



Seminar on

SAFE TAILINGS DAM CONSTRUCTIONS

Gällivare, 20-21 September 2001

Technical Papers



Swedish
Mining Association



EUROPEAN COMMISSION

DIRECTORATE-GENERAL

ENVIRONMENT

Directorate A – Sustainable Development and Policy Support

ENV.A2 – Sustainable Resources

SAFE TAILINGS DAMS CONSTRUCTIONS

Seminar in Gaellivare Sept 19-21, 2001

Agenda:

Sept 20

- 09.00- 09.20 Opening of seminar. Alexandre Paquot, DG Environment
- 09.20- 09.40 Introduction paper. Chairman of the seminar, Dr Arthur Penman UK
- 09.40- 10.10 The society and the role of the authorities. Olle Mill The Swedish Dam Safety Agency
- 10.10- 10.50 Safe dam constructions. Åke Nilsson SwedPower AB
- 10.50- 11.10 Coffee
- 11.10- 11.40 Tailings dam constructions. Annika Benckert Royal Inst. of Technology
- 11.40- 12.10 Discussions
- 12.10- 13.40 Lunch
- 13.40- 14.20 Risk analyses of tailings dam constructions. Dr A Penman
- 14.20- 15.00 Stability and environmental aspects of tailings dams. Dr N R Morgenstern, Alberta Canada
- 15.00- 15.40 Long term aspects on wet and dry covers of tailings dams. Dr S Vick, Denver USA
- 15.40- 16.00 Coffee
- 16.00- 16.20 Initiative by Swedish Mining Associations (SMA) to improve tailings dam safety. Fred Mellberg SMA
- 16.20- 16.40 Preparations for the BREF-notes on mine tailings inclusions. Nils Eriksson SMA
- 16.40- Discussions

Sept 21

- 09.00- 09.30 Presentation of the dam collapse at Boliden Aitik. Site Manager Rolf Ritzén Boliden
- 09.30- 10.00 Critical aspects of the dam collapse at Aitik. Richard Holmgren, the County Adm Board Luleå
- 10.00- 12.00 Site visit at Aitik
- 12.00- 13.30 Lunch at the mine
- 14.00- 15.00 Discussions
- 16.00 Bus transport to the airport



Why an EU initiative on Mining Waste ?



Commitment of the Commission in the Communication on the safety of mining activities *[COM(2000) 664 final]*

- Two major recent accidents (AznaIcollar, Baia Mare)
- 3 key initiatives
 - Seveso II (consultation process - Proposal in 2001)
 - Mining Waste Directive (consultation process)
 - BAT Reference Document on Tailings and Waste-Rock
- European Parliament : Resolution 19 June 2001
 - Strong support of Commission



Why an initiative on Mining Waste ?



Key environmental issues:

- Potential environmental risks during disposal
 - Safety of waste facilities (in particular dam safety)
 - Operational waste management issues (acid mine drainage, possible contamination of the environment)



Why a seminar on dam safety ?



- Join initiative Sweden / Commission
 - Part of a larger consultation process on the management of mining waste
 - Working document
(www.europa.eu.int/comm/environment/waste/mining.htm)
 - Meetings with Member States and stakeholders in July 2001
 - Written comments to working document
-



Legal Context



Waste Framework Directive 91/156/EC:

- Waste resulting from prospection, extraction, treatment and storage of mineral resources is covered by the waste framework Directive due to absence of specific Community legislation on mining waste
- Commission Communication clarifies this point



Legal Context



List of waste:

- Commission Decision 2001/118/EC (modification of the list of waste - amendment of Decision 2000/532/EC and Decision 94/3/EC)
- 'Mining waste' covered by Chapter 01 (waste resulting from exploration, mining, quarrying, physical and chemical treatment of minerals)
- Certain waste entries classified as hazardous



Legal Context



Landfill Directive 1999/31/EC

- 'Waste resulting from prospection, extraction, treatment and storage of mineral resources' covered except if non-hazardous and inert (Article 3.2)
- 'Mining Waste' non hazardous and non inert can be exempted from certain technical requirements (Article 3.3)
- Problems raised by the implementation of the Landfill Directive to the disposal of mining waste



Proposed approach



- **Preparation of a Directive**
- **Scope: all waste?**
- **Objectives: high level of environmental protection for the management of mining waste**
- **Main instruments discussed:**
 - Permitting conditions
 - General obligations for waste management
 - Waste characterisation
 - Safety of disposal installations
 - Closure plans and financial security
 - Inventory for remediation
 - Input from BAT Document for most technical decisions



Objectives of the seminar on Dam Safety



- Input from highly qualified international experts
- Public Authorities and Industry
- Technical and scientific approach
- Input to preparation of the Mining Waste Directive and the BAT Document



Objectives of the seminar on Dam Safety



- Mining operations without dams?
- Is it possible (and how) to ensure a very long term safety of tailing dams?
- No wet cover in the future?
- Which minimum sets of technical requirements during design, construction, operation, monitoring and closure of dams?
- ...

The society and the role of the authorities

Olle Mill¹

Introduction

In societies that care about dam safety, the normal aims with their actions are:

- To, as far as possible, ensure that dam accidents with serious consequences will not occur.
- To be prepared to mitigate the consequences in case of dam accidents.
- To make the dam safety situation transparent to the public.

How to achieve those aims probably requires different methods in different societies. In this paper I will briefly describe the Swedish way to handle dam safety.

The Swedish Background

There are approximately 10.000 dams in Sweden. About 190 hydropower dams and 15 tailings dams are high dams according to ICOLD's definition. I.e. the height from the foundation level to the crest is 15 meters or more. The estimated numbers of hydropower dams that are high consequence dams according to RIDAS² are about 100.

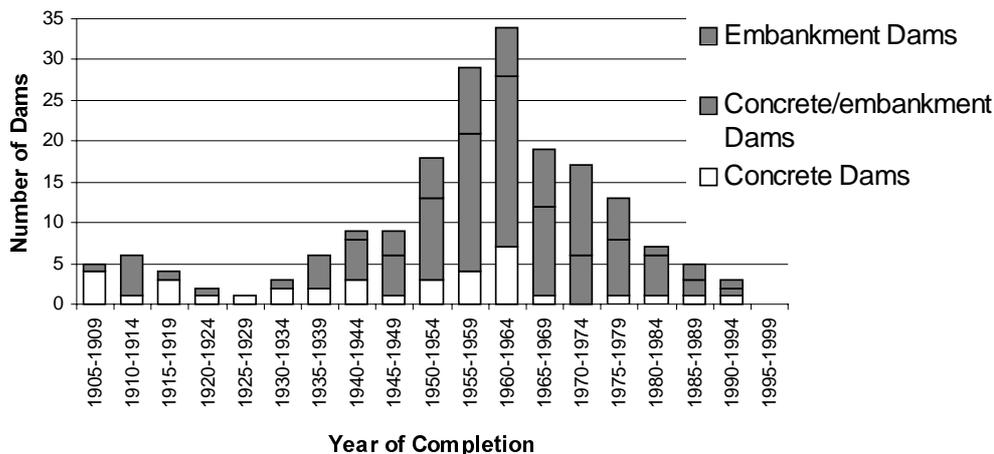


Figure 1. Large hydropower dams in Sweden arranged by year of completion. Source: ICOLD's World Register of Dams, 1998.

Construction of structures in water needs a permit issued by an environmental court. Most of the large dams have been examined under the old Water Act from 1918. There were no specific regulations about dam safety in that legislation. The main structure and layout was normally described in the application to the court, but it was up to the dam owner to decide the technical aspects in detail of design and construction of their dams. Most of the Swedish dams are consequently designed and constructed without intervention on technical aspects by the authorities. However the Swedish dam owners in general have been aware of their responsibility and used the knowledge and experience available at each time. They have also supported research and development in the field of dam design and management.

¹ Olle Mill, Svenska Kraftnät, Box 526, SE-162 15 VÄLLINGBY, Sweden. E-Mail olle.mill@svk.se.

² RIDAS is the Swedish dam safety guidelines provided by the Swedish Power Association (now Swedenergy).

The Swedish Power companies realized the need for consistent and common guidelines on maintenance and safety surveillance of dams in the middle of the 1960-ies. In 1968 the first guidelines was provided by VAST. The guidelines were modified in 1970.

Sweden has so far, with just a few exceptions, not experienced dam accidents with severe consequences. In 1973 a small dam in a tributary to the river Klarälven breached and one person was killed. Due to the accident, dam safety in Sweden was discussed in media, the Government and in the Parliament. As a result of this the county administrative boards were given legal means to take actions against owners who neglected to maintain their dams. An official commission with the assignment to prepare a bill for a new Water Act was now given an additional assignment to propose how to arrange authority surveillance of dams.

The Swedish Power Association³ also increased their dam safety efforts after the accident in 1973. VAST⁴ was assigned to provide guidelines in detail on how the member companies should manage their dam safety work. In 1977 VAST published “Recommendations regarding supervision of dam maintenance and safety.”

The Power Association with their members of private companies in collaboration with the state owned power company, Vattenfall, also established a special Board on dam safety with the assignment to prepare recommendations on dam safety supervision. Even though it was the power companies in collaboration that established the Board on dam safety, the Government found the initiative to be of great importance. In 1982 the Government appointed the members of the Board.

The task of the dam safety Board was to produce and publish reports with recommendations on maintenance and supervision of dams. The Board should also, on request, recommend skilled engineers qualified for examination and inspection of dams. The Board published notifications with advices on dam safety management from 1983 to 1999. The Dam Safety Board was dissolved in 1999 when Svenska Kraftnät was authorised by the government to undertake key central assignments within the dam safety arena.

The County Administrative Boards were assigned to be the supervisory authorities by the new Water Act that came into force in 1984. Although this meant new tasks for them to manage they were not reinforced. The advice from the Dam Safety Board therefore became important support to the County Administrative Boards. The Dam Safety Board established among other things a list of skilled people, with competence in dam safety, which the County Administrative Boards could consult if needed for examinations etc.

As a consequence of a flood situation in the river Oreälven in September 1985 the dam structure at Noppikoski power station collapsed. There were no casualties but the accident drew a lot of public attention in media. As a consequence of the event the Government assigned a special commission in December 1985 to analyse, “Dam safety and protection against flood”. The official report was delivered in 1987 (SOU 1987:64) and established that “the dam safety situation in Sweden is to a large extent good and it is on its way to become even better”. Anyhow the official report suggested among other things that the Water Act should be amended regarding dam safety aspects.

³ The Swedish Power Association was earlier the name of the trade association now reformed into Swedenergy.

⁴ VAST was the foundation for technical research and development of the Swedish Power Association at this time.

In the spring of 1985 the Swedish Power Association in collaboration with the Swedish Metrological and Hydrological Institute, SMHI, established a committee on design flood. Their final report that was published in 1990 stated that design flood had been underestimated in many cases. New guidelines for design flood were given in the report. The Power Association informed the Government on its conclusions and the decision of its members to act for and follow the new guidelines.

As a consequence of frequent floods and inundation of large areas in the early 1990-ies the Government assigned another commission on dam safety and protection against floods. The official report in 1995 (SOU 1995:40) like the earlier one stated, "the dam safety situation in Sweden is to a large extent good and is on its way to become even better". The report still suggested a number of improvements concerning regulation and supervision by the society, for instance:

- Establishing of coordinating structures for each river (later called river groups). "River groups" are networks for improvement of competence and communication.
- Establishment of a central authority in the field on dam safety and protection against flood.
- The authorities should participate in support of research and development as a complement to the existing support from the Power Association.
- A complete system for reporting of dam incidents.

In February 1997 a main document with general guidelines on dam safety, RIDAS, was provided by the Swedish Power Association. Besides technical advices the guidelines contains suggestions for management, supervision and maintenance and emergency planning. Standards and requirements in detail concerning the application of the advices in the main document were provided in year 2000. The mining companies in collaboration have decided and declared that they will follow the same guidelines when it is applicable. The Swedish Mining Association plans a special appendix to RIDAS concerning tailings dams.

Some County Administrative Boards, according to the suggestion in the official report, SOU 1995:40, have established river groups that now have existed for some years. The groups have done an important job in developing networks for improvement of competence and communication in the fields of dam safety and protection against floods but a lot more has to be done. One conclusion is that the river groups are a useful structure for handling those issues. The county administrative board convenes the groups once or twice a year for seminars and study tours. Participators are representatives from concerned organisations and authorities. For instance town planners and rescue planners in the municipalities along the river, dam owners, water regulating enterprises, Swedish National Road Administration, SMHI etc. The river group is not operational but each participating actor is so, in its own field.

Another result of the official report (SOU 1995:40) is that a central authority on dam safety is established since 1998. The Swedish utility that owns and operates the national electricity grid, Svenska Kraftnät, is authorized to follow the development in the field of dam safety and to act for improvements. The authority is also assigned to act for utilisation of possibilities to reduce damage caused by floods and support research concerning dam safety and flood issues. They shall also regularly report about the development in this field to the Government.

The Swedish Environmental Code that came into force on the 1st of January 1999 and an act with special regulations concerning activities in water (1998:812) enshrines those regulations earlier found in the Water Act of 1984. The assignment to the County Administrative Boards being the supervisory authority that since 1984 was stated in the Water Act is now regulated in the Environmental Code Chapter 26, and in a supplementary ordinance on the subject.

Basic principles in the Swedish Environmental Code

Swedish dam owners hold full responsibility and liability for their dams. A general set of rules and regulations for activities, which may have environmental consequences, are enshrined in the Environmental Code, which also governs water rights and dam safety. Within this set of rules and regulations there are also government ordinances concerning operator's control and the role of supervisory authorities. Some important sections relevant to dam safety are described briefly as follows.

About permission

- *A permit (by an environmental court) must be obtained for water operations within the meaning of the Environmental Code (EC). (EC chapter 11, section 9)*
- *“A judgement granting a permit for an activity shall, where appropriate, include provisions concerning:; 2. the purpose, situation, scope, safety and technical design of the activity; 3. supervision, inspections and checks;” (EC chapter 22, section 25)*
- *“Work may commence without prior permission if it is necessary due to damage or need to prevent damage, to without delay carry out alterations or repairs for which a permit is required. However, an application for approval of the operations shall be submitted as soon as possible.” (EC chapter 11, section 16)*
- *“Measures contrary to the provisions concerning the storage and release of water may be undertaken without prior permission where this is necessary in order to avert danger to life or health, to save valuable property or for similar reasons. However, an application for approval of the measures shall be submitted as soon as possible.” (EC chapter 11, section 16)*

About careful management

- *Persons who pursue an activity or take a measure, or intend to do so, must possess the knowledge that is necessary in view of the nature and scope of the activity or measure to protect human health and the environment against damage or detriment. (EC chapter 2, section 2)*
- *Persons who pursue an activity or take a measure, or intend to do so, shall implement preventive measures, comply with restrictions and take any other precautions that are necessary in order to prevent, hinder or combat damage or detriment to human health or the environment as a result of the activity or measure. For the same reason, the best available technology shall be used in connection with professional activities. ... (EC chapter 2, section 3 and 7)*

About maintenance

- *Owners of water structures shall maintain them in such a way to prevent damage being caused to public or private interests by changes in water conditions. (EC chapter 11, section 17)*
- *Persons who are responsible for maintaining a dam for water regulation are liable for damage caused by the failure of the dam to give the intended protection against*

escaping water (dam breach). This shall apply even when the damage is not caused either by the person responsible for maintenance or a person for whom the former is responsible. Nevertheless, where a person responsible for maintenance shows that the dam breach was caused by an act of war or similar act in connection with an armed conflict, civil war or rebellion, he shall not be held responsible. (EC chapter 11, section 18)

Operator's control

- Persons who pursue an activity or take a measure that may cause detriment to human health or affect the environment *shall continuously plan and monitor the activities* in order to combat or prevent such effects. (EC chapter 26, section 19)
- Persons who pursue such an activity or take such measure *shall also keep themselves informed, by carrying out investigations on their own initiative* or by other means, about the impact on the environment of the activity or measure. (EC chapter 26, section 19)
- At the request of the supervisory authority, a person who pursues such an activity *shall submit proposals for control programmes or remedial measures to the proper authority.* (EC chapter 26, section 19)
- The Government or the authority appointed by the Government may issue rules concerning controls. (EC chapter 26, section 19)
- In all activities there shall be established documentation of how the responsibility regarding compliance with the Environmental Code is shared. (Ordinance on Operators Control (1998:901))
- Persons who pursue an activity must have routines for continuous control that equipment etc, used to run and control the activity, are in good conditions in order to prevent detriment to human health or the environment. (Ordinance on Operators Control (1998:901))
- Persons who pursue an activity must continuously and systematically examine and assess the risks with the activity due to human health and the environment. The results from those examinations and assessments should be documented. (Ordinance on Operators Control (1998:901))
- An operational disturbance that would be harmful to human health or the environment should be reported to the Supervisory Authority (Ordinance on Operators Control 1998:901)

Supervision by the authorities

- The purpose of supervision shall be to ensure compliance with the objectives of the Environmental Code and rules issued in pursuance thereof. (EC chapter 26, section 1)
- For this purpose the Supervisory Authority shall, to the extent necessary, supervise compliance with the provisions of the Environmental Code and rules, judgements and other decisions issued in pursuance thereof and take any measures that are necessary to ensure that faults are corrected. (EC chapter 26, section 1)
- The supervisory authorities shall also contribute to attainment of the objectives of this Code by giving advice and information and similar activities. (EC chapter 26, section 1)

Supervisory authorities

There are 21 County Administrative Boards in Sweden, which are assigned to be the supervisory authorities on dam safety. Their supervision focuses on the operators routines for management and control of dam safety. The extent of operator's control and supervision of the authorities should be relative to potential consequences in case of a dam breach. Another important objective of the authorities is to attain transparency for the public.

Svenska Kraftnät – a central authority on dam safety

Svenska Kraftnät is a state-owned utility, which operates the Swedish national grid. In 1998 Svenska Kraftnät was authorised to undertake key central assignments within the dam safety arena. Flood mitigation and dam safety are subjects that the authority is dealing with. Svenska Kraftnät shall furthermore follow up the needs for research and development related to dam safety. The Government has also authorised Svenska Kraftnät to develop and implement a protocol for County Administrative Boards to follow for the supervision, follow-up and reporting of dam safety.

Svenska Kraftnät has appointed an advisory committee on dam safety. This comprises representatives from authorities and organisations concerned, and has 12 members and two deputies. The chairman is a lawyer who has gained experience in dam safety and the members are representatives of the power industry, the mining industry, the County Administrative Boards, the local authorities, the Swedish Meteorological and Hydrological Institute, the Swedish Rescue Services Agency and Svenska Kraftnät.

A suggestion to protocol for the County Administrative Boards to follow for the supervision of dam safety

As mentioned above Svenska Kraftnät has the assignment by the Government to develop and implement routines for the County Administrative Boards for supervision, follow-up and reporting of dam safety. The proposed routines are described in a preliminary report sent out for consideration on 18 June 2001.

The supervision of the authorities should be performed in ways that strengthen the ability of the owner to shoulder their responsibility. Examples of basic activities suggested for the supervisory authority are to keep a register on dams in the county and ask the dam owners for an annual report concerning their dam safety activities.

The intention with the proposal is to, by collection of key information give the authority a survey of the dam safety situation in the county. In this way the authority gets basic facts

- to select the most urgent dams for further supervision,
- for order of precedence in emergency planning,
- to make the dam safety situation transparent to the public.

A questionnaire form is proposed in which the dam owner is asked to answer questions about

- what dams he owns in the county,
- who is the person responsible for the dam safety on each of those dams,
- consequence classification for each dam,
- facts about control activities, inspections, examinations etc pursued by the owner,
- if any grave weakness exists concerning dams with serious consequences in case of dam breach,
- information about planned or carried out measures that can have importance for the dam safety.

The Swedish Dam Safety Guidelines – an initiative of the dam owners

As mentioned earlier in this paper, the Swedish Power Association provided general guidelines on dam safety, RIDAS, in 1997. The mining companies in collaboration have decided and declared that they will follow the guidelines as well when applicable. The mining companies of Sweden are planning a special appendix to RIDAS concerning tailings dams. The main document of RIDAS contains the general dam safety guidelines. Coupled to this are various standards and requirements, see *Figure 1* below.

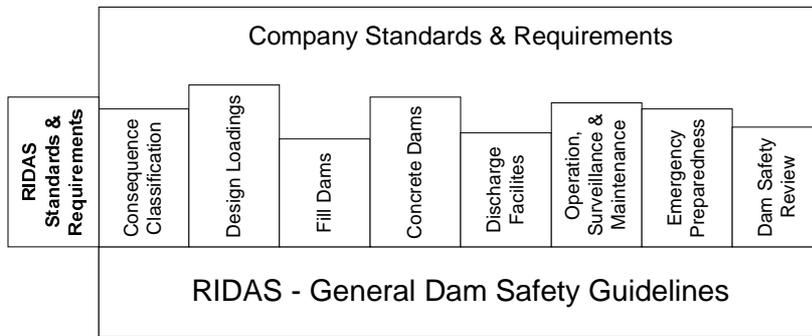


Figure 2. Structure of RIDAS, the Swedish Dam Safety Guidelines

On top of RIDAS, which defines the minimum requirements, the individual dam owner may apply its own requirements. Legislation does consequently not enforce the guidelines. Under the Environmental Code each dam owner is responsible for doing what is needed to ensure dam safety.

The Dam Safety Policy of the guidelines is presented in *Table 1*.

Table 1. Dam Safety Policy of RIDAS, the Swedish Dam Safety Guidelines

Dam owners shall
<ul style="list-style-type: none"> • design, construct, operate and maintain their dams so that <ul style="list-style-type: none"> - the risk for dam breach with serious consequences in as far as possible will be eliminated - the risk for damage to dams and operations disturbances will be kept at the lowest reasonable level
<ul style="list-style-type: none"> • by means of action plans be prepared to minimise the consequences in case of breach of or damage to a dam
<ul style="list-style-type: none"> • provide for good dam safety by means of quality assurance
<ul style="list-style-type: none"> • develop the dam safety in a long-term perspective

Consequence Classification of Dams

According to RIDAS dams are to be categorised with regard to the potential consequences of a dam failure. The classification involves four classes, 1A, 1B, 2 and 3, where class 1A represents the most severe consequences.

The consequence classification system is presented in two tables. Table 2.1 lists the risk of loss of human life or serious injuries. Table 2.2 supplements Table 2.1, listing societal, environmental and economic values that could be lost in a dam failure. The table stating the most serious consequence classification also decides the consequence class labelling of a dam.

Table 2.1 Classification as to the risk of loss of human life or serious injuries

Consequence class	Type of risk at failure	
1A	Evident risk of	loss of human life or serious injury.
1B	Not negligible risk of	loss of human life or serious injury.
2		
3		

Table 2.2 Classification as to the risk of damage to infrastructure, environment and property

Consequence class	Type of risk at failure	
1A	Evident risk of	severe damage on important traffic route, important dam or comparable facility, or to significant environmental values
	Evident risk of	major damage to economic values
1B	Considerable risk of	severe damage on important traffic route, important dam or comparable facility, or to significant environmental values
	Evident risk of	major damage to economic values
2	Not negligible risk of	Considerable damage to traffic route, dam or comparable facility, environmental values or property belonging to others than the dam owner.
3	Negligible risk of	Considerable damage to traffic route, dam or comparable facility, environmental values or property belonging to others than the dam owner.

Design Flood Determination

The Guidelines for Design Flood Determination have been incorporated into the RIDAS framework as one of the "standards & requirements"- documents described above. For high consequence (class 1) dams the guidelines propose a deterministic approach, similar to the probable maximum flood (PMF) procedure, with emphasis on critical timing of flood generating factors. The precipitation input is however not based on estimates on probable maximum precipitation (PMP), but rather on an evaluation of observed maximum rainfalls. For a low hazard dam the 100-year flood is used as the design flood.

Of the 1 000 hydropower stations and adherent dams about 500 have been subject for revised calculations at this stage. About 100 of these are regarded as high consequence dams. Necessary measures have been identified at some 40 dams. Measures have until now been

performed at about ten dams. Typical measures involve increasing of spillway capacity in order to safely release extreme inflows, and allowance for temporary storage above the normal high water level by raising the crest of the core.

The guidelines are developed for hydropower conditions, normally with large catchment areas. When it comes to tailings dams the catchment areas are often rather small. There is consequently a need for development of the guidelines on that point.

Conclusions

How to achieve the aims of the society concerning dam safety, requires probably different methods in different societies. The Swedish structure at present can briefly be described as follows

- The set of rules and regulations provided by the authorities are general.
- Each dam owner has the responsibility to consider what's needed to ensure dam safety.
- The trade associations of the power- and mining industries support the dam owners with development of guidelines, standards and requirements.

Some proposals to improvements in Sweden:

- Development and implementation of an appendix to RIDAS concerning tailings dams for improvement of safe management of tailings dams.
- Consideration and implementation of a protocol for the supervisory authorities to follow for improved supervision of dam safety.
- Development and implementation of guidelines for design flood determination for small catchment areas.

References

The Swedish Environmental Code (shortened in this document to EC)

Bergman M. 2001. Transfer and progress of knowledge in embankment dam engineering. ICOLD European symposium, June 2001, Geiranger, Norway.

RIDAS, Kraftföretagens riktlinjer för dammsäkerhet. 1997. VASO och Kraftverksföreningen

Flödeskommittén 1990. Riktlinjer för bestämning av dimensionerande flöden för dammanläggningar. Statens Vattenfallsverk, Svenska Kraftverksföreningen, SMHI

Dammsäkerhet, egenkontroll och tillsyn. Remissutgåva juni 2001. Svenska Kraftnät.

Safe dam constructions

Åke Nilsson

SwedPower AB, Dam Safety, P.O. Box 527, SE-162 16 Stockholm, Sweden.
ake.nilsson@swedpower.vattenfall.se

Orientation

The information compiled for this presentation has been extracted mainly from the Swedish Dam Safety Guidelines but also from guidelines from other countries such as Canada and Norway. In addition, the ICOLD Bulletins dealing with tailings facilities have been used, see references listed at the end of this description. Finally some of the figures have been collected from the Internet site www.antenna.nl/wise/uranium.

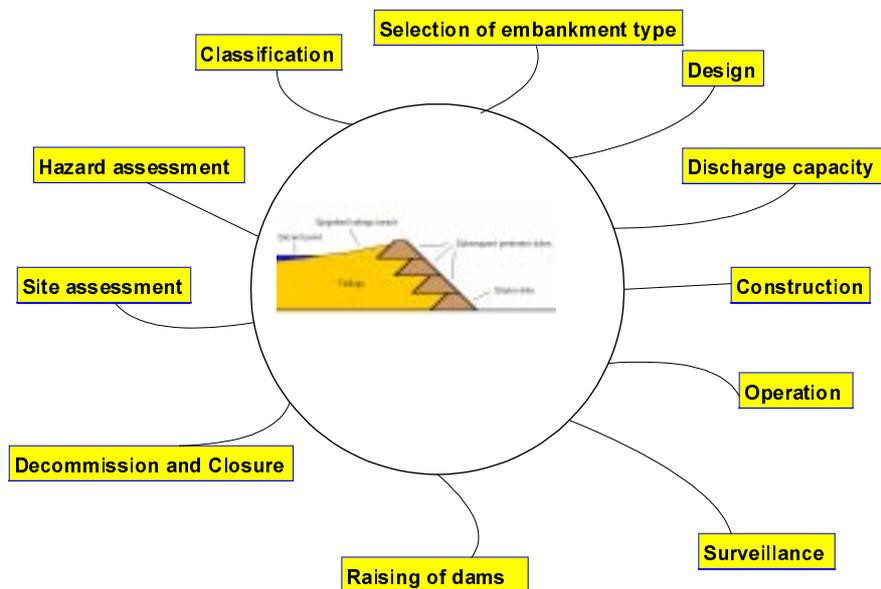


Figure 1 Dam safety management of tailings facility

Dam safety management of tailings dams comprises many parts as shown in **Figure 1**.

This presentation will comprise different parts of **dam safety management** and will be concentrating on the parts “classification”, “embankment types” and “surveillance”.

New Swedish Dam Safety Guidelines

In addition to main document of the “Dam Safety Guidelines” (a translation is available at this seminar) there is also a part with a detailed specification, where the meanings of guidelines as well as accepted design are covered in more detail.

The guidelines are now written for conventional dams (e.g. hydroelectric water retaining structures). However, the mining industry is planning to include a section for tailings dams in the next edition of the guideline.

Some of the elements in the guidelines are:

- Severity classification for a failure of the dam
- Hazards and design flood
- Embankment dams, concrete dams, discharge facilities
- Requirements for internal control systems (inspections, engineering inspections, reassessment reviews)
- Requirement for the dam to withstand large leakage
- Qualification requirements for personnel involved in with the operation and evaluation of dams.
- Emergency preparedness planning

In other countries tailings dams are incorporated in the dam safety guidelines e.g. the guidelines from Canadian Dam Association, January 1999, where the guidelines also apply to tailings or industrial dams, or perimeter containment structures around any tailings facility.

The main difference between a conventional dam and a tailings facility is the tailing dam operation phases as shown in **Figure 2**. Each phase has different dam safety requirements. In some tailings facilities surveillance in some kind will be needed hundreds of years after closure.

For conventional dams three faces can be identified (construction, operation and abandonment). These phases can not fully be compared to any of the phases in terms of design and other safety evaluation requirements.

Another difference is that for tailings dams there is a necessity for the design engineer's input all throughout the production phase. In the case of conventional dams, the design engineer's input ends shortly after the first filling when the dam is handed over to the operator.

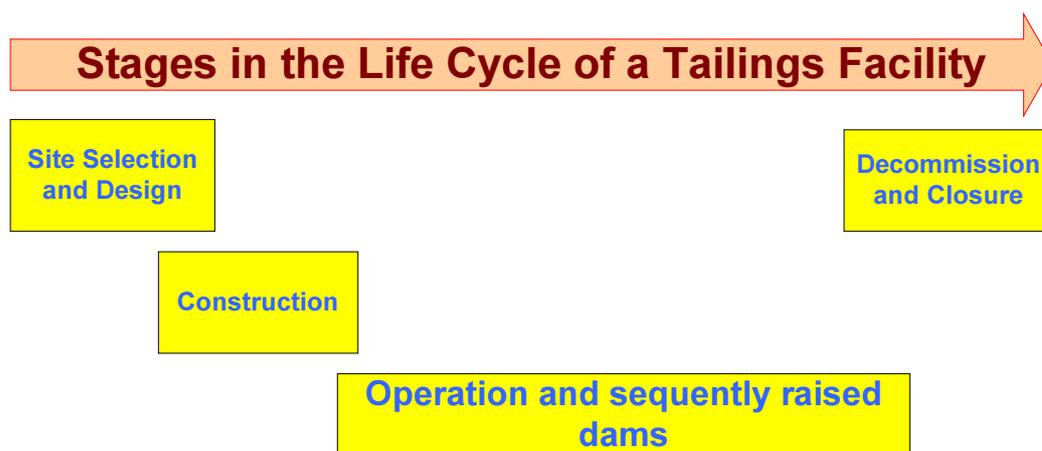


Figure 2 Stages in the life cycle of a tailings dam

Classification

The classification in accordance with the *Swedish guidelines* has been shown in se previous presentation in this seminar. In the detail requirements to the guidelines the economic value for *major damage* means that the is specified as damages above approximately 10 MEuro. ➔ category 1A eller 1B, and *moderate damages* on other properties means that the economic value will be less than approximately 0.5 MEuro ➔ category 2.

The Swedish classification can be compared with the *Norwegian classification* as shown in the following table.

Cosequence class		Affected dwelling units
Class 1	Low hazard	0
Class 2	Significant hazard dams	0 – 20
Class 3	High hazard dams	More than 20

Table 1 Classifications of dams in accordance with the Norwegian legislation

Relevant mapping and site visits shall be used as the bases for the assessment. Both class 3 and 2 are effecting housing units and have population at risk. The classification shall also consider e.g.

- Potential damaged of major roads or railways
- Economical and environmental damages

The final consequence class is thus subjected to a certain amount of judgement.

The classification and any re-classification shall be undertaken by those responsible and be presented to Norwegian Water Resources and Energy Directorate (NVE) for approval.

The *Spanish regulations*, see Table 2, have a similar classification as in Norway. However, the numbers of housing units are slightly different.

Dam Category	Risk for population	Essential Services	Material Damages	Environmental Damages
A	Serious effect on towns or more than 5 inhabited dwellings.	Serious	Very Serious	Very Serious
B	Would affect a small number of dwellings (from 1 to 5)	-	Serious	Serious
C	Incidental loss of life (no inhabited dwellings in the area)	-	Moderate	

Table 2 Classifications of dams in accordance with the Spanish legislation

Of the 1300 large dams in Spain, approximately 85% are classified into Category A.

Tailings Dam Types

Various classifications of tailings dams may be used for different purposes. The most known is the classification based on the methods of construction, upstream, downstream and centreline tailings dams, see *Figure 3*.

Types of sequentially raised tailings dams

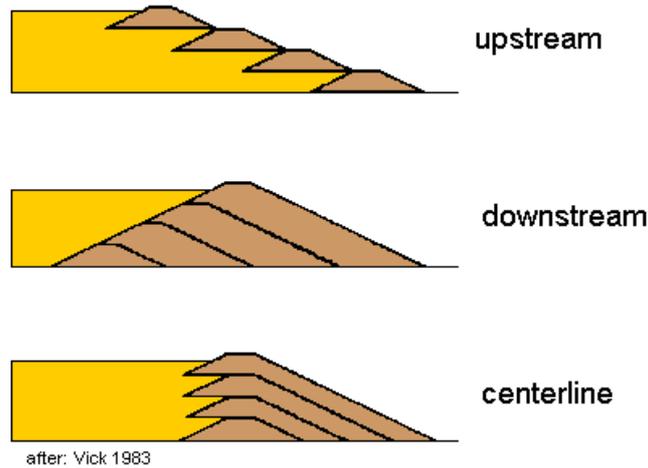


Figure 3
Types of sequentially raised tailing dams

Tailings dams are sometimes also constructed as traditional embankment dams, see *Figure 4*.

Water-retention type dam for tailings storage

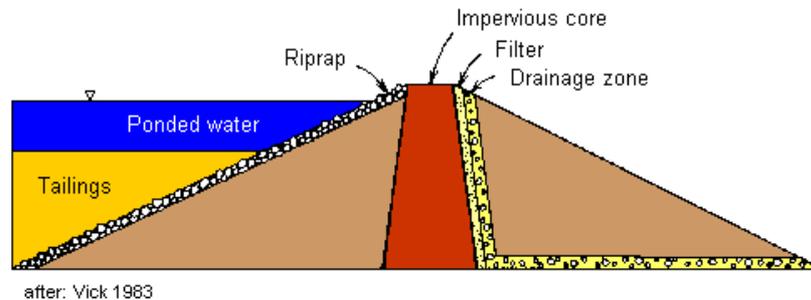


Figure 4 Tailings dam constructed as a traditional zoned embankment dam

Considering tailings dam closure phase following classification can be useful:

- Highly pervious (e.g. rockfill dam with upstream filter zone and tailings deposit serving as a semiimpervious element)
- Pervious (e.g. dam constructed entirely of tailings or other semi pervious materials)
- Low permeability (e.g. embankment type with core and grout curtain)

This classification allows for identifying a general preference as to the type of tailings for the closure design.

The third type with an impervious core could be urged to be the last desirable type, while the first highly permeable type would be best when considering long term physical stability.

The safety for different types can briefly be summarised in following points:

- The upstream construction method, while available at low cost, implies a number of specific hazards for dam stability.
- These hazards require a thorough assessment and continuous monitoring and control during siting, construction, and operation of the dam.
- Downstream-type and water-retention type embankments provide for better safety margins for dam stability
- Another option for a safer tailings management is paste disposal rather than slurry disposal

Failure modes

Usually following failure modes are considered:

- Instability
- Overtopping
- Internal erosion

Also the long-term safety and failure modes other than complete embankment failure should be considered e.g. such as seepage, dust, long-term erosion. Tailings may retain their hazard potential for hundreds of years, which requires efficient measures to contain these hazards in the long term.

From the report of the International Task Force for Assessing the Baia Mare and Baia Borsa Accident (Rumania in January and mars 2000) it can be seen that usually there is a combination of reasons for the failure:

The accidents were in summary caused by:

- Firstly, by the use of an inappropriate design
- Secondly, by the acceptance of that design by the permitting authorities; and
- Thirdly, by inadequate monitoring and dam construction, operation and maintenance.

Design faults:

- Use of a closed circuit with no specific provision for the emergency discharge/storage of excess water
- Inadequate dam wall construction due to lack of homogeneity of the tailings
- Non operation of the hydrocyclones in very low temperatures

Operational faults:

- Failure to observe the design requirements for tailings grades for embankment wall construction

Surveillance

In the dam safety guidelines there is usually a requirement for internal control system including a programme for inspection. For conventional Swedish dams there is following inspection program:

INSPECTION TYPE	FRECUENCE	PERSONNEL
Informal observations	Ongoing	Dam operators
Maintenance inspection	1 - 2 per year	Engineer/supervisor
Technical inspection	Every 3 or 6 year	Team of experts
Dam safety review (SEED)	Every 15 or 30 year	Team of experts

For tailings dam during the operation stage the following program may be more appropriate. The more frequent dam safety reviews could be justified when the dams are raised in stages every 3 or 5 year and the review is conducted in conjunction with the design for each stage raise.

INSPECTION TYPE	FRECUENCE	PERSONNEL
Dam surveillance (DS)	Ongoing	Dam operators
Dam safety inspection (DSI)	1 - 2 per year	Engineer
Dam safety review (DSR)	Every 3 - 5 years *)	Team of experts

After closure a much less frequent program may be appropriate e.g. in accordance with following table:

INSPECTION TYPE	FRECUENCE	PERSONNEL
Dam surveillance (DS)	-	-
Dam safety inspection (DSI)	1 per year	Engineer
Dam safety review (DSR)	Every 5 or 10 year *)	Team of experts

*) Consequence category high and low, respectively

The results of the different inspection types needs to be incorporated in a “Dam Safety Programme” illustrated in the following flow chart:

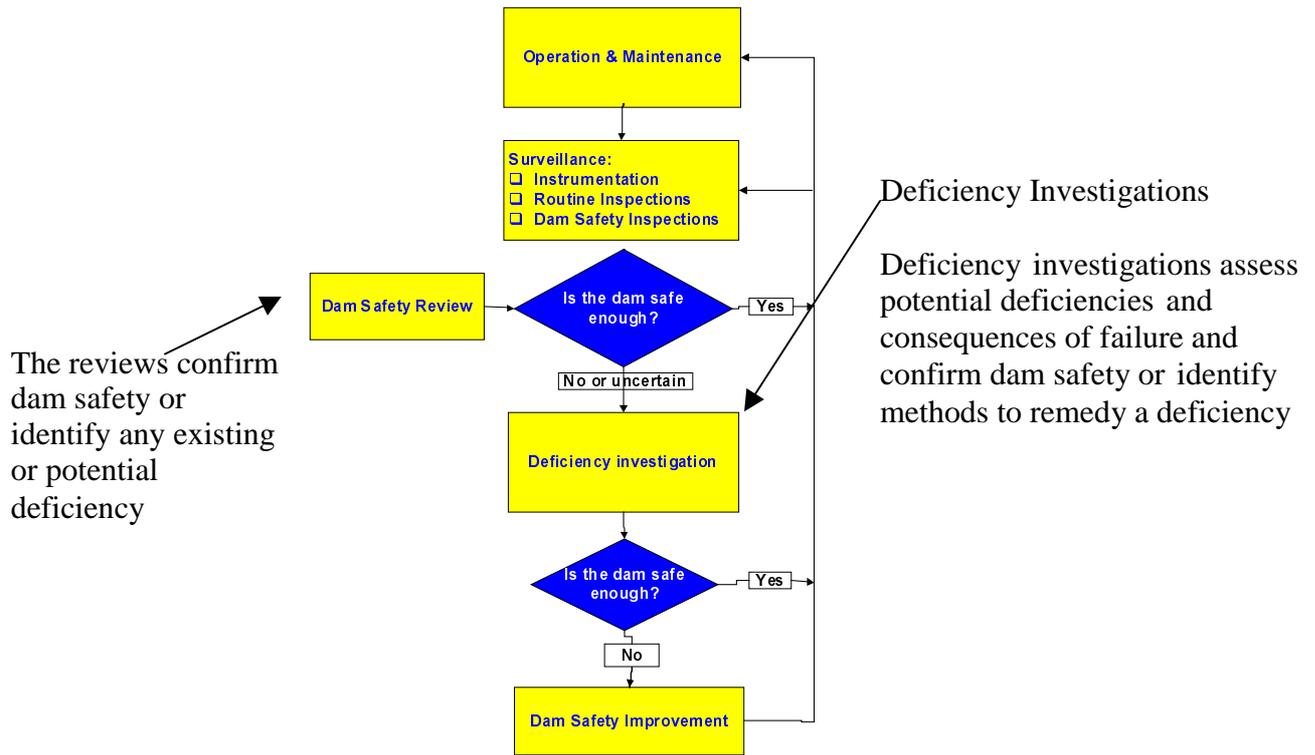


Figure 5 Different types of surveillance incorporated in a “Dam Safety Programme”

Design leakage

For a dam in the highest consequence category (1A and 1B) the supporting and drainage zones shall according the Swedish Dam Safety Guidelines withstand every possible leakage which possible can be expected during the life time for the dam. Especially important is to secure the toe of the dam.

For embankment dams many possible failure modes e.g. initiated by internal erosion results in seepage followed by slope unravelling or scouring at the downstream toe. The risk for a progressing failure is usually assessed assuming that the governing factors are discharge flow, toe-stone size and slope angle.

This requirement will result in that many of the Swedish embankment dams will be strengthened by toe berms in principle as shown in **Figure 6**.

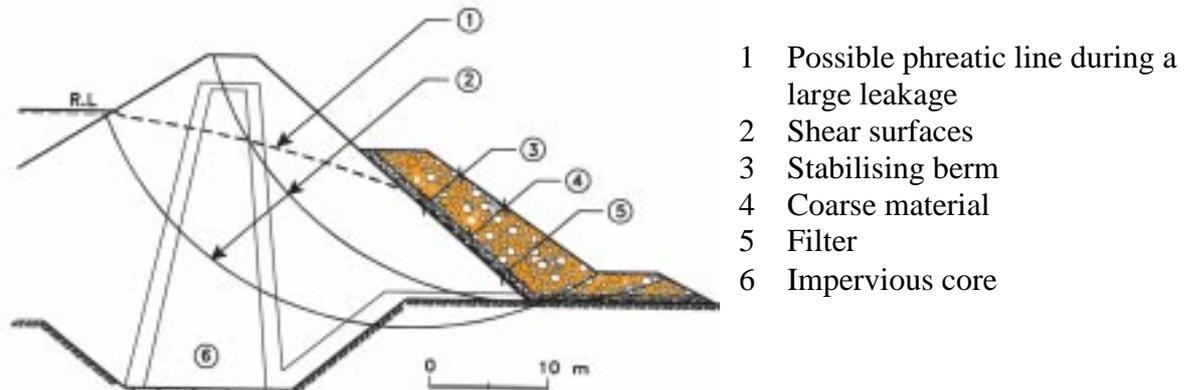
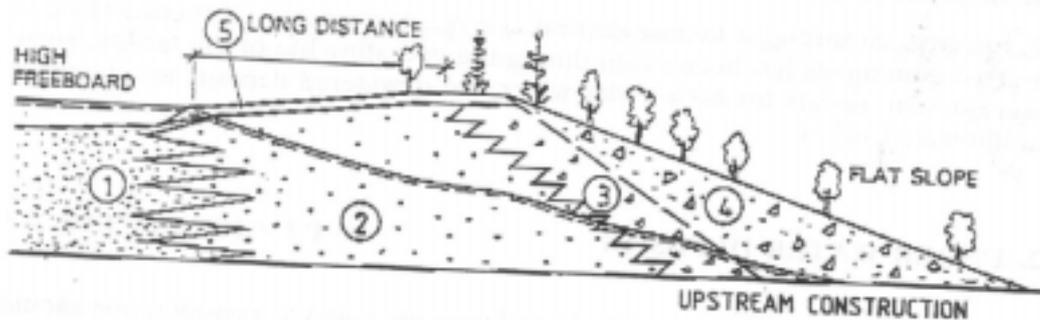


Figure 6 Strengthening of the downstream toe to withstand large leakage

Decommission and Closure

Decommission and closure have been comprehensively presented in the ICOLD Bulletin 103, (1996). The design for dams for under water deposits are shown in **Figure 7**. It should here be noted that the phreatic surface must be controlled by adequate drainage.



- 1 Fine tailings (from operation face)
- 2 Coarse tailings (from operation face)
- 3 Support fill (from operation face)
- 4 Support fill, long-term stable (modification on closure)
- 5 Impervious cover and erosion protection (modification on closure)

Figure 7 Closure of dams for under water deposits

Summary – conclusions

“Safe tailings facilities” require safety awareness throughout the whole process from planning to closure and in some cases hundreds of years thereafter.

There are large differences in the dam safety guidelines from country to country;

- The duties of regulatory agencies
- The guidelines are developed to different levels
- The consequence classifications varies
- The requirements varies for:
 - Dam safety reviews
 - Operation, maintenance and surveillance
 - Emergency preparedness planning
 - Qualifications for personnel involved etc.

“Dam Safety Guidelines for conventional dams” needs to be modified in order to also apply for tailings facilities.

References

- (1) Dam Safety Guidelines, Canadian Dam Association, 1999.
- (2) A Guide to the Management of Tailings Facilities, The Mining Association of Canada 1998.
- (3) Dam Safety Guidelines, 2001. Norwegian Water Resources and Energy Directorate

- (4) ICOLD Bulletin 74, 1989. Tailing Dam Safety, Guidelines.
- (5) ICOLD Bulletin 97, 1994. Tailing Dams Design of Drainage, Review and recommendations.
- (6) ICOLD Bulletin 101, 1995. Tailings dams – Transport, placement and decantation.
- (7) ICOLD Bulletin 103, 1996. Tailings dams and environment, Review and Recommendations.
- (8) ICOLD Bulletin 104, 1996. Monitoring of Tailings Dams, Review and recommendations.
- (9) ICOLD Bulletin 106, 1996. A Guide to Tailings Dams and Impoundments.
- (10) M. B. Szymanski, 1999. Tailings Dams – From the perspective of conventional dam engineering, CDAs annual conference in Sudbury 1999.
- (11) Dams in a European Context, 2001. Proceedings of the ICOLD European Symposium, Geiranger Norway.

Tailings dam constructions

Annika Benckert¹ and Jan Eurenus²

¹Royal Institute of Technology and Boliden Mineral AB, 936 81 BOLIDEN
annika.benckert@boliden.se

²Sweco AB, P.O. Box 34044, 100 26 STOCKHOLM

Abstract: Looking at the agenda of this seminar more or less all papers discuss the subject of this paper; Tailings dam construction. The subject “Tailings Dam Construction” will hopefully not be separable from the previous paper “Safe Dam Construction”. However, I will try not to repeat what others have written and still cover the subject of tailings dam construction including comparison of tailings dams and conventional water dams, design methods, Swedish tailings dams and Swedish philosophy for remediation.

Introduction

Tailings are a waste product from mining activities. The ore is in the process ground-up to a size less than 0.01-1.0 mm, the metal content is removed and left is the waste product -the tailings. Usually the tailings are pumped in a slurry form to a sedimentation pond, which is surrounded by natural heights and/or dams. As more and more tailings are deposited in the pond, the dams are continuously raised.

People in general are familiar with conventional water dams, but Tailings dams or ponds, on the other hand, are a construction hardly known by others than “experts” in the field. Still tailings are, by volume, probably the most handled product in the world (app. 25-30 Mt per year only in Sweden). This product, the tailings, contain remains from the ore, with possible negative impact on the environment if left unattended. Therefore specific measures has to be taken.

Comparison to Conventional water dams

Even though there are several similarities between water and tailings dams some significant differences exists. Table 1 highlights the main differences.

Firstly the tailings dam is constructed to store tailings (solids or saturated solids) and not just water. This will affect both design and methods of construction. The tailings dam will be exposed to different kind of loads, water pressure combined with the load from the tailings itself. There are always also a risk for liquefaction of the saturated tailings and liquefied tailings are capable of doing a lot more harm than plain water in case of a failure. The tailings dam is built in stages; as the tailings are deposited the surrounding dam wall is raised continuously. This makes the construction process an ongoing process for as long as the mine is operating. Review of the tailings facility therefore becomes very important to make sure existing conditions are incorporated at all times. The tailings can and are also often used as construction material for the dam wall. As a crushed material it will have a more angular shape than natural material and as a man made material the process to produce it can be

controlled which will give a more homogenous material. The choice of location differ as well, as a water dam is constructed to store water its location is chosen to get a catchment area as large as possible, but the Tailings dams, on the other hand, are usually located with a small catchment area, sometimes just the pond area itself. Problems due to flood control are therefore reduced compared to conventional water dams.

Secondly there is a big difference in that a conventional water dam technically can be removed when not needed, but a tailings dam can not, and will therefore be left for the future, i.e. thousands of years. This has been highlighted during the last decade and will be discussed later on in this paper, under “Remediation”.

Conventional water dams are often operated from a control room, sometimes not even located at the site. And from a control room a limited staff can be controlling several dams. During operation the mine site is always manned, which provides good resources for visual supervision of the tailings dam during operation. Skilled staff with the right training will therefore be an invaluable complement to instruments for operating the dam safely.

	Tailings dams	Water dams
Design objectives	Contain wastes from mineral processing (tailings) and some water (or saturated tailings) in a safe, stable and environmentally acceptable manner.	Safely contain and control water for any purpose.
Engineering design criteria	Static and seismic stability. Hydrology based on downstream flood, environmental risk and process needs.	Static and seismic stability. Hydrology based on downstream risk.
Environmental criteria	Minimise environmental impact to an acceptable level throughout construction, operation and closure. And minimise emissions to the surrounding environment throughout operation and after closure.	Minimise environmental impact.
Construction	Staged construction during operation to suit storage requirements.	Single construction phase.
Operation	Ongoing design, construction and storage control to meet waste disposal, environmental and flood control requirements.	Reservoir level operation.
Closure	Closure when mineral extraction/ processing ceases to create a safe and stable structure, and an environmentally sustainable closure solution for thousands of years.	No specific closure requirements, unless breaching is required for environmental reasons.

Table 1 Differences between tailings and water dams.

Design methods

Design methods for tailings dams vary a lot as it is affected by;

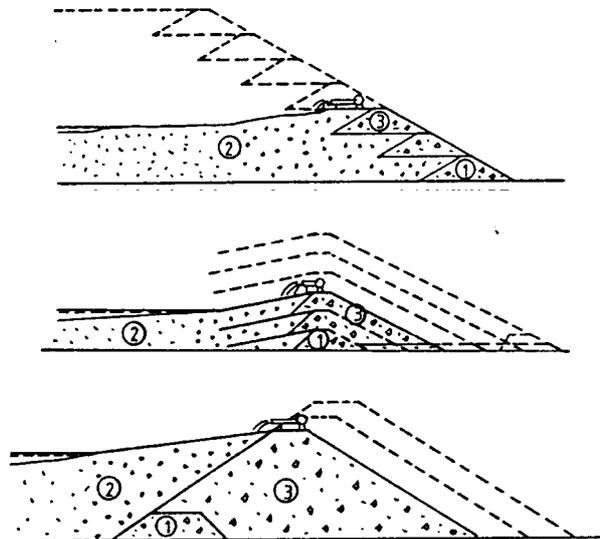
- tailings characteristics and mill output
- site characteristics as;
topography, hydrology, geology, groundwater, seismicity and available material
- disposal methods

There are almost as many different tailings dam construction methods, as there are tailings dams, but generally they can be divided into three different methods; upstream, centreline and downstream, see figure 1.

-With the upstream method the crest of the dam moves progressively upstream as the impoundment is raised. The method requires tailings with a coarse fraction large enough to form a stable foundation for the next raise. Economically the upstream method results in relatively low costs, as the material volumes needed are low. The weakness of this method is it's relatively sensitivity to construction method and seismicity.

-Using the downstream technique the crest of the dam wall moves progressively downstream as the impoundment is raised. For each raise the volume of material needed will increase exponentially, which will result in relatively high construction costs. The footprint area will successively increase as well. The downstream dam is not as sensitive as the upstream dam as the dam is built on "hard ground" instead of deposited tailings.

-With the centreline method the crest remains in a constant position in plan. The method is basically a combination of the upstream and downstream method and all qualities are in-between the qualities of the two other methods.



Figur 1 Upstream, Centreline and Downstream construction using tailings as construction material.

(① Starter wall, ② deposited tailings, ③ support fill)

To construct a safe tailings dam all objectives through all phases of a tailings dam has to be well understood and considered, and also continuously reviewed as conditions change with time. Management and operation also need to have the right knowledge and the right means of assistance.

Swedish Tailings dams

Sweden is a large mining company in Western Europe, but compared to the rest of the world we are not. Mining has been present in Sweden for over 1 000 years and evidence of this can be found at several places in the central and northern parts of Sweden. During the first half of the twentieth century mining companies dealt with the tailings them selves. During 1960 and 1970 expertise was consulted for advice and when problems arouse. On an average this kept one consultant specialised in tailings dams busy at half time. The mining companies civil engineering departments then started to close down and the need of consultants increased. Since 1996 the Swedish expertise in tailings dams has expanded to include 3-4 people, who keeps another handful of consultants busy. This fast expansion in the field of tailings dams is a result of increasing height of the dams, the publics and authorities increasing consciousness and the recent failures that have occurred. The mining industry as well as Universities and consultants are today very interested in increasing the knowledge in the field, which is mainly shown by ongoing research projects and conference attendance.

In Sweden basically three mining companies are operating today, namely;

- Boliden Mineral AB
- LKAB and
- Zinkgruvan Mining.

Together they operate eight tailings dams. Table 2 below shows some basic data for the main dam for these tailings dams.

Name	Start	Ore	Construction		Foundation material	Height	Capacity**	Owner
			type*	material				
Gillervattnet	1953	Zn,Cu, Pb,Ag, Au	ds	moraine	moraine	13 m	20 M(m ³)	Boliden
Ryllshytte-magasinet	1965	Cu,Zn	ds	moraine	moraine	19 m	6.5 M(m ³)	Boliden
Svappavaara	1965	From Kiruna	us	moraine	moraine	18 m	6 M(m ³)	LKAB
Aitik	1967	Cu,Ag, Au	us	moraine, tailings & waste rock	moraine	50 m	250 M(m ³)	Boliden
Enemossen	1976	Zn,Pb, Ag	ds, cl & us	moraine waste rock	moraine/rock	25 m	7 M(m ³)	Zinkgruvan Mining
Kiruna	1976	Fe	cl	moraine	moraine	15 m	10 M(m ³)	LKAB
Laisvall***	1978	Pb,Zn, Ag	us	tailings & moraine	moraine	40 m	20 M(m ³)	Boliden
Malmberget	1978	Fe	ds	moraine & waste rock	moraine	32 m	20 M(m ³)	LKAB

* ds = downstream, us = upstream and cl = centerline

** includes storage capacity for both tailings and water (clarification ponds excluded)

*** will be closed down at the end of the year.

Table 2 Data of Swedish tailings dams in operation 2001.

In addition to the data in Table 2 the following could be mentioned:

Moraine has very often been used as a construction material for Swedish tailings dams and the reason is simply the easy access, nearly 60% of Sweden is covered by moraine. The principal use of moraine is changing due to restrictions for use of natural construction material and as a result tailings and waste rock are becoming more and more commonly used. All tailings dams above have a separate water pond, clarification pond, for a second final sedimentation phase. Most of these dams also store water to be re-circulated back to the process. Water being discharged to recipient are strictly controlled and when needed lime is added. The largest clarification pond is situated at the Aitik mine and has a capacity of 15 M(m³) of water.

Some incidents have occurred in Sweden, all only minor incidents with regard to the environmental consequences. In the list below are the incidents known to the authors shortly mentioned.

- 1976 Malmberget: Leakage through the underground at first water fill before operation started. Part of the core was found to be deficient and was therefore removed and replaced.
- 1977 Zinkgruvan: Settlements due to leakage through the underground shortly after commissioning. The underground consists of fissure rock where the leakage took place. The ground was sealed on the upstream side using filters before tailings were deposited on top.
- 1996 Laisvall: Uncontrolled erosion at an internal dam due to earth works resulted in high flows into the pond downstream. A lot of water went through the emergency outlet in the downstream dam and caused some damage at this dam. The excess water that was discharged went over old remediated tailings dams to finally be collected in the clarification pond.
- 1997 Garpenberg: Leakage through the underground. Waste rock was placed on the downstream slope to stabilise the dam wall and the investigation showed that an over 100 years old pile of slag was imbedded in the foundation and crossing the dam body.
- 2000 Aitik: This dam failure will be presented in the paper; "Dam failure at the Aitik mine: Investigations, conclusions and measures taken" by Manfred Lindvall

Incidents nationally and internationally have highlighted the issue of dam safety. In Sweden dam safety became a field of interest within the mining industry in 1995. That year a thesis work at the Royal Institute of Technology included an inventory of all operating tailings dams in Sweden, and some remediated. In 1997 Boliden took the initiative to develop operation manuals (OMS-manual, Operation, Supervision and Maintenance manual) for each tailings dam. The manuals basically follow the new Swedish Dam Safety Guidelines (RIDAS). The other Swedish mining companies soon followed Boliden's example and today all tailings dams have a site specific operation manual. As for water dams are now tailings dams being subjected to Dam Safety Reviews by technical experts. Staffs at all levels are also going through suitable training programmes.

Remediation

The public's as well as the mining industry's increasing environmental consciousness over the last decade has resulted in "new environmentally thinking". The philosophy of tailings dam's remediation in Sweden has been the same as for nuclear wastes. The remediation of a tailings dam should therefore be designed to last until the next ice age, which anticipated is within

10 000 years. For design purposes the long-term is defined to be 1 000 years. But still, looking at this technically, one can easily understand the complexity to assure a structure to be stable for a period that long. The goal for the long-term phase is to reach a point when monitoring and surveillance is not needed and the “tailings dam” can be part of the nature.

A tailings dam goes through different phases, which generally are; operation, transition and the long-term phase. Environmental impacts occur during all phases, but are easier to control during operation of the mine. When the mining company leaves the site measures have to be taken to make sure the impact on the environment doesn't increase. These measures have to consider;

- environmental safety
- land productivity
- aesthetics

The main factors for an environmentally safe tailings dam are the physical and chemical stability of the dam. This can be achieved by using different methods. One common method is “the dry cover method”. The tailings will then be dewatered before the whole tailings dam is covered with suitable natural materials to prevent oxygen diffusion and infiltration. The second method is “the under water method” when the tailings are covered by water. The dry cover method possesses hardly any problems due to physical stability of the dam wall itself as all the water is removed, but to design and construct a cover with physical integrity lasting for the next 1 000 years some problems arise. The huge volume of natural material for the cover will lead to enormous costs and impacts on the environment. To put the tailings under water will on the other hand require a dam structure with capacity to withstand water pressure during the long-term phase, which often requires measures to be taken. Chemically the flooded method will be a more safe cover as long as the water cover is maintained. Other methods are constantly being investigated, for example “the saturated cover method”.

The fundamental failure mechanisms to consider for all cases are;

- long-term stability
- extreme events and
- slow deterioration

In the following the under water method will be considered, as the mechanisms above have a higher impact on this method.

-Long-term stability for a dam exposed to water pressure is basically defined by the phreatic surface. The flatter the phreatic surface the lesser is the risk of inner erosion and the higher will the stability of the dam become. (In some cases this is more easily achieved for upstream than for downstream embankments, especially if a downstream embankment has a core on the upstream slope.) If the angle of the phreatic surface is half the friction angle of the downstream material the dam wall can be said to be exposed to ground water instead of water pressure. This requires that the phreatic surface be situated well below the frost depth. This is only verified by experience, but has been the practise in Sweden for some years now.

-Extreme events are difficult to predict and design values tend to increase with time.

However, for tailings under water the most critical event in Sweden seem to be overtopping. To deal with this mechanism a tailings dam covered with water need proper outlets that have sufficient capacity. (In other countries factors like seismology might pose a more critical event.)

-Slow deterioration actions can harmfully affect the dam over time. Therefore the material used (both construction and cover material) has to be persistent natural material, which we in

Sweden fortunately have easy access to. No artificial material can be accepted for the long-term phase. Experiences and studies of natural formations similar to tailings dams indicate that a slope flatter than 1(V):3(H) has been stable for water and wind erosion, frost and weathering for the last 10 000 years (i.e. since the last ice-age). An angle flatter than 1:3 will also support vegetation, which will decrease the impact of slow deterioration actions.

Land productivity and aesthetics are also objectives to be considered after closure. The tailings dam should be remediated to form a natural part of the surroundings. Dam walls should be contoured in an aesthetical way and the area should be brought back to the same level of productive use as prior to mining. This must include wildlife, agriculture, forestry, recreation or otherwise acceptable from an environmental point of view.

References

- Annika Benckert & Pia Ahnström 1997. Thesis M Sc; "Gruvdammar, Planering, utformning och efterbehandling samt sammanställning av svenska förhållanden", (only in Swedish)
- Steven G. Vick 1990. "Planning, Design, and Analysis of Tailings Dams",
- Mike Cambridge 2001. Article in International Water Power & Dam Construction, May 2001
"A review of Tailings dam failures"
- Göransson, Benckert, Lindvall, Ritzén 2001. "Dam failure at the Aitik mine: Investigations, conclusions and measures taken".
- ICOLD Bulletin 74, 1989. Tailing Dam Safety, Guidelines
- ICOLD Bulletin 97, 1994. Tailings Dams Design of Drainage, Review and Recommendations
- ICOLD Bulletin 101, 1995. Tailings Dams – Transport, Placement and Decantation.
- ICOLD Bulletin 103, 1996. Tailings Dams and Environment, Review and Recommendations
- ICOLD Bulletin 104, 1996. Monitoring of Tailings Dams, Review and Recommendations
- ICOLD Bulletin 106, 1996. A Guide to Tailings Dams and Impoundments
- ICOLD/UNEP Bulletin 121, 2001. Tailings Dams, Risk of Dangerous Occurrences

Risk analyses of Tailings Dam constructions

A.D.M. Penman, Geotechnical Engineering Consultant, Harpenden, AL5 3PW, UK.

Chairman ICOLD Committee Tailings Dams and Waste Lagoons.

BACKGROUND.

Mankind required mining for the development of his civilization and for its continuation. Aeroplanes, trains, buses, cars and the fuel to drive them all come from materials extracted from the thin outer layer of our one world globe. Our industrial development has depended on metals and our demand for them continues, although many of the richest ore bodies have already been worked out and we have to use ores of ever lower metal content. This results in an increasing proportion of waste material for each amount of useful metal obtained from the ore.

The method used for extraction involves crushing the ore into small sized particles to produce a large surface area for the extraction of the metal, which may be less than 0.5% of the ore, leaving a great deal of fine rock particles as waste for disposal. The crushing and milling tends to produce particles of more angular shape than the smooth particles produced from the same rock by natural weathering, giving the waste material potentially better strength characteristics when it is placed and compacted as a fill, so that with correct design and construction methods, it can form a valuable civil engineering material for the construction of embankments. Clearly use of tailings for the construction of tailings dams is one of the cheapest methods, is attractive to mine management, and has been used for a long time.

After extraction of the useful metals from this crushed rock by a wet process, the waste material comes from the tail end of the processing plant as a wet slurry that is made to flow to the disposal site. The water content of this particulate material has to be made high enough for it to be pumped through pipelines, but for use as a construction material, the water content must be reduced. If it is to be compacted into place, the water content should be reduced to an optimum value. In the early days when crushing and milling was less

efficient, tailings often contained a range of particle sizes from coarse sand of 0.5 to 0.1 mm to fine silt of 0.06 to 0.006 mm. It was clearly of advantage to use the coarsest sizes for dam construction. Separation of sizes for one of the first methods of tailings dam construction, referred to as the upstream method, was effected by use of a beach. Tailings discharged from the dam crest flowed slowly down a fairly flat beach, allowing the coarsest sizes particles to settle out first, with ever finer material being deposited further down the beach leaving only the finest particles to be carried into a pond, where they settled out, and clear water was decanted, often down a vertical pipe tower for discharge through a culvert under the dam. Sections were added to the pipe tower as the level of the tailings in the impoundment rose, and the crest of the dam was slowly raised to keep ahead of the impoundment level and moved upstream to maintain a suitable downstream slope for the dam. Drainage and drying produced some suction in the pore water between the particles, tending to pull them together, but this was the only form of compaction commonly available. Tailings that had to be pumped through the delivery pipeline could come out with some velocity. This was turned to advantage by the development of simple hydro-cyclones to separate out the larger size particles. The cyclone consists of a steel cylinder with funnel shaped base and an entrance pipe coming in tangentially near the upper end of the cylinder. The rate of flow of the tailings causes it to rotate within the cylinder, throwing the larger sizes to the outside, leaving the finest material in the middle. A vertical pipe dips down from the upper end plate and the fine tailings flows through it to be discharged well into the impoundment. The coarse fraction falling from the funnel is used for dam construction, and in some cases can be machine compacted. Adjustable nozzles on the end of the funnel can be used to control the sizes of the particles included in this coarse fraction, but the volumes that can be used depend on the proportion of coarse particles in the tailings as delivered from the processing plant, and the volume required for dam construction has to be sufficient to keep it high enough to retain the impounded tailings.

Terzaghi described the principle of effective stresses in English for the first time in 1936, although he gave it in German in 1925. Geotechnical engineers are now very well aware of this principle that controls the strength of particulate materials and so are able to design tailings dams that can permanently retain these impoundments of waste tailings. A major problem is the control of water and the water content of the tailings forming the dams. The climate of the area for the impoundment plays a vital role. It is much easier to construct stable dams in regions of low rainfall and high evaporation as found in parts of South Africa, Australia and Central America, than where there is the reverse of low evaporation, high rainfalls and the possibility of frost.

Because of its greater density, tailings can cause much greater damage than water. The uncontrolled release of water from a reservoir due to dam failure can cause damaging floods, but it can flow through and around buildings without destroying them and persons may be rescued before they drown. But the release of liquefied tailings from an impoundment can destroy buildings and crops and cause the deaths of persons. The cost to a mining company of the failure of one of their tailings dams, in lost production, repair or construction of another means for tailings storage, repair to third party damage, compensation for loss of crops, livelihood and even life itself, is so great that it would not be expected for any mining company to take the risk. Engineering knowledge today is quite adequate to enable of the safe design, construction and maintenance of tailings dams. Yet throughout the world, they have failed at an average rate of 1.7 per year for the past 30 years. In many cases failure has been due to silly mistakes: a lack of full attention to detail. An exception may be due to the violent forces caused by earthquake, but even in highly seismic regions, types of construction and special provisions can be made to minimise the risk of major damage.

EXAMPLES OF FAILURES.

There were many impoundments retained by dams built by the upstream method associated with the copper mines in Chile. That country is subject to earthquakes and failures were not uncommon. A well known example is that of the El Cobre old dam, built

to a height of 33 m between 1930 and 1963, with a downstream slope of 1 on 1.2 to 1.4. Two years after its construction stopped, the area was struck by the 1965 La Ligua earthquake, which occurred during daylight. Eye witnesses said dust clouds came up from the dam, obstructing it from view as it failed, releasing the liquefied tailings to flow down the valley, engulfing the miners' village and continuing for a further 5 km. Many lives were lost. This failure and others in Chile, have been described by Dobry and Alvarez (1967).

The release of dust is typical of the failure of dry loess slopes and is caused by the volume reduction on shearing that occurs in loose particulate materials. Air from the voids is expelled, carrying dust with it. The downstream face of the dam had clearly been relatively dry before it disintegrated allowing the release of all the unconsolidated tailings slurry.

In Japan, the Mochikoshi impoundment was being built in a hollow near the top of a hill to store gold mine tailings and was retained by three tailings dams. These were being built by the upstream method from very sound starter dams made from the local volcanic soil. The dams were raised by building dykes from the volcanic soil placed on the beach and compacted. The impoundment was subjected to a ground acceleration of 0.25g from the Iso-Oshima earthquake of magnitude 7.0 that occurred on 14th January 1978. The highest of the three dams failed during the main shock, releasing 80,000 m³ of tailings contaminated by sodium cyanide through a breach 73 m wide and 14 m deep. The tailings flowed 30 km and into the Pacific Ocean. The second highest dam failed next day, 5 hrs. 20 mins. after an aftershock, releasing a further two to three thousand cubic metres of tailings through a breach 55 m wide and 12 m deep. These and other earthquake related failures led to recommendations that the downstream method of construction should be used in earthquake areas, rather than the upstream method. In this method, coarse material, possibly from cyclones, is placed on the downstream part of the dam where effective drainage measures can be employed and the fill can be compacted. Alternatively the dam can be built from borrowed fill, as with water retaining dams.

Stava At 12.23 on 19th July 1985 two tailings dams, one above the other and both built by the upstream method, collapsed. A total quantity of 190,000 m³ of tailings slurry was released and flowed, initially at a speed of 30 km/hr down into the narrow, steep sided valley of the Rio Stava, demolishing much of the nearby small village of Stava and continued, at increasing speed, estimated to have been 60 km/hr to another small town, Tesero about 4 km downstream, at its junction with the Avisio River in northern Italy. The only surviving eye-witness, a holiday maker, had the horrifying experience of watching the disaster from the hillside and saw the hotel where his family were taking lunch being swept away by the torrent of tailings. The damage caused by tailings is very much more than would be caused by the same flood of water, because the tailings are so heavy. Where water could flood a building, tailings can push it over and sweep it along with the flow. This failure caused 269 deaths.

The tailings dams as indicated by Fig.1, were for a fluoride mine that was begun in 1962 and were sited on a side slope of 1 on 8. The decant was in the form of a concrete culvert laid up the sloping floor, with coverable openings about every 0.5 m vertical rise. Water from the pond decanted into the openings, which were covered, one by one, as the level of the tailings rose. The lower dam was built by the upstream method to a slope of 1 on 1.23. When it reached a height of 19 m, the second dam was begun at the upstream end of the impoundment and built to a slope of 1 on 1.43. When it reached a height of 19 m, further planning consent was required. This was given on the condition that a 5 m wide berm was constructed at that level and permission given for the dam to be built to a height of 35 m. Construction continued at the same slope of 1 on 1.43 and the failure occurred when it was 29 m high. The cause is thought to be due to a combination of blockage and leakage from the culvert under the toe of the upper dam, thereby raising the phreatic surface sufficiently to cause a rotational slip, as indicated by Fig.1. Six months before the failure, a local slide occurred in the lower portion of the upper dam on its right side, in the area where the decant pipes pass underneath the dam, due to freezing the service pipe during a period of intense frost, according to Berti et al (1988). For the next three months water was observed

Fig. 1. Stava tailings dams. Detail shows concrete culvert with coverable openings for decanting.

seeping from the area of the slide. A month before the failure, the decant pipe underneath the lower impoundment fractured allowing the free water and liquid mud from the pond to escape towards the Stava river, creating a crater above the point of fracture. A bypass pipe had to be installed through the top portion of the lower dam, and the broken decant pipe blocked to restore use of the system. During this operation the water level in the upper impoundment was lowered as far as possible, then just four days before the failure, both ponds were filled and put back into normal operation. 53 minutes before the failure a power line crossing below the impoundments failed, then only 8 minutes before, a second power line failed. The tailings from the failure reached Tesero about 4 km distance, within a period of 5 to 6 minutes. As a result of this failure, the strict Italian law governing the design and construction of water retaining dams, according to Capuzzo (1990), is being extended to include tailings dams.

Merriespruit The Virginia No 15 tailings dam had been built by the 'paddock' method that is used extensively in South Africa's gold mining industry. It was a long dam encircling and retaining an impoundment of 154 ha holding $260 \times 10^6 \text{ m}^3$ of gold mine tailings containing cyanide and iron pyrite. The foundation soil was clay and drainage was required under the dams. General experience was that drains were often blocked by iron oxides and other residue. The impoundment formed one of several similar impoundments of the Harmony Gold Mine near Virginia in the Orange Free State. The suburb of Merriespruit containing about 250 houses had been built near the mine in 1956. Virginia No 15 lagoon was begun in 1974 and a straight northern section of the dam nearest the suburb was placed only 300 m from the nearest houses. Dam construction and filling of the lagoon continued until March 1993, when the section of the dam closest to the houses was 31 m high.

The summer of 1993/4 in the Orange Free State had been particularly wet and on the night of Tuesday 22nd February 1994 there were violent thunderstorms over Virginia and a cloudburst when 40 mm of rain fell in a very short time. The water level in the lagoon rose due to direct catchment: there was no stream or other natural source of water that came into the lagoon, which while operational, had a launder system that removed the transportation water decanted from the tailings slurry that had been delivered into the impoundment. During the early evening at about 19.00, water was found running down the streets and through gardens and an eye witness saw water going over the crest of the dam above the houses. The mining company and contractor were informed, but when their representatives reached the site it was already dark. One of the contractor's men rushed to the decants and found water lapping the top rings but not flowing into the decants. He removed several rings to try to get the water flowing, but the main pool was next to the north dam crest with no direct connection to the decants. At the same time, another contractor's man was near the downstream toe of the dam, and saw blocks of tailings toppling from a recently constructed buttress that had been built against a weak part of the dam. An attempt was made to raise the alarm, but before anyone had been contacted, there

Fig.2. Section of Virginia No.15 dam. (a) Critical section of dam during early stages of failure. (b) Critical section of dam during failure. (*from Blight 1997*).

was a loud bang, followed by a wave of liquefied tailings that rushed from the impoundment into the town. Cross sections of the dam during early stages and during failure, given by Blight (1997) are shown by Fig.2.

A breach 50 m wide formed through the dam, releasing $2.5 \times 10^6 \text{ m}^3$ of tailings that flowed for a distance of 1,960 m, covering an area of $520 \times 10^3 \text{ m}^2$. The flow passed through the suburb where the power of the very heavy liquefied tailings demolished everything in its path, houses, walls, street furniture and cars, carrying people and furniture with it. According to newspaper reports, people already in bed at about 21.00 hours when the mudflow struck, found themselves floating in their beds against the ceiling. 400 survivors

spent the night in the Virginia Community Hall, a kilometre away. Hetta Williamson said that her husband had gone back in daylight to their former home and found nothing but the foundations. It is remarkable that only 17 people were killed.

Apparently this north section of the enclosing dam had been showing signs of distress for several years, with water seeping and causing sloughing near the toe. A drained buttress constructed from compacted tailings had been built against a 90 m long section, but continued sloughing had caused the mine to stop putting the normal flow of tailings into the impoundment more than a year before the failure, i.e. the impoundment had been closed. At that time the freeboard was, according to the contractor, a respectable 1 m. But sloughing at the toe continued, and construction of the buttress was continued. Not long before the failure, slips had occurred in the lower downstream slope just above the buttress. In fact, although the placement of tailings had been stopped, wastewater containing some tailings continued to be placed and the water overflowed into the two decants. Unfortunately there formed a sufficient deposit of further tailings to cut off the decants and cause the main pool of water to move towards the crest of the north part of the dam, leaving a freeboard of only 0.3 m, and water was still being pumped into the impoundment from the mill on the night of the failure. Evidence of what had been going on since supposed closure was provided by satellite photography. A Landsat satellite passed over the area every 16 days and the infrared images revealed the positions of the tailings and the water pool.

Government Mining Regulations that had come into force in 1976, required a minimum freeboard of 0.5 m to be maintained at all times for this type of impoundment, to enable a 1 in 100 year rainstorm to be safely accommodated without causing overtopping. Evidence of the level of tailings in the Virginia No 15 lagoon showed that the tailings had been brought up to within 15 cms of crest level prior to abandoning this storage in March 1993. Had the government regulations required inspection of the dam, particularly at closure, the very small freeboard would have been noticed and a further raising of the dam crest enforced to prevent overtopping in the event of a maximum probable precipitation.

A failure at Baia Mare.

The expanding city of Baia Mare in Romania was beginning to encroach on old mining areas where there were disused impoundments of tailings. Removal of these impoundments and their retaining tailings dams would both release valuable land for city development and allow extraction of remaining metals from the old tailings. The scheme at Baia Mare involved construction of a new impoundment and a new efficient processing plant that would accept tailings removed from the old impoundments. Initially three were to be reworked and pipelines were laid out to transmit water from the new impoundment to be used for powerful jets that would cut into the old tailings, producing a slurry that would go to the new processing plant for extraction of remaining metals, with the tailings from it flowing to the new impoundment. The system used the same water going round and round with no interference with the environment.

Fig.3. Baia Mare. Plan of new impoundment showing position of eventual overtopping and breach.

The site for the new impoundment, well away from the city, was on almost level ground, with its main axis 1.5 km long, sloping down only 7 m from NE to SW with a width of about 0.6 km, as indicated by Fig.3. An outer perimeter bank 2 m high with 1 on 2 side slopes, as shown by Fig.4, was built from old tailings, and the whole area of about 90 ha, lined by HDPE sheet, anchored into the crest of the perimeter bank. Drainage was installed to collect any seepage, that would be pumped back so that there should be no escape of contaminated water into the environment. About 10 m inside the perimeter, starter dams

Fig.4. Section of perimeter bank and starter dam showing position of the HDPE sheet liner.

were built, also with 1 on 2 side slopes, to heights of about 5.5 m along the SW lower edge of the impoundment, tapering down to 2 m height about half way along the sides, with the remainder around the NE end of the impoundment, about 2 m high. Cyclones mounted along the crest of the SW starter dam and part way along the side starter dams accepted the tailings piped from the new processing plant, discharging the coarser fraction on to the downstream side to fill the space to the perimeter dam, and raise the whole dam, with the main volume of fine tailings slurry being discharged into the impoundment. Collected water was discharged into the central decant, drained through a 450 mm diameter outfall pipe embedded under the HDPE liner and pumped back to operate the monitoring jets in the first of the old impoundments, 6½ km away, and close to the city. Cyanide was used in the new processing plant for the extraction of gold, so that the tailings and water in the new impoundment contained considerable amounts of cyanide. No water should leak from the pipework circuit, although the water used in the cutting jets flowed over the unlined floor

of the old impoundment where it could soak into the ground. First discharge into the impoundment was in March 1999, and during the summer everything worked well, particularly during June, July and August when the average evaporation was 142 mm per month, although the delivered tailings did not contain quite as much coarse material as had been envisaged and the rate of height increase of the dams was lower than intended.

During the winter, however, conditions became greatly changed. The temperature fell below zero on 20 December and remained low during most of January, freezing the cyclones and producing a layer of ice over the impoundment, which became covered by snow. Tailings from the processing plant was warm enough to keep the operation working, but there was no further height increase for the dams because the cyclones were out of action. Precipitation during September to January averaged 71 mm per month and fell as rain and snow on both the whole area of the impoundment but also on the old tailings impoundments that were being worked. This extra water was stored in the impoundment causing the level to rise under the now thick layer of ice and snow.

On 27th January there was a marked change in the weather. The temperature rose above zero and there was a fall of 37 mm of rain. The ice and snow covering melted and the dams, half way along the sides of the impoundment, where they were only starter height, were lower than the developing water level. At 22.00 hours on 30th January 2000, a section overtopped, washing out a breach 25 m long that allowed the escape of about 100 000 m³ of heavily contaminated water that flowed following the natural slope of the area, towards the river Lopus. This in turn fed into the rivers Somes, Tisa and Danube, eventually discharging into the Black Sea. A very large number of fish were killed with serious consequences for the fishing industry for a time. The Hungarian authorities estimated the total fish kill to have been in excess of one thousand tonnes. Water intakes from the rivers had to be closed until the plume of toxic contaminate had passed and for some time afterwards until the purity of the water could be confirmed. The cyanide plume was measurable at the Danube delta, four weeks later and 2000 km from the spill source.

The concept of a closed system in which none of the process water should escape into the environment should have been excellent, with the new tailings impoundment

completely lined with plastic sheeting and provision for the collection of any seepage. Unfortunately no provision had been made for the additional water that would accrue from precipitation, nor had the problems of working at low temperatures been addressed. The scheme was one that could have worked well in the hot and dry conditions found in some parts of Australia and South Africa.

ICOLD INVOLVEMENT.

The Civil Engineering profession has become increasingly involved in the design of tailings dams, and mining companies engage dam experts both to assess the stability of many large existing tailings dams and to make designs for new dams. In particular dam engineering expertise is called for to advise on remedial measures when tailings dams, continually being raised, show signs of distress. The International Commission on Large Dams (ICOLD) had not considered tailings dams as dams worthy of consideration and when the World Register of Dams was first being compiled, tailings dams were specifically excluded. By the mid 1970's however there were many tailings dams higher than 100 m and following the greater involvement of dam design engineers in the problems of tailings dams, they were included as a subject for discussion by the 12th Congress on Large Dams, held in Mexico City in 1976. So much interest was expressed that ICOLD decided to establish a Committee to consider tailings dams. This Committee on Mine and Industrial Tailings Dams immediately began the task of preparing a Manual on Tailings Dams and Dumps, a Bibliography and, to compliment the World Register of Dams, a World Register of Tailings Dams. These three Bulletins were published in 1982. At that time, there were at least 8 tailings dams higher than 150m and 22 higher than 100m. It was estimated that tailings production exceeded 5×10^9 tons annually, far exceeding the volumes of fill involved in all civil engineering projects.

ICOLD has more than 80 member countries, spread throughout the world, from which the Committees can seek advice. Initially a Committee is limited to about 15 members and each must represent a different country. By seeking representatives from those countries heavily involved in mining, tailings dams and lagoons, the Committee contained within

itself a considerable expertise. In addition, when a new Bulletin has reached the stage of a final draft, this is sent to every member country for constructive criticism and a period of at least 6 months is set aside for their replies. Provided that all countries study the draft bulletins in detail and give their considered opinions, the ICOLD Bulletins contain a unique amount of worldwide knowledge. The Committee has continued to look at the problems confronting those involved with tailings dams and has prepared several more Bulletins. In view of the number and serious consequences of failures of tailings dams, advice on keeping them safe was of paramount importance. The failure of the two small tailings dams at Stava gave added emphasis and accelerated the work on a Bulletin (No.74) giving Guidelines on Tailings Dam Safety that was published in 1989.

Those familiar with the behaviour of homogeneous dams know the dangers of permitting the phreatic surface from rising too high under the downstream slope of the dam. In a water-retaining dam this is prevented by providing a filter drain mattress under the downstream part of the dam. This by itself may not be sufficiently effective. In the design by Terzaghi for the 50 m high Vigario dam, built in 1947 near Rio de Janeiro, a vertical wall filter drain was provided in the downstream shoulder to intercept pore water and guide it down into the mattress drain, thereby keeping the downstream part of the shoulder free from seeping water. This design has become known as the Brazilian section and has been used for many dams. The Vigario was renamed the Terzaghi dam in 1964. Clearly drainage plays a vital role in maintaining the stability of downstream shoulders and is essential for tailings dams. By the method of construction, it is extremely difficult to make Brazilian type sections for tailings dams, but correct drainage can vastly improve the safety of dams built by the economical upstream method. For this reason a Bulletin has been prepared describing good practice in provision of drains. Entitled 'Tailings Dams; Design of Drainage'. This Bulletin (No.97) was published in 1994.

As we have seen from many failures, tailings impoundments are susceptible to damage by earthquake, so the Committee's next concentrated effort was to make a review and recommendations on seismicity in relation to tailings dams. No embankment dam, designed and built to modern standards, has failed as a result of earthquake shaking, yet,

according to a recent compilation of tailings dams incidents worldwide (USCOLD 1993), tailings dams, particularly those built by the upstream method, are very prone to damage including failure, caused by shaking. The Bulletin (No.98) on Tailings Dams and Seismicity was published in 1995.

One of the most common causes of the failure of a tailings dam is due to “overtopping” by water from the pond. The transportation water, mixed with the tailings enabling them to flow through flumes and pipes, has to be efficiently removed from the impoundment together with any other water that enters as a result of rain and snow melt. This is usually done through a decant tower which is constantly raised as the impoundment grows higher. It often discharges through a culvert that passes through the dam itself. This can be damaged by excessive settlement of the tower due to negative skin friction from the surrounding settling tailings, or by crushing under the ever increasing weight of the impounded tailings. It can also be blocked by debris falling down the tower and collecting at its base. Any of these things, if not noticed, can lead to rising water level in the impoundment. With an upstream construction, the rising water can flood the beach, thereby getting into the more sandy downstream part of the shoulder, producing a very high phreatic surface that can cause failure even before the dam becomes overtopped. This often happens, but the failure is attributed to overtopping, because the first eye witnesses see water coming over the crest of the tailings dam where it has suffered settlement due to the slope failure caused by the high phreatic surface. The importance of these aspects has led the Committee to produce its publication Tailings Dams. Transport, Placement and Decantation: Bulletin 101. Bulletins 103 and 104 dealing with the environment and monitoring tailings dams followed this Bulletin. As an overall guide to the design, construction, use and rehabilitation the Committee has produced its particularly valuable Bulletin 106 (1996).

Despite all the advice given by these Bulletins, together with text books and many other papers, tailings dams continue to fail. During the last three decades the rate has averaged at 1.7 a year. The first year of the new millennium excelled itself by providing four failures, two in Romania, one in the far north of Sweden and one in the china-clay mines of Britain.

It is not that the safe methods for the design, construction and operation of tailings dams are not understood, but that somehow they are not correctly applied. In an attempt to draw to the attention of mine owners, managers and others associated with tailings dams, some of the silly things that can go wrong and the types of incidents that have caused failures, the Committee has drafted a Bulletin with the title, “Tailings Dams: Risk of dangerous occurrences. *Lessons learnt from practical experience.*” It contains 221 cases of incidents and failures, with general explanations about the types of reasons for these incidents. This latest Bulletin No. 121, has been published in conjunction with the United Nations Environmental Programme; an organisation that is taking an ever-increasing interest in tailings dams and the damage they can cause to the environment when they misbehave.

CONCLUSIONS.

Geotechnical knowledge with engineering experience can enable safe tailings dams to be designed and constructed, but the current rate of tailings dam failures that have averaged 1.7 a year during the past 30 years shows that this knowledge and experience has not been applied in every case. A failure can stop production, and clean-up operations, compensation for damage and in some cases death, plus finding new storage for tailings, can be so extremely expensive for a mine that it would be expected that every care would be taken to avoid failure. It would appear that management fail to engage staff able to understand tailings dams sufficiently to be able to detect deficient design or construction procedures, so that dangerous conditions can be allowed to persist until failure occurs. In order to improve the situation the International Commission on Large Dams with the United Nations Environmental Programme has recently published ICOLD Bulletin Number 121 that gives 221 examples of incidents with tailings dams and discusses causes, with the aim of helping those in charge of tailings dams to understand some of the simple mistakes that continue to occur.

REFERENCES.

Berti G, Villa F, Dovera D, Genevois R and Brauns J (1988). The disaster of Stava/Northern Italy. *Proc. Specialty Conf. "Hydraulic fill structures" GT Div/ASCE, Fort Collins, CO, pp 492-510.*

Blight G.E. (1997). Insight into tailings dam failures – technical and management factors. *Proc. Intn. Workshop on Managing the Risk of Tailings Disposal, Stockholm, Sweden, May, pp 17-34.*

Capuzzo D. (1990). A brief description of the main causes underlying the collapse of Stava tailings dams, Trento - Italy. *Proc. ICOLD Intn. Symp. Safety and Rehabilitation of Tailings Dams, Sydney, Australia, vol 2, pp.64-66.*

Dobry R. and Alvarez L. (1967). Seismic failures in Chilean tailings dams. *Jour. Soil Mech. and Fdn. Eng. A.S.C.E. vol 93, no. SM 6, pp. 237-260.*

Report, Cyanide Spill at Baia Mare, UNEP/OCHA Assessment Mission Report, April 2000. Available at www.natural-resources.org/environment/BaiaMare

ICOLD (2001). Bulletin 121. Tailings dams: Risk of dangerous occurrences. Lessons learnt from practical experience. *International Commission on Large Dams, 151, Boulevard Haussmann, 75008 PARIS. 144 pps.*

GEOTECHNICS AND MINE WASTE MANAGEMENT - UPDATE

Norbert R. Morgenstern
University Professor (Emeritus) of Civil Engineering
University of Alberta, Edmonton, Alberta, Canada T6G 2G7

Abstract: Experience in recent years within the mining industry, particularly with tailings dams and other aspects of mine waste management, indicates that the technical and managerial challenge of responsible mine waste management is under-recognized and that the contributions that geotechnical engineers can make to meet this challenge is under-appreciated. Conclusions will be drawn based on recent case histories of failures and successes. Recommendations are made for improved practice.

Introduction

Based on my experience in recent years with the mining industry, particularly with tailings dams and other aspects of waste management, it has become apparent that the technical and managerial challenge of responsible mine waste management is under-recognized and that the contributions that geotechnical engineers can make to meet this challenge is under-appreciated.

In the following, a table of selected recent failures of containments and dumps will be presented and a number of conclusions will be drawn from this evidence. The presentation concludes with recommendations for improved practice.

Selected Failures

Table 1, which is by no means complete, illustrates the wide range of mine waste structures that have failed since 1985, often with either loss of life or serious environmental consequences, and sometimes with both.

Failure of the Stava tailings dam (e.g., Berti et al., 1988) involved 269 deaths. Onerous legal action was taken against engineers and managers who had been involved in the dam. The examples of Cerro Negro No. 4 and Veta de Agua No. 1, in Chile, have been selected to illustrate the vulnerability of some tailings dams to earthquake loading. Ollinghouse is a minor structure, only 5 m high, that collapsed on saturation, with breach of the dam. The tailings flowed out a distance of 1.5 km. The dam was uncompacted and constructed without engineering supervision (USCOLD, 1994). That such practice can persist in 1985 is remarkable.

Jingshan is one of many recent failures in China. It involved a flow of 700,000 m³ of slimes, 19 deaths and 95 injured people (Author's files). Metachewan is interesting in that it was a non-operating mine. Following a breach of the tailings dam, this did not protect the responsible corporations from being fined and management indicted for non-compliance with environmental legislation in the Province of Ontario (Baker et al., 1996).

Catastrophic failures are not restricted to tailings dams. Greenhills was a non-active coal mine dump in British Columbia that collapsed and flowed. Failure resulted in 1 death. The failure of Coal Mountain dump in 1996, with resulting 2 deaths, indicates that the problem persists in the coal mining operations of British Columbia (Author's files).

Failure at Merriespruit resulted in 17 fatalities (Wagener et al., 1997). The Omai failure will be discussed briefly in a subsequent section. Marcopper involved failure of a drainage adit and

uncontrolled release of a substantial volume of tailings. The mine has closed and management have been under threat of criminal proceedings (Author's files). Porco Dam is a recent failure during construction of an upstream dam.

USCOLD (1994) lists 185 tailings dams incidents. Even this comprehensive synthesis is incomplete. For example, additional cases cited in the Financial Post (Canada) of October 3,1995, included the 1990 failure at the Brewster Gold Mine, South Carolina, the 1993 toxic leak from the Zortman Landusky Mine, Montana and the 1995 failure at the Gilt Edge Mine, South Dakota.

Problems are encountered in both developed and developing countries. Problems do not simply reflect past antiquated practice. Instead, they are a reflection of current practice in the industry. The database is compelling.

Table 1. - Some Recent Failures

<u>Site</u>	<u>Year</u>
Stava, Italy	1985
Cerro Negro No. 4, Chile	1985
Ollinghouse, U.S.A.	1985
Veja de Agua No. 1, Chile	1985
Jingshan, China	1986
Xishimen, China	1987
Metachewan, Canada	1990
Greenhills Dump, Canada	1993
Merriespruit, South Africa	1994
Omai, Guyana	1995
Marcopper, Phillippines	1996
Coal Mountain Dump, Canada	1996
Porco Dam, Bolivia	1996
Pinto Valley Mine	1997
Kennecott Copper	1998
Las Frailes	1998
Baia Mare	2000
Inez	2000

Conclusions:

Conclusion No. 1

There are too many failures involving mine waste containment structures.

Conclusion No. 2

The reliability of mine waste containment structures is among the lowest of earth structures and risk-taking on the part of all stake-holders is excessive.

Conclusion No. 3

Design and performance requirements have changed in recent years.

The mineral industry has always placed an emphasis on safety. Past tailings management practice also stressed minimum capital cost, minimum operating cost and simplicity. The traditional upstream construction tailings dam evolved out of this practice. Such dams are entirely suitable under certain circumstances.

Modern waste management practice must take a broader view. Safety is still paramount. Risk management must take a wider project view and costing of waste management should be related to total project cost. There are permitting considerations and environmental restraints to be considered. There are legal obligations and corporate responsibilities that flow to individuals at the highest corporate level, which need to be recognized. Lease-closure requirements should be factored in early in the planning for development and in the operation of a property. Many properties become dominated by waste-handling issues as they reach the end of their economic life. Finally, to operate successfully the mineral industry to-day requires a clearer understanding of its ethical standards, particularly within the context of sustainable development.

The case history of the Matchewan Consolidated Mines tailings dam failure provides an interesting example of the changing business environment (Baker, et al., 1996). The mine, in northern Ontario, operated first as a gold mine and then as a custom milling operation for other mines over the period from 1933 to 1953. Tailings containment was developed using the upstream method. After 1953 the site was left unmanaged until the time of failure.

The development of the tailings basin was such that it connected with nearby Otisse Lake. On October 17, 1990 a section of the tailings dam failed, releasing 190,000 m³ of tailings that caused considerable downstream environmental and property damage. The dam failure most likely resulted from the encroachment of Otisse Lake into the tailings basin. The water level of the Lake had risen over 2 metres since mine operations had ceased and this likely caused overtopping. However the possibility of failure by piping and/or liquefaction cannot be ruled out.

The primary cause of its failure was unchecked growth of a beaver dam at the outlet from Otisse lake which prevented water within the watershed of Otisse lake from flowing away from the tailings area. It had nothing to do with on-going operations of a mine.

Under the Environmental Protection Act an order was issued requiring the Mine and its principals to study the impact of the spill and to take measures to remediate it. They failed to comply. Subsequently court appearances occurred and convictions were obtained resulting in fines not only levied on the corporate structure but also on a director of the Mine, under the section of the Environmental Protection Act that relates to the duty of a Director or Officer of a company. Conviction under environmental legislation is a criminal matter.

The recent experience at Ok Tedi in Papua, New Guinea is also illustrative of the changing climate affecting waste management in the mineral industry. It had originally been planned to store tailings from this operation behind a tailings dam but the site was destroyed by a landslide during construction. Studies for a new site indicated that a suitable tailings dam could only be built with difficulty and considerable cost. Ultimately the Mine was given permission to discharge its tailings directly into a water course, ending up in the Fly River. The tailings are non-toxic and it was argued that the sediment load in the Fly River is already high.

The Mine operated in compliance with governmental regulations and the government had participation in it. Considerable aggradation developed on the Fly River and a class action was brought against the Mine on behalf of the people of the Fly River. Some early reaction in the industry considered this frivolous but it proved not to be so. Ultimately the matter was

settled with an agreement to seek to improve tailings management at a cost of many tens of million of dollars to the Mine.

To quote a senior mining executive:

"It is no longer just a question of having relevant government permits".

Conclusion No. 4

The technical requirements for design, construction and performance have never been more challenging.

Tailings dams are being constructed to unprecedented heights, over a wide range of foundation conditions, under diverse climates. In most instances closure is a design issue requiring considerations of longevity, sometimes involving mitigation of acid mine drainage, and ultimately passive maintenance of the resulting structure and contained deposits. Under some jurisdictions it is both difficult and time-consuming to permit new land for waste disposal structures and this provides an additional incentive to maximize the utilization of footprints on land already permitted.

In Chile the Los Leones Dam is under construction and it will be 160 m high measured from the dam axis (Edwards, 1994). As a result of the valley gradient, it is 135 m high at the upstream toe but 200 m high at the downstream toe, making it one of the highest tailings dams constructed in the world. Based on technical design restraints and availability of local construction materials, an earth fill dam constructed of local borrow materials has been selected as the appropriate structure.

In Arizona at the Cyprus Bagdad Mine operation the Upper Mammoth Dam is currently under construction. As planned, the ultimate structure will be about 210 m high (Beckwith, 1996). Permitting issues were a consideration in site selection and storage objectives. Foundation conditions are better than at Los Leones and the dam is being constructed in a centreline configuration with a downstream slope of 3:1. The pond from an adjacent tailings storage downstream will flood the downstream base of the Upper Mammoth Dam. Therefore the initial phase of the dam, to a height of about 75 m is being built by compacted cell construction, in advance of flooding. One innovation in this project is the use of an HDPE pipe under-drainage system to bring the sands to an appropriate compaction water content rapidly. No problems have been encountered in achieving 100% Standard Proctor Density.

Precedent setting heights obviously require strong foundations which are not always available. In Northern Québec a number of modest size tailings dams have been constructed on very soft deposits with initial undrained shear strengths in the range of 10-20 kPa. At several properties the question is being asked how high can one go with such structures. There is increasing pressure, from the perspective of both avoiding needless cost and complex permitting processes, to utilize such sites to their safe limit. These are challenging questions and their response requires a comprehensive understanding of modern soil mechanics.

Mineral development occurs within the full range of climate diversity. In some instances water is abundant, while in others it is scarce. Some process affected waters are benign and can be readily discharged to the environment while others must be stored and treated before discharge is permissible. Wet climates with intense rainfall are an impediment to construction affecting earthworks and eroding material already in place. Cold climates affect construction productivity but they may be used to advantage in some tailings disposal schemes. For example at the Raglan Mine in Northern Québec it is proposed to thicken the tailings and maintain them in a frozen state (Matich, 1996). Dry climates and the potential to utilize desiccation in design and construction have been a major factor in the evolution of tailings dams in the South African gold industry (Blight and Steffen 1979).

Conclusion No. 5

The geotechnical engineer is capable of responding to the needs of the mining industry given the appropriate fiscal and technical management environment.

Illustrations in support of this conclusion are provided by examples of tailings dams constructed for the oil sands industry. Geotechnical issues in this industry are summarized by Morgenstern, Fair and McRoberts (1988) and Morgenstern (1991). The two commercial mining operations, Suncor and Syncrude currently produce about 120×10^6 barrels of synthetic crude oil per year and the industry is poised for a major expansion. Tailings management are important issues in both current and future operations.

Tar Island Dyke (TID) was the first tailings dam constructed in the industry. Its history and performance are summarized by Mittal and Hardy (1977) and Morsey, Morgenstern, and Chan (1995). TID is a hydraulic fill structure about 3.5 km in length and up to 90 m high. It is founded in part on a deep stratum of alluvial clay and, in response to the high thrust developed, the structure has displayed a unique history of lateral creep.

TID was never intended to be this high. Some thirty years ago designers might even have judged that it would not be feasible to construct such a dam on a weak foundation. The initial characteristics of oil sand tailings were incorrectly evaluated and tailings and water storage requirements grossly underestimated. Recurrent innovation on the part of the original designer, the late Dr. R.M. Hardy, and subsequent collaborators account for the successful completion of this structure.

Entirely different foundation conditions control the main tailings dam at the nearby Syncrude Canada Ltd. This structure is a closed containment, about 18 km long with a height varying from 40 m to 88 m. In terms of volume of engineered fill, it appears to be the largest earth structure in the world. Design and performance have been summarized by Nicol (1994) and an advanced analysis of performance has been published by d'Alencar, Morgenstern and Chan (1994).

Parts of the foundation beneath this structure are controlled by glacial drag of high plasticity clay shales creating a foundation with extraordinary low strength. The residual strength is $8^\circ - 9^\circ$, high pore pressures are induced during construction and they dissipate only very slowly. These conditions were not invoked in the initial design, but the observational method was adopted in a consistent and comprehensive manner to make adjustments as the locally weak foundation conditions began to dominate performance. This required not only developments in instrumentation and monitoring protocols, but also evolution in design criteria. Ultimately it did not prove practical to control construction in terms of Factor of Safety and methods had to be developed to evaluate allowable strains in the restraining portions of the weak foundation. The ultimate configuration was tuned to accommodate the variable response of the foundation as it became better understood during construction.

Conclusion No. 6

The role of geotechnical engineering is not restricted to the design and construction of passive containment; it has much to offer in the development of new processes for waste management.

Thick mud discharge and paste technologies provide examples where geotechnical principles and process engineering converge to develop new and potentially useful disposal methods. Geotechnical contributions to fine tails management in the oil sand industry illustrates Conclusion No. 6.

In the oil sands industry tailings are disposed of by hydraulic means, some of the sand fraction being utilized for containment structures and the rest is placed in the pond. The stream out of the plant is a segregating mixture. On deposition for construction purposes or during

disposal itself, the fines fraction segregates and enters the pond on its own. This sediments relatively quickly to about 20% solids content, but the resulting fine tails mixture of silt and clay, with some sand consolidates thereafter only very slowly. Mature fine tails achieves a solids content of about 35% and there is only very slow consolidation beyond this, creating very substantial long term storage problems. In addition the release water contains substances such as naphthanic acids that are toxic to fish and that require some time to degrade. More details characterizing this fine tails issue have been presented by Morgenstern and Scott (1995).

It had been demonstrated that naphthanic acids degrade in natural systems and a strategy of long term containment of fine tails beneath water-capped lakes, that would act as a bio-reactor, had been developed for incorporation into closure planning. The industry was on its way to accumulating as much as $1 \times 10^9 \text{ m}^3$ of fluid fine tails that would require management in lakes for very long periods of time, in excess of the forecastable commercial life of the operations. While conceptually feasible, it is unattractive to absorb such long term liabilities and to rely on fluid retention structures for periods much in excess of engineering time scales. Moreover, the choices for reclamation of disturbed areas become more limited.

Many of these restrictions have been overcome by transforming the tailings stream into a non-segregating mixture. Geotechnical research showed that the addition of modest amounts of calcium based minerals, such as lime or gypsum, creates such a non-segregating mixture. Sedimentation is rapid and subsequent consolidation is also rapid and readily interpreted within the framework of finite strain consolidation theory. A sand-supported soil structure is formed with the fines in the interstices. The potential for dry landscape reclamation is greatly enhanced. Some details are provided by Caughill, Morgenstern and Scott (1993).

Both commercial mine operations have piloted this new technology, called CT (composite tails or consolidated tails) and are switching to it as rapidly as they can. It is one of the cornerstones underpinning the major new investment in the industry, projected for the next few years.

Conclusion No. 7

Design for lease closure is geotechnically intensive.

The mine operator is a temporary custodian of the land and the objectives of lease closure involve fundamentally a transfer of this custody. This transfer must be sensitive to the desires of a variety of stakeholders, depending upon the jurisdiction. Closure plans are more than simple reclamation as prescribed by government regulations. The ethic of sustainable development must be recognized and a balance struck between environmental performance, mine economics and residual liability. Mining regulations increasingly require closure plans as a condition for permitting.

Geotechnical engineering provides an understanding of the sub-strate and landforms that characterize the disturbed landscape following mining. This landscape can be engineered to develop groundwater and surface drainage conditions that will in turn exercise control on the biological productivity and diversity that will follow.

Closure design involves time frames that exceed the performance history of most engineered structures. A variety of perspectives can be utilized to overcome the limits of experience. They include the study of natural analogues to understand long term response of landforms, engineering critical structures so that they come into environmental equilibrium in shorter periods of times and designing for robustness that incorporates self-healing characteristics in the engineered landscape.

The integration of these considerations to provide a landscape that will evolve and which can be assessed by forecast performance indicators is being called Landscape Engineering. Geotechnical Engineering is an integral part of Landscape Engineering.

McKenna (1996) describes how Landscape Engineering is being utilized to assist Syncrude Canada Ltd., which has to consider some 200 km² of disturbed land, in their lease closure planning.

Conclusion No. 8

Mine waste materials are complex; sometimes they behave better than expected.

While mine waste streams do not display the heterogeneity of many natural deposits, they are invariably placed by processes that differ both from those encountered in nature and from those utilized in high performance earthworks. The geotechnical performance of a man-made deposit depends not only on its composition, but also on how it is placed. The control exercised by placement method should not be underestimated.

Following the collapse of several upstream construction tailings dams in Chile as a result of earthquake loading, the view emerged with some justification that this type of construction was intrinsically unsafe when subjected to severe earthquakes. Chile and some other countries no longer permitted upstream construction. However, as will be illustrated below, upstream construction can be developed under certain circumstances to form earthquake resistant structures.

In July, 1976 a major earthquake struck the Tangshan region of Hebei province in North China. It had a Magnitude $M=7.8$. This earthquake was the most damaging of this century since much of the city of Tangshan was destroyed. It was followed by another earthquake nearby with Magnitude $M=7.1$. Although one tailings dam collapsed, all other tailings dams in the region survived. They were all constructed using the upstream method.

To understand more about these dams, the Dashihe Dam was selected for study by a joint Canada-China team funded by the International Development Research Centre in Canada. The tailings arise from the concentration plant at the Dashihe Iron Mine.

The Dashihe Dam is a typical upstream tailings dam sealing off a natural storage area. In 1961 a 14 m high, 338 m long starter dyke was constructed of compacted sand and silt, overlying 10 m of silt, sand and cobbles on top of granite gneiss bedrock. By 1976 the tailings had reached a maximum height of 37 m at a rate of about 2 m per year. Tailings were spigotted from several locations along the 2 m high sub-dikes erected to facilitate construction. The downstream slope was 5:1. At the time of the earthquake the freeboard was 8 m. The average slope of the beach to about 50 m from the spiggotting points was 8% and from 50 to 300 m from the spiggotting points was 1.6%. The tailings tend to be coarse with only 21% finer than No. 200 mesh and the discharge concentration is low with a solids concentration of about 18%.

During operations prior to 1976 some seepage problems were encountered because of a very high phreatic surface in the downstream section of the tailings dam. In 1969, horizontal internal drains were installed on the inner slope of the starter dyke. But by 1976 these drains were not operating properly and in May, 1976 a large slide occurred on the outer slope. The initial drains were repaired and a number of vertical relief wells were installed. Fortunately, these measures lowered the phreatic surface by about 12 m just before the Tongshan earthquake in 1976. Additional drains were installed in 1980. However, as the tailings dam continued to rise in height the phreatic surface has also risen and at the time of investigation, water is again close to the downstream slope of the dam and to the crest of the starter dyke.

During the 1976 earthquake, the dam experienced minor cracking on the downstream slope. At the fifth sub-dyke, 10.7 m above the starter dyke, a number of fissures developed parallel to the dam axis. The widths of these were about 20-30 mm and they were about 10-20 m in length. Many sandboils and water spouts were observed on the beach near the pond. The largest sandboil was about 2 m in diameter. Fissures were also found parallel to the pond margin, between the pond and about 80 m from the crest. The closer to the pond, the

denser became the concentration of fissure. There were many tensile cracks, 20-700 mm wide, 3-10 m in length and up to 1 m in depth. These fissures were parallel to each other. The elevation drop across the fissures reached a maximum of about 0.5 m. From this, it is inferred that there was some sliding from the beach towards the pond. Sandboils and water spouts were also observed on parts of the saturated foundation soil downstream from the dam.

Details of the comprehensive site investigation, laboratory testing and analyses are found in reports by the study team. The site studies conducted in 1990 included mud rotary boreholes with Standard Penetration Tests (SPT), sampling (with post sampling freezing), Cone Penetration Testing (CPT), shear wave velocity measurements, nuclear logging and trial pits. Several cross-sections were investigated. Laboratory testing involved both undisturbed piston samples and reconstituted samples. Analyses for liquefaction were carried out using the empirical approach developed by Seed et al (1984) based on field observations from previous earthquakes and SPT data, as well as non-linear finite element analyses using a computer program (TARA-3) developed at the University of British Columbia.

The sections developed revealed sandy soils grading finer with increasing distance from the downstream slope, which is consistent with construction by spigotting from the crest of sub-dykes and the formation of long gentle beaches. As a result of upstream construction, the crest had migrated over former pond deposits. It was particularly interesting to find that the soils that make up most of the dam were medium dense. This was supported by all in-situ tests. The finer soils closer to the pond were weaker and produced smaller penetration resistance values.

Both empirical and advanced analyses predicted liquefaction in some areas of the beach close to the pond but relatively low pore pressures were predicted under the crest and adjacent to the downstream slope of the dam. The results of analyses, including calculated displacements, were generally consistent with the description of post-earthquake damage.

Contrary to prior expectations, this study showed that tailings dams constructed using the upstream method can withstand significant earthquake loading providing certain techniques are followed. The main features of the Dashibe Tailings Dam that appear to have improved its stability during the 1976 earthquake are as follows:

- 1) Tailings Deposition – The tailings are deposited onto a long gentle beach that allows segregation of the tailings and the formation of relatively dense deposits of sand soil. No sands are deposited under water. The fine tails enter the pond. The tailings concentration is low and beach seepage gradients likely contribute to densification.
- 2) Downstream Slope – The downstream slope at Dashibe is about 5(H):1(V). This relatively flat slope produces low static shear stresses making it harder to trigger flow liquefaction behavior.

Conclusion No. 9

Mine waste materials are complex; sometimes they behave worse than expected.

The same preamble following Conclusion No. 8 can be repeated here. The geotechnical performance of a man-made deposit depends not only on its composition, but also on how it is placed. The control exercised by placement method should not be underestimated.

Waste dumps constructed under seemingly dry conditions are among the simplest of geotechnical structures and, provided they are located on strong foundations, might be thought to present few problems. Unfortunately this has not proven to be the case in the coal industry of British Columbia.

There are currently ten Western Canadian Rocky Mountain coal mines producing about 30 million tonnes of coal mainly for the export metallurgical market. These mines haul about 200-250 million bank cubic metres of waste rock per year. Mining is carried out in steep

mountainous terrain and haulage costs are very sensitive to the proximity of the free dump waste piles to the pit areas. Since the late 1960's, when higher production mining was initiated, there have been incidences of long runout waste dump flowslides, mostly in the British Columbia mountain coal mines. The number of incidences increased during the 1980's as coal production increased. Background information, case histories and an explanation of these features may be found in (Dawson, Morgenstern and Stokes, 1998).

These waste dumps are typically end-dumped fills placed on foundation slopes steeper than 15°. The foundation materials overlying bedrock typically consist of granular colluvium derived from weathering and slope wash and/or alpine dense strong glacial tills.

There have been about 50 high runout failures during the last 25 years with a mean runout of 980 m and a maximum exceeding 3,000 m. An industrial survey conducted at 31 active mine sites documented 18 instabilities (minor sloughs and slumps not included) out of 81 individual dumps. About 14 of these failures occurred at coal mines, suggesting that up to 30% of active coal mine waste dumps are potential high runout flowslide hazards. Most dumps with substantial runout were founded on dense till or colluvium. Failures of dumps, including fatalities, have occurred at abandoned dumps indicating that the processes triggering mobility are not uniquely tied to active dumping. Fortunately, many of these dumps are in remote areas and the consequences of failure have often been minimal. However, this has not always been the case and it is essential that these processes be understood so that risks associated with waste dumps can be managed in a rational manner.

Detailed field, laboratory and theoretical studies have shown that the most plausible failure mechanism is static collapse inducing liquefaction flowslides. The materials composing the dumps are sandy gravels in grain size and they form layers parallel to the dump face as a result of end-dumping. They exhibit collapse behaviour at void ratios greater than 0.3, which readily develops in the upper 50 m of the dump. Water is needed to generate high pore pressure. Limited perch water from captured snow, infiltration or blocked springs is adequate to facilitate liquefaction. High mobility results from the strain-weakening behaviour of the loose fill.

Geotechnical engineering is not only capable of explaining these otherwise enigmatic and dangerous events but is also capable of outlining practical means to mitigate them.

Conclusion No. 10

Case histories reveal that risk is not generated by technical limitations alone.

Stava Tailings Dam

On July 19, 1985 two upstream construction tailings dams near Stava, Italy failed catastrophically, resulting in the destruction of two villages and causing extensive property damage. A total of 190,000 m³ of liquefied tailings flowed down the Stava valley resulting in the loss of 269 lives. The flow reached the village of Tesero, a distance of 4 km from the mine, in only minutes. The failures occurred without any warning and are not attributed to earthquake shaking or storm water flooding.

A history of the dams and explanations of failure have been published by Berti et al. (1988), Genevois and Tecca (1993) and Chandler and Tosatti (1995). The Author and Dr. E. D'Appolonia were also involved in a forensic investigation after the failure (D'Appolonia and Morgenstern, 1988) and our reasons for the failure which have not been published previously, will be presented here.

Construction of the lower dam began in 1961. Once the 9 m high starter dam was constructed of locally available material, the lower dam was raised by use of two moveable hydrocyclones, building the dam in an upstream fashion. Sands deposited by the cyclone formed the shell of the dam, with finer particles carried further onto the beach areas. The sand

shell was never compacted. Supernatant water formed in a pond at a distance from the dam and was decanted and recycled. The downstream slope of the lower dam was constructed with an angle of about 32° to an ultimate height of about 26 m. The pond water appears to have been kept back from the sand shell at all times during this period of operation.

Construction of the upper dam began around 1970. The design followed the methods used for the lower dam. No foundation improvements were involved and shallow groundwater flow was noted during excavation operations for the 5 m high starter dam. Expansion of the dam was initially by the centreline method using the hydrocyclone. The downstream slope was 39° requiring shallow stabilization. When a dam height of about 3-5 m was reached, operations converted to the upstream method.

Once a dam height of 14-19 m was reached a stability analysis was performed and the design was modified. A 4-5 m wide bench was left on the crest of the dam, after which construction continued by the upstream method. The downstream slope was maintained at 34°. The pond water was kept back from the sand shell and a program of routine inspection was maintained. No problems were encountered with either dam during this period of operation. In 1978 the mine shut down and the dams were abandoned. At that time 260,000 m³ of tailings had been stored and the height of the upper dam was about 28 m. A pond was maintained in both dams to manage precipitation runoff.

Under new ownership, mining operations recommenced in 1982. At this time, the technique of embankment construction was switched from hydraulic to mechanical placement. Soils for embankment construction were obtained from areas near the upstream edge of the supernatant pond, above the tailings dam. This material, consisting of sands and gravels, was placed in a somewhat segregated manner. Routine inspection of the facility was not carried out by the new owner.

Tailings were deposited through a single fixed cyclone which was located on the left side (looking downstream) of the basin. This manner of deposition resulted in a significantly flatter beach deposit, allowing pond water to encroach on the dam. Eventually, the cyclone was completely abandoned in favour of a single, fixed spigot point discharge. Tailings deposited in this area formed a sloping delta, displacing the pond water, and allowing the pond to encroach on the main embankment.

In January, 1985 a small slump occurred on the lower slopes on the right side of the upper dam and a sinkhole formed in the upper basin. At the time, this was attributed to the freezing and plugging of a decant pipe which was located in the same general vicinity as the slump. In early July, 1985 a 30 m wide, 3 m deep sinkhole formed in the lower basin. Water and slimes flowed into this sink hole and into the decant pipe, draining the lower basin. Both basins were drained for about a week in order to repair this decant pipe.

On July 15, 1985 both basins were refilled with water. Water in the upper dam was allowed to rise about 2 m (1-2 m below the crest) in 2 ½ days. Collapse occurred a few days later.

Previous studies have speculated that the proximate cause of failure was: 1) malfunction of the decant system or 2) excess pore pressures in sensitive parts of the foundation or 3) undrained yielding due to dam raising. This is not the place to provide a detailed rebuttal. Suffice to say that the views put forward by D'Appolonia and Morgenstern (1988) appear to be more compatible with the available evidence.

In their view, failure of the upper dam was caused by a high phreatic surface within the steep sand shell, causing the initial failure which strained sufficiently to induce liquefaction of the sandy materials. The operational characteristics of the facility changed appreciably starting in 1982 when the method of cycloning was discontinued in favour of single point discharge of tailings and mechanical placement of the embankment material. The pond was allowed to encroach on the main dam at this time, changing seepage patterns. Since the dam was constructed with sand, but with extensive gravel layers, the water had a direct conduit through

which to enter the sand shell. D'Appolonia and Morgenstern (1988) calculated that a 7.5 m wide zone of saturation within the sand shell would have been sufficient to cause instability.

The dam did not fail at the time the slump occurred along the lower slope of the upper dam. Although seepage was increasing at this time and flow was noted for some time after the slump, the extent of the seepage must not have been extensive enough to cause failure at this time.

During the repair process to the decant pipes in May and June, 1985, the water from the upper basin was drained for a week. Once the repairs were completed, the water was allowed to rise in the upper basin at about 2 m in 2 ½ days. The water elevation was 1-1.5 m higher than when the January, 1985 slump occurred. Based on stratigraphic details, the elevation corresponded to an extensive gravel layer in the dam which would have become submerged.

As a result of the high pond water elevation and its close proximity to the sand shell along with the presence of gravel layers in the dam, water was allowed to flow into the shell, thereby establishing a phreatic surface within the sand shell. This saturated zone increased in size with time and once it incorporated an extensive region about 7.5 m wide, general failure was initiated under drained conditions. Since the sand shell was in a loose state, the straining which took place generated positive pore pressures, sufficient to induce flow liquefaction under static loading conditions. The sand shell then began to flow. This then triggered undrained failure of the slimes as they suddenly lost their confinement.

It is evident that the Stava Dams reflect design and construction practices that would not be acceptable to-day. However there are other troublesome lessons from this case history. The residual liabilities that flowed to both corporations and individuals, long after the dams had been abandoned and after they were being operated by others, are particularly noteworthy.

Omai Tailings Dam

The Omai Tailings Dam failed on or about August 19, 1995. It is located in Guyana, on the banks of the Omai River which is a small tributary of the much larger Essequibo River. The dam contained the tails produced by Omai Gold Mining Ltd. which were mainly fine grained, containing some residual cyanide. The technical findings from the failure investigation are readily accessible (Vick, 1996) and will only be summarized briefly here.

Leakage was first detected on August 19 at 23:40 by a haul truck driver who noticed water flowing across the Batch Plant Road which bordered the tailings pond facility. The dam had been inspected that day at 16:30. No cracking or other signs of distress were detected. Failure was sudden and catastrophic with large seepage flows and extensive longitudinal cracking of the upstream face of the dam. Approximately $2.9 \times 10^6 \text{ m}^3$ of mill effluent containing about 25 ppm cyanide reached the river. Fortunately it degraded quickly and no measurable effects on the downstream environment and human health were detected. Nevertheless the failure was a very serious technical, economic, social and political event.

The dam configuration involved an upstream sloping compacted sapolite zone (core), which was the impervious member, followed by filter sand resting on rockfill which was buttressed by an extensive zone of sapolitic mine waste. The starter dike contained a 900 mm diameter corrugated steel pipe to pass steam flows temporarily during starter dike construction. Problems had been encountered during backfilling the conduit.

Extensive studies were undertaken after the failure both by the Mine and by the Dam Review Team established by the governmental Commission of Inquiry. It soon became evident that the transition rockfill adjacent to the sand filter was too coarse to prevent piping. Even upon wetting, this sand could drop freely into the voids of the rockfall, undermining the compacted sapolite and contributing to its cracking potential. This process is thought to have been initiated by internal erosion within the conduit backfill soils. As water rose behind the inclined compacted sapolite core, collapse and flow of the sand filter developed, resulting in loss of support for the core.

The Omai Tailings Dam was not constructed according to well-established principles and modern experiences with earth dams. It was a significant structure that warranted the highest level of attention. That such failures can occur with a well-intentioned mine operator and knowledgeable consultants is a significant lesson for us all.

Conclusion No. 11

A well-intentioned corporation employing apparently well-qualified consultants is not adequate insurance against serious incidents.

Table 2 presents a list of recent incidents in mine waste management known to the author. These are all examples of impacts on public safety and/or negative environmental impact and/or mine production impact. There is no regional or socio-economic pattern among the cases and they reflect the current state-of-practice in the industry.

One common element is that all cases involved to varying degrees recognized geotechnical consultants qualified by either national or international standards. In no case, to the knowledge of the author, was there systematic third party review.

Table 2. Recent Incidents In Mine Waste Management

Name	Country	Year
Omai Gold Mines Ltd.	Guyana	1995
Manila Mining Corp.	Philippines	1995
Golden Cross	New Zealand	1995
Marcopper Mining Corp.	Philippines	1996
Coal Mountain Dump	Canada	1996
Compania Minera del Sur	Bolivia	1996
Golden Sunlight Mine	USA	1996
BHP - Pinto Valley Mine	USA	1997
Kennecott Utah Copper Corporation	USA	1998
Trapiche Dam	Peru	1998
Boliden-Los Frailes	Spain	1998
Aitik	Sweden	2000
Baia Mare	Romania	2000
Inez	USA	2000

Recommendations

The mining industry must take action to reduce risk associated with waste management by:

- Improving quality control
- Documenting construction and quality control by more use of as-built records
- Improving construction procedures consistent with recommendations from well-qualified geotechnical engineers familiar with the mining industry
- Utilizing more third party reviews
- Ensuring that there is no conflict between short term profitability and long term integrity of containment
- Ensuring that the responsibility for failure of waste containment structures is understood at the highest corporate levels and that the standard of care is set by senior mine management

Consultants should involve Failure Modes/Effects Analyses or equivalent risk analyses at an early stage of project development.

Regulatory Agencies should devote more concern to the details of corporate policy regarding mine waste management procedures as opposed to being rule driven.

Acknowledgement

The Author is grateful to Mr. Bryan Ulrich for conducting a comparative study of the explanations for the Stava Tailings Dam failure.

References

- Baker, F., Cook, D., Deem, J., Letient, H., and Walsh, H., 1996. Matachewan Mines Tailings Dam from failure to rehabilitation. Proceedings Canadian Dam Safety Association Conference, Niagara Falls, 14 p.
- Beckwith, G., 1996. Personal communication.
- Bertie, G., Villa, F., Dovera, D., Genevois, R., and Brauns, J., 1988. The disaster of Stava. Proceedings Special Conference on Hydraulic Fill Structures, ASCE, Special Geotechnical Publication, No. 21, p. 492-509.
- Blight, G.E. and Steffen, O.K.H., 1979. Geotechnics of gold mining waste disposal. In "Current Geotechnical Practice in Mine Waste Disposal", ASCE, p. 1-52.
- Caughill, D.L., Morgenstern, N.R., and Scott, J.D., 1993. Geotechnics of non-segregating oil sand tailings. Canadian Geotechnical Journal, Vol. 30, p. 801-811.
- Chandler, R.J. and Tosatti, G., 1995. The Stava Tailings Dams failure, July, 1985. Proceedings Inst. Civil Engineering, Geotech. Engineering, Vol. 113, p. 67-79.
- D'Alencar, J., Morgenstern, N.R., and Chan, D., 1994. Analysis of foundation deformations beneath the Syncrude tailings dyke. Canadian Geotechnical Journal, Vol.31, p. 868-884.
- D'Appolonia, E. and Morgenstern, N.R., 1988. Evaluation of the cause of failure of the Stava Embankment. Report submitted to Montedison S.A., (unpublished).
- Dawson, R.F., Morgenstern, N.R., and Stokes, A.W., 1998. Liquefaction flowslides in Rocky Mountain coal mine waste dumps. Canadian Geotechnical Journal, in press.
- Edwards, G.R., 1994. Los Leones tailings disposal dam constructed by stages. Proceedings 18th Congress on Large Dams, Durban, Vol.1, p. 271-291.
- Genevais, R. And Tecca, P.R., 1993. The tailings dams of Stava (Northern Italy): an analysis of the disaster. Proceedings International Conference on Environmental Management, Geo-Water and Engineering Aspects, Wollongong, Australia, p.23-36, Balkema.
- McKenna, G.T., 1996. Concepts in lease-closure landscapes. Bulletin Canadian Institute Mining and Metallurgy, Vol. 89, p. 89-95.
- M.A. Matich, 1996. Personal communication.
- Mittal, H.K. and Hardy, R.M., 1977. Geotechnical aspects of a tar sand tailings dyke. Geotechnical Practice for Disposal of Solid Waste Materials, ASCE, p. 327-347.
- Morgenstern, N.R., 1991. Geotechnical engineering and the mining industry – a case study. Proceedings 9th Pan-American Conference Soil Mechanics and Foundation Engineering, Santiago, Vol. 4, p. 1507-1520.
- Morgenstern, N.R., Fair, A.E. and McRoberts, E.C., 1988. Geotechnical engineering beyond soil mechanics – a case study. Canadian Geotechnical Journal, Vol. 24, p. 637-661.
- Morgenstern, N.R. and Scott, J.D., 1995. Geotechnics of fine tailings management. Geoenvironment 2000, ASCE, p. 1663-1673.
- Morse, M., Morgenstern, N.R., and Chan, D.H., 1995. Simulation of creep deformation of the foundation of Tar Island Dyke. Canadian Geotechnical Journal, Vol. 32, p. 1002-1023.

- Nicol, D., 1994. The Syncrude Mildred Lake Tailings Dyke redesign. Proceedings 18th International Congress on Large Dams, Durban, Vol. 1, p. 145-184.
- Seed, H.B., Tokimatsu, K., Harder, L.F., and Chung, R.M., 1984. Influence of SPT procedures in soil liquefaction resistance evaluation. Earthquake Engineering Research Center, Report No. UCB/EERE-84/15, University of California, Berkeley.
- U.S. Committee on Large Dams, 1994. Tailings Dam Incidents, USCOLD, Denver.
- Vick, S.G., 1996. Failure of the Omai Tailings Dam. Geotechnical News, Vol. 14, p. 34-40.
- Wagener, F., Strydom, K., Craig, H., and Blight, G., 1997. The tailings dam flow failure at Merriespruit, South Africa: causes and consequences. Tailings and Mine Waste, 1997, Balkema, p. 657-666.

Stability aspects of long-term closure for sulfide tailings

Steven G. Vick¹

Abstract: Geochemical research on the phenomenon of acid rock drainage (ARD) has resulted in two current strategies for long-term closure of affected tailings impoundments: “dry” closure by cap-and-cover, and permanent submergence by water cover. Since ARD hazard lasts indefinitely, these strategies must assure both physical and chemical stability in perpetuity while avoiding the need for perpetual care and maintenance. Of these requirements, physical stability has received less emphasis but can be the most difficult to achieve. The stability and tailings dam safety implications of these ARD closure strategies are explored, with a view toward comparing the long-term risks, risk tradeoffs, and emerging alternative technologies.

Introduction

The past two decades have brought widespread awareness of a naturally-occurring environmental problem in mining known as “acid rock drainage” or ARD. Though difficult to reliably predict and quantify, ARD is associated with sulfide orebodies mined for Pb, Zn, Cu, Au, and other minerals including coal. While ARD can be generated from sulfide-bearing waste dumps, pit walls, and underground workings, only mill tailings are considered here.

The valuable minerals in sulfide orebodies occur in sulfide form, galena (lead sulfide) being one example, and these are concentrated as the product of mill processing. Iron sulfides usually occur in association with such ores as well, principally as pyrite but also pyrrhotite and marcasite. Ordinarily having no commercial value, these iron sulfides are rejected with the other barren particles and report to the tailings impoundment. Here they can undergo various reactions to produce reduced pH and elevated sulfates, along with metals in solution particularly harmful to salmonid fish, some of which may also bioaccumulate and biomagnify in the food chain. In response to this problem, the mining industry has conducted considerable research into the chemical processes that produce ARD. Several strategies for reducing the generation and/or transport of ARD constituents in tailings deposits have emerged, recognizing that these measures must remain in effect for as long as the sulfide minerals are present — in essence, in perpetuity.

The generation of acidic conditions in tailings and the accompanying mobilization of such metal cations in solution as Pb, Zn, Cu, and Cd proceeds by a complex series of chemical reactions on the surfaces of sulfide mineral grains, aided at key stages by the bacterium *thiobacillus ferrooxidans* as a catalyst. As oxidation reactions, they require the presence of oxygen to initiate and sustain them. They ultimately convert iron sulfides to ferric cations, sulfate anions, and most importantly sulfuric acid, which then dissolves other metals contained in the tailings and makes them available for transport to surface or ground water. Prediction of ARD is complicated by neutralization and precipitation produced by carbonate minerals. If present in the tailings in sufficient quantity, and depending on reaction rates, these carbonates may precipitate and immobilize the metals within tailings void spaces to reduce or eliminate ARD effects. Because lime is often introduced into the tailings stream to maintain the neutral or slightly alkaline conditions required for mill processing, acid generation may be delayed until this

¹ Consulting Geotechnical Engineer, 42 Holmes Gulch Way, Bailey CO 80421, USA:
sgvick@uswestmail.net

carbonate source is depleted, only appearing many years after the tailings are deposited. The problem may also become more acute over time as greater impoundment surface areas become exposed to oxygen and as drainage of water from the tailings deposit promotes oxygen entry into interstitial voids.

Apart from their chemical and biological complexity, another feature of these reactions is their longevity. This makes ARD problems even more difficult than those associated with cyanide, which is chemically unstable and does not persist in the environment. Mines worked by the Romans in Spain and the Vikings in Scandinavia continue to generate ARD today, and once exposed to oxygen ARD reactions on mineral surfaces will continue for thousands of years. Even sulfide-bearing tailings isolated from oxygen will remain available for initiation of these reactions indefinitely should they be exposed at some future time. Indeed, the effects of ARD were known to medieval miners like Georgius Agricola, whose incomparable *De Re Metallica* in 1556 described the arguments of early detractors of mining thusly:

“...Further, when the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away...Thus it is said, it is clear to all that there is greater detriment from mining than the value of the metals which mining produces.”

Though it took over 400 years for contemporary critics of mining to seize upon the observations of their predecessors, by the 1980's ARD was becoming recognized as mining's environmental Achilles' heel. In a comparatively short period of time, the industry organized a concerted effort to attack the ARD problem. For existing tailings deposits and other sources already generating ARD, there was little to be done except damage control. Here, the low-pH effluent would have to be collected and treated by lime addition to precipitate and remove the metals. But not only was the cost of doing so over essentially indefinite periods of time objectionable, the ever-growing volumes of precipitate sludge might eventually approach even that of the tailings, introducing further concerns for its own long-term disposal, chemical stability, and future metal release. Clearly it was preferable to prevent the occurrence of ARD in the first place, and for sulfide-bearing tailings deposits two main closure strategies emerged: dry closure, and permanent submergence.

“Dry” closure is a conventional cap-and-cover solution common to other waste materials. Following termination of mining and cessation of active tailings deposition, ponded water is removed from the surface of the tailings deposit and the surface allowed to dry, although much of the finer-grained tailings remain soft and saturated. A low-permeability cover is then constructed over the surface and graded to enhance runoff, sometimes incorporating pervious layers for drainage, monitoring, or capillary breaks. In principle, such a cover achieves two purposes. It restricts oxygen from the surficial tailings and oxygen diffusion into void spaces, reducing reaction rates and therefore ARD generation. At the same time, the cover acts to prevent ponding and reduce infiltration of surface water, thereby restricting transport of reaction products. In practice, however, for a variety of reasons these effects can be hard to assure and may be only partially realized. Moreover, suitable cover materials may not be locally available, and the cost and difficulty of earthwork operations on the soft tailings surface can be considerable.

Permanent submergence provides an alternative closure strategy. Elegant in simplicity and minimal in cost, the entire surface of the tailings deposit is flooded with water and maintained in this condition indefinitely. The tailings voids remain permanently water-filled and

thus unavailable to oxygen, while a water depth of two to three meters sufficiently reduces dissolved oxygen at the submerged tailings surface. Both laboratory and field demonstrations, notably from the Canadian MEND program, have shown submergence to be virtually 100 percent effective from a geochemical point of view: the water “smothers” the oxidation reactions in the same way as when sprayed on a fire. Thus, permanent submergence has come to be viewed by some as the preferred closure strategy for tailings ARD control.

Largely neglected in this geochemical perspective, however, has been the “permanent” in permanent submergence. Since the water cover must remain present in perpetuity, so too must the tailings dam that retains it. And simply put, perpetuity is an exceedingly long time.

Long-term closure objectives

A fundamental if unstated premise underlying any closure strategy for ARD control is that the tailings dam which confines the deposit will remain permanently stable. This is endorsed by the prevailing view in the dam engineering profession that, properly monitored and maintained, there is no reason why conventional water-retention dams should not last indefinitely. But few conventional dams have been designed with this as a stated criterion, and such requirements have seldom been considered explicitly.

An exception lies with uranium tailings whose primary radiological constituent Ra^{226} has a half-life of 1620 years. Closure strategies must consider the performance of the deposit over corresponding periods of time, which first requires that performance objectives be defined. One available precedent is the UMTRAP program conducted by the U.S. Department of Energy for stabilization of 24 inactive uranium tailings deposits primarily in the western United States. The eventual cost of this program far exceeded the value of the minerals originally extracted from the ores, and it is not suggested here that it would be applicable to sulfide tailings in every detail. Nevertheless, as a potential source of environmental contamination, sulfide tailings have no half-life and retain their full capacity for ARD initiation for as long as the deposit exists.

In contrast with more conventional engineering approaches, long-term closure objectives developed for UMTRAP and related low-level radioactive waste repositories emphasize the operation of natural processes over geologic time scales. To the extent possible, these objectives seek to act in concert with natural biologic and geomorphic processes rather than defeat them with engineered measures whose long-term performance may be difficult to guarantee. Caldwell (1992) observes that this requires a departure from conventional engineering thinking:

□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 into the future as possible. □

With this in mind, three closure objectives for sulfide tailings deposits can be described as follows.

1) chemical stability. The most evident closure objective is to maintain chemical stability of the tailings sulfides by preventing release of oxidation products to the surrounding environment, whether this accomplished by preventing oxidation reactions from occurring, preventing the transport of these products beyond the site boundaries, or both. Natural processes can strongly

influence how this objective is achieved. For example, measures to restrict infiltration into the deposit may be preferred over those such as low-permeability bottom liners with accompanying hydraulic gradients that promote contaminant transport (the so-called “bathtub” effect). Biological processes may also play a role, since organisms have adapted over millions of years to overcome the kinds of conditions engineered measures seek to impose. UMTRAP studies found that the most significant pathway for contaminant release was through uptake by the deep-rooted and moisture-seeking *artemisia tridentata* (sagebrush) that introduced these contaminants into the food chain by grazing animals. But biological processes have also been exploited to advantage through the use of “vegetative covers” which encourage the establishment of self-sustaining grasses and forbs on inert cover materials that reduce infiltration by enhancing evapotranspiration.

2) physical stability. Notwithstanding its order of presentation here, physical stability must be the primary objective of long-term closure. No means for controlling ARD can succeed unless the tailings are first made to stay in one place, and anything that violates this provision will necessarily compromise all others. While the importance of physical stability can be overshadowed by geochemical concerns, one need look no further than the recent Los Frailes failure in Spain to appreciate the difficulties in controlling ARD effects when widespread release of sulfide tailings occurs. There will be more to say about the factors that influence long-term physical stability, after considering a third closure objective that exerts a dominant influence on the first two.

3) care and maintenance. A fundamental goal of long-term closure is to achieve “walk-away” conditions that assure both physical and chemical stability without the need for long-term monitoring, maintenance, or repair. This objective derives from the limited prospects in any realistic sense that society will have the motivation, or in some cases the ability, to care for today’s mining wastes for numberless centuries and millennia to come. Equally, it springs from a moral obligation to avoid passing the burdens of today’s resource extraction to future generations who will inevitably bear those of their own.

Here, institutional, cultural, and socioeconomic factors play key roles. Should tailings deposits require perpetual care, some societal entity must assume responsibility for carrying this out. Few of today’s corporations survive for more than a few decades, and even governments for more than a few centuries as history shows. The only major institution in Western civilization that has thrived continuously over as much as a millennium is the Roman Catholic Church, and its cathedrals are the only engineered structures that have been dutifully cared for and maintained to perform their intended function over corresponding periods of time. This, of course, is because these structures have great cultural value, an attribute that abandoned tailings deposits can hardly be said to possess. Perpetual care and maintenance comes about only if the structure has some intrinsic value to society consistent with its cultural setting, institutional capabilities, and socioeconomic conditions. And although mining is by nature an international activity, technical factors sometimes do not translate well across these boundaries. In Ireland, where land has long been the object of great tradition and revered as a cultural icon, it was once suggested that permanent submergence of a sulfide tailings deposit would be valued as a recreational lake - complete with speedboats and water skiing. In another case involving a subsistence economy remote in the Andes, it was proposed that dry closure of a tailings deposit would provide a convenient site for a golf course. Many developing countries have neither the technical nor administrative capability to carry out the kinds of activities that post-closure care and maintenance require, and to develop these capabilities would detract from efforts more essential

to their welfare like those directed toward basic health and sanitation.

Therefore, if this objective is to be satisfied, it cannot be assumed that closure of the tailings facility will be accompanied by monitoring, maintenance and repair throughout the long term. This is in contrast to the proviso that accompanies customary engineering confidence in the longevity of dams, and some of the implications for tailings dam stability can now be explored.

Dam safety issues in long-term physical stability

These long-term closure objectives can be considered in the context of tailings dam design and dam safety practices required for perpetual stability. Differences from conventional practice arise in several areas, and these are considered in turn.

extreme events. All dams, tailings and otherwise, are designed to remain stable under the influence of some chosen magnitude of floods and earthquakes, such as the Probable Maximum Flood (PMF) or Maximum Credible Earthquake (MCE). The corresponding design values are established within the framework of the hydrometeorological and seismotectonic understanding of the region, and are thus a function of the state of knowledge at the time they are derived. However, this state of knowledge continually changes as understanding of technical factors improves and occurrences of large floods and earthquakes accumulate. So the original design estimates change over time as well, but they will always increase in magnitude and never reduce. As time goes on, the largest event to have been experienced can always be exceeded but can never be made smaller. In fact, the bulk of dam safety expenditures for most owners of conventional hydroelectric dams are devoted to improving spillways and foundations to accommodate these new and higher values. But for tailings dams under post-closure circumstances, this kind of upgrading cannot be performed without violating the “walk-away” objective. Without it, they will be unable to sustain the extreme event estimates that future knowledge provides.

cumulative damage. A related factor involves cumulative damage from repeated occurrences of extreme events, or progressive processes like internal erosion, that degrade dam stability over time. For earthquakes, conventional dam safety practice is to undertake repairs immediately after a damaging event. But for tailings dams, not only does the need for these repairs run counter to the walk-away objective, but the repairs may be physically impossible to accomplish. For conventional dams, drawdown of the reservoir can be required to repair major damage and is also an important emergency response. But a reservoir containing tailings solids cannot be reduced in level. Moreover, a tailings dam will experience repeated occurrences of extreme events during the indefinite future, their number depending on time and recurrence rate which for major earthquakes in some mining regions is on the order of only hundreds of years. An example of the cumulative effects of seismic shaking is provided by La Villita Dam in Mexico, which has experienced progressively increasing crest settlements during four separate episodes of major seismic shaking in just 30 years (USCOLD, 2000). Cumulative damage also results from simple deterioration with age. No concrete structure — spillway, decant facility, or tunnel lining — lasts forever without continuing maintenance and repair.

climate change. The effects of long-term climate change are of intense interest and great uncertainty. Yet for a tailings dam to remain stable in perpetuity requires somehow that the influence of these changes on floods and spillway capacity be accurately predicted, something that even climate experts are not able to do. Climate change may also affect both physical and

chemical stability in other ways. Frozen conditions are relied upon to reduce ARD reaction rates at some mines in arctic and subarctic regions, where certain tailings dams also depend for stability on the presence of frozen ground. And it goes without saying that permanent submergence requires sufficient water, even during sustained drought, notwithstanding any future changes in climate.

geologic hazards. While tailings dams are designed to accommodate geologic hazards known to exist at the time they are constructed, in the indefinite future they will eventually be subject to the full suite of geomorphic processes operating at their sites. These include the kind of landslides and rock avalanches notorious in the Alps, destructive debris flows and landslide dams characteristic of the Andes, volcanic activity in Central America and the Pacific Rim, soil creep common to New Guinea, and karst collapse in any number of areas. Like the occurrence of extreme events, the damaging effects of these processes is only a question of time and recurrence rate, a factor particularly difficult to predict for most large-scale geologic phenomena. Even more benign processes of alluvial deposition will eventually fill water conveyance facilities unless they are continually cleared of sediment and debris.

biologic effects. Further to their influence on long-term chemical stability, biological factors can affect physical stability as well. Conventional dam safety practice recognizes the detrimental effects of burrowing animals and root penetration as matters to be addressed with continuing maintenance. Other problems may be more unexpected. As that country's national symbol, the beaver is ubiquitous to Canada, and its habits are well known to engineer and biologist alike. Its propensity to undertake its activities in response to the sound of running water has been acknowledged as a serious long-term closure issue for tailings dams through blockage of diversion facilities, and has been documented as a cause of tailings dam failure in the past. Here it is noted that the European beaver, which became extinct in Sweden in the 1870's, was reintroduced courtesy of Norway in the 1920's and is now thriving successfully.

These factors make it apparent at a more detailed level the extent to which long-term dam safety depends on the presumption of continuing maintenance, modification, and repair, and conversely how difficult it is to assure stability in the long term without these activities in perpetuity. There is one additional factor, however, that overshadows all others in its importance to physical stability. It is unique to tailings dams, and fortunately its influence is favorable.

The stability of a tailings dam depends most fundamentally on whether or not ponded water is present on the surface of the tailings deposit. During operation of the impoundment, varying amounts of surface water are produced by sedimentation of the hydraulically-discharged tailings slurry. Following termination of discharge and impoundment filling, however, significant amounts of surface water from are typically present only occasionally if at all. The terms "active" and "inactive" are used here to designate these two surface-water conditions.

USCOLD (1994) provides a systematic survey of tailings dam failures and accidents. Of the 106 failures identified from a variety of causes, only 9 involved inactive tailings dams despite their vastly greater numbers. Flood overtopping was found to be the dominant cause of these failures, with those from other common instability mechanisms almost entirely absent. A considerable body of tailings dam field performance experience therefore shows that tailings dam failure does not occur under post-closure conditions if overtopping is prevented and surface water is removed from the impoundment. This can ordinarily be achieved through closure measures that avoid routing surface flows through the impoundment or using it for water-storage purposes.

Additional insight can be gained by more closely examining the worst case: behavior of the least intrinsically stable variety of tailings dam constructed by the “upstream” method, under their most damaging failure mode — earthquakes. The propensity for upstream tailings dams to experience large-scale liquefaction flowsliding during moderate to severe seismic shaking is well known from a number of such failures and resulting fatalities worldwide. However, these flow failures have been observed to occur only for such dams in active operation at the time of the earthquake. By contrast, their stability improves markedly when they become inactive and surface water is no longer present.

Vick, et. al. (1993) review the seismic performance of inactive, upstream-type tailings dams. In over 20 cases of seismic shaking from earthquakes up to M7.8 and ground motions up to 0.40g, no flow failures were experienced. These dams, which had been inactive at the time of earthquake occurrence for periods ranging from 2 to 20 years, experienced mainly minor cracking. Several were directly adjacent to similar such dams in active operation which did experience flow failure under identical ground motions and foundation characteristics, a side-by-side comparison that points to the importance of surface water presence. Though some have attributed this improvement in stability to increase in tailings strength over time (Troncoso, 1990), it also seems clear that reduction in saturation levels and beneficial changes in pore pressure magnitude and distribution play a major if not primary role. Whatever the reasons, the fact remains that even the most seismically vulnerable tailings dams are observed to become immune from major flow failure within a few years after water is removed from the impoundment. This observation has major implications for stability and dam safety aspects of long-term closure, and it should not be surprising since the majority of tailings dam failures have been attributed in one way or another to inadequate impoundment water control (ICOLD, 2001).

Portfolio risks and tradeoffs

In risk analysis terminology, “portfolio” risk is that which accrues collectively over some inventory of individual risks. It depends on the number of individual risks, their magnitudes, the size of the inventory, and the duration over which risk occurs or “exposure period.” Dry closure and permanent submergence differ markedly in these characteristics, giving rise to substantial differences in their respective portfolio failure risks. For dry closure, the exposure period is limited essentially to the active life of the impoundment during mine operation, after which the probability of large-scale flow failure diminishes to effectively zero due to absence of surface water. For permanent submergence, on the other hand, the exposure period is of unlimited duration because the water cover remains in perpetuity, while the inventory of such dams also continues to increase.

To illustrate these effects, consider Sweden’s portfolio where there are reported to be 12 mines exploiting sulfide orebodies in current operation. Assume that each mine has a tailings impoundment with the potential to produce ARD, and assume also that mining continues at a constant total rate of ore production, such that when one mine’s reserves are exhausted another is opened at 1:1 replacement. Further suppose that the life of each mine is 10 years.

To begin with, consider the case where each tailings dam has an annual probability of failure of 10^{-4} while in active operation, a value commonly cited for the failure frequency of conventional earthfill water-retention dams. To simplify, we ignore systematic variations like cumulative damage or climate change and assume that this value remains constant over time. If

each dam is taken as independent with no common-cause failure modes (i.e., no two dams are affected by the same flood or earthquake and no cascade failures occur), then the possibility of failure of each dam in each year can be represented as a series of Bernoulli trials. From the binomial theorem:

$$p_n = 1 - (1 - p_i)^n$$

where:

p_i = probability of failure occurrence in any given trial

n = number of trials

p_n = probability of at least one failure in n trials

Note also that the expected number of failures in n trials is simply $(p_i)(n)$. For this example, we will assume that any dam which fails is repaired and returned to the inventory.

If Sweden were to adopt dry closure practices for all of its sulfide tailings dams, the inventory of active dams subject to failure would remain constant at 12, each having an exposure period of 10 years while surface water is present. The mining of sulfide orebodies began in Sweden about 1000 years ago, and a corresponding period of 1000 years into the future is evaluated here. From the above, it is easily shown that for a failure probability of 10^{-4} /dam-year, there will be a 70% chance of having experienced at least one failure after 1000 years, and the expected number of failures at the end of this period will be 1. Continuing further in time, it would take 1900 years for the probability of at least one failure to reach 90%, designated here as t_{90} .

The portfolio picture changes substantially, however, for permanent submergence. While the number of active dams (again, those containing surface water) starts out with the initial 12 in operation, they retain their water cover and hence remain active and susceptible to failure over the entire remaining 1000 years. As each of these dams is filled and replaced by a new one, there will be 24 active dams at the end of 10 years, 36 after 20 and so forth, until the active inventory totals 1212 dams after 1000 years have elapsed. Accounting for the varying exposure periods of each such generation of dams, there will be a 90% probability of at least one failure after 190 years, and in 1000 years there are 13 expected failures.

But suppose that Sweden is not so diligent in its tailings dam safety practices, or that some of the previously-discussed factors influencing long-term stability become operative such that the failure probability for active dams is 10^{-3} /dam-year. From similar calculations, t_{90} now becomes 190 years for dry closure, with 12 expected failures after 1000 years. But for permanent submergence, t_{90} is only 60 years, and 115 expected failures will have occurred during the 1000-year period. These results are compared in Table 1.

Table 1. Portfolio risks for example illustration ¹

dam failure probability	closure strategy	t_{90} (yrs) ²	active dam inventory at $t=1000$ yrs ³	expected number of failures at $t=1000$ yrs
10^{-4} /dam-yr	dry closure	1900	12	1

dam failure probability	closure strategy	t_{90} (yrs) ²	active dam inventory at $t=1000$ yrs ³	expected number of failures at $t=1000$ yrs
	permanent submergence	190	1212	13
10^{-3} /dam-yr	dry closure	190	12	12
	permanent submergence	60	1212	115

¹ 12 mines, 10-year mine life with 1:1 replacement, one tailings dam per mine

² time required to reach 90% chance of having experienced at least one failure

³ number of dams whose impoundments contain surface water

Some of the long-term implications of tailings closure strategies now become more apparent. Dry closure presents a low portfolio risk from the standpoint of physical stability. With good design and dam safety practices, it should be possible to achieve a safety level in the neighborhood of 10^{-4} /dam-yr during active operation, similar to conventional dams, and no maintenance is required thereafter to assure physical stability. Here, a single failure of an operating dam per millennium might not be considered an unreasonable price to pay in comparison to environmental hazards posed by many other industrial activities over similar periods.

The portfolio risk for permanent submergence, however, is very sensitive to the level of safety achievable in the long term, as the number of failures at the 10^{-3} /dam-yr level shows. Without assurance that a much greater degree of safety could be consistently and perpetually sustained, it is unlikely that the prospect of 115 failures continuing throughout the next 1000 years would be tolerated in Sweden or elsewhere, especially since this results from only 12 operating mines at any given time. Portfolio risk at this safety level is also strongly influenced by the number of dams in the inventory, so that portfolio effects for countries with greater mining activity will be considerably magnified unless they are able to increase dam safety in proportion.

Balanced against these risks to physical stability are those for chemical stability. To the extent that permanent submergence might be seen as more effective than dry closure in reducing ARD effects, this could offset its physical risks somewhat. The choice between these two closure strategies would therefore involve a tradeoff between risks of a physical and chemical nature. A portfolio of impoundments employing dry closure might entail a greater risk of chronic, low-level ARD releases, but with little chance of much larger releases from catastrophic dam failure. Conversely, the geochemical security of permanent submergence is purchased at the price of more long-term failures that increase exponentially with time.

The nature of this tradeoff depends on the conditions at hand. In general, permanent submergence will be more viable for sites conducive to long term stability, such as those with subdued topography, geologically mature landforms, and few seismogenic features. By contrast, permanent submergence can be viewed as altogether unsuited to areas of steep topography, active geomorphology or tectonics, or extremely high precipitation — all detrimental to long-term stability. Risk analysis techniques have been used to evaluate these tradeoffs systematically, with examples provided by Dushnisky and Vick (1996). But formal assessment may not be required to arrive at sound closure decisions that recognize the operable time frames and natural

processes; respect institutional and cultural frameworks; and apply simple engineering good sense.

These decisions also are matters of public policy, and different jurisdictions have treated them in different ways. In the U.S., the Environmental Protection Agency applies prescriptive standards requiring cap-and-cover closure for acid-generating tailings the same as for any other waste classed as hazardous. EPA has not accepted permanent submergence as a long-term closure strategy, though this has little to do with any considered assessment of long-term risk tradeoffs since EPA addresses a post-closure period of only 30 years. By contrast, permanent submergence has been endorsed by certain provinces of Canada where physiographic, climatic, and geologic factors are often favorable to long-term stability. Resource extraction has traditionally been part of the socioeconomic and cultural fabric of many communities, and the chemical security of permanent submergence is viewed as important to continued mining activity. Implied in this policy is that these governmental entities are as confident of their own durability as they are of the tailings dams for which they will be forever responsible.

But despite the rather narrow public policy precedents for permanent submergence, it has frequently been exported elsewhere, as representing best industry practice, to other settings much less conducive to either physical or institutional stability. One of these places is Peru, which contains among the most seismogenically and geomorphologically active features on earth, and at the same time faces serious social and institutional challenges in meeting the everyday needs of its people. In developing countries that count heavily on mining as a socioeconomic lifeline, the ability to prudently balance the associated risk tradeoffs may become problematic, while the long-term portfolio implications of permanent submergence may raise legitimate questions of equity in the distribution of risks and benefits from worldwide mineral production. The government of Peru, however, is not unaware of these issues. Through internationally-funded efforts it has undertaken a thorough review of the physical and chemical tailings management practices best suited to its conditions. And one of the outcomes to emerge has been an emphasis on alternative tailings technologies more specifically adapted to these conditions.

Alternative closure technologies

It is customary to view tailings as waste and nothing more. It would no sooner occur that one might change tailings characteristics to suit disposal requirements than it would to change the composition of one's household garbage for convenience of the trash collector. But tailings are not materials with properties predetermined by nature. They are manufactured, and their properties can be designed as for any engineered material to best suit the needs they must serve. Their chemical characteristics can be modified — indeed, this is how extractive metallurgy obtains minerals in the first place from the ores that produce them. Their moisture content can be changed by the same processes used to dewater the mineral concentrates. And their fine and coarse fractions can be easily separated with the kind of equipment already used in the milling process, to produce materials with distinct engineering properties that can be used to advantage. Designing the physical and /or chemical properties of the tailings to better suit closure requirements opens up a whole new range of closure strategies which can help to avoid the kind of risk tradeoffs that security in perpetuity otherwise entails.

Removal of pyrite from the tailings stream by froth flotation is not metallurgically challenging. This can leave the bulk of the tailings in a non-acid generating condition, with lesser volumes of pyrite concentrate for secure storage elsewhere. For underground mines, a convenient

repository for this concentrate can be the mine itself, where its placement as underground backfill can make it immune from acid generation in cases where the mine will flood after closure. As an emerging technology familiar to the mining industry, pyrite separation is beginning to be adopted as an ARD-control strategy, as has been proposed for the Galmoy Pb/Zn mine in Ireland.

Dewatered tailings disposal is also seeing some application, particularly for smaller mines. By reducing the moisture content of the tailings using filters, transporting them by truck or conveyor, and compacting them in-place, the physical stability of the deposit is assured in the long term and during operation as well. At the Las Cruces copper mine in Spain, it is proposed to encapsulate the dewatered sulfide tailings and cover them with low-permeability marl in cells constructed sequentially as mining proceeds. Where conditions are favorable, “thickened tailings” methods can also enhance stability, as practiced at the Aughinish alumina operation in Ireland. Both of these methods rely fundamentally for achieving stability on the absence of surface water.

A promising technology yet to see widespread application is that for so-called “saturated covers.” By hydraulically depositing a chemically inert layer of fine tailings or other such material that retains a high moisture content, a surface layer is produced that can reduce infiltration and oxygen diffusion without the need for a surface water or compacted soil cover (Nicholson, et. al., 1989). Alone or in combination, these are the kinds of new technologies that take advantage of natural physical and chemical processes, as opposed to trying to defeat their long-term operation. But change has been slow, and two reasons have become apparent.

One has to do with the financing process, a large factor in such a capital-intensive industry as mining. Financial commitments must be secured at the feasibility stage of mine design, and this is also when tailings planning becomes definitive. Since advanced (kinetic) geochemical testing can take up to a year, the ARD potential of the tailings may not be fully resolved. This circumstance can favor conventional dry closure and permanent submergence strategies which are able to be applied as “add-ons” pending the outcome of more detailed ARD assessments, whereas newer technologies must be implemented from the very start. And because the costs of innovative technologies accrue throughout the operation, they may be at a disadvantage in discounted cash flow analysis to conventional add-on closure strategies whose costs are incurred only at the end. Moreover, lending institutions often look more favorably on established technologies, equating them with proven technologies, though as shown here there is little that can be proven in perpetuity. The benefits of security in the long term may not appear in the financial balance sheet unless a well-informed public demands them as a condition of mine permitting.

The other reason is simply that geochemists, tailings dam engineers, and metallurgists — not to mention financial analysts and government regulators — have always operated in their own separate spheres. But solutions that are optimal in each separate domain may not be globally optimal, nor will any one solution be best for every case. And just as long-term closure requires going beyond the usual engineering perspective, so too will long-term solutions for ARD problems require collaboration that jointly attacks all aspects of the problem. The ARD phenomenon is still new to industry, government, and the professions alike. Only if the door is left open to thinking that cuts across disciplinary and institutional boundaries can needed advancements occur.

References

- Agricola, G. 1556: *De re metallica*, H.C. Hoover and L.H. Hoover (trans.), Dover, 1950.
- Caldwell, J. 1992: □Engineering perspectives for near-surface disposal. In: C. Reith and B. Thompson (eds.) *Deserts as dumps? The disposal of hazardous materials in arid ecosystems*, Univ. of New Mexico Press.
- Dushnisky, K. and Vick, S. 1996: Evaluating risk to the environment from mining using failure modes and effects analysis. In: C. Shackelford, et. al., (eds) *Uncertainty in the geologic environment - from theory to practice*, Geotech. spec. pub. no. 58, ASCE.
- ICOLD 2001: *Tailings dams, risk of dangerous occurrences - lessons learnt from practical experiences*, Bull. 121, Int. Commission on Large Dams.
- Troncoso, J. 1990: Failure risks of abandoned tailings dams. In: *Proc. int. symp. on safety and rehabilitation of tailings dams*, Australian Nat. Committee on Large Dams/ICOLD.
- USCOLD 1994: *Tailings dam incidents*, U.S. Committee on Large Dams (USSD).
- USCOLD 2000: *Observed performance of dams during earthquakes, vol. II*, U.S. Committee on Large Dams (USSD).
- Vick, S., Dorey, R., Finn, W. and Adams, R. 1993: Seismic stabilization of St. Joe State Park tailings dams. In: L. Anderson (ed.) *Geotechnical practice in dam rehabilitation*, Geotech. spec. pub. no. 35, ASCE.