending on the conditions, rates of erosion can be extensive. Examples from unprotected tailings slopes (gold tailings) in South Africa show that losses of 50 kg/(m^2*year) are common and losses exceeding 100 kg/(m^2*year) have been recorded (Blight and Amponsah-Da Costa, 1999). These losses are roughly evenly divided between water and wind erosion and indicate the possible extent of erosion problems if not dealt with properly.

The most important factors that affect the rate of erosion and that can be controlled are according to Blight and Amponsah-Da Costa (1999):

- slope length,
- slope angle and
- surface shear strength (the author assumes this is the shear strength, i.e. friction angle, of surface material, as the shear strength of the surface is zero if the cohesion is zero).

A factor that cannot be controlled is rain intensity.

Observations of the interaction between these parameters have shown that erosion rates increase with slope length, but decrease both at very flat and very steep slope angles. The larger the friction angle and the possible cohesion of a slope, the lower the rate of erosion becomes. Obstructions that roughen a slope surface, such as a discontinuous layer of stone chips, rock fragments or boulders, also help to reduce erosion by dissipating the energy of water and wind moving over the slope (Blight and Amponsah-Da Costa, 1999).

Slopes potentially affected by erosion on most tailings dams are the outer surfaces of the embankments and to a lesser degree the long, flat, beach slopes on the upper surface. The appearance of both of these types of slopes will vary depending on construction method, material used and local custom. Differences in local custom have the effect of giving different results even though the same method and material is used. Any construction technique using tailings as the outer facing of the embankment will, however, be vulnerable to wind erosion. The slopes should therefore be protected against erosion, for example by covering the slope with material stable to water and wind erosion and vegetated if possible.

Vegetation covers used to prevent erosion may function well under normal conditions. Extreme events, such as floods, droughts, high winds, cold weather (i.e. permafrost etc.) and fires may, however, damage the vegetation cover. This might result in the vegetation cover requiring maintenance, which should be avoided in the long term design if possible.

6.4.3.3 Internal erosion

Internal erosion in dams is the transport of particles within the pores of the dam construction material, This is caused by seepage water flowing through the dam. The transport of particles is controlled by hydraulic and geometric conditions. Fine

particles (normally silt fractions) starts to move with the water flow when the hydraulic gradient becomes high enough, i.e. the water flow reach a velocity high enough to move particles. (Bartsch, 1995). This may increase seepage flow and an extension of the seepage area. After some time of continuous loss of fine material the soil structure collapses and material from above or upstream replaces the material lost. The seepage will then decrease as the "hole" has been sealed. However, a new weakness has developed where the replacing material came from and the process of material transport starts again. This course of event can, after some time, result in sinkholes at the surface of the dam or the phenomena known as "piping". Piping can be described as backward internal erosion as seepage causing material transport develops erosion in the opposite direction of the seepage flow. In severe cases this can lead to dam failure. (Johansson, 1997).

The development of internal erosion in dams is a complex process of which little is known (Johansson, 1997), especially during the long term phase. The process of material transport is a slow process and can go on for long periods of time before it is detected and/or the result or consequence can be seen. The consequences on the function of the dam may then already be severe.

Causes of internal erosion include:

- Inadequate particle distribution within a material or between zones of different material (i.e. filter and drainage zones in conventional dams) in relation to the hydraulic gradient.
- Differential settlements causing cracking. If the water level reaches above the cracks and there are no adequate filters and drains, internal erosion will start and may lead to piping and ultimately failure of the dam. (Pells and Fell, 2003)
- Hydraulic fracturing due to differential settlement leading to zones of low stress and cracks or saturation leading to collapse settlements resulting in water entering the crack which brings in the water pressure and expand the crack. (Bartsch, 1995 and Rönnqvist, 2002)
- Arching due to insufficient compaction of fill material in conjunction with other structures like concrete culverts, towers or spillways etc., resulting in zones with low stress below the "arch" where concentrated seepage can take place. (Rönnqvist, 2002)
- Separation of coarse and fine fractions at the times of placing the fill materials result in zones with coarser material and higher hydraulic conductivity causing concentrated seepage. (Bartsch, 1995).
- Exceeding the critical hydraulic gradient (De Graauw et. al., 1983 and Skempton and Bogan, 1994 both in Rönnqvist, 2002). This is based upon the idea that a critical gradient exist in a given material.

There are basically two general conditions that have to be fulfilled to initiate internal erosion in a soil material (Rönnqvist, 2002):

a) a particle structure that allow particles from adjacent pore system to be transported through its voids without successively sealing the voids between the particle structure
b) a water flow through the soil material sufficiently strong to initiate internal erosion and here by moving the finer particles from their original position in the particle structure. This happens when the hydraulic gradient in the material exceeds the critical hydraulic gradient.

Rönnqvist has not defined the critical gradient and how such a gradient is determined for a material. Supposed that such a gradient can be defined the author believes that for most tailings dams the latter condition (b) will be possible to control and preserve in the long term if the hydraulic gradient is low, i.e. in the order of the hydraulic gradient in natural formations of the same type, i.e. same geometry, material, etc.. In Sweden natural formations exposed to natural hydraulic gradients have been stable since the last glacial period. It should therefore be possible to design and construct long term stable dams. However, the knowledge about the long term stability of natural formations and tailings material have neither been collected nor analysed. The first condition (a) has to be fulfilled internally for each material and not by the use of filters and drainage as it is difficult to assure that they do not get blocked in the long term. The long term effect on the material of which filters and drainage are constructed of is difficult to predict. Dimension criteria for filters are empirical and do not incorporate hydrodynamic factors of the hydraulic gradient. Filter criteria has recently been reviewed and updated in many countries like USA, Canada, Norway and Sweden, see for example RIDAS (2002), which according to the author is due to deficiencies in filter function now detected in dams constructed during the 1960's and 1970's. The function of filters and drainage is therefore often neglected in the long term phase in order to assure that the stability of the dam structure will be on the "safe side".

6.4.3.4 Frost and Ice Forces

Ice forces can be external and/or internal. External ice forces act for example on the dam face due to freezing of the impounded water. Internal frost and ice forces are normally related to freezing and thawing of the ground and frost damage resulting in cracks (MiMi, 2004).

Frost and ice forces are cyclic processes and mainly an action to be considered in the cold climate areas. These actions can also be divided into particle and structural level. Frost forces can make the particles crack and thawing and freezing can change the structure and the properties (hydraulic conductivity, void ratio etc.) of the material. The significance of the changes will to a large extent depend on the type of material and of the initial composition of the material and its relative density, i.e. if it is loose or dense (Viklander, 1997, Knutsson et.al., 1996). The water within a saturated material expands during freezing and reduces its volume at thaw. The cracks left after a cycle of freezing and thawing may result in a more loose material. It should be stated that freezing and thawing might cause compaction and consolidation of the material. Weather it will become denser or looser depend on the type of material, i.e. grain size, structure etc., availability of water, freezing rate etc.. Critical sections within a dam

requiring compacted dense material therefore need to be at a depth below the maximum frost penetration. Sensitive sections within a tailings dam are sections of dense material requiring a low hydraulic conductivity (i.e. for example the core of a zoned dam). Filters and drains are sensitive to freezing due to the reduced capacity where ice are present in the voids. Therefore these sections need to be at depth below maximum frost penetration.

MiMi (2004) present a simplified equation based on a statistical approach, which can be used to estimate the maximum frost penetration for bare ground as well as for snow covered ground.

6.4.3.5 Clogging

Chemical clogging of dam construction material may become a long term problem. During operation chemical clogging of drains can be controlled by keeping the drains flooded, provide surplus drainage capacity or construct embankments of free draining material. These methods will allow passage of seepage water even if the drains are blocked, (Caldwell and Robertson, 1986). However, in the long term phase the process of clogging is more difficult to control and the long term design therefore needs to allow for this when it occur. Further discussion on this subject is beyond the scope of this report.

Physical clogging of filters or drains may be a consequence of internal erosion described in 6.4.3.3.

6.4.3.6 Intrusion by vegetation and animals

In the long term period it must be foreseen that the vegetation on the surfaces of the remediated TSF will become the same as the surroundings. Special measures should therefore be taken in order to reduce the risk of root penetration, harmful for the dam structure or cover structure. If roots penetrate a zone of a dam, or cover structure, they will cause permeable channels through this zone. Two examples will be given here:

- In a sealing layer roots will create leakage channels when the roots die and leave open channels through the sealing layer. It might therefore be necessary to increase the "freeboard", i.e. the distance between the free water and the dam crest. This prevents roots from penetrating the dam down to the free water. This will also reduce the risk of overturning trees causing holes in the dam that may lead to open seepage.
- In a capillary breaking layer the root itself will become a fibrous material transmitting water. The effects of these changes to material properties need to be considered as to their overall impact on long term behaviour. One way to protect sensitive layers, like sealing and capillary breaking layers, are to have a protection layer thick enough to prevent root penetration.

Roots from certain trees (for example Pine) are able to penetrate ground to depths of up to 6 m below the ground surface, if water is available. However, a more normal depth is about 2 m. To be able to penetrate into a soil, the roots must be able to

penetrate into the pore structure. In well compacted fine grained soil the pores are normally smaller than the roots and they must therefore be able to cause a deformation of the soil to be able to penetrate. Compaction can therefore be a protection against root penetration. (MiMi, 2004). Knowledge about the required porosity to allow for root penetration is well known within the field of agriculture.

As well as the surrounding vegetation must be allowed to spread on to a remediated tailings facility, there must be an allowance for animals as well. Animals like burrow and rodent animals may cause problems as they move onto/into the dam. Burrow animals may dig through sealing or cover layers when creating their burrows. The rodent animal, beaver, may for example block seepage water downstream the dam due to their construction of beaver dams. The effects of animals must be incorporated in the design by taking possible scenarios into account, as they are difficult to stop in the long term.

6.5 Aesthetics

Aesthetic acceptability is difficult to define, as different parties and every individual have his or her own definition. However, most people would like the tailings dam to become part of the surrounding landscape.

6.5.1 Landform

Mine closure landforms are generally accepted when they are aesthetically consistent with the regional context; that is, they should not be dissimilar, in shape and in scale, to the landforms of the region. While this objective is predominantly driven by landform stability, it can also be viewed as potentially improving landscape values.

Most natural slopes that are not rock outcrops have relatively small inclination to the horizontal plane (at least less than 30°). The slope is normally “S” shaped with curved and not flat surfaces. These natural landforms are the result of extremely long periods of natural erosion and deposition and they demonstrate the importance of curves, rather than flat surfaces and straight lines (in both vertical and horizontal planes). This natural response to the erosion forces result in the natural landform attaining long term stability, whereas the unnatural, man made flat surfaces and straight lines may appear to be stable in the short term, but are inherently unstable in the longer term. Thus gently sloping, rounded tailings dam faces are preferred to steeper, planar slopes. Further, stream diversions with suitably curved channels are preferred to straight drains.

These shapes have evolved to allow the hills to shed the majority of incident rainfall with minimal erosion. Creation of these configurations may require considerable reworking at closure if the remediated TSF is to have a landform similar to the surrounding natural landforms.

6.5.2 Revegetation

The purpose of revegetation is to turn disturbed land back into the natural environment in an ecological stable manner in relation to the surrounding landscape. The strategy for revegetation is to use long term stable vegetation covers tolerant to drought, fire, grazing and flooding and to choose vegetation suitable for the surrounding environment. Plant species to discourage deleterious effects of human use (spiny and brushy plant along with rocks) can be used if appropriate. The purpose of revegetation is not to destroy any remediation measures and therefore the risks of vegetation have to be understood, see section 6.4.3.6 “Intrusion by vegetation and animals”.

Revegetation of disturbed land is firstly dependent on the local climate and secondly on available soils. Land use must be considered as well. Each tailings site is unique, but for example SNV (1999) shows that there are a number of universal questions, problems and solutions. General knowledge requirements, to base decisions on, of what kind of vegetation that will be suitable, include (SNV, 1999):

- Macro- and microclimate and their effect on growth
- Type of tailings or soil
- Physical and chemical properties of the material (tailings and cover materials)
- Effects of lime, fertilizer and other soil improving methods

When fundamental knowledge has been gathered a revegetation plan should be developed, which include (SNV, 1999):

- Appraisal vegetation suitable for the tailings/soil
- Site specific preparation
- Spreading of lime and fertilizer
- Choosing species
- Providing organic matter, mulching, chemical stabilizers and other means of soil improving methods.

Where it is practical, establishing vegetation on the tailings dam should be undertaken as soon as possible. When using the upstream construction method for tailings dams the outer slopes can be remediated and have vegetation established progressively as the dam is raised. The centreline and downstream construction cannot be vegetated until the dam has reached its final height as the raises are constructed on the existing downstream slope of the dam.

At remediation the cover material used on the outer slopes and the beaches of a tailings dam should facilitate plant growth under existing climatic conditions. Natural materials facilitate plant growth more often than tailings. Tailings material have many characteristics that render them difficult for plant growth as they often contain low levels of essential plant nutrients (e.g. nitrogen, phosphorous) and also are generally deficient in terms of natural organic matter and associated microbial populations (Dean et al. 1986; Emerson et al. 1992). Tailings also often contain high levels of salts (Petersen 1992) and heavy metals, which can act as phytotoxicants (Ritcey 1989).

The physical composition of tailings are often unconsolidated fine sand (i.e. silty sand), which when uncovered, can both sandblast and bury plants when mobilised by wind. Intense reflection (on light coloured tailings) or absorption of solar radiation (on dark tailings surfaces) may cause physiological stress to plants (Emerson et al. 1992).

To create a medium suitable for revegetation, environmental practitioners attempt to amend inhospitable tailings. Early work attempting to revegetate gold tailings in South Africa (Chenik, 1963; cited in Barth 1988) found that most general amendments to the tailings were unsuccessful, but placement of natural soil in potholes, constructed on the tailings, did establish grasses. Effectively this process is the micro scale application and use of a soil cover. Since that early work by Chenik, Dean et al. (1986), Barth (1988) and Jennings et al. (1993) suggest that a combination of physical (i.e. soils or cover materials etc.) and biological (i.e. vegetation) cover is the best way to stabilise a tailings dam, and improve the aesthetics of a disturbed area.

Apart from moraine and gravel, sewage sludge has been used in Sweden as a combined soil cover and fertiliser for revegetation of TSF. Boliden Mineral AB initiated their first project at a tailings dam in the central parts of Sweden in 2001. The area was covered with approximately 0,3 m sewage sludge and revegetated with grass. The results were extremely positive as the luxuriant growth came immediately and then increased every year. The amount of nutrients are probably the reason for the success. Before this method can be evaluated more years of experience is needed (Isaksson, 2004). For water covered tailings dams, this can maybe be used for the downstream slopes of the dams if the long term properties are evaluated.

6.6 Post-operational Land Use

Many factors play part in planning the remediation of a TSF. These may include:

- company environmental policy
- climate
- an understanding of the requirements for vegetation
- policies of the principal regulatory authorities
- the varied and diverse needs of other stakeholders

While all of these factors drive remediation and closure planning, it is the final land use that ultimately should be the prime consideration for the remediation plan. Mine closure requires returning the land to a useful purpose, (Worldbank/IFC, 2002).

There are examples around the world where remediated mine sites, including tailings facilities, have become wetlands, water storage dams, tourist sites, golf courses, fish farms, water ski and windsurfing parks, motor sport complexes, rowing courses and even amphitheatres, (AGDEH 2002).

It is also a historical fact that many tailings deposits have been re-mined as technology has improved. Whilst this should not be used as an excuse for not undertaking a

comprehensive remediation, the proposals should be checked for the possible impact on, or from, a subsequent re-mining operation.

6.7 Performance Assessment

Performance assessment has been carried out within the Swedish research programme "Mitigation of the environmental impact from mining waste", (MiMi, 2004). The methodology used was the Interaction Matrix and scenario analysis described briefly in the following and more thoroughly in MiMi, 2004.

Assessment of long term performance of tailings dams must be based on a firm scientific comprehension of governing processes. To be able to address the long term evolution of processes where the time spans are far beyond what is possible to observe in experiments, we must rely on predictive modelling. Formulation of scenarios is a way to describe possible sequences of processes and events influencing the release of contaminants and the long term stability of dams. Scenarios should be regarded as stylised representative futures which, when summed, span the variety of possible futures. The generic methodology adapted from the field of radioactive waste was a new approach in the MiMi project. (MiMi, 2004).

The interaction matrix methodology is used as a tool for identification and structuring of features, events and processes (FEP) in the system, see Figure 27. The basic principle of the interaction matrix is to list the main features or properties of the system along the leading diagonal elements of a square matrix. The interactions between these main features or properties occur in the off-diagonal elements, see Figure 28. Defined interactions should be binary and they are prioritised including a motivation and the knowledge level of the person setting the priority.

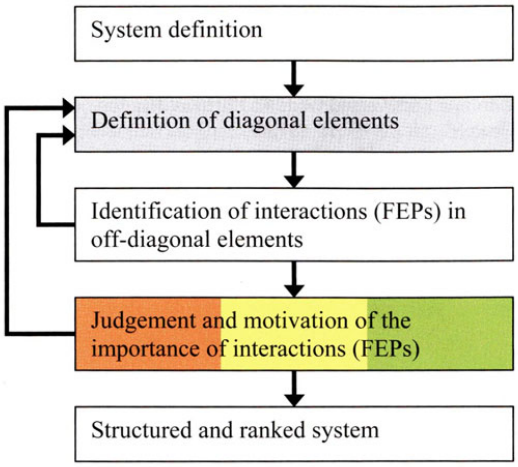
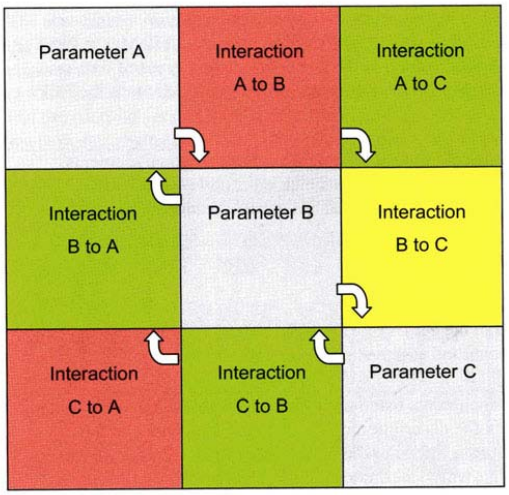


Figure 27 Procedure for defining an interaction matrix. From MiMi (2004).



Priority	Definition
3 red	Important interaction – should be included in the performance assessment (PA)
2 yellow	Interaction identified – should probably be considered in the PA – may require further research
1 green	Interaction identified – need not be considered in the PA
0 white	No identified interaction
grey	Diagonal element with its parameters

Figure 28 Principle of the interaction matrix, indicating a colour scheme for ranking the importance of the different interactions (FEPs). From MiMi (2004).

The "base case", that has been used in the interaction matrix for the remediation method; water cover, was defined according to Figure 29 and with the following assumptions made:

- the water depth is 2 m
- the tailings dam is stable
- the tailings is not covered by any sediments
- the design is such that wave action will not influence the tailings
- the tailings will always be maintained as originally deposited
- negligible resuspension will take place
- the water covering the tailings is fully saturated with oxygen
- there will be a water inflow to the impoundment that is sufficient to maintain the water cover at all times
- there is a discharge of water, resulting in a water exchange at a certain rate

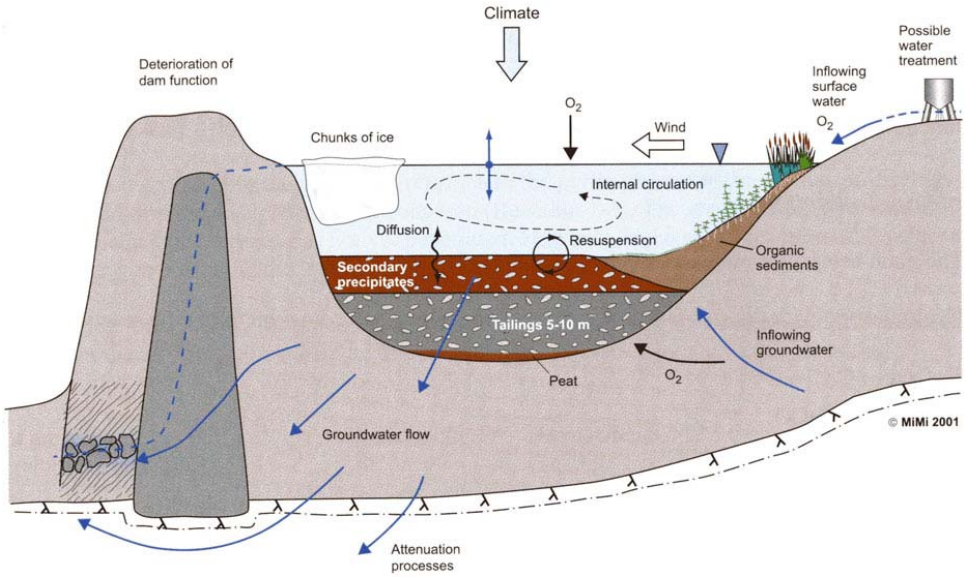


Figure 29 MiMi Base case for water cover remediation. Schematic illustration of principles and processes for a water cover case. From MiMi (2004).

MiMi (2004) defines data needed for the performance assessment as well as values for geometrical, physical, kinetic and other data, which will not be repeated here. The main focus of the MiMi research project was the environmental aspect and not the aspect of dam stability.A number of workshops, where 5 to 6 persons met, resulted in a system definition of the base case for the matrix and the matrix itself, see Figure 30 and Figure 31. Due to the finite time of the research project, the exercise was never finalised.

The boundary conditions for the matrix were defined in the first and last diagonal element as, see Figure 31.

(01.01): climate, topography and drainage area
(14.14): dam toe

The diagonal elements in between were:

(02.02): water cover
(03.03): water movement in water cover
(04.04): tailings
(05.05): sediments – natural and artificial
(06.06): dam core
(07.07): filter and drainage
(08.08): support fill
(09.09): erosion protection
(10.10): foundation
(11.11): spillways (outlets)

(12.12): water flow
(13.13): water composition and temperature

Possible interactions between diagonal elements were discussed and documented. Within the matrix each box shows, in the upper left corner, the number of the diagonal element initiating the interaction with another diagonal element, for example 02.06, which is the interaction of the water cover on the dam core. To the left in the middle of the box a "?" or a number is given, which shows the number of defined processes involving these two diagonal elements. To the right in the middle of the box a "?" or "OK" is shown, which indicate if the importance of the interactions are evaluated (i.e. "?" if they are not evaluated and "OK" if they are). The level of importance is shown at the bottom of the box and is divided into three levels; "red" for important, "yellow" for intermediate importance and "green" for insignificant importance.

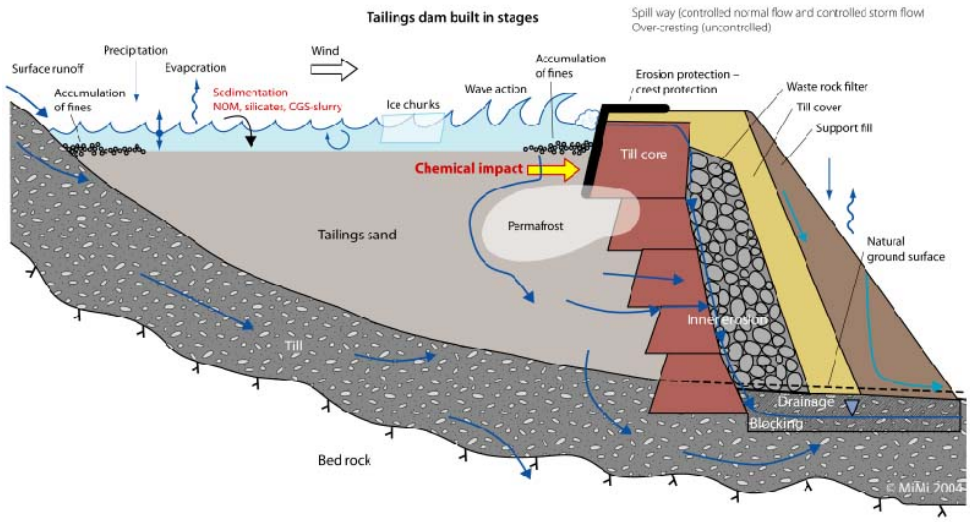


Figure 30 The system definition of the water cover closure case for the MiMi matrix performance assessment. (Höglund, 2005).

The methodology proved to be an effective way to establish a deeper understanding among the different researchers of the complexity of all the process interactions within the deposits. It also proved the need for a multidisciplinary approach and common effort to be able to address all critical issues. However, it also proved to be a very demanding method and was therefore not used to its full potential with in the MiMi project.

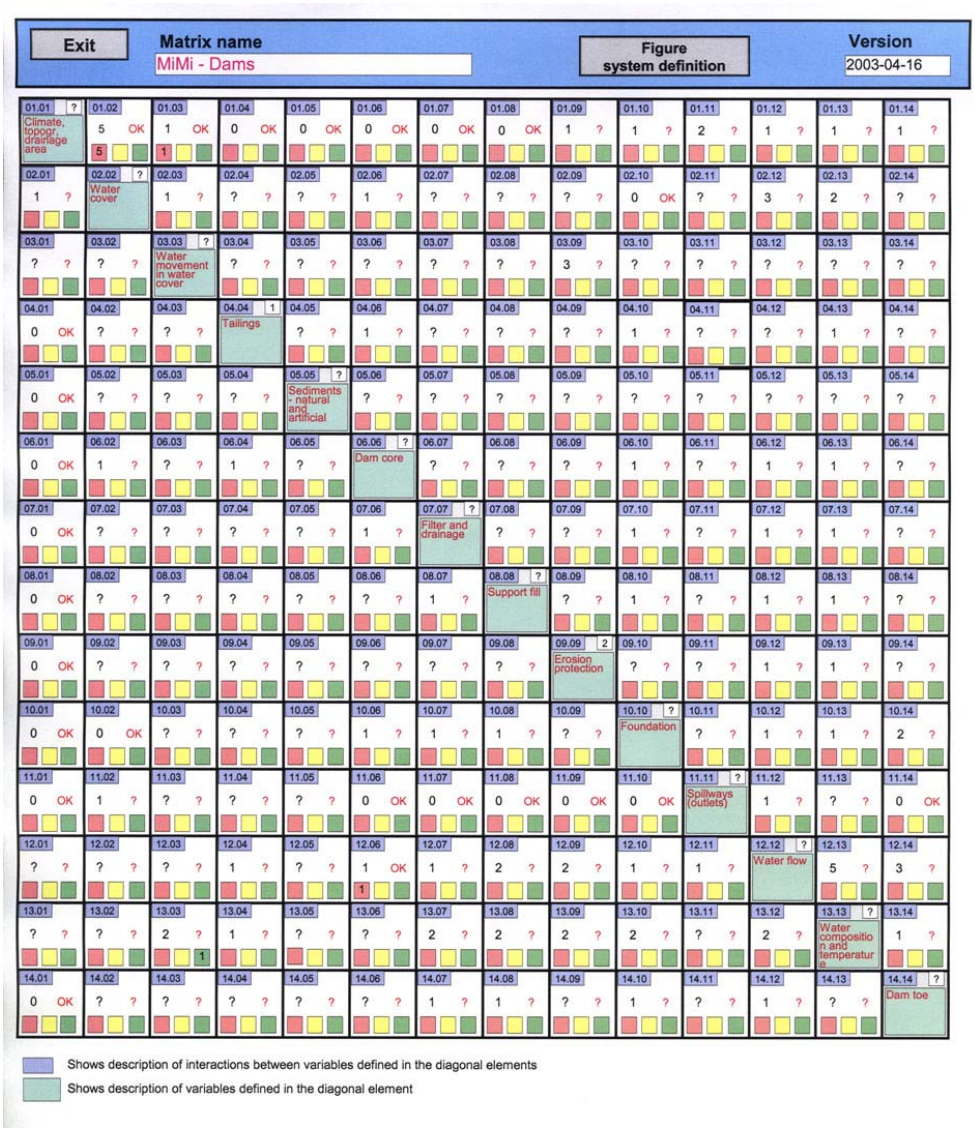


Figure 31 The matrix derived at the performance assessment exercises performed within the MiMi program. Developed according to the description in MiMi (2004).

6.8 Existing Guidelines etc.

There are several existing guidelines, codes etc. on tailings dam closure, but no specific criteria for the long term dam stability. Full details of the guidelines listed below are given in 10 "References" or in Appendix A: "Bibliography".

Author/publisher and name of Guideline	Reference	Ref. found in: Ref.	App. A
Australian Government, Department of the Environment and Heritage: *Environmental Risk Management.*	AGDEH (1999)		X
Australian Government of the Department of the Environment and Heritage: *Mine Decommissioning*	AGDEH (2002)	X	
Australian and New Zealand Minerals and Energy Council (ANZMEC) and Minerals Council of Australia (MCA): *Strategic Framework for Mine Closure*	ANZMEC/MCA (2000)		X
Department of Minerals and Energy of Western Australia (1999): *Mine Closure Guideline for Minerals Operations in Western Australia*.	*Same as name*		X
Department of the Environment. Commonwealth of Australia: *Cyanide management. One booklet in a series on Best Practice Environmental Management in Mining.*	Environment Australia (1998)		X
Gouvernement du Québec (1997). *Guidelines for preparing a mining site rehabilitation plan and general mining site rehabilitation requirements*.	Gouvernement du Québec (1997)		X
International Council on Metals and the Environment (now ICMM): *The Management of Cyanide in Gold Extraction*	ICME (1999)		X
International Cyanide Management Institute: *The International Cyanide Management Code for the Manufacture, Transport and Use of Cyanide in the Production of Gold. Developed*	ICMI (2002)	X	
International Commission on Large Dams. Bulletin 74: *Tailings Dam Safety –Guidelines*.	ICOLD (1989)	X	
International Commission on Large Dams. Bulletin 103: *Tailings Dams and Environment – Review and Recommendations.*	ICOLD (1996a)	X	
Jewell, RJ, Fourie, AB and Lord, ER: *Paste and Thickened Tailings A Guide*.	Jewell et. al. (2002)		X

Mitigation of the environmental impact from mining waste: *MiMi-Performance Assessment Main report*	MiMi (2004)	X	
Northern territory Department of Mines and Energy: *Mine Close Out Critera: Life of Mine Planning Objectives*.	Northern territory Department of Mines and Energy (1997)		X
Queensland Mining Council: *Guideline for Mine Closure Planning*	Queensland Mining Council (2001)		X
The Mining Association of Canada: *A Guide to the Management of Tailings Dams.*	MAC (1998)		X
World bank and International Finance Corporation: *It's not over when it's over: mine closure around the world.*	World bank/IFC (2002)		X

7 Comparison with Other Fields/Sciences

Research on remediation of tailings dams can be related to other research fields, especially when it comes to cover design. The methodology in designing covers, as well as the potential problems, are the same or similar, for landfill covers and for remediation of industrial waste deposits (Carlsson, 2002). For remediation by water cover, where dam stability is critical, possible comparisons are more severe. However, there are some adjacent fields of interest from which some experiences can be useful for the design of the long term stability of tailings dams. These are described and discussed below.

7.1 Ancient structures

7.1.1 Earthen Mounds

Blight and Amponsah-Da Costa (1999) have investigated ancient mounds in China, comparable to tailings in order to find out what an erosion resistant tailings slope should look like. Several ancient man-made monumental mounds have stable slopes with a slope angle varying from 16° to 28°, see Figure 32. The mounds around Xi'an (i.e. slope 2, 3 and 4 in Figure 32 with slope angles between 16° and 28°) are all constructed of fine sandy silts from river alluvium and loess. The semi-arid climate has distinct wet and dry seasons. The annual rainfall is between 500-1000 mm and there is an annual water deficit. The mound around Yinchuan (i.e. slope 1 in Figure 32 with a slope angle of 54°) is of loess, but in a desert climate. See a summary of the data in Table 7.

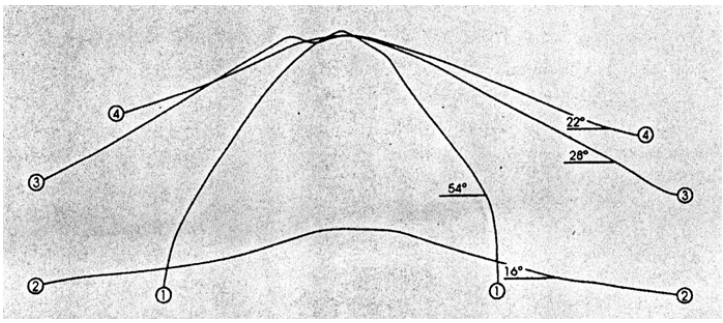


Figure 32 Profiles of ancient earth mounds in China (Blight and Amponsah-Da Costa, 1999).
1-Xia Kingdom (900-700 BP) (desert climate) near Yinchuan
2-Qin Shi Huan (2200 BP), said originally to have been 116 m high, now 52 m high
3-Liu Che (2100 BP), now 46 m high
4-Gaozong (1320 BP)
2,3 and 4 have semi-arid climates and are situated near Xi'an

Table 7 Compilation of data on ancient mounds in China investigated by Blight and Amponsah-Da Costa (1999).

Name	Date, BP	Slope angel	Height now	Material	Climate
Xia Kingdom	900-700	54°	-	loess	desert
Qin Shi Huan	2200	16°	52 m	alluvium and loess	semi-arid climates
Liu Che	2100	28°	46 m		
Gaozong	1320	22°	-		

The characteristics of a natural erosion-resistant slope were by Blight and Amponsah-Da Costa (1999) deduced to be:

- relatively flat slopes,
- increasing percentage of vegetation counting from top to bottom (i.e. more vegetation at the bottom of the slope compared to the top),
- decreasing percentage of gravel and boulders (i.e. more gravel and boulders at the top of the slope compared to the bottom) and
- decreasing percentage of bare soil (i.e. more bare soil at the top of the slope compared to the bottom).

Lindsey et.al. (1983) investigated the long term stability of man-made earth structures for the purpose of long term stabilisation techniques for uranium tailings impoundments. The mounds, burial or entombment sites, were about 6000 years old and younger. Table 8 shows the age and size of some of the sites investigated.

Table 8 Compilation of data on long term stability of man-made earth structures by Lindsey et.al. (1983). Structures are burial and entombment sites.

Continent	Year old	Dimensions in meters [m]		
		L x W	ϕ	H
Polen	5 600	50-100 x 7-10		3-4
British Isles	5 200	40 x 6-12		2-3
	4 600		165	40
Russia	3 200		45	4-9
Asia	2 700		270	50
North Africa	2 000		76	11
Eastern America	3 000-3 500		1200	2
	1 300-3 000		200	23
Western America	1 000	29 x 22		3

Legend: L=length, W=with, ϕ=diameter, H=height.

The conclusions of the investigation by Lindsey et. al. (1983) are that the following design features and location conditions for long term stable dams should be aimed at, due to stability reasons:

- use of long term stable materials in surrounding dams.
- use of flat slopes.
- use of rock covering.
- located far away from river migration.
- no use of brick-like materials for construction as it is sensitive to settlements (leading to cracks).
- unfriendly environment for rodents as they dig burrows and displace cover material.
- unfriendly environment for large trees as their roots penetrate the cover.
- no sharp edges or corners as they are subjected to erosion and weathering.

Since the construction of the investigated mounds the effect of erosion over time has affected the mounds differently. Some has experienced more erosion than others. The design features and construction methods of the more stable mounds, according to Lindsey et. al. (1983), are:

- the use of protective rock cover to protect against erosion and to maintain a soil moisture content.
- layered and compacted construction of the earthen covers.
- the use of stage construction where each stage is stabilized before others are added, (for example Silbury Hill, Brittish Isles, see Figure 33). Larger mounds appear to have been built in stages spanning over long periods of time, in some cases several hundreds of years.
- designs that use interior stabilisation such as radial and concentric circular walls.
- the use of terraced embankments for slope stability and the provision of solid foundations for each successive stage.

- the use of stable foundation such as bedrock or a well compacted foundation.
- the use of established vegetation where climate permits.
- the opportunity for an initial maintenance period and design flexibility to mitigate instabilities. This would coincide with stage construction. Long construction and occupation periods were advantageous for archaeological mounds because they allowed for maintenance and design revision.

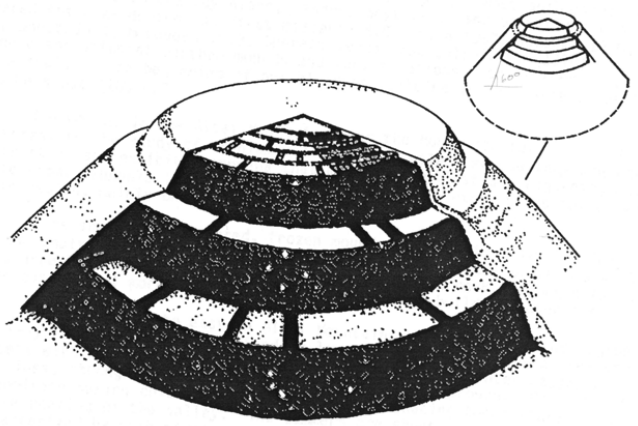


Figure 33 Silbury Hill, Brittish isles, 4 600 years old. Construction in stages with a base diameter of approximately 165 m, height of about 40 m and slopes of about 1:2. From Lindsey et. al. (1983)

Additional comments regarding the stability of ancient mounds are, according to Lindsey et. al. (1983):

- results from semi-arid regions and some slightly humid regions do not indicate any disruption from tree growth. Disruptive tree growth seems to occur in extremely wet climates.
- embankment collapse failures seem to be predominant in the more humid climates and sheet erosion is more common in the more arid climates. The wetter climates support vegetation, which would effectively prevent serious overland erosion, but excessive soil moisture combined with steep side slopes could easily result in slumping.
- clay caps have proved very beneficial for insuring the stability of mounds in wet climates. The clay caps act as a barrier to water infiltration.

What Lindsay et. al. (1983) found impressive was that the survival rate of the investigated mounds was remarkably high. Although erosion forces have affected the structures, the activities of man seem to have contributed to most of the destruction. According to the data presented above, the author believes that, it should be possible to design long term stable man-made structures today.

7.1.2 Pyramids

Mendelssohn (1971) writes about the pyramids in "A Scientist Looks at the Pyramids". To some extent a comparison to tailings dam closure is relevant, as these man-made structures are about 5 000 years old. The first huge pyramids were built in steps with each step having an angle of 72° (3:1) and the overall angle of 52°, see Figure 34. This corresponds to the ratio of circumference to height being 2π. Some of these stone pyramids are in remarkably good state. Only the edges of the lowest step and the smooth casing stones have disappeared. Others have been robbed as antiquity. Single stones have been subjected to large stresses and therefore collapsed, resulting in changes similar to plastic flow. This has lead to part of the pyramid being collapsed.

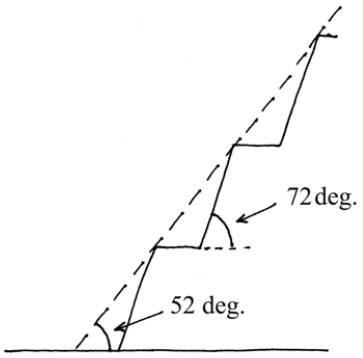


Figure 34 Typical angles of the steps of the first huge pyramids.

The pyramids are evidence of man-made structures designed without large safety margins, but stable for thousands of years. Compared to tailings dams the pyramids differ quite much as the pyramids are constructed of stone blocks and the tailings dams of sand. This make the tailings dams much more susceptible to erosion and weathering forces. However, the evidence of the pyramids being stable for thousands of years, indicate that it is possible to design long term stable structures, and therefore it is hypothesized that also long term stable tailings dams can be constructed.

7.2 Nuclear Waste

Remediation of tailings dams and handling of nuclear waste have to deal with the same time frames. These two fields of science have the long term perspective in common, as well as negative environmental impacts if the problem is not dealt with properly. Within the MiMi programme (MiMi, 2004) the methodology of performance assessment and the use of interaction matrix have been taken directly from the research on nuclear waste storage, where it was originally developed.

8 Discussion

Tailings dams have similarities and differences compared to WRDs, as mentioned in section 4.4 "Comparison with Water Retention Dams (WRD)". It is important to know the similarities and within these areas exchange knowledge. The differences may, however, be more important. In order to simplify this statement it can be generalised that a geotechnical engineer with extensive experience from tailings dams will more easily be able to work with WRDs, compared to the other way around which to some extent will be more difficult. The reasons for this are mainly:

- Tailings dam design requires knowledge about the whole mining operation and the history of the dam. This includes knowledge about processed materials, volumes, physical and chemical properties, of both deposited tailings and processed dam construction material. It also includes knowledge about the skills of the staff operating the dam. Depending on the skills of the staff, simplicity in construction may be preferred compared to effective design and material use.
- Tailings dams are constructed and designed over long periods of time. At some sites construction is more or less an ongoing process and at other sites a staged process. It is therefore important to know and understand the function of the tailings dam over time and have an ongoing dialog between the geotechnical engineer and staff on site.
- Preferably the same geotechnical engineer should be involved in the design over time. This because the more people involved over time, the higher the risk become for loosing the overall function of the dam and for making mistakes. To achieve a suitable level of dam safety, external audits should be carried out regularly, which is the same for WRDs.
- Finally, the long term perspective and closure of tailings dams requires a different perspective compared to any other design or construction (except nuclear waste storage). This has to be incorporated already at the planning stage.

Tailings dams have a history of about 100 years. Before that time tailings was discharged in "suitable" locations near the mine. Compared to WRD the history of tailings dams is short. In Sweden, and probably in many other countries, tailings dams have traditionally been located in relatively remote areas. Often the mine has given rise to communities of which some have developed into towns. Mine owners have naturally been focusing on the ore production. For almost a century the focus from society and regulators has concerned the mine and later on (during the last 30-40 years) the discharge rates of environmentally harmful substances. Tailings dams have only come into focus the last 10 years. The dam failures having occurred in Europe during this period of time have increased this focus even further. This has affected mining and tailings dam operations all over the world. Dam safety programmes have been initiated and awareness and education have increased in Sweden and internationally. Incidents and failures are being analysed in order to transfer gained knowledge to others (for example ICOLD, 2001 and Bjelkevik, 2005). Mine owners are about to reach to the level of dam safety that we have for WRD, even though there still is scope for improvements, especially with regard to long term safety of tailings dams.

No matter how safe tailings dams, or other constructions, are, there will always be a risk involved. This risk can never be completely eliminated, but have to reach an acceptable level in order to be accepted by society. This immediately raises the question: What is an acceptable level? To be able to answer this question the benefits and the disadvantages from, for example mining, has to be incorporated, i.e.: What risks are we, the society, prepared to take for the ability to use metals? If we need the metals, we also have to be prepared to accept some associated risks. This does not mean we should accept TSFs to just be left when mining activities come to an end.

This means that we will never be able to completely eliminate risks at remediation of a TSF. The level of knowledge and experience of remediation will increase with time and remediation plans have to be updated continuously to reflect best practice. Remediations carried out today may require improvements in the future. A mining company will not exist forever, and at some stage we need to accept that everything reasonable to do, with regard to the knowledge available at the time, has been done. In Sweden this "time", or "after care period", is expected to be 30 years. However, there is no remediated tailings dam in Sweden that has past this period yet.

The question of responsibility of remediated tailings dams will not exist if it is evident that it is possible to design long term stable tailings dams, not require surveillance or maintenance. If this is possible or not, we do not know today. The opinions about this differ widely internationally and nationally. However, the author is of the opinion that the goal must be to achieve long term stable tailings dams and if that can not be achieved society will need to be part of the solution. Mining companies cannot be expected to exist forever and if long term supervision is required for all old operations a mining company may come to the point where continued mining is not feasible due to too high costs for old operations. However, an old mining operation needs to be remediated properly, which is equal to that the mining company takes its responsibility in doing what can possibly, technically and economically, be done at remediation. Even if the mine site is long term stable remediated, the society will always have to keep the knowledge about the site in order to prevent future activities that might destroy the remediation. So, one way or another the society will have to take responsibility to some degree, and the degree will depend on the success of the remediation carried out.

In the order to gain experience and learn from the past, ICOLD (2001) have compiled and analyzed the international statistics of failures and incidents of tailings dams. The conclusions from ICOLD's study are, that many factors influence the behaviour of tailings storage facilities. Accidents and other incidents are often the result of:

- inadequate site investigation
- design
- construction
- operation or monitoring of the facility
- a combination of these factors

These conclusions are drawn from a base of data including 199 active and only 22 inactive tailings dams despite their vastly great number. The term "inactive tailings dam" is not defined, so it is not clear if the 22 inactive tailings dams represent remediated tailings dams or not. A tailing dam can be inactive when deposition is not ongoing, without being remediated. This considerable base of data on tailings dam field performance shows that tailings dam failures seldom occur under post closure conditions (Vick, 2001). ICOLD Tailings Committee (ICOLD, 2001) have stated that the technical knowledge exists to allow tailings dams to be built and operated at low risk, but that accidents occur frequently because of lapses in the consistent application of expertise over the full life-time of a facility and because of lack of attention to

details. It is not obvious if this statement is applicable to remediation of tailings dams as well, or if it is just applicable to the operational phase.

In general, cover designs should be kept as simple as possible to control cost and to improve robustness and long term integrity (i.e. the more steps or functions, the more occasions to make mistakes), Myers and Crews (2002). The present general methods discussed, accepted and used for remediation of TSFs are:

- dry covers
- water covers
- wetland covers

All three methods have their benefits and disadvantages. For the water cover method the benefits are basically low cost and virtually 100% effective cover performance from a geochemical point of view (Vick, 2001), and the disadvantages are that the tailings dam need to remain stable in perpetuity, which is an exceedingly long lime!

In Scandinavia and, other places, that have experienced glacial periods, nature may help us in finding out how long term stable formations are designed. There are several examples in Sweden of lakes dammed by natural formations, i.e. natural dams (see section 6.3.3 “Examples of lakes dammed by natural dams (i.e. soil formations)”). Thorough investigations of these sites may reveal the structure of formations stable since the last glacial period, and if these structures can be copied for tailings dams, long term stability will most probably be achieved. However, it is very important to remember that local conditions need to be considered when designing for closure (and operation). One technology that might balance environmental and dam safety risks in a relatively favourable setting at one geographical location, can have much more serious and latent effects when applied elsewhere, Vick (1999).

The author has not found any official design criteria for long term stability of tailings dams, i.e. slope stability or factor of safety (FS) against slip surfaces for a long term perspective. The probability against failure, should probably not be lower for long term design compared to that during operation. The loading conditions need to change as the tailings dam most likely will be exposed to more severe loads in a long term perspective than during operation. Which loading conditions represent the long term? Events classified as extreme during operation may be normal in a long term perspective. The loading conditions change in a long term perspective and so need the design criteria do.

Internal erosion is a common phenomenon for both tailings dams and WRD and is equally a frequent cause of failures and incidents. The development of internal erosion is a complex process of which little is known (Johansson, 1997). The mechanisms that may cause internal erosion are, however, described by Bartsch (1995), Rönnqvist (2002) and others, see section 6.4.3.3 “Internal erosion”.

In comparing WRD and tailings dams there are some differences that may affect the process of internal erosion. For WRD the zones of different materials are normally

optimized, i.e. as less material as possible are used in order to achieve a cost effective design. For tailings dams, especially if constructed of processed material, volume normally replace quality, as the material is easily available in large quantities. This and/or the construction method itself, normally result in tailings dams having a lower hydraulic gradient compared to WRD as described in section 4.4 “Comparison with Water Retention Dams (WRD)”.

Requirements for filter and drainage design as well as construction are developed for WRDs. The requirements are based on the hydraulic gradients normally present in that kind of dams. For tailings dams, however, with a lower hydraulic gradient, it might be possible to decrease the requirements on filter material without reducing the level of safety. The effect of the hydraulic gradient on the process of moving fine particles in a soil structure exposed to an internal flow of water is not investigated, it is just known to have an effect.

Another difference is, that tailings dams store tailings and water, not just water as WRDs does. This result in the tailings dam having a large storage of fine material upstream the dam, which can be used for self-sealing if a seepage path develop due to internal erosion. As the design of a long term remediation of a tailings dam should strive for a hydraulic gradient as low as the levels that can be found naturally, the hydraulic gradient will correspond to a small force acting on the particles within the material. This small force is hopefully too small to initiate erosion. Under the conditions of a low hydraulic gradient the most important factor for the tailings dam seems to be that the construction material is internally stable.

The Worldbank/IFC (2002) states that the three key lessons for a successful closure are:

- to start closure planning early
- work together (authority, company, locals)
- that government needs to lead the process, with company support

This does not fully reflect the situation in Sweden, as it is here the companies leading the process. However, the cooperation of all parties involved is fundamental and there are examples in Sweden, and around the world, where remediated mine sites has become an asset for the society. TSF have been turned into wetlands, water storage dams, tourist sites, golf courses, fish farms, water ski and windsurfing parks, motor sport complex, rowing courses and even amphitheatres. The ongoing use of the mine site area should continue to be beneficial to the local community and the environment if possible. Mine closure planning must continue to be a dynamic process driven from the top of the mining company organisation (DEH, 2002). This way of turning the TSF into something “useful” may be an answer to how long term responsibility can be transferred to the society without becoming a burden, which was one of the questions raised at the conference in Freiberg (2002).

8.1 Future Research

Closure and remediation of TSF is an extensive field where research has been going on for some time. More or less all projects have focused on the cover methodologies, i.e. the performance and the weaknesses of soil covers, water covers and the wetland covers. Not much attention has been paid to the long term dam stability. Therefore there is a whole technical field that need to be explored. Without the long term stable dam, there will not be a water cover or wetland on top of the tailings.

Mining companies, regulators, NGO's etc. need sufficient criteria to assess weather a facility is long term stable or not. To develop such criteria several processes important for long term performance need to be investigated. Some of the more important can be mentioned here:

- internal erosion
- long term changes in material properties
- the effect of the hydraulic gradient on slope stability
- interaction between tailings material and sealing elements/foundation within the tailings dam
- external erosion
- seepage points

One appropriate way forward, is probably to carefully investigate natural land formations that have been damming water for thousands of years, i.e. since the last glacial period in Sweden. As several detailed investigations of specific processes are needed, a team of researchers are required to achieve useful results in a reasonable time scale. Natural formations should be investigated not only within Sweden but, within Europe or even globally. I believe that a research project similar to the MiMi programme is required, maybe as a EU-project.

Below are some citations from other reports about important research fields:

MiMi (2004) identifies 12 items as the most important research needs for the future. Two of them are:

- Finding design criteria for inherently long term stable tailings dams without the need for maintenance.
- Systematically improving the understanding of the processes of importance for the long term integration of tailings deposits with the surrounding biosphere.

MMSD (2000a) say, that there should be a search for more appropriate technological alternatives for implementing a mine closure plan and for more economically appropriate alternatives for carrying out mine closure. Specific standards or closure requirements should reflect a careful balance of the benefits and costs of the standards or requirements. Policies should be designed to encourage or provide incentives for technological innovation in mine closure, to reduce costs of compliance.

Other fields needing further research are sampling methods, in-situ testing and evaluation of in-situ results and laboratory results, i.e. calibration against tailings

material and not natural materials. Are there any differences in crushed and natural material resulting in limitations in the standard, and widely accepted methods, used for sampling and testing of natural materials?

9 Conclusions

TSF cannot be removed and therefore they need to be long term stable. The philosophy in Scandinavia is that TSFs should be stable to the next glacial period. We do not believe it is possible to design structures that will survive a glacial period. TSFs should therefore be designed for a lifetime of maybe 10000 years and this task is challenging enough.

The review carried out in this report found numerous documents, papers and articles, on remediation of TSF. Papers are found in for example:

- Organisations (ICOLD, ICMM, etc.)
- Projects (TailSafe, ClotDam, etc.)
- Journals (Mining Journal, Canadian Geotechnical Journal, Mining Engineering, etc.)
- Guidelines (national, provincial, etc)

There is, however, basically no information on long term physical stability of tailings dams. Most literature cover remediation and closure of TSF with regard to cover design (dry, water and wetland covers), chemical, biological and environmental aspects. It is often mentioned in the literature that remediation measures need to be long term stable. Long term being defined as more than 1000 years, but how to achieve this is not mentioned or discussed. Criteria for long term stability of cover structures and of long term stability of dams are not developed nor defined.

In summary it can be concluded, that the design practice for long term stability of tailings dams have to result in a safety that is higher than the stability during operation. Natural analogies can be used, when possible, in order to find out what kind of design that may be a long term stable construction in a certain location and use that information in order to design long term sable tailings dams. Different locations with different conditions need different solutions. One factor, being a whole field of its own, is the climate change, which will affect the safety of closed TSF.

The major conclusion from this study is that much more research needs to be performed and more experience has to be gained before criteria for long term stability of tailings dams can be defined.

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In this section literature not referred to or literature concerning related topics are listed. To make it easier to find a document of interest the list has been divided into different subheadings.

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Here all documents in Swedish relevant for tailings dams are listed.

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Appendix B: Glossary

Definition of terms used in the field of closure and remediation of tailings dams are given here. In the first column both the English and Swedish term is given. The purpose of the Swedish terms is to try and bring some clarity to use of Swedish terms as well.

Definitions of the terms have been quoted from the following references European Commission (2004), Ministerial Council on Mineral and Petrolium Resources and Minerals Council of Australia (2003), ANZMEC/MCA (2000), ICOLD (1989), UNEP and ICME (1998), MMSD (2002a) and Rehbinder et.al. (1995). Details on the references are found under 10 References. Most definitions are not directly taken from a reference, but reworked from several references and/or influenced by the author.

English Term ***Svensk benämning***	**Meaning/Definition**
Acid mine drainage (AMD) or Acid rock drainage (ARD) *Surt lakvatten*	Acidic drainage/seepage (pH <4.5) stemming from open pit, underground mining operations, waste rock or tailings facilities that contains free sulphuric acid and dissolved metals sulphate salts, resulting from the oxidation of contained sulphide minerals or additives to the process. The acid dissolves minerals in the rocks, further changing the quality of the drainage water.
After care *Kontrollfas*	The last phase of closure with the purpose of verifying the quality of remediation actions.
Clarification pond, Return water dam or Clearwater dam *Klarningsmagasin*	An impoundment separate from the tailings impoundment, surrounded by dams and/or natural boundaries and used for a second clarification step and/or an extended storage of process water. The pond/dam is normally located close to the tailings pond and the dams are usually designed as conventional earth fill dams and.
Closure *Nedlägging*	Shutting a mine and a tailings dam down when operation has ceased. Normally includes decommission, remediation (reclamation or rehabilitation) and after care at the site and for the tailings dam in particular.

Appendix B

Dam failure *Dammbrott*	An event resulting in the tailings dam structure failing to retain what it is designed and constructed to retain, causing an emergency situation due to the spill of tailings and/or water. Consequences can be human, environmental, economical or cultural. After closure a dam failure must not cause an emergency situation, as there will not be anyone on the site to act.
Dam incident *Dammincident*	An unexpected event that happens to a tailings dam that poses a threat to the over all dam safety and needs response quickly to avoid a likely dam failure.
Decommission *Avveckling*	Close down of operations and removal of unwanted structures, like infrastructure, buildings, pipelines, services etc..
Environment *Miljö*	Interrelated physical, chemical, biological, social, spiritual and cultural components that affect the growth and development of living organisms.
Erosion *Erosion*	Detachment and subsequent removal of material by wind, rain, wave action, freezing, thawing and other processes.
Hydraulic gradient *Hydraulisk gradient*	Difference in hydraulic head between two points divided by the travel distance between the points.
Long term phase *Långtidsfas*	The period of time for which closure is designed and that starts after completion of the after care phase. Often a period of 1 000 years or more.
Phreatic surface *Portryckslinje*	The surface between the zone of saturation and the zone of aeration; that surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere.
Probable maximum flood (PMF)	The most severe precipitation and/or snowmelt event considered reasonably possible at a particular geographic location. A site-specific determination, based on the possible range in meteorological and hydrological events and conditions. Variables include the duration, the area and the time of the year.
Remediation *Efterbehandling*	Measures required to secure the long term stability and environmental safety of structures like tailings dams and impoundments left at the mine site.

Rehabilitation *Efterbehandling*	Restoration of land affected by mining activities to its original land use. (Another word for closure, used primarily in countries other than the United States.)
Reclamation *Efterbehandling*	Restoration the land affected by mining activities into useful land use, not necessarily to its original use. The physical aspects of earth moving, regrading and revegetation.
Seepage point *Källsprång*	The point where the hydraulic gradient exit the downstream slope.
Tailings *Anrikningssand*	The fine-grained waste material remaining after the economically recoverable metals and minerals have been extracted. The material is rejected as worthless slurry at the "tail end" of the process with a particle size normally ranging from 10 μm to 1.0 mm. See 3 Tailings.
Tailings beach *"beach"*	The area of tailings between the edge of free water and the crest of the dam, resulting from the settled solid fraction of a tailings slurry deposited in the section of the pond not covered by free water.
Tailings dam (Tailings embankment or Tailings Disposal Dam) *Gruvdamm*	An artificial embankment, dam wall or outer impounding structure, designed to enable the tailings to settle and to retain tailings and process water.
Tailings impoundment *Sandmagasin*	The storage within the tailings dam, where tailings is deposited and stored. The extent of the impoundment is to the bounds of the tailings dams and/or natural boundaries.
Tailings management facility (TMF) *Gruvdammsanläggning*	The whole set of structures needed for the handling of tailings. Starting at the point where the tailings leave the plant to the point for final settling. See Figure 1.
Tailings pond or supernatant pond *Fri magasinsvattenyta*	The free water contained within the tailings impoundment.

Appendix B

Tailings sand *Anrikningssandens grovandel*	The sand obtained from the total tailings for use in construction of the tailings dam. Usually produced by cycloning the total tailings.
Tailings slimes *Anrikningssandens finandel*	The fine portion of the total tailings. Slimes generally range from a maximum particle size of about 75 μm to clay size.
Tailings slurry	The suspension of liquids (water) and solids (tailings).
Tailings storage facility (TSF) *Gruvdammsanläggning*	A facility used to confine tailings including tailings dam (impoundment and pond), decant structures and spillways. See Figure 1.
Weathering *Vittring*	Processes by which particles, rocks and minerals, are altered on exposure to surface temperature and pressure, and atmospheric agents such as air, water and biological activity.