GUIDELINES ON TAILINGS DAMS

PLANNING, DESIGN, CONSTRUCTION, OPERATION AND CLOSURE

MAY 2012

ANCOLD

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The committee wishes to thank all persons who commented on drafts of these guidelines and helped to ensure the coverage was appropriate to current practice at the time of preparation.

Foreword

ANCOLD produced their "Guidelines on Tailings Dam Design, Construction and Operation" in 1999. Since that time the publication has been widely used within Australia and internationally where the expertise of Australian practice has been recognised.

In the ten years since the release of these Guidelines there has been a considerable increase in the recognition of environmental responsibilities by the mining industry and its regulators, particularly in addressing the concept of sustainable mining. This has culminated in Australia with the release of "Tailings Management" one of a series of publications outlining "Leading Practice Sustainable Development Program for the Mining Industry" published by the Australian Government Department of Industry, Tourism and Resources (DITR, 2007).

ANCOLD has prepared these new Guidelines to provide a single base document that supports the DITR publication and others like it, with engineering detail that can be accepted by all relevant government authorities and national and international companies involved in tailings dam development, allowing them to undertake design and construction consistent with leading industry practice. The new Guidelines include much of the original Guidelines but with appropriate updating. There is considerable new information on a design for closure and on the use of risk assessment techniques to assist in design and management.

ANCOLD is pleased to make this contribution towards safe and cost-effective tailings dams. The work is the result of the Tailings Dam Sub-committee of ANCOLD and I take this opportunity to thank these members for the unselfish contribution of their time and experience.

These Guidelines are not a design, construction or operation code, and dams personnel must continue to apply their own considerations, judgements and professional skills when designing and managing tailings dams. As time goes on there will no doubt be improvement in contemporary tailings dam practice and it is intended that these Guidelines will be updated as circumstances dictate. ANCOLD welcomes comments on these Guidelines which will assist with future revisions.

Neil Blaikie

Chairman, ANCOLD

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1.0 SCOPE

ANCOLD's charter is to promote and assist in the development of safe and technically appropriate dams. This charter includes a focus on dams used for the containment of tailings and other wastes, which, along with the normal hazards associated with water dams, have the additional potential for major environmental impact if not properly conceived, designed, constructed, operated and closed in an appropriate manner.

1.1 Introduction

These Guidelines have been produced by ANCOLD to update and extend the previous ANCOLD Guidelines on Design, Construction and Operation of Tailings Dams, 1999. The revised Guidelines were seen as necessary, not only to review the general technical content of the original document but specifically to highlight the consideration of risk through all aspects of the tailings dam life cycle, and to extend the advice on designing for the closure and post-closure phases. The Guidelines are intended to support existing guidelines such as "Tailings Management", one of a series of publications outlining "Leading Practice Sustainable Development Program for the Mining Industry" published by the Australian Government Department of Industry, Tourism and Resources (DITR, 2007). It is intended that the ANCOLD Guidelines provide additional advice to designers intending to achieve sustainable development as defined by the Bruntland Report (UNWCED, 1987) and adopted by the International Council on Mining and Metals (ICMM) as being:

> *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs".*

In the mining and metals sector, this means that investments should be financially profitable, technically appropriate, environmentally sound and socially responsible (ICMM, 2003).

Attention is also drawn to an International Commission on Large Dams (ICOLD) Bulletin on Sustainable Design and Post-Closure Performance of Tailings Dams, currently (2012) in draft form, that reinforces many of the parameters described in this ANCOLD Guideline.

These ANCOLD Guidelines introduce the concept of design evolution, whereby initial design should adopt conservative, "best estimate" design parameters on the basis of available data that can be progressively verified, validated, or refined, as real data becomes available. This is commonly known as "the observational approach" to design.

These Guidelines are primarily directed at providing advice on the above ground storage of tailings but many of the principles apply to other forms of tailings containment.

1.2 Tailings Dam *vs* Tailings Storage Facility (TSF)

These Guidelines use the term "Tailings Dam" to represent the structure built to contain the tailings as well as the tailings stored. The scope of the Guidelines does not extend to all aspects of the Tailings Storage Facility (TSF) which may include a range of associated structures and infrastructure.

The Guidelines focus on the dam structure and the management of tailings and water within the storage. The Guidelines do not provide detailed guidance on tailings distribution or water management infrastructure.

1.3 Past Lessons Learnt

The mining industry has learnt from many tailings storage failures and incidents in recent decades that are helping to develop leading practice tailings management. ICOLD Bulletin 121 (2001) provides a comprehensive report on some of these lessons, drawing from a range of TSF failures and incidents. The main causes of failures and incidents identified were:

- lack of control of the water balance;
- lack of control of construction;
- a general lack of understanding of the features that control safe operations; and
- lack of responsibility and ownership by operators.

Tailings containment wall failures were caused by (in order of prevalence):

- poor water control e.g. overtopping;
- slope instability;
- earthquake loading;
- inadequate foundations; and
- seepage.

Tailings incidents historically appear to have been more common where upstream construction was employed compared with centreline or downstream construction. This could be due to poor practices in design and construction in the past and modern design methods should have improved this imbalance. Tailings containment walls constructed using the downstream method appear to have performed similarly to water-retaining embankments.

ICOLD Bulletin 121 also concluded that successful planning and management of tailings storage facilities could benefit greatly from:

- the involvement of stakeholders;
- understanding of risks and commitment from high level management;
- thorough investigations and risk assessments;
- comprehensive documentation; and
- tailings management integrated into mine planning, operations and closure.

1.4 Sustainable Use of Dams for Tailings Storage

Tailings, or contaminated waters associated with tailings have the potential to be one of the most significant environmental impacts from a mining or processing operation, not only during operations but also long after closure of the mine or processing plant.

Over the last 30 years there has been a substantial improvement in our understanding of the design requirements and methods to allow design of safe tailings storage structures. This knowledge must now be extended to cover the safety of the storages into the extreme long-term, well after the closure of the mining operation, extending the concept of stewardship and enduring value.

The viability of a surface storage tailings dam needs to be properly explored, taking into account the potential costs of closure and long-term post-closure maintenance. There will be a range of alternative possibilities, some of which may offer substantial benefits with regard to the long-term stability and environmental risk. Possibilities could include:

- backfilling of mine voids, including underground workings;
- alternative use (e.g. as a construction material);
- reprocessing to remove problematic components; and
- lacustrine or deep sea disposal in a non-sensitive location.

1.5 The need for these Guidelines

Tailings dams have many similarities to conventional water holding dams. However, there are sufficient important differences to justify specific guidelines for tailings dams.

Tailings dams comprise structures to store unwanted waste from a mineral extraction, power generation or manufacturing process. This gives rise to the following particular features which differ from conventional dams:

- the embankments must store solids, usually deposited as a slurry, as well as manage free water;
- both the solids and water stored in tailings dams may contain contaminants which have the potential for environmental harm if not contained both now and in the future;
- their operating life may be relatively short but they are potentially required to safely store the tailings for extremely long periods of time, possibly “in perpetuity”;
- they are often built in stages over a number of years;
- the construction, particularly any subsequent raising, sometimes may be undertaken by mine personnel without the level of civil engineering input, or control, applied to conventional water dams;
- the materials, both those used for embankment construction and the tailings themselves, are likely to vary during mine life;
- water management is crucial, particularly if harmful materials are contained;

seepage and dust may have a major impact on the environment;

daily operations such as placement of tailings and recovery of water may be critical to:

the safety of the storage;

the filling rate, the ultimate height and even the overall storage configuration may well change in unforeseeable ways during construction and operation; and

the storage must be designed with mine closure in mind, so as to create a permanent, maintenance free deposit that does not pose any unacceptable long-term environmental impact or risk.

To highlight these differences, the term Tailings Storage Facility (TSF) is often used, instead of "dam". In some cases, tailings storage can be successfully achieved with minimal requirement for embankment dams in the traditional sense.

The primary objectives for the design of a TSF are:

the safe and stable containment of tailings and contaminants;

the safe management of decant and rainfall runoff;

the management of seepage;

the ability to achieve long-term effective closure, leaving no unacceptable environmental legacy; and

the meeting of these objectives in a cost effective manner.

1.6 Australian Regulations and Guidelines

The regulation of tailings dams in Australia comes under State Government legislation. Each State has its unique Legislation and Regulations and some have Guidelines. Generally these refer to ANCOLD Guidelines, some making compliance mandatory. These Guidelines on Tailings Dams have attempted to provide a common reference for State based Regulation to develop a common ground throughout the Australian mining industry.

In Western Australia, the Department of Mines and Petroleum (DMP), through the Mining Act 1978, Mining Act Regulations 1981, Mines Safety and Inspection Act 1994 and Mine Safety and Inspection Regulations 1995, regulates safety and environmental aspects of tailings disposal.

Western Australia has produced three guidance manuals to improve tailings management, namely:

The Guidelines on the Safe Design and Operating Standards for Tailings Storage (DMPWA 1999);

Guidelines on the Development of an Operating Manual for Tailings Storage (DMPWA 1998); and

Water Quality Protection Guidelines No .2 – Tailings Facilities (DMPWA 2000).

In Victoria, the Minerals and Petroleum Division (MPD) of the Victorian Department of Primary Industries (DPI) is responsible for regulating the minerals, petroleum and extractive industries within Victoria and its offshore waters, including Commonwealth waters. The MPD manages the administration of the Mineral Resources Development Act 1990 and the Extractive Industry Development Act 1995.

Victoria has produced a document entitled, *Management of Tailings Storage Facilities* which sets out regulatory policies and provides guidelines for tailings storage in the state of Victoria (DPI, 2003).

In Queensland, while the mining and other extractive industries are regulated under industry specific legislation, tailings storage facilities are regulated by setting conditions of approval under the Environmental Protection Act 1994. The administrating authority has issued guidelines to assist in the process. These are available on-line. The *Technical Guidelines for Environmental Management in Exploration and Mining Industry 1995* contains specific guidelines, amongst many others, on Tailings Management, Site Water Management and Water Discharge Management (DERM, 1995).

In Tasmania a mining lease is required under the Mineral Resources Development Act 1995. Dam safety is handled under The Water Management Act 1999 which highlights in part 8, the regulations on dam construction maintenance and decommissioning. This includes tailings dams. There are no specific regulations or tailings management guidelines for tailings storage facilities in Tasmania.

In South Australia there are no specific regulations on tailings storage and guidelines for tailings impoundment construction and operation have been adopted from Western Australia and Victoria. South Australian regulators are moving away from prescriptive regulations to more objective methods and risk management.

In New South Wales (NSW) tailings dam safety is handled under the Dams Safety Act 1978 overseen by the NSW Dams Safety Committee. The NSW Department of Primary Industries also handles operational matters relating to mining under the NSW Mining Act. The NSW Dams Safety Committee in June 2010 produced a number of updated "Guidance Sheets" covering a range of aspects related to dam safety. In particular DSC3F (NSWDSC, 2010) covers tailings dams, but many of the others are relevant.

In 2007 the Australian Government through the Department of Industry, Tourism and Resources, published a Manual entitled *"Tailings Management"*, which was one of a series of publications outlining *"Leading Practice Sustainable Development"* for the Mining Industry (DITR, 2007). These Guidelines outline a risk based approach to tailings management that synthesises the understanding of key issues affecting sustainable development.

Prior to publication of the Tailings Management Manual, the Ministerial Council on Mineral and Petroleum Resources and the Minerals Council of Australia produced a document entitled, *Strategic Framework for Tailings Management* (MCMPR-MCA, 2003). This document focused on stewardship, stakeholder engagement, risk management, implementation and the closure aspects of tailings storage (MCMPR and MCA, 2003). These were not intended to provide a detailed set of guidelines on tailings management, but to complement tailings regulations and State specific tailings guidance manuals where they exist. The goal of this document was to establish regulatory and industrial input to develop more consistent guidelines for tailings storage within Australia.

1.7 Consultations

A key success element of an extractive industry is acceptance by the community that the industry is operating in a sustainable manner, wherein the benefits to the community and the environment outweigh the disturbance caused by the operation of the industry. Tailings dams, open cut pits and rock waste dumps are the main visible legacies left behind by extractive industries. Most of the Australian Regulations and guidelines require some form of consultation with stakeholders at various stages in the development of a project involving tailings dams. Prior knowledge of likely impacts amongst stakeholders could avoid issues associated with the appearance of the impacts. With tailings dams, the key stakeholders are usually:

- The background land owners (farmers, traditional owners, etc.);
- The surrounding community (neighbours, etc.);
- The Local Government Authority (roads, support infrastructure etc.); and
- The Industry Regulatory Authority (approvals, surveillance, etc.).

Persons involved with Planning, Design, Construction, Operation and Closure of tailings dams need to be aware of the consultation requirements in each State.

1.8 Procedure for Tailings Dam Life Cycle Management

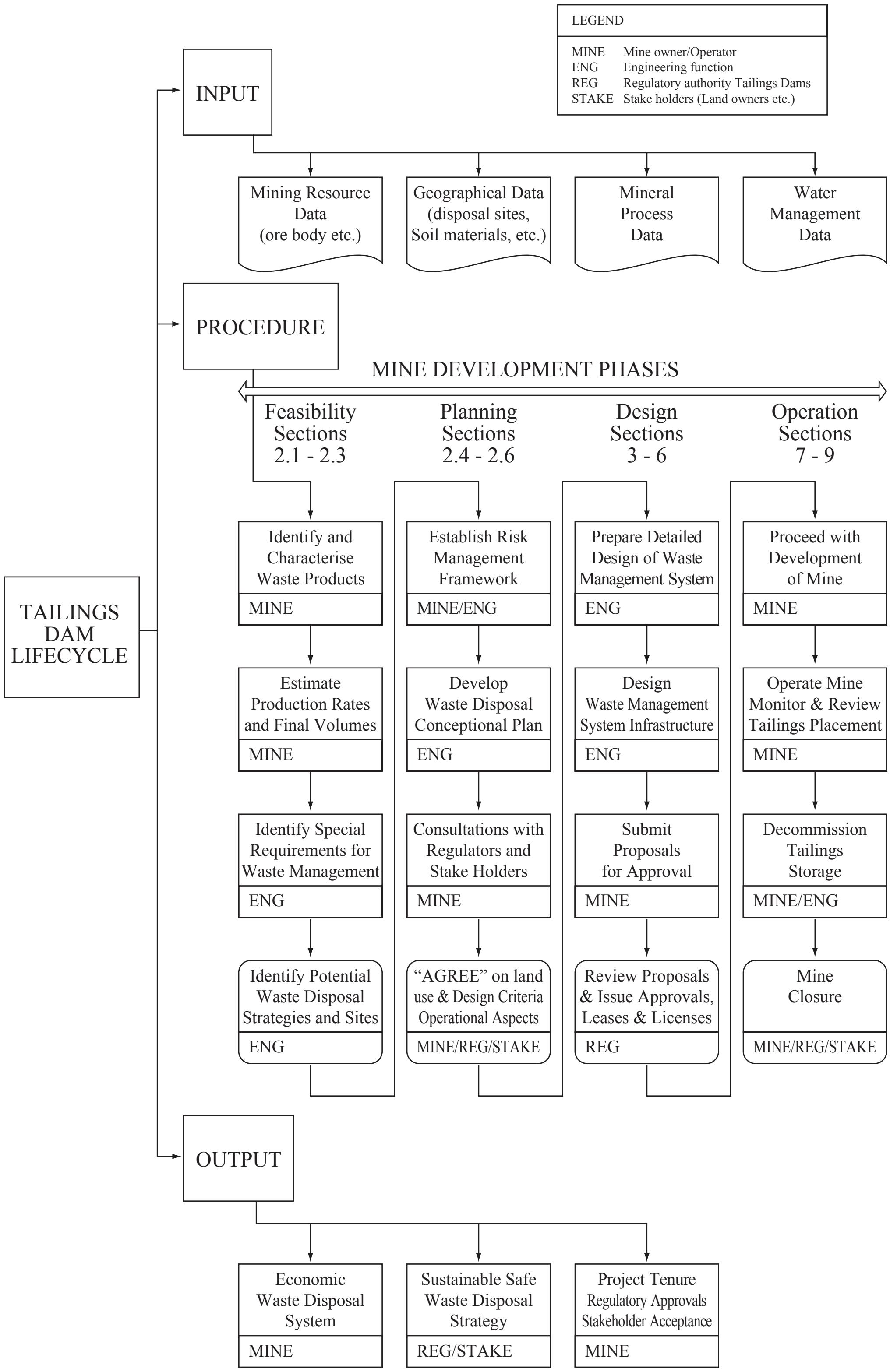
Tailings storages must meet local legislative requirements and generally conform to recognised guidelines. The process needed to authorise and manage a tailings dam is similar, irrespective of the location or nature of the project. A typical process is described in Figure 1.

Activities are grouped within functional interest groups (lower left corner of an activity box) as follows:

- MINE represents the project owner, including commercial interests, project management, operations, safety, liability, etc.;
- ENG representing activities which predominantly require the application of engineering and other professional skills;
- REG representing the regulatory functions required by laws that have to be met so that the project can take place; and
- STAKE representing the community and other stakeholders affected by a project including land owners, local authorities, infrastructure support, environmental values, heritage, etc.

The outputs described in the bottom activity boxes reflect the primary objectives of project tenure within a supportive community, resulting in safe, sustainable and cost-effective tailings storage.

Figure 1 Procedure for Planning, Design, Construction, Operation and Closure of Tailings Dams over the TSF Lifecycle



1.9 Definitions

Acid and Metalliferous Drainage (AMD) – also known as acid mine drainage, or acid rock drainage (ARD), refers to the outflow of polluted water to the environment. Usually the water is acidic but not necessarily. AMD occurs naturally within some environments as part of the rock weathering process but is exacerbated by large-scale earth disturbances characteristic of mining and other large construction activities, usually within rocks containing an abundance of sulphide minerals.

Annual Exceedence Probability (AEP) - the probability that a particular storm or event will be exceeded in any year eg. 1 in 1000 AEP Storm (or 1 in 100 AEP or 1 in 10,000 AEP) - a storm event which produces a rainfall that is statistically likely to occur once in a 1000 years (or 100 or 10,000 years) at the site under study.

Bulk Density – the overall density of a material being the mass of solids and water per unit volume of the solids plus liquids plus air voids. Also see ”dry density”, ‘particle specific gravity”.

Consequence Category - The ranking of the severity of the consequences of dam failure as defined by ANCOLD Guideline on Consequence Categories of Dams, (Draft released April 2011). This term supercedes Hazard Rating used in earlier guidelines.

Decant Pond – A pond within a tailings dam to allow collection and clarification of stormwater and tailings water released on settling and consolidation of tailings.

Dams Engineer – An engineer experienced in investigation, planning, design, construction or management of dams and qualified to undertake work in the field of dams. Some aspects of tailings dam engineering may require specialist input. A Specialist would be a person with special skills such as geochemistry, hydrogeology, etc.

Designer - Person with appropriate qualifications and experience responsible for the design of the tailings dam.

Design Storage Allowance - This is the remaining safe storage capacity that needs to be provided in a non-release dam to accommodate tailings (solids and water), rainfall and wave action with a sufficient safety factor against overtopping and spillage of contaminated water. The design storage allowance must consider the post-wet season time that it may take to return the pond level to its normal operating level, or the time required (considering weather delays) to construct an incremental increase in storage capacity (new dam or raise of existing embankment).

Dry Density - mass of solids per unit volume of the solids plus liquids plus air voids.

Earthquake -

Operational Basis Earthquake (OBE) - That earthquake which, considering the regional and local geology and seismology and specific characteristics of local subsurface material, could reasonably be expected to affect the dam site during the operating life of the dam; it is that earthquake which produces the vibratory ground motion for which those features of the dam necessary for continued operation without undue risk to the health and safety of the public are designed to remain functional.

Maximum Design Earthquake (MDE) - The earthquake selected for design or evaluation of the structure. This earthquake would generate the most critical ground motions for evaluation of the seismic performance of the structure. The dam could be expected to be damaged by this earthquake but would retain its functionality.

Maximum Credible Earthquake (MCE) - The largest hypothetical earthquake that may be reasonably expected to occur along a given fault or other seismic source. It is a believable event which can be supported by all known geologic and seismologic data. A hypothetical earthquake is deterministic if its fault or source area is spatially definable and can be located a particular distance from the dam under consideration. A hypothetical earthquake is probabilistic if it is considered to be a random event, and its epicentral distance is determined mathematically by relationships of recurrence and magnitude for some given area. The MCE can be associated with specific surface geologic structures and can also be associated with random or floating earthquakes (movements that occur at depths that do not cause surface displacements).

Failure - the occurrence of an event outside the expectation of the design or facility licence conditions, that could range from the uncontrolled release of water including seepage, to a major instability of an embankment leading to loss of tailings and/or water.

Freeboard – Freeboard is a vertical distance between a water level within a dam and a critical design level. For tailings dams there are various freeboards provided for different purposes as follows:

Total Freeboard. The vertical distance between the Maximum Operational Pond Level and the crest of the dam, and represents the capacity of the dam to pass an extreme storm by combination of extreme storm storage, spillway discharge depth, wave freeboard and contingency freeboards to prevent overtopping of the dam.

Tailings Storage Allowance The volume of tailings allowed for at the design period of tailings dam operation stage, prior to closure or raising, calculated as the expected dry tonnage of tailings produced at the expected dry density to be achieved within the storage.

Minimum Decant Storage Allowance The expected minimum volume of water to be held on a tailings dam to achieve the desired water quality for discharge conditions, either to the environment if appropriate or to return to the process plant for treatment and recycle.

Wet Season Storage Allowance The volume allowed for wet season water storage which could conservatively be required to be held in a tailings dam by a combination of excess wet season rainfall run-off from the tailings dam catchment and decant water from process inputs that cannot be progressively be extracted from the dam.

Extreme Storm Storage Allowance The volume allowed for storage of an extreme storm event to prevent spill from the dam.

Contingency Storage Allowance The additional freeboard allowed on top of the tailings, decant pond, wet season storage and extreme storm allowance to cater for wave run-up and uncertainty in the values adopted for the defined items.

Operational Freeboard This is the vertical distance between the top of the tailings and the adjacent embankment crest. A minimum operational freeboard is normally specified to minimise the potential for backflow and overtopping as a result of tailings mounding at discharge points;

Maximum Operating Level - The maximum extent of a decant pond under normal operating conditions. This is the maximum level to which the water level can rise at which point the deposition of process tailings and water must cease, and the Dam Safety Emergency Plan will be activated.

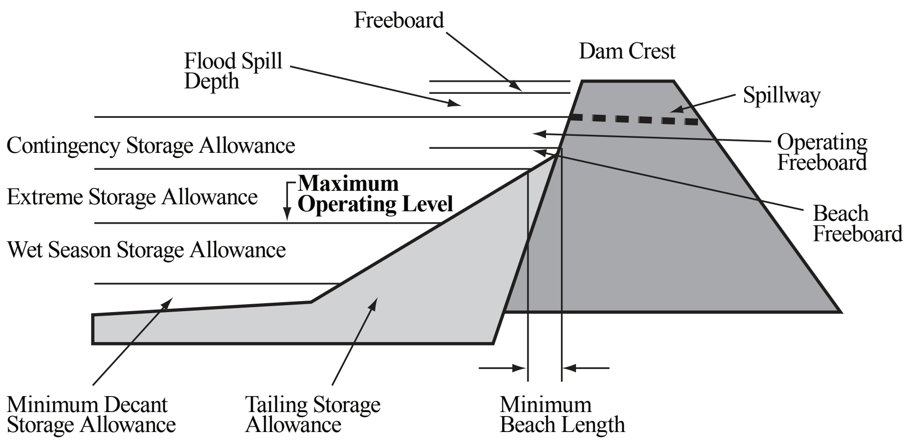
Flood Spill Depth The depth of water flow over the spillway for the design flood event. This can be assessed by routing flows through the storage utilising any Extreme Flood Storage and Contingency Storage Allowance.

Wave Freeboard An allowance for wave run up over and above the maximum calculated flood level.

Beach Freeboard For upstream and centre lift tailings dams without internal filters, it is crucial to control the phreatic surface level against the upstream face to minimise piping risks and maximise stability. This is achieved by placing tailings against the upstream face and maximising the distance between the decant pond and the embankment. A minimum beach freeboard is specified for these dams, defined as the vertical distance between the top of the tailings, abutting the upstream face of the dam, and the tailings pond level after an appropriate extreme storm event.

Illustrative representations of these freeboard criteria are set out in Figure 2.

Figure 2 Freeboard Definitions



Long Term – For these Guidelines the term "long-term" has been assigned a nominal period of 1000 years. This applies to the consideration of the potential design life of the post-closure landform.

Mine Closure – A process being undertaken between the time when the operating stage of a mine is ending or has ended and the final decommissioning or rehabilitation is completed. Closure may only be temporary or may lead to a period of care and maintenance.

Mine Completion – The goal of mine closure where mining lease ownership can be released and responsibility accepted by the next land user.

Moisture Content - (geotechnical definition) mass of evaporable water as a percentage of the mass of solids. Also see "solids content", "water content".

Particle Specific Gravity (or Soil Particle Density) - mass per unit of solid volume of the solids particles in the tailings.

Post-Closure – The period after Mine Closure where the Tailings Dam is expected to perform safely into the long-term.

Probable Maximum Flood (PMF) - the largest flood hydrograph resulting from PMP and, where applicable, snowmelt, coupled with the worst flood-producing catchment conditions that can be realistically expected in the prevailing meteorological conditions.

Probable Maximum Precipitation (PMP) - the theoretical greatest depth of precipitation for a given duration that is physically possible over a particular catchment.

Responsible Engineer - Person with appropriate qualifications and experience responsible for the supervision of construction, or subsequent raising of the tailings dam. Ideally this should be the Designer, or if not, a well-defined linkage between the design and supervision personnel should be developed to ensure that design requirements are met by the construction and operational phases.

Risk Management Process (AS/NZS ISO 3100:2009) - systematic application of management policies, procedures and practices to the activities of communicating, consulting, establishing the context, and identifying, analysing, evaluating, treating, monitoring and reviewing risk.

Slimes - silt or clay size material, usually with a high water content.

Slurry Density (or Bulk Density or Pulp Density) - total mass of slurry per unit of total volume of the solids plus liquids.

Solids Content (or concentration) - mass of solids as a percentage of the combined mass of solids plus liquids in a slurry.

Storage Capacity - The potential containment capacity of the facility, usually referred to in units of dry tonnes. This requires knowledge of the in-situ dry density of the tailings likely to be achieved in the storage.

Tailings (or Tailing or Tails) - Tailings, or "tails" comprise the residue or waste that comes out of the "tail" end of a processing plant. The processes that produce tailings can be:

mineral processing to extract metals or compounds from ore;

beneficiation processes that upgrade ore, coal or mineral ores by removing some or all of unwanted materials;

washing processes including sand or coal washing and clay upgrade;

residue (ash or fume) from combustion of coal, or from blast furnaces; and

by-products from chemical reactions within a process (e.g. gypsum).

These processes generally produce fine-grained products as a result of ore crushing, pre-existing grain sizes or chemical precipitation. The processes themselves are generally water based and the tailings are, for the most part, produced as a slurry of solid particles suspended in water.

Waste products that are essentially liquid only are not considered as tailings, although a number of principles for storing such products are similar to those outlined in these Guidelines.

Tailings Dam - a structure or embankment that is built to retain tailings and/or to manage water associated with the storage of tailings, and includes the contents of the structure. This does not include separate water dams (e.g. seepage collection dams or clarification ponds) that may be part of the overall TSF.

Tailings Storage - a site where processing wastes are temporarily or permanently stored, not necessarily formed by a dam structure.

Tailings Storage Facility (TSF) - includes the tailings storage, containment embankments and associated infrastructure.

Water Content - (process engineering definition) mass of water as a percentage of the combined mass of solids plus liquids. See also "moisture content".

2.0 KEY MANAGEMENT CONSIDERATIONS

The objective of planning is to ensure a commitment to managing an appropriate level of risk during all phases of the life cycle of a tailings dam, including concept development, design, construction, operation, decommissioning, rehabilitation, ongoing monitoring and the extended post-closure period.

2.1 Selection of Waste Management Strategy

2.1.1 Management Strategies

A tailings management strategy will describe the selected method of transporting, discharging, storing and permanent retention of tailings waste products.

A management strategy must be selected to suit the type of process, the final volumes, the tailings characteristics, the nature of the available disposal area, the local climate, long-term requirements including capping, environmental impacts and any Statutory requirements, including occupational health and safety (OH&S) requirements. The strategy must consider the closure and post-closure costs to ensure that the correct decisions are made during concept development.

Management strategies need to consider both the method of containment, the method of disposal and the method of closure, post-closure monitoring and ultimate relinquishment or maintenance.

Containment Methods Include:

- single-stage embankment;
- multi-stage raising, possibly using tailings as a construction material;
- stacked, dry tailings;
- within voids created by waste rock piles;
- backfilling of open cut mines;
- underground mine/stope fill; and
- seabed disposal (not covered by these Guidelines).

Disposal Methods Include:

- sub-aerial beaching on areas exposed to the atmosphere;
- hydrocyclone beaching and separation;
- sub-aqueous into areas where water covers the deposit;
- thickened slurry (high density paste or central thickened discharge);
- co-disposal with coarse rejects or waste rock;
- mechanical or solar drying and dry stacking;
- commercial use (where possible); and
- further processing.

Closure

- many options depending on post-closure goals.

2.1.2 General Principles for Above Ground Tailings Dam Disposal

Generally accepted principles for the management of tailings disposal in above ground dams are listed below. In some circumstances the designer may need to promote certain principles at the partial expense of others.

- Tailings dams should be used primarily for the containment of tailings. The amount of water stored on a tailings dam should be minimised to encourage drying and consolidation of the tailings except where specific design requirements dictate otherwise, such as sub-aqueous disposal to mitigate oxidation or other chemical reaction or dust suppression.
- Where tailings dams are used as water storages for process waters, balancing storages, control of acid generation, or for the storage of harvested runoff waters, consideration should be given to the potential lower in-situ density of the tailings and the increased risk of seepage and overtopping in this situation.
- The need for suitable lining or underdrainage to minimise or manage seepage should be assessed at the initial planning stage, based on thorough hydrogeological studies, chemical analysis of leachate toxicity and impact studies. Seepage from tailings dams should be contained if necessary by downstream collection dams.
- Water quality monitoring appropriate to the nature of the overflow or seepage waters and associated

control and treatment systems may need to be installed between the storage and any release point to the external environment.

Thick deposits of wet slimes should be avoided where they might negatively impact on the storage performance. They commonly result in poorly consolidated and weak tailings, which require greater storage volume and are difficult to cap and rehabilitate in the long-term.

Deposition of coarse tailings against embankment walls is to be encouraged for sub-aerial disposal where upstream lifting is proposed to ensure rapid consolidation, drying and gain in strength.

Tailings may be stored to a level higher than the crest of the tailings dam wall (e.g. beaching or 'dry stacking') provided that such heaped tailings can be demonstrated to be geotechnically stable under all conditions including earthquakes.

Deposition procedures or landforms, which facilitate excessive dust creation, leaching of tailings and leachate transport should be avoided.

The storage facility should be designed with consideration to the potential for adverse chemical reactions within the tailings mass, foundations, and storage structures.

All storages must be designed with adequate freeboard to retain design floods, normally with spillways to pass higher floods without damaging the dam. Even structures designed to prevent discharge of water need consideration of safe spillage in an event exceeding the design condition.

Location of tailings dams must take into account any risks associated with proximity to existing or potential future underground or adjacent open cut voids and the consequences of failure on the environment and downstream populations.

All tailings dams must be monitored to enable performance to be compared with design assumptions, and the facility then modified as necessary.

Staged construction should be used where practical to minimise initial capital cost and to enable changes to improve performance and/or process operations and/or production to be accommodated in future stages.

The design must take into account the requirements for long-term closure, which may include the expectation of producing a long-term stable landform with ongoing maintenance requirements similar to that for natural landforms or similar land uses.

2.2 Risk Management

2.2.1 Risk Management Process

Major tailings dam failures may be relatively infrequent, but the rate of failure has not been reduced in numbers over the years, with still 1-2 major tailings dam failures per year in the world! The consequential harm from these failures is very significant. Past failures have led to loss of life, catastrophic environmental damage, public outrage, restrictive regulatory intervention and associated financial losses and costs for the company responsible. There are significant measurable financial, reputation and sustainability benefits associated with achieving leading practice tailings management that effectively manages the potential risks associated with tailings dams during and after their operating lives.

Irrespective of the detail and quality of the design, failures can occur if any tailings facility element (e.g. drains, filters) and the system as a whole, are not designed, constructed and operated in accordance with the primary intent of controlling and managing risk.

Leading tailings management practice recognises potential design limitations and uncertainties by applying a risk-based management approach throughout the life of the facility – from project conception, through design, construction, operation and closure.

AS/NZS ISO 31000:2009 Risk management - Principles and Guidelines provides a generic guide to managing risk and the key elements of the risk management process.

In focussing primarily on those issues that are material to achieving the performance objectives, the risk management process becomes a robust and effective management tool. Activation of this approach at the start of the project provides the dam owner with greater confidence in the design and provides the designer with the ability to tailor the design towards meeting the required risk profile. The risk management process should start at the project conception stage, with risk treatment options being considered in attempting to eliminate or reduce the quantity and improve the quality of the waste. Risk treatment options (AS/NZS ISO 31000:2009) may include:

- avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk;
- taking or increasing the risk in order to pursue an opportunity;
- removing the risk sources;
- changing the likelihood;
- changing the consequences;
- sharing the risk with another party or parties; and
- retaining the risk by informed decision.

A tailings dam risk management process may start with the consideration of alternative storage methodologies such as in-pit disposal or co-location of tailings within waste dumps. Where applicable, these techniques can reduce the complexity of the containment structures and their failure likelihood and consequence.

The risk management process then continues into the tailings dam design and operational phases. Operations should include risk monitoring and review processes in their tailings management plans (AS/NZS ISO 31000:2009) that encompass all aspects of the risk management process for the purposes of ensuring that controls are effective and efficient in both design and operations. This should include:

- obtaining further information to improve risk assessment;
- analysing and learning lessons from events (including near misses), changes, trends, successes and failures.
- detecting changes in the external and internal context, including changes to risk criteria and the risk itself which can require revision of the risk treatments and priorities; and
- identifying emerging risks.

As tailings dams and the loads applied to them are constantly changing as they store more tailings, tailings dam risk management and planning must also consider these changing circumstances. Managing such change should be a core consideration in the planning, design, construction, closure and rehabilitation of tailings dams.

2.2.2 Risk Assessment

Risk assessment is the overall process of risk identification, risk analysis and risk evaluation. ISO/IEC 31010 provides guidance on risk assessment techniques.

Risk assessment is used in varying forms to evaluate specific tailings design and operational risks (individual or combined). The type of assessment chosen depends on the complexity of the risk, the criticality of the element under consideration (related to safety, health, environment, business continuity), the potential consequence of a failure, and the quantity and quality of available data. A risk assessment of a tailings dam should clearly identify the leading indicators of potential failures, either of individual elements, or in combination where a number of individual issues combine to result in a failure.

Quantitative risk assessment is frequently used by designers of high and extreme consequence category dams to quantify and evaluate the risk tolerability of specific elements or features of a tailings dam such as spillway capacity (ANCOLD, 2003).

Qualitative or semi-quantitative assessments are often used to rank and prioritise risk controls and risk action plans, or to demonstrate the risk associated with a combination of events e.g. fault event tree.

2.3 Consequence Category

There are two Consequence Categories that need to be assessed as part of Tailings Dam design. These are the Dam Failure Consequence Category and the Environmental Spill Consequence Category. These are used to determine various design and operational requirements including design of spillways and for flood storage requirements.

2.3.1 Dam Failure Consequence Category

The Dam Failure Consequence Category is determined by evaluating the consequences of dam failure with release of water and tailings through a risk assessment process. This will lead to selection of appropriate design parameters to manage the risks. The assessment is undertaken by considering the potential failure modes of the facility and the resulting consequences to the business, the social and natural environment and the potential for loss of life as described in Guideline on the Consequences of Dam Failure (ANCOLD, 2012).

There are likely to be significantly different consequences for some failure modes, depending on the life stage of the project. For example, erosion would be readily repaired during operation but could become a potential mechanism for large-scale failure post-closure when limited maintenance is likely. Similarly, seepage of contaminated water can be readily collected and treated during operation but could lead to significant environmental impact following closure. The impact of large scale failure of a tailings dam could increase significantly with time as the structure increases in scale and height. It is therefore necessary to undertake individual consequence assessments for each of the different phases of dam life.

The Dam Failure Consequence Category should be established using the methodology described in Consequence Guidelines (ANCOLD, 2012), with appropriate consideration of the potential increase in damage and safety consequence associated with mine process tailings. The critical input to determining the Consequence Category is the assessment of the consequences of failure. This involves considering a "dam-break" simulation under various conditions of flooding, including "sunny day" (no flooding) and extreme flood events.

The methodology for the "dam-break" analysis can involve complex hydrological studies, or for simple cases could follow simple empirical or qualitative methods. For tailings dams the simulation often assumes that tailings are replaced with water, or use more sophisticated methods to model mudflow. Modelling of the flow of mixed tailings and water is complex. Considerable judgement would be needed to determine a realistic mudflow scenario.

The resulting water or mudflow is mapped in relation to the topography of the areas downstream of the dam, to determine the inundation area and the depth and velocity of potential flows. The consequences of this inundation are then evaluated and ranked in accordance with the Population at Risk (PAR), the nature of the receiving environment and the potential severity of impact in relation to the nature of the released material. The response/survival of the PAR associated with a tailings dam break (resulting in a mudflow of hazardous material) would be different from that under the failure of a water-supply dam. Consequently, the Potential Loss of Life (PLL) from a tailings dam failure should be conservatively estimated.

The revised ANCOLD Guidelines on the Consequence Categories of Dams (2012) differ from the previous guidelines in that the term "Consequence Category" replaces the term "Hazard Rating", and a new level of severity of impact, "catastrophic" has been introduced. Table 1 summarises the severity levels for various impact types from ANCOLD Consequence Guidelines (2012).

With tailings that contain potentially harmful materials, the assessment needs to include other potential health and environment impact pathways. Owners and designers need to take account of the different physical and geochemical nature of tailings and transport water, as compared to clean water, when assessing the consequences of failure of a TSF using these guidelines.

Table 1 Severity Level impacts assessment - summary from ANCOLD Consequence Guidelines (2012)

DAMAGE TYPE	MINOR	MEDIUM	MAJOR	CATASTROPHIC
Infrastructure (dam, houses, commerce, farms, community)	<$10M	$10M-$100M	$100M-$1B	>$1B
Business importance	Some restrictions	Significant impacts	Severe to crippling	Business dissolution, bankruptcy
Public health	<100 people affected	100-1000 people affected	<1000 people affected for more than one month	>10,000 people affected for over one year
Social dislocation	<100 person or <20 business months	100-1000 person months or 20-2000 business months	>1000 person months or >200 business months	>10,000 person months or numerous business failures
Impact Area	<1km^2	<5km^2	<20km^2	>20km^2
Impact Duration	<1 (wet) year	<5 years	<20 years	>20 years
Impact on natural environment	Damage limited to items of low conservation value (e.g. degraded or cleared land, ephemeral streams, non-endangered flora and fauna). Remediation possible.	Significant effects on rural land and local flora & fauna. Limited effects on: A. Item(s) of local & state natural heritage. B. Native flora and fauna within forestry, aquatic and conservation reserves, or recognised habitat corridors, wetlands or fish breeding areas.	Extensive rural effects. Significant effects on river system and areas A & B. Limited effects on: C. Item(s) of National or World natural heritage. D. Native flora and fauna within national parks, recognised wilderness areas, RAMSAR wetlands and nationally protected aquatic reserves. Remediation difficult	Extensively affects areas A & B. Significantly affects areas C & D. Remediation involves significantly altered ecosystems.

Table 2 shows the recommended Consequence Category cases (ref. ANCOLD 2012). As can be seen the “catastrophic” impact classification results in a High Consequence Category even when there is no population at risk. As the Consequence Categories are used to determine design parameters and operational requirements for tailings dams presented in later Chapters of these Guidelines., this means that risk assessment using these ANCOLD Guidelines is likely to recommend higher design parameters for earthquake and flood than previous guidelines. This is considered to be appropriate, particularly when taking into account that the majority of tailings dams fall into a high or extreme consequence category when considering their operational risks and extended (post-closure) design life.

Table 2 Recommended consequence category

(Adapted from the ANCOLD Consequence Guidelines Table 3 - the worst case of the Severity Level of Damage and Loss- from Table 1, combined with the Population at Risk determines the Consequence Category)

Note: A, B and C are subdivisions within the HIGH Consequence Category level with A being highest and C being lowest.

Population at Risk	Severity of Damage and Loss			
	Minor	Medium	Major	Catastrophic
<1	Very Low	Low	Significant	High C
>1 to 10	Significant (Note 2)	Significant (Note 2)	High C	High B
>10 to 100	High C	High C	High B	High A
>100 to 1,000	(Note 1)	High B	High A	Extreme
>1,000		(Note 1)	Extreme	Extreme

Note 1: With a PAR in excess of 100, it is unlikely Damage will be minor. Similarly with a PAR in excess of 1,000 it is unlikely Damage will be classified as Medium.

Note 2: Change to "High C" where there is the potential of one or more lives being lost. The potential for loss of life is determined by the characteristics of the flood area, particularly the depth and velocity of flow.

2.3.2 Environmental Spill Consequence Category

The Environmental Spill Consequence Category can be determined using similar methods to the Dam Failure Consequence Category by considering only the effect of spilling of water from the dam during a flood event or extreme wet weather period. The impact is normally likely to be limited to environmental impacts. As such it is likely that the resulting Environmental Spill Consequence Category may be lower than the Dam Failure Consequence category, particularly if no loss of life is expected. However extreme environmental consequences can still lead to a High Consequence Category.

2.4 Planning

2.4.1 Life of Mine Planning

Tailings dams must be designed to safely contain water and tailings in a dynamic environment, not only during the operational life of the mine, but also for many years after closure of the mine has occurred. There is a wide variation in current acceptable design life periods, varying up to 1000 years in the USA and to 1000-2000 years in the EU noting that closure design is tending to be defined in a geological timescale. The period of 1000 years is considered reasonable, given that in Europe there are currently examples of water storages in excess of 800 years old that are being actively monitored.

Planning should integrate all the processes, systems, procedures and other activities required for a safe and economical TSF. Issues influencing the design and management of TSFs include the following:

The conceptual design of appropriate transport, disposal and storage methods (Chapter 3 - Tailings Storage Methods and Deposition Principles);

The anticipated tailings properties during the life of the mine, and how these may vary (quantity and quality) (Chapter 4 - Characterisation and Behaviour of Tailings);

The storage capacity and the management of water; either left over from the transportation of the tailings in a slurry, or from rainfall events (Chapter 5 – Water Management);

The detailed analysis and design of the facility and its various components including the design of raises and closure (Chapter 6 - Design and Analysis);

The construction of the facility (Chapter 7 - Construction) including the construction of intermittent raises;

The operation of the storage facility (Chapter 8 - Operation) including tailings deposition planning, budgeting for intermittent raises, monitoring of environmental and stability indicators to reconcile performance against design and emergency management planning; and

Decommissioning and closure to ensure that the post-closure performance will meet stakeholder expectations and regulatory requirements (Chapter 9 - Decommissioning and Closure).

Integrated Life of Mine planning should take account of the potential activities that will take place through the total life of the structure. This will include the initial "mine life" but also consider potential extension of mining or changes in tailings properties that might affect the design.

Integrating the planning for tailings storage into Life of Mine planning should also take account of impacts or synergies with all aspects of the mine operation. It can be particularly important to take advantage of other mine wastes for construction, water management impacts on mining and processing and particularly on closure methodology. Often cost and environmental benefits can be made for the overall project with minor extra effort or cost impost on one aspect. Tailings storage considerations should be part of optimising mine or processing operations. An example of this could be the inclusion of strategic waste rock placement as part of tailings dam construction at a small cost premium during operations to facilitate major cost savings at closure.

2.4.2 Key TSF Planning Objectives

The key objectives of integrated planning include:

1. A TSF design that is optimal (financially and environmentally) in terms of the whole-of-life storage methodology and design through full consideration of all potential alternatives;
2. Planning should consider the full cost of tailings disposal from conceptualisation to final decommissioning and rehabilitation, including long-term post-closure maintenance considerations. Considerations should include social, geochemical, environmental, technical and economic aspects, particularly the long-term impacts;
3. Appropriate designs through the full understanding of the setting, the operating environment and the potential risks including mitigatory measures to prevent adverse impact;
4. Key decisions must be based on all issues involved, particularly when using discounted cash flow methods that may minimalise the financial impacts associated with long-term risks issues. Decision making should be based on the whole of life evaluation of the potential consequences (cost, health, safety, environmental and community);
5. Decision making and implementation should allow an adequate margin of safety, and risks should be kept below levels that place an undue exposure to hazards on third parties or the environment;
6. Environmental impacts are minimised by initial design and also through an ongoing and continuous programme of management and monitoring;
7. Development of a robust closure plan taking into account the potential final landform, land use and environmental protection systems and the potential for post-closure environmental impact;
8. A management process that optimises and improves the TSF operation and manages risks so that they do not escalate during the operation;
9. Plan all phases of a tailings dam's life to ensure adequate storage capacity and optimum performance including consideration of potential changes to storage volumes through either early closure or extended mine life;
10. A full, whole of life valuation of the TSF including all phases of its life; and
11. Planning should consider possible developments beyond the immediate economic mine life. The life of a mine may be extended beyond the initial development stage, often for many decades. Planning should provide a degree of flexibility that might allow significant strategic and economic benefits to be achieved in the future with minimal cost in the present. This could be particularly important with tailings that could be at risk of generating AMD.

2.4.3 Important TSF Planning Data

In order to plan and design tailings dams the following data are required:

estimates of the incremental and final volumes of tailings to be stored;

land available for tailings storage which will exclude areas set aside due to ore reserves, environmental or archaeological (including Aboriginal) factors, plant construction, other industries, etc.;

basic environmental limitations; tailings disposal plans should be developed as part of the

- Environmental Impact Statement (EIS);
- basic tailings properties both geotechnical and chemical including process conditions, added chemicals and expected changes with time;
- storage capacity requirements, tailings production rates and delivery conditions, how they will change with time and the potential for planned or unplanned changes to the delivery conditions;
- for tailings dams that are raised incrementally to provide additional ongoing storage capacity, tailings drying and strength properties, safe incremental raise heights and raise construction durations. Information for raises is required so that the raises can be planned and implemented to avoid production interruptions that may occur when extreme wet weather periods occur at the same time that the remaining storage capacity is being used up;
- design life and total storage requirement with consideration of potential future changes, such as development of new ore bodies;
- topography of potential disposal sites;
- consideration of the consequences of failure of the storage, which will assist in risk assessment and selection of design parameters to be used;
- foundation conditions including geology, hydrogeology, groundwater quality;
- potential impacts on existing or possible future mine voids;
- seismicity of the area and seismic design parameters;
- available construction materials including geotechnical properties;
- long-term weather conditions including rainfall, evaporation, wind and extreme storms, with consideration of potential climate change;
- rainfall runoff conditions, both on the storage and from surrounding catchment areas;
- existing hydrological, suspended solids, dissolved solids and water chemistry data for nearby surface and groundwater resources;
- stormwater storage requirements and means to deal with excess stormwater; and
- long-term stable landform requirements including future land use and revegetation.

A major part of the planning process is to identify the data required, determine what data are available and to develop programs to obtain the remainder. In some cases this may involve monitoring of the early operations to confirm design assumptions that were based on experience or simply estimated due to the impracticality of obtaining such data at the design stage.

2.5 Tailings Management Plan

2.5.1 Levels of Planning

A Tailings Management Plan (TMP) is required for the complete life of the project including closure and any post-closure care and maintenance. The Plan should address design, construction, operation, closure and rehabilitation. Ideally the Plan should link tailings production characteristics to the consequential construction and operation requirements of the tailings dam, to highlight the impact of one on the other.

The Plan should account for any staged development. For example, lead times for design and construction of new storages should be clearly identified relative to the estimated time of filling of existing storages.

Since changes commonly occur throughout the life of a project, which can affect the operation of the tailings area, the Plan should be flexible and capable of modification. To this end the Plan can be subdivided into Short, Medium, and Long-Term Plans.

The Long-Term Plan provides the overall objectives, planning criteria, control points and goals for achieving satisfactory tailings disposal over the remaining life of the project. This long-term Plan ensures that there is sufficient storage capacity for the projected mine life and takes into account potential mine life extensions. This Plan should provide a link to the Closure Plan, discussed later in these guidelines.

The Medium-Term Plan provides management information and detailed schedules of the anticipated construction and capital expenditure necessary to maintain the tailings disposal area for the next few years, typically 3 to 5 years. The goals for the medium-term Plan are dictated by the Long-Term Plan.

The Short-Term Plan provides the month to month operating framework for the tailings storage. This includes the management of tailings beaches and wet season storm-water runoff. Modifications to the Short-Term Plan can be made to suit operating conditions provided they fall within the goals specified in the longer-term plans.

Plan Reviews should be carried out at least annually based on the performance of the whole disposal system and updated future production rates. Tailings dams often do not operate exactly as planned. Therefore it is critical that regular reviews are carried out and plans revised. One common outcome from out-dated plans is the unexpected 'discovery' that a tailings dam is filling early and the panic construction of a new storage with consequent impact on cash flow, compromises in the standard of design and risk of environmental impact.

2.5.2 Preparation of Tailing Management Plan

The basic steps towards preparing a tailings management plan should include the following:

2.5.2.1 Design Planning

The TMP must take into account that tailings dam design is not completed at the start of a project. It is more likely that the design will evolve over a number of years during operations. Accordingly, the TMP should include a design plan providing information on the basis of design and a methodology for a design review process. The design plan should include:

- an estimation of the total long term storage requirement;
- broad topographic and local land use survey of the project area with assessment of the compatibility of the tailings disposal and storage options;
- detail on the physical and chemical nature of the tailings to be stored;
- tailings characteristics such as beaching angle, settled density, and strength from laboratory tests or pilot trials to be updated as practical experience is gained;
- any special health and safety, handling and containment methods required, including statutory requirements and approval processes;
- tailings disposal method, rate(s) and period;
- estimated volume of liquids to be reclaimed and likely variability and a method for confirmation;
- local meteorology (wind, rain, evaporation) and seismicity of the area;
- a water balance model for the proposed tailings storage area;
- freeboard, overflow, and storage requirements and restrictions;
- estimated rate and quality of seepage losses;
- concept future storage requirements and area staged construction plan that meet the requirements;
- site investigation data identifying foundation and groundwater conditions and sources of construction materials;
- selection of final disposal area(s);
- assessment of rehabilitation requirements;
- final design and construction plan; and
- site monitoring equipment.

2.5.2.2 Construction Planning

A construction plan, by the designer, is required to list the order in which the various elements of the tailings dam are assembled and how the various items of work interrelate. In addition, long-term construction planning identifies latest dates by which new works must be commissioned. Typical elements would be:

- contract tender period, award and mobilisation;
- foundation preparation;
- construction of earthworks and/or embankment;
- construction of tailings discharge system (pipework, outlets, controls);
- construction of water reclaim and overflow systems; and
- installation of monitoring and security systems.

2.5.2.3 Operation Planning

Long, medium and short-term management plans should be prepared to ensure:

- efficient filling of the disposal area;
- transfer and reclaim of any decant liquors;
- safe containment or control of flood waters;
- periodic raising of embankments;
- surveillance and maintenance;
- progressive rehabilitation where possible; and
- accommodation of any variations from initial planning criteria.

2.5.2.4 Emergency Response Plan/Dam Safety Emergency Plan

An Emergency Response Plan (ERP) or Dam Safety Emergency Plan (DSEP) outlines the required procedures to:

- protect a dam and the associated community in the event of an emergency which may threaten the dam's security;
- define the basis of communication and responsibility in an emergency;
- notify the Emergency Authorities during a potential dam failure emergency;
- provide relevant information to assist the Emergency Authorities in its emergency planning for areas affected by dam breach and loss of water and tailings;
- provide guidance on action that could prevent or minimise dam failure in the event of a safety incident. This could include actions such as placing rockfill in piping breaches, raising the crest during overtopping events, etc.

An ERP/DSEP outlines the required actions of owners and their personnel in response to a range of possible emergency situations.

The ERP/DSEP should be prepared in accordance with Guideline on Dam Safety Management (ANCOLD, 2003).

2.5.2.5 Closure and Rehabilitation Planning

Closure and Rehabilitation Planning should ensure that the tailings disposal area is left in such a way that it is able to:

- be structurally stable;
- maintain an acceptable impact on the environment;
- be resistant to deterioration through erosion or decay;
- be compatible with the surrounding unmined landform; and
- be functionally compatible with the agreed post-mining land use.

The above criteria should apply over the perceived time frame of the post-closure period, which may be indefinite. If there is no defined post-closure design life, ANCOLD recommend adopting 1000 years as a reasonable period as being considered "in perpetuity".

2.5.3 Observational approach

Tailings impoundments take many years to construct and can experience many changes which may require operational response. During the design phase, geotechnical predictions are often based on limited knowledge. The observational approach is a process of verifying design assumptions and using additional data, knowledge and lessons learned to revise, improve and optimise the design.

Central to the observational approach is an instrumentation and monitoring program to observe and record key leading indicators associated with design and performance criteria (e.g. seepage, phreatic surface, density, strength parameters).

The observed values are compared against the design predictions to evaluate if any changes in operation or design are needed. Instrumentation data reviews are helpful in identifying any imminent problems. However, more subtle behaviours may only be identified by yearly review. It is essential to react to changes well before they become a serious problem. The observational method provides the ability to address concerns through "prevention" rather than "cure".

The observational approach has proved to be of value in reviewing pore water pressure predictions. It is unrealistic to expect that the pore pressure conditions within a TSF could be accurately predicted throughout its operational life. During TSF operations it is common that conditions (depositional, mineralogical, process, weather etc.) change, leading to changes in the pore pressure conditions within the impoundment. The observational method addresses this uncertainty by checking the validity of the design pore pressure conditions and giving a basis for reviewing and revising models.

Another benefit of the observational approach is that it can reduce the upfront capital cost of a project. The design is based on "best estimate" conditions and the observational approach is utilised to check estimated parameters. The "best estimate" design is checked against actual conditions. Upgrade measures might be required following start-up if "best estimate" assumptions are incorrect. The observational approach is used to decide if and when any upgrade measures need to be constructed.

The observational approach can be a very effective way of optimising a Tailings Dam design but relies on a consistent input from competent personnel throughout the operation phase.

2.6 External (Third Party) Review

Planning should allow for strategic review by independent parties at critical phases of the TSF life cycle. Review could take place during concept and feasibility studies, design, construction and closure. Third party review is also recommended during operations.

These reviews are in addition to dam safety reviews referred to in Section 8.

3.0 Tailings Storage Methods & Deposition Principles

The objective of tailings storage is to minimise the current and future risks from the storage. This will be achieved by ensuring the physical and geochemical stability of the tailings deposit over the whole of life of the storage.

3.1 System Components

The main system components to a tailings storage facility are:

- environmental protection measures;
- a method for the delivery of tailings to the disposal site;
- a method for the distribution, discharge and deposition of tailings within the storage;
- a method for containment of the deposited tailings; and
- a method for water management.

The design and operating practices for tailings transport, discharge, deposition, and water management (decant recovery) are closely inter-related. Suitable combinations will depend on environmental values, the terrain, tailings characteristics, water balance including climatic factors, and the method of containment.

3.2 Environmental Protection Measures

3.2.1 Overview

A tailings dam development needs to consider the potential impact of the system on the surrounding environment so as to minimise the operational and future risks from the storage.

The normal situation at a mine site will be that environmental performance requirements will have been defined by an Environmental Management Plan (EMP) or similar. It is of particular importance that tailings dam designers and environmental personnel have adequately communicated during the project development phase to ensure that realistic targets are set and that the design, construction and operational methods allow these to be achieved.

The principle environmental values that need consideration are:

- the community, which includes safety, people and their support infrastructure and industry;
- waters, which includes immediate receiving waters, watercourses, groundwater, water storages and potable water supply sources;
- air, which can be a transport vector for dust contaminants and fugitive gases;
- land, which includes fauna and flora support ecosystems; and
- heritage.

Recognised potential sources of environmental harm associated with tailings dams include:

- energy of stored tailings or water (dam break);
- toxicity of stored substances (tailings, water or fugitive emissions such as gas, fibres, dust and radioactivity; and
- toxicity of substances within a processing plant and associated works.

Recognised potential mechanisms of environmental harm associated with tailings dams include:

- uncontrolled mass release of flowable substances, either tailings and/or water, by collapse or failure of the containment embankment (dam break);
- uncontrolled limited release of contaminated flowable substances into environmentally sensitive places (spillway discharge, seepage to water resources);
- operational failure (pipe burst, pump failure, etc.); and
- transport of fugitive emissions (gas, dust) to environmentally sensitive places by wind.

Environmental risks should be managed by, in order of preference, following the principles of:

- avoidance by design;
- separation by distance;
- isolation by barriers; and
- management by operational control within tolerable risk limits.

3.2.2 Protecting the Community

The protection of the community is of primary importance. It is best achieved through avoiding situations where emissions from a tailings dam could, or be perceived to, adversely impact on the community. Experience has shown that locating tailings storages immediately above residential areas, process plants and other mine infrastructure where people could be exposed should be avoided if possible.

3.2.3 Protecting Waters, Air and Land

Some recognised principles to protect waters include:

- avoid placing tailings dams on natural drainage lines (rivers, creeks, valley floors) with significant upstream catchments;
- avoid placing tailings dams immediately upstream of water resources (dams, creeks, lakes, aquifers, water holes, etc.);
- make provisions in the design for the detection, collection and management of seepage to prevent emissions to the environment;
- make provisions in the operational control to minimise the risk of uncontrolled discharge through spillways; and
- manage, through deposition practices and other means, moisture content of tailings on beaches to minimise oxidation that could lead to acid and metalliferous drainage (AMD).

Some recognised principles to protect air include:

- manage, through deposition practices and other means, moisture content of beaches to minimise salting and dusting;
- application of dust suppressants (polymers etc.); and
- use of barrier layers (coarse rejects, waste rock, water) to prevent wind accessing tailings.

Some recognised principles to protect waters include:

- minimisation of the TSF footprint;
- minimise external borrow pits; and
- minimising groundwater rise that could affect vegetation or soil.

3.2.4 Protection of Fauna

Tailings dams have potential for environmental harm to the surrounding land through the potential to harm fauna accessing the tailings dam.

Some recognised principles to prevent access by fauna are;

- isolation by fences (animals); and
- isolation by netting (birds).

3.2.5 Protecting Heritage

Avoidance by design should be adopted wherever possible.

3.3 Delivery

Selection of the transport system is generally based on economic considerations of capital and operating costs but could be dictated by other design considerations.

The design of transport systems should include provision for instrumentation, monitoring, methods for checking for leaks, and spill containment methods for line breaks or malfunctions.

Options available for transport of tailings include:

- pipelines (gravity or pumped);
- channels/flumes;
- direct discharge (to the head of the storage or into a natural channel leading to the storage);
- conveyed/trucked (for “dry” or mechanically de-watered material); and
- specialised transport or disposal systems including:
  - pneumatic – for dry materials such as fly-ash, fume, and
  - crew conveyors - for drier or denser material over short distances.

Pipelines conveying pumped tailings slurry remain the most common form of delivery. Design considerations in this case include the following:

- thinner slurries involve transport of excessive water and hence may increase overall pumping costs; high density thickened tailings or paste will involve lower volume but higher friction losses;
- all except very dilute slurries behave as non-Newtonian fluids. Thicker slurries typically have distinct non-Newtonian properties which may vary according to rate of shear, shear history, chemical effects etc. This is a specialised area of rheology and testing and subsequent design requires great care in simulating the likely range of conditions;
- slurries containing coarser sand or gravel particles require certain minimum velocities to prevent settlement of particles, although some systems use "partially sanded" lines with a moving bed of particles in the lower portion of the delivery line. This practice is useful where there are significant variations in process rates and hence flow velocities;
- blockages in low points during stoppages;
- set up of high density or thixotropic tailings in the pipeline during stoppages (a standby system capable of flushing pipelines, even in a power outage, may be required); and
- corrosion/abrasion/scour of delivery pipelines.

ICOLD Bulletin 101 and Paste and Thickened Tailings - A Guide (Jewell et al., 2010), provide additional detail on design of tailings transport systems.

3.4 Methods of Containment

3.4.1 Constructed Storages

Storages constructed using retaining embankments are the most common form of tailings dam, and fall into two main types:

- cross valley or gully impoundments; and
- off-valley impoundments (including side-hill and fully contained ring-dyke or paddock type impoundments).

Cross-valley sites often feature relatively low earthworks volumes per unit volume of storage. However, they will have incoming run-off from the stream and adjacent slopes requiring special attention to water control. Side-hill impoundments generally require more embankment length and will have potential runoff from the uphill slope. Paddock impoundments which include embankments on all four sides, have minimal or no runoff into the storage.

Embankment types may be classified firstly by their required function, and secondly by the method of construction.

Embankments may be designed with the function of either:

- retaining water and solids; or
- retaining solids only.

Embankments designed to retain both water and solids will require many of the features of a conventional water storage dam, including low permeability clay zones or upstream liners, filters and drainage features, and foundation improvement measures to limit seepage.

Embankments designed to retain solids only will often include filter/drainage zones to permit safe passage of seepage. Alternatively, they may be used in systems where the depositional strategy is designed to minimise the occurrence of high phreatic surfaces within the embankment region and less elaborate measures may be justified.

3.4.2 Self-Stacking Tailings

Down-slope discharge of non-segregating thickened tailings, or discharge from a raised central point (central thickened discharge) will minimise the need for retaining embankments, but may require higher thickening and pumping costs.

This method usually requires a design beach slope to be maintained throughout the operation. The consequences of this are that the design needs to cater for:

- variability of ore and underflow density;
- a continuous lateral spread of the edge of the tailings stack, or incremental raising of external bunds;
- potential process upsets; and
- stormwater management.

Advantages of the method are:

- reagent and water recovery are maximised;
- minimal embankments and hence low construction costs;
- low operating costs at the TSF;
- the large beach area maximises the opportunity for evaporative drying and hence the density and strength of the tailings can be high;
- the runoff/decant pond can be located off the tailings which may allow better management;
- the final profile is self-shedding (of rainfall) on closure;
- the final landform may be in keeping with the surrounding topography; and
- almost immediate access after deposition ceases.

Disadvantages of the method are:

- the large area required for placement;
- possible need to allow storage of large quantities of runoff water from extreme rainfall events;
- the negative effect on storage capacity if thickener performance deteriorates or varies below design assumptions;
- the dependence on evaporative drying to achieve enhanced strength and density;
- the capital cost of thickeners, and the operating costs associated with high flocculant usage;
- pumping costs associated with high viscosity slurries;
- erosion of slopes in high rainfall regions;
- difficulty of controlling dusting over large areas;
- rehabilitation is required over a larger area (but unit costs may be lower); and
- potential acid and metalliferous drainage (AMD) from non-saturated sulphide tailings.

3.4.3 Existing Voids

Tailings may be contained at low cost in worked out pits, voids in waste dumps or in underground workings.

3.4.3.1 Open Pits

Disposal into open pits can be used in a multi-pit operation or where abandoned pits are available nearby.

Relevant considerations include:

- sterilisation of underlying or adjacent resources;
- interaction with potential under-ground resources;
- interaction with groundwater;
- the rate of rise will affect the degree of evaporation and consolidation that will occur during filling, which influences:
  - placement density;
  - water recovery from the tailings;
  - access for final capping;
  - post-filling consolidation settlement;
- the effectiveness of under-drains; and
- the static head for pumping decant/runoff from the pit.

In-pit disposal is a preferred approach for some situations e.g. to reduce the risk of uncontrolled post-closure release of tailings into the environment by surface erosion. Use of tailings for backfill may be appropriate if pit backfill is required for other reasons.

3.4.3.2 Voids in Waste Dumps

In some open-pit or open-cut mines there may be a possibility to modify the shape of waste dumps or spoil piles to provide for containment of tailings.

Relevant considerations in this instance include:

- the particle size distribution of the waste, and its ability to physically retain the tailings;
- the fate of tailings water infiltrating into the dumps; and
- potential effects of infiltrating water on the stability of the dump.

3.4.3.3 Underground Mine Disposal

Some underground mining methods require previously excavated stopes to be progressively backfilled. Tailings are a possible backfill material but, being in slurry form, are usually slow to drain and consolidate. For this reason the coarser fraction is often separated from the fine tailings fraction and used as backfill, commonly after stabilising with cement or lime. Alternatively thickeners or mechanical filters may be used to de-water tailings to a paste consistency, allowing greater percentages of fines to be incorporated in the backfill (ACG, 2005).

This is a specialised procedure requiring considerable research, experience and design including assessment of the effect on deeper or adjacent stopes that might be operating. There may also be occupational health risks associated with discharge of tailings underground.

3.4.4 Co-Disposal

The technique of co-disposal (Morris, 1997) applies in processes that produce rock waste and tailings in two or more separate size streams where the fine fraction is able to be incorporated into the voids of the coarser material (e.g. coal, mineral sands).

Historically, these components were disposed of separately, typically by treating the coarse waste as a solid (i.e. conveying or trucking), and the fine fraction as conventional tailings (slurry).

Co-disposal involves mixing of the waste streams for the purpose of:

- facilitating transport; and/or
- improving the properties of the waste product after placement.

Co-disposal mixes can be transported either by pipeline as a slurry, or by truck or conveyor if the mix has sufficient strength and does not segregate during handling.

Because of the problems associated with pumping dense mixes, co-disposal transport often uses very dilute slurries. Features of these types of systems are:

- large pumps and pipelines;
- pipeline wear issues;
- requirements for supply and recycle of dilution water;
- segregation of the coarse and fine fraction on discharge;
- blocking of pipelines; and
- formation of a separate coarse section and a slimes pond in the storage.

Attempts have been made to pump dense slurries so that at deposition the slurry is non-segregating, with the resulting benefits of self-stacking tailings. Slurries with high solids concentrations are required which are difficult to pump using centrifugal pumps. Positive displacement pumps are required with commensurate capital and operating cost implications. An alternative approach is to mix the coarse and fine fractions at the point of discharge (eg mineral sands).

Where co-disposal is undertaken with the aim of improving the properties of the final mix, the intent is usually to have the particles comprising the coarser fraction in contact, with the interstitial voids filled by the fines, plus the water. If this is not achieved, the properties of the mix will simply be governed by the properties of the fines. There is therefore a practical limit of tailings that can be co-disposed with the coarse fraction.

3.5 Methods of Discharge and Depositional Strategies

3.5.1 Methods of Discharge

Decisions about the discharge method are made at the design stage. In due course the operators must be made aware of the requirements and good operating principles to implement these procedures effectively (see also ICOLD Bulletin 101, 1995).

For any impoundment type storage, it is necessary to ensure a method of distribution which will efficiently utilise the storage. Typical discharge methods to achieve this from slurry tailings are:

- Single Point - For some depositional strategies and surface topography, a single discharge point will be possible. However, if the discharge point is kept in one location, tailings may build up from this point and the filling of the impoundment may be uneven and inefficient. With thickened tailings a version of single point discharge can be central discharge where a cone of tailings is developed from a vertical discharge riser pipe.
- Alternating Single-Point – Involves discharging the full stream of tailings from a single point at any one time, but with a number of alternative points available. Discharge points are alternated from time to time. This method may be utilised where there are separate valleys to the storage and evenly distributed filling is required.
- Multiple Discharge/Spigoting - A header main is installed along sections of the storage perimeter with multiple valved outlets located at intervals (e.g. 10 m or 20 m centres). The discharge can then be rotated around the storage by using a limited number of outlets for a time, then closing them and opening the next series of outlets. This technique is known as spigoting and is used to achieve a uniform thin, well segregated beach able to dry to maximise density.

Hydrocyclones - Where tailings contain a significant proportion of sand, hydrocyclones may be used to separate the coarser, more freely draining material from the finer fraction. The coarser fraction is discharged as "underflow" with relatively low water content. Following drainage, this material is then used to construct/raise the embankment, typically by centreline or downstream methods, including provision for compaction. Good separation of the sand from the fines (i.e. low fines in the produced sand) is important to ensure drainage and stability of the embankment. The finer fraction plus most of the water is discharged separately as "overflow" into the storage.

Other methods such as conveyor and truck haulage are possible with dry stacking systems using filtered tailings.

3.5.2 Depositional Strategies

Basic strategies are:

Sub-aqueous where the tailings surface is continuously submerged below free water. Separation of the tailings solids from the liquid phase occurs by the processes of sedimentation and submerged consolidation only. This type of deposition should only be adopted deliberately where climatic conditions and the design ensure reliable year round coverage by water, and that coverage is determined to be essential for environmental or health and safety reasons dictated by the physical and/or chemical properties of the tailings e.g. to prevent oxidation of sulphides or to reduce radon emissions from radioactive tailings. In other cases, management of site water may not be possible without accepting free water ponded or flowing over the tailings. In containment systems of limited surface area, the rate of rise of the tailings may be so great that no effective surface drying occurs, resulting in an essentially sub-aqueous system.

Sub-aerial deposition where placement of tailings forms an exposed beach over most of the storage area. The evaporative drying of the surface improves the density of the tailings. A minimal pond area will reduce total evaporation losses. Where beach density needs to be increased beyond the level achieved by simple drying, this can be achieved by mechanical working. An example of this is the use of "mud-farming" in red mud ponds, where mechanical equipment such as amphi-rollers are used to dry and compact the tailings.

"Dry stacking" systems involve de-watering the tailings (e.g. using mechanical filters) to a state where they can be handled by earthmoving machinery or conveyors.

Design considerations include:

The effect of variations in evaporation from summer to winter on strength and density;

The implications and management of water that may accumulate during wet / winter seasons or following storms;

Initial placement in narrow valleys and/or when the first filling rise rate is high and will not allow drying. This effectively is sub-aqueous placement even though the long-term system is designed as sub-aerial, and the implications of pockets of low strength material must be fully evaluated in the design;

Multiple Storages - Rotating discharge between several cells allows the central pond in one cell to dry out whilst it is being rested. The accumulation of wet low strength slimes in the centre of the storage is thus minimised. Seepage flows through the base are reduced due to the regular interruption, and scheduling of embankment raising is easier since it is not necessary to be discharging into and raising the same storage simultaneously; and

Point of Discharge Flocculation - Significant de-watering of a slurry may be achieved by heavy dosing with chemical additive ("flocculent") at the point of discharge from a pipeline. This results in a higher initial settled density, improved water recovery, and the potential for higher final density depending on site evaporation rates. It also imparts additional viscosity to the slurry and a steeper beach slope results giving improved runoff and drainage. It appears to be most effective in the case of tailings slurries with high/plastic fines content.

3.5.3 Segregation and Beach Slope

In slurries at low solids content, the segregation of coarser particles towards the top of the slope will give a classical concave beach profile (Blight, 1994). Reasonably steep slopes (5% or higher) may be obtained locally near the discharge, but the down-slope angles may be close to horizontal.

The coarser material on the upper part of the beach may be subsequently utilised in embankment construction or for mine backfill. If this method is used, due allowance must be made in the design for the changed properties of the residual slimes, compared to the original "all-in" tailings.

As the tailings slurry is thickened, it eventually becomes non-segregating and remains as a homogeneous slurry. The resulting beach slope will be more uniform and steeper overall. Advantage can then be taken of these properties to stack the tailings. Typical overall beach slopes obtained by thickening are in the range 1% to 4%.

3.5.4 Decant Pond

The size and location of the decant pond is influenced by the method and direction of discharge, the geometry of the tailings dam, the climate, decant recovery rate and the settling characteristics of the tailings. The pond location may have a critical influence on the quantity of seepage that occurs, and on the static and seismic (liquefaction) stability of the storage.

The storage capacity can potentially be greatly increased by discharging downslope towards the embankment, as shown in Figure 3. However, the decant pond will form against or near the embankment. This will generally lead to a higher phreatic surface through the embankment, which will adversely affect embankment stability. The embankment height may also need to be increased to provide the necessary freeboard for water management.

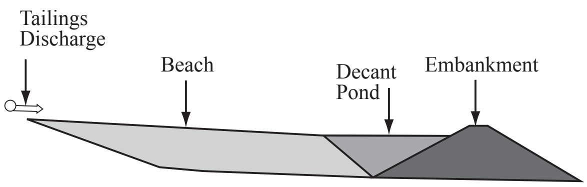


Figure 3 Downslope Discharge

The relative slopes of the ground and the tailings beach influence whether down-slope discharge will be advantageous. Concave beach slopes from segregating slurries will lose much of the advantage. Hence down-slope discharge will be most effective with thickened, non-segregating tailings that will form a steeper overall beach slope.

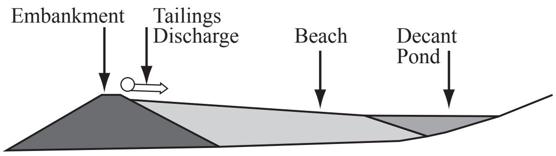


Figure 4 Upslope Discharge

In some circumstances there will be virtually no decant pond. However some form of runoff/decant dam will probably be required to manage wet season and storm runoff.

Where the upslope method is used (discharge from the embankment, as shown in Figure 4), the storage can be maximised for a given embankment height by minimising the beach length, thus favouring a relatively centrally located decant pond.

3.5.5 Control of AMD (see also 4.3.1)

Tailings containing sulphides can be at risk of generating AMD with potential to create long-term environmental legacy requiring on-going active treatment and preventing release of mine leases post-closure. The assessment of AMD risk and development of subsequent management systems is a specialist field and professional advice on this area should be sought early in the planning phase. AMD is caused by oxidation of sulphides generating sulphuric acid and consequential solution of metals, creating potentially polluting leachates or discharge. Even where tailings include neutralising minerals that control pH, the effluents can be saline, particularly high in sulphates.

There are a wide range of methodologies available to control AMD, some with higher risk than others. Some examples are:

Sub-aqueous discharge - maintaining saturation can prevent oxidation;

Underground disposal such as mine backfill, where tailings could end up submerged below the long-term water table;

Limiting beach exposure - frequent recovering with fresh tailings can maintain saturation and limit oxygen contact, particularly when tailings contain sufficient neutralising capacity to provide a "lag" time before acidic conditions develop;

Processing to remove sulphides in order to provide a majority tailings product with reduced AMD risk and a lesser volume of sulphide tailings that can be disposed of in an appropriate manner.

Care should also be taken to ensure that tailings dam construction materials are not prone to AMD. This can be a problem where waste mine rock is used for dam construction.

3.6 Discharge to Environment

Disposal of tailings into rivers or shallow marine waters generally has significant negative environmental implications. Any tailings disposal method that may result in serious or irreversible environmental damage is not viewed as appropriate tailings disposal methodology by the community or by the mining industry.

Deep sea tailings placement techniques may be acceptable where deep water is close to the mine and if appropriate criteria are met. The depth of water required is likely to make the method unsuitable for the Australian continental shelf.

3.7 Method of Construction

3.7.1 Staged Construction

Initial construction of tailings dams to their full final height is rare as this requires large material quantities and significant capital expenditure. Hence a scheme of staged construction is commonly adopted.

An initial "starter" embankment will have a life typically of about one to three years. The primary reasons are to minimise the initial capital cost and, to provide the opportunity in the design for the tailings themselves to be used in or to form part of the future embankment.

The design must anticipate the future needs of the embankment right through to completion and rehabilitation. Thus features such as foundation cut-offs, underdrainage, linings, and decant provisions must be constructed at the same time as the starter embankment. Access to construct any of these items or to undertake remedial work may not be available later in mine life. In addition access to construction materials initially obtained from within the storage area may not be available for future stages.

Following the completion of a starter embankment or initial stage, there are three basic methods of staged construction. These are:

Downstream, incorporating a starter dam;

Centreline, where part of the raised embankment is built on tailings with the rest by downstream construction; and

Upstream, where most of the embankment is built over the tailings beach.

ICOLD Bulletin 106 contains further information on these methods of construction.

4.0 Characterisation and Behaviour of Tailings

It is not possible to properly design, operate or close a tailings dam without adequate knowledge and understanding of the tailings properties.

4.1 Introduction

Design of a tailings dam should include adequate testing of representative samples of the tailings and include field testing where possible.

In general, testing should include:

- physical characteristics of the tailings (both as a slurry and as "solids"), including allowance for particle segregation;
- engineering characteristics, such as settled bulk density, dry density, specific gravity, shear strength parameters, consolidation and permeability characteristics;
- chemistry of the process liquor;
- mineralogy / geochemistry (including assessment of discharge water quality and potential for impact on the receiving environment); and
- rheological properties (see Section 4.4).

In the case of initial design for a new mine/ore body, available samples may be limited to proto-type tailings (e.g. residue from metallurgical process design testing on limited samples of ore), or tests on tailings from a similar ore-body from another mine. The quantity of material available may limit the amount of testing that is possible. In these cases the results should be treated with due caution. A conservative approach should be adopted until the design parameters are confirmed by follow up tests on production tailings and observation of field performance.

Wherever possible, testing should be undertaken on the range of tailings types that might be anticipated at the site. This can be extremely important in ensuring that worst case properties are determined.

The amount of testing necessary may be reduced in cases where the properties are already well known, provided monitoring confirms that properties are not changing.

4.2 Physical and Engineering Characteristics

4.2.1 Laboratory Testing

Typical tailings may include sand, silt and clay sized particles. As a result of water based processing technologies, tailings are typically produced in slurry form.

Physical tests for tailings should recognise that:

- some tailings behaviour and test results will be influenced by processes applied to the slurry prior to discharge, such as flocculation, thickening, and pumping;
- some tailings behaviour and test results will be influenced by processes which occur after deposition, such as segregation; and
- tailings deposited sub-aqueously, particularly through deep water, are likely to segregate. Segregation also typically occurs for tailings slurries of low solids concentration deposited sub-aerially.

The chemistry of the slurry water, in particular pH and salinity, can significantly impact on the tailings behaviour on drying and rewetting.

The characteristics (including density, strength and compressibility) of the various components following segregation will not be the same as those for the initial "all in" tailings. It is therefore necessary to consider if segregation will occur, and (if it does), the properties of the segregated components.

Sample preparation prior to testing must also take account of the origin and nature of the sample. Some tailings properties may be strongly influenced by slurry history. Samples which have been obtained from an existing process may have already been flocculated and thickened. Alternatively, samples derived from metallurgical test-work are unlikely to have been flocculated and thickened. Storage time can be an important consideration, as some materials will change characteristics when stored for extended periods.

Tests which should be carried out and that are generally not influenced by slurry history include:

- soil particle density (specific gravity);
- particle size distribution; and
- maximum/minimum dry density.

Tests influenced by slurry history typically include:

- plasticity (Atterberg Limits);
- settled density;
- density after drying;
- segregation characteristics; and
- rheological parameters.

In these cases it is desirable that the tests should be carried out on samples that have been taken, or prepared, to replicate actual conditions.

Rheological testing undertaken for the purpose of thickener design (sizing and torque calculation) is typically carried out on settled slurry without pre-shearing. Many slurries are thixotropic and/or subject to shear thinning. Tests on samples that have not been pre-sheared may be misleading if used for purposes of pipeline design, or for beach slope estimation.

4.2.2 Compression/Consolidation Tests

An estimate of the density of the deposited tailings at the end of filling is a common design requirement. Consolidation tests (often using a "Rowe cell" apparatus (Sarsby, 2000)) are frequently carried out to provide data for this analysis.

The increase in effective stress (resulting in consolidation and increased density) in a tailings deposit is likely to be the result of a combination of two mechanisms:

- development of negative pore pressure due to evaporation from the surface; and
- increase in overburden stress due to self-weight consolidation.

Generally:

- gravel, sand or sand / silt mixes will settle relatively rapidly to form a soil-like mass little affected by subsequent drying;
- fine silts and clays will settle slowly to form a soft, soil-like mass of low density which will continue to settle (consolidate) under its own weight with time according to the speed at which the contained water in the tailings voids can escape; and
- mixtures of grain sizes may segregate in the storage with coarser particles settling near the discharge outlets and the finest particles being carried to the furthest parts of the storage.

With due allowance for low densities and some possible chemical effects, most deposited tailings eventually behave in a similar manner to soils of the same grain size and shape. In the interim, however, finer grained material may remain as a fluid or as a thixotropic material for extensive periods.

4.2.3 Permeability Tests

The permeability (hydraulic conductivity) of tailings is dependent on the particle sizes, degree of segregation, the amount and type of clay minerals present in the tailings, and the density achieved in the material at a given time. Laboratory consolidation tests carried out on tailings samples can provide permeability data for low density tailings that cannot be tested by conventional permeameters. Field tests in boreholes or pits are useful as they also include the influences of layering and shrinkage cracking.

4.2.4 Dust Generation Tests

Wind tunnel tests can be used to assist in the prediction of dust generation from exposed tailings beaches. Tests should also consider potential site specific factors.

4.2.5 Strength Tests

Triaxial tests are the preferred method of strength testing, although shear box methods are still sometimes used. Triaxial tests with pore pressure measurements should be considered in order to obtain the pore pressure parameters in addition to traditional effective and consolidated undrained shear strength parameters.

Strength tests may be carried out on "undisturbed" samples recovered as part of a site investigation program. This may require specialised sampling, handling and transportation techniques and even then it may be very difficult to achieve a good sample.

Alternatively, specimens may be prepared in the laboratory from either sedimentation and consolidation from a slurry, or dry/moist preparation followed by saturation and consolidation.

In all cases it is critically important to ensure that specimens are not pre-consolidated or tested at a density that is unrealistic compared to the actual in-situ conditions and that correct stress conditions are produced.

It is important to characterise both the drained and the undrained shear strength properties of tailings, together with residual shear strength parameters if large deformations are expected, particularly under earthquake loadings.

4.2.6 In-situ Testing

The condition (or state) of existing tailings deposits may need to be evaluated by in-situ testing. The reasons for investigation may include:

- sampling for chemical or geochemical reasons;
- assessment of in-situ strength and/or degree of consolidation;
- assessment of dry density;
- permeability evaluation;
- evaluation of phreatic surface and/or degree of saturation; and
- potential for liquefaction.

The scope of any investigation work must be closely tied to the aims of the investigation.

Suitable methods are heavily influenced by trafficability and access, or on the stability of any test hole/excavation.

Typical investigation methods include:

- boring in cased holes, with Standard Penetration Test (SPT) and undisturbed tube sampling;
- cone penetration tests (CPT), preferably in conjunction with pore pressure probes (CPTu);
- shear vane tests;
- dynamic cone testing;
- in-situ density evaluation by the sand replacement test;
- hand auguring and test pitting; and
- geophysical methods.

In-situ test penetration methods are useful for evaluation of the liquefaction potential of a deposit, and of the post-liquefaction shear strength.

In principle, both SPT and CPT methods can be used. In practice, SPT methods are not continuous, and not sufficiently sensitive to low strength materials, and CPT methods are increasingly preferred. (Robertson and Fear, 1995, Olsen and Mesri 1970)

4.2.7 Field Trials

Field trials (such as trial embankments) can be used to confirm properties of tailings and proposed construction techniques.

Beaching trials can be conducted in association with thickener pilot plant trials.

4.3 Mineralogy and Chemistry

4.3.1 Geochemistry of the Liquid and Solid Components

Tailings and transport liquors may contain deleterious substances such as acids or alkalis, high salt levels, cyanide, heavy metals, radioactive elements, etc. Knowledge of the mineralogy and chemistry of the contained solids and fluids is therefore essential to the proper environmental design of a storage area.

There may also be ongoing chemical reactions within the storage, some of which are deleterious. Examples include:

- oxidation of sulphide ores to create acidic water;
- base exchange with cyanide compounds into non soluble forms;
- binding of metals onto clay particles; and
- release of gases, sometimes toxic (e.g. gypsum stockpiles).

Apart from environmental considerations, knowledge of mineralogy and chemistry also helps predict the behaviour during disposal, the consolidation phase and for eventual rehabilitation.

Fine tailings of apparently similar particle grading, can consist of finely ground rock particles or alternatively of an aggregation of many clay particles which have been flocculated by surface charges of individual clay particles. Behaviour during deposition and consolidation may differ markedly since flocculated clays may disperse in fresh water (from rainfall). Conversely, apparently fine grained materials may flocculate in the presence of saline process water or concentrated decant water. Testing procedures should assess these effects and potential changes with time.

Some processes add lime, which can cause flocculation, or dispersants/frothers which can cause dispersion. The addition of gypsum or lime to a consolidating clay tailings deposit can markedly improve soil conditions for rehabilitation.

Some tailings change grain size upon exposure as a result of oxidation, whilst others form a cemented mass due to chemical changes or precipitation of dissolved chemicals as drying continues.

It is therefore imperative that knowledge of mineralogical and chemical aspects be gained, together with knowledge of possible variations in ore types, processing variables, and potential reactions on exposure to rain and air. Any testing should take place using fresh, saturated samples with actual or simulated process water. Further testing with rainwater and pre-dried samples would give comparative results which may help to identify relevant issues.

Testing may consider both short-term and long-term leachate quality effects with simulated flushing rates. Leachate water quality assessment should consider neutral leaching, redox reactions and, if present, AMD processes.

4.4 Rheology and Transport of Tailings

Rheology of tailings affects the delivery and discharge characteristics and may become important at higher solids concentrations. The determination of rheological characteristics is a specialised field. Test methods can include rheometer and/or pipe loop tests.

The most common method of transport is as a slurry, generally within the range 20% to 65% solids content by weight. The actual solids content that may be adopted for design is a function of:

- the specific gravity of the solids;
- the solids content at the end of the process;
- whether thickeners / filters are used for water or chemical recovery or to reduce the volume for tailings pumping; and
- rheological properties and pumping costs.

In some cases the initial settled density of tailings is a function of the density at discharge i.e. some thickeners produce settled tailings at a higher density compared to simply sedimented/settled tailings.

4.5 Tailings Beaches

Beach angles can be approximated from laboratory trials but are neither reliable nor consistent with actual beach behaviour. Theoretical calculations based on rheology or shear strength may be imprecise due to material variability and the difficulty in determining the low shear strength of recently settled material. If there are existing or nearby tailings beaches of similar material, grading and process, then these will be a useful guide.

Beach angles are also a function of the method of operation of a storage. Beach angles below water are complex due to various influences that can occur, but are generally steeper where the beach enters the water.

The slope of the beach depends on the rheology of the tailings, the nature of tailings including the tendency to segregate at low beaching velocities, the energy of deposition (flow rate), and possibly the distance to the decant pond (ICOLD Bulletin 101, 1995). Steeper beaches can cause significant “air-space” volumes in the basin that develops and can thereby increase the storm storage capacity but reduce the tailings storage capacity. The beach may be influenced by potential slumping under earthquake or storm loading, or by rainfall erosion of upper slopes leading to sediment deposition on lower slopes.

5.0 Design - Tailings Storage Capacity and Water Management

The objective of providing adequate tailings and water storage capacity is to ensure that the risks posed by water to the structural integrity of the storage and to the wider environment are adequately managed and that the water resources of the site are utilised responsibly.

5.1 Design Criteria

Tailings dams have somewhat different storage capacity and water management requirements to normal water storage dams in that allowance needs to be made for both dam safety and environmental safety in an operational situation where the remaining water storage capacity is continually being reduced by the deposited tailings solids and water quality may be unsuitable for release to the environment. The dam safety requirements will determine the spillway design to avoid overall embankment failure, whereas the environmental issues will determine the storage allowance to be provided to reduce the risk of spill from the dam. A flow chart of the design process for spillways and flood storage is presented in Figure 5. The differing design issues are discussed as follows:

5.1.1 Tailings Storage Capacity

The purpose of a tailings dam is primarily to store solids but this is often complicated by:

a) Staged construction; and

b) Uncertainty as to the tailings dry density that will be achieved in the dam.

Accordingly, appropriately conservative assumptions need to be made regarding the storage volume allowance for any design period of a tailings dam life.

In addition, the timing of construction of the following stage of storage, being a new dam or a raise of an existing dam needs to be carefully considered to make sure that production is not compromised by lack of available storage. In most areas there will be more appropriate seasons for earthworks construction that will need to be factored in. In wet climates for example the construction season may be limited to around six months of the year. The time for construction is also important as it is likely to take six months to construct a typical tailings dam raise, or potentially longer for the ever increasing size of tailings dam being undertaken as mine projects expand in production rate.

The physical climate, political climate, potential construction time and the importance of maintaining continuous production should be taken into account in establishing the tailings storage allowance. This should be set so that there is at least 6 months excess capacity remaining at the time the next stage of storage capacity is expected to be available. This contingency may not be sufficient for some industry sectors or individual operations where up to 3 years excess capacity may be appropriate to cover unexpected delays due to weather, construction equipment or labour unavailability, or other issues.

5.1.2 Minimum Decant Storage Capacity

There will normally be some minimal level of decant storage required to allow settlement of decant water or chemical equilibrium development prior to water removal from the tailings dam. This will vary depending on production rates, the tailings settlement characteristics and the climate. It is likely that this volume will need to be determined by experience. Normally it is desirable to minimise the pond size to maximise the extent of tailings beach development to achieve good drying and consolidation. However, during wet weather the pond size will need to be increased to prevent carry-over of tailings solids. This will require a decant system which can be controlled, either by operation of a valve on gravity flow systems or by controlling the pump output for pumped systems.

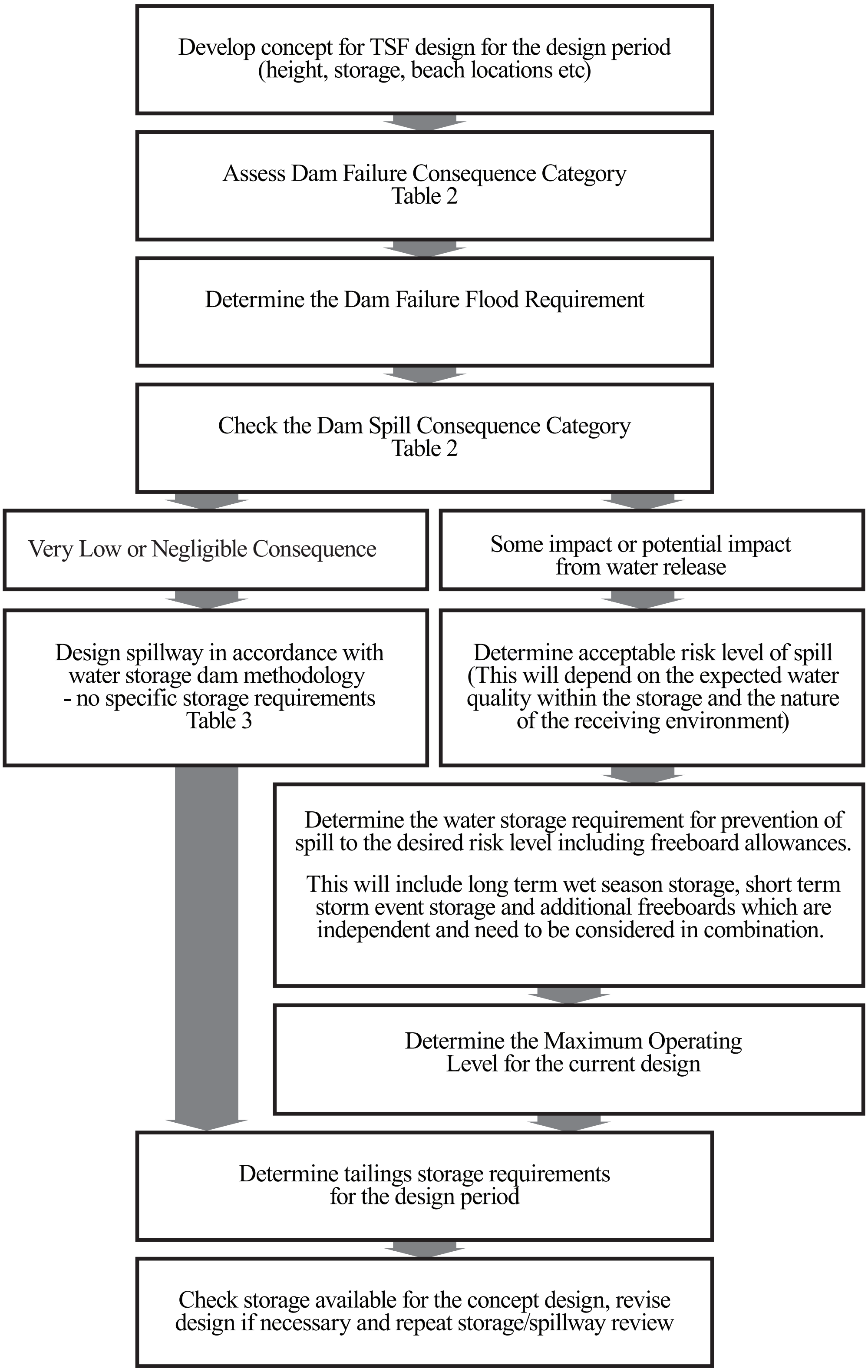


Figure 5 Flow Sheet for Tailings Dam Spillway and Storage Design

5.1.3 Non-Release Dams - Design Storage Allowance

Where water quality within the storage is unsuitable for release during normal conditions, appropriate wet season storage, extreme flood storage and appropriate contingency storage allowances are made to ensure that the risk of spillage is reduced to an acceptable level.

The design storage capacity must be sufficient to accommodate the solids and liquid inputs until such a time as excess accumulated water can be recovered, or until additional storage capacity can be provided by constructing a new dam or raising the embankments of an existing dam. Where ongoing storage capacity is provided by incremental raising of existing dams, it is good practice to provide the contingency storage capacity.

For extreme consequence dams, the design storage allowance should be developed using quantitative risk analysis methods. For high and low consequence dams, semi-quantitative risk analysis methods should be used. Alternatively, minimum allowances may be determined using a fall back method as per examples in Table 3, Table 4 and Table 5 below. These show only the additional storage allowance for stormwater. Tailings solids and liquid volumes expected over the design life for the particular storage period need to be added.

Because rainfall in a wet season can occur on previously wet catchments over a short period of time with minimal evaporation possible, wet season assumptions for fall back methods should be assessed using a run-off coefficient of 1.0 and no evaporation.

Probability objectives applied to more rigorous methods such as calibrated hydrological models will have to be lower, due to less conservative assumptions. Refer to Section 5.4 for run-off calculations.

For the tables below, the Dam Spill Consequence Category should be based on the consequence of release of stored water from the dam. This may be different from the Dam Failure Consequence Category which considers failure of the embankment.

It is imperative that the maximum operating level is identified for each individual dam. If the water in that dam reaches the maximum operating level, the deposition of tailings (and all process water streams) into that dam must cease, and the relevant sections of the Dam Safety Emergency Plan must be initiated.

Table 3 Minimum Wet Season Water Storage Allowance - Fall-back method – Queensland (capacity to be available on 1st November, i.e. before start of wet season)

Dam Spill Consequence Category	Design Storage Allowance (DSA)
Low	1:5 notional (note 1) AEP wet season (note 2) runoff
Significant	1:10 notional AEP wet season runoff
High	1:100 notional AEP wet season runoff
Extreme	1:1000 notional AEP wet season runoff

Note 1 The term “notional” is used because of the conservative assumptions made in the method.

Note 2 The Wet Season is the period in which 70% of the annual rainfall occurs on average. In Queensland it can be 2, 3 or 4 months long.

Table 4 Minimum Extreme Storm Storage – Fall–back method

Dam Spill Consequence Category	Extreme Storm Storage Allowance
Low	Determine by risk assessment
Significant	1:100 AEP, 72 hr flood
High C	1:100 AEP, 72 hr flood
High B	1:1000 AEP, 72 hr flood
High A/Extreme	1:10000 AEP, 72 hr flood

Table 5 Recommended Contingency Freeboards

Dam Spill Consequence Category	Wave Run-up	Additional Freeboard (m)
Low	nil	nil
Significant	1:10 AEP wind	0.3
High C	1:10 AEP wind	0.5
High B	1:50 AEP wind	0.5
High A/Extreme	1:50 AEP wind	0.5

5.1.4 Spillways

The design flood requirement for spillway design can preferably be determined by risk assessment methods and Guidelines on Design Floods for Dams (ANCOLD, 2000). The design flood magnitude should be determined based on the Dam Failure Consequence Category of the dam as determined from Section 2.3 and then determining an appropriate flood magnitude on the basis of AEP. These requirements are summarised in Table 6. The design flood may need to be varied during different phases of the Tailings Dam life cycle if the Dam Failure Consequence Category varies. In addition the AEP selected should take into account the risk over the expected operating life of the dam and also the As Low As Reasonably Practical (ALARP) risk principal. The values in Table 6 should be treated as minimums and design for more severe conditions should be adopted where possible.

A spillway should always be provided - even where "no spill" design requirements are in force, to guard against overtopping in extreme, or unexpected, events that could lead to failure of the dam embankment. The only exception to this guideline is where extreme flood storage (storage specifically provided to contain an extreme event) is provided for within the structure and that overtopping is inconceivable. Where no extreme flood storage is provided, or if flood storage is for long-term flood storage, such as a "wet season storage", the spillway depth should allow for passage of the design flood, assuming an initial water level is at the spillway invert prior to the occurrence of the design flood. Where short-term extreme flood storage is provided, the spillway sizing may be determined based on routing calculations taking the extreme flood storage allowance and any contingency freeboard into account.

Even if design allows for extreme flood storage, it is recommended that a conservative emergency spillway capacity is provided, which is independent of operational assumptions. The cost of additional spillway capacity to meet conservative assumptions is small compared to the potential consequences.

Additional wave-freeboard, above the maximum flood water level to the dam crest might be required to prevent wave action overtopping the crest, depending on the potential for damage or environmental impact.

It may also be appropriate to add additional freeboard to allow for wind set-up in larger storages and for uncertainties of calculation, particularly if erosion has the potential for embankment breaching.

At the end of mine life, closure spillways should be designed for PMF flows for all Consequence Categories, given the time frame of the expected life in the order of 1000 years. In addition the freeboard at closure should take into account potential settlement of the embankment due to consolidation and earthquake induced deformation. For the post-closure design period the impact of multiple events should be considered. This could include cumulative settlements from a number of earthquakes with Annual Exceedence probabilities less than that of the MDE.

5.1.5 Non-release Dams - Emergency Spillways

In addition to the provision of a conservative dam storage allowance for no-spill tailings dams, it is also good risk management practice to provide an emergency spillway. An emergency spillway is a strong preventative control against overtopping and hence against the potential for extreme consequences associated with catastrophic failure of the dam embankment.

If good operating practices have been followed in the lead up to the emergency spillway release, only a small quantity and flow of significantly diluted water will occur, reducing the potential impact associated with such a release. The downstream receiving environment is also likely to be severely flooded, further diluting any contaminants and reducing the potential environmental or health impacts.

Table 6 Recommended minimum design floods for spillway design and wave-freeboard allowance during operation phase

Dam Failure Consequence Category	Design Flood AEP (Note 1)	Wave Freeboard Allowance
Low	1:100	Wave run-up for 1:10 AEP wind
Significant	1:1000	Wave run-up for 1:10 AEP wind
High	1:100,000	Wave run-up for 1:10 AEP wind
or	PMF	None
Extreme	PMF	To be determined by risk assessment

The design and sizing of the emergency spillway needs to consider the worst case flow that must be routed through the spillway. This in turn depends on the controls that are in place to ensure that a conservative design storage allowance is in place at any point in time.

5.2 The Water Balance

An important design task is the development of a water balance model for the tailings dam. The water balance model will help understand the ways water might affect the design and subsequent operational limitations and risks.

Water used in tailings transport is likely to make up a significant proportion of water use at a mine site. Much of this water will be retained in the tailings storage trapped within the pores. A portion will be returned to the process or released if environmental conditions allow. Some water will be lost through evaporation and/or seepage, particularly from lake areas. Water gains from the natural environment into the disposal area can include surface streams, groundwater inflow and rainfall.

The total of water inputs into a tailings dam will be balanced by recovery, disposal or losses from the area. The "water balance" will determine the performance characteristics of the tailings disposal system, including flows and losses such as seepage that would need to be managed during its operation and final abandonment. Any imbalance can lead to progressive changes in the volume stored in the pond.

For many parts of Australia there are now in excess of 100 years of accumulated rainfall records. Reference to these data provides a good indication of the rainfall extremes (both wet and dry) which are likely to occur throughout a mine's life. In many cases water balance modelling will necessitate running selected years, or alternatively the entire record. The analyses may need to be done on the basis of monthly rainfall, or in critical cases, and to meet regulatory requirements in some States, daily rainfall.

Water balance modelling may also need to take account of variations in tailings properties, quantities and levels with time, and the proposed schedule of dam raises. This typically means that some years in a mine's life are more susceptible to extreme rainfall events than others. The consequences of these occurrences are better analysed using a properly set up and calibrated water balance model.

Similarly the variation of climatic conditions needs to be included in any modelling to predict the potential range of water balance outcomes. For example rainfall, the effects of water quality within the tailings dam and location need to be taken into account as these can significantly reduce evaporation.

Water balance calculations frequently utilise spreadsheets, modelling packages, or purpose written programs. These should be preserved and the modelling reviewed when actual field data becomes available after start-up, to calibrate the model.

Most water balance modelling deals just with water quantity. However, where water quality is an issue and monitoring data is available, it is possible to incorporate this into water balance calculations. Provided source concentrations can be reasonably specified, it is relatively easy to carry out a balance for ions such as chlorides, but for unstable species such as cyanide, a decay series must be incorporated. An appropriate rate of decay may need to be determined by project specific test work. Modelling of heavy metals can also be carried out, but in the absence of allowances for precipitation, adsorption, etc., may lack relevance.

Modelling of water quality can be contentious in cases where oxidation of sulphides is expected to occur on tailings beaches where acid drainage is likely to develop. In these instances it is difficult to predict the ongoing flux of additional dissolved compounds into the system.

Where estimation of water quality using the model is difficult or contentious, estimates of likely impacts for consequence assessment (spills or embankment failures) can be based on water quantity modelling combined with estimates of likely or worst case assumptions of contaminant concentrations at spill/failure. The latter can be based on monitoring of facilities taking tailings from similar ore sources.

5.3 Stream Management

The tailings area is often separated from the surrounding stormwater streams to minimise flood design requirements, to maximise settling of tailings and to minimise the volume of water which may need special management due to water quality issues.

Tailings dams should ideally be located away from significant streams or at the head of valleys where catchment outside the storage is limited. Any streams that develop above the tailings dam should be diverted past the storage where this is practical. The design flow capacity of diversion works should relate to the relevant predicted flood flows and the need to protect the tailings dam from flood inflow. However, if the diversion works have limited capacity then the consequences of overtopping need to be taken into account in the capacity of the tailings dam and its outlets. The potential failure of a diversion system is likely during extreme flooding and the added inflow to the tailings dam should be considered.

Tailings dams design criteria normally require consideration of ultimate abandonment. Any diversions must then be adequate for long-term, low maintenance performance and allow for erosion and degradation of structural elements.

Diversion of external stormwater inputs may be less critical when the tailings are required to be stored under water. It may be necessary to divert an expanded catchment to the tailings dam to provide sufficient water to keep tailings covered during extreme dry periods.

5.4 Rainfall Run-Off

Rainfall can be a major component of water inflow, with catchment runoff mixing with decant water in the pond area.

Run-off calculations should be made in accordance with normal hydrological methods, as outlined in Australian Rainfall & Run-Off (The Institution of Engineers, Australia, 1999). Run-off from the contributing land surfaces, either as direct or indirect (pumped) catchments, any tailings beaches and from the pond area itself, will need to be taken into account. In regions with highly seasonal rainfall, runoff coefficients need to take account of pre-existing soil moisture conditions.

Tailings beaches can vary considerably in their run-off characteristics. Coarse tailings, particularly when cycloned for embankment construction, can be quite permeable and well drained. This can lead to a reduced coefficient of run-off but increased movement of rainwater into the tailings and/or groundwater system. However, most "all-in" fine tailings have a low permeability and are readily saturated resulting in a comparatively high coefficient of run-off if not subject to deep desiccation cracks.

5.5 Tailings Decant Water

Tailings normally settle on beaches, thus decanting a proportion of the transport water over a short time frame. This would be followed by a longer term release of transport water as consolidation of the tailings takes place for both sub-aerial and sub-aqueous methods of discharge. Further water is lost where there is evaporation from exposed beaches.

It is commonly found that the increase in density is much greater in sub-aerial deposition than in sub-aqueous deposition. This applies not only to the initial water loss but also to the long-term consolidation phase due to the extra effective weight caused by lowered water levels. As tailings dry, the capillary tension in the pores causes major consolidation forces.

5.6 Evaporation

Evaporation from tailings beaches and ponds can lead to significant water loss from the system. Losses from ponds can be evaluated from pan-evaporation data using appropriate adjustment factors or by calculations utilising wind speed, temperature, solar radiation, etc. Losses from beaches can similarly be evaluated.

A factor of 0.7 to 0.8 is commonly used as a multiplier to adjust evaporation rates from water ponds as compared with measurements in standard Class A evaporation pans with bird screens. Evaporation is also directly proportional to wind speed and exposed locations will develop higher evaporation losses than sheltered locations. Losses from exposed beaches are a complex function of solar radiation, colour, degree of saturation, permeability, depth to saturation, capillary effects, temperature of tailings, etc. A common assumption for wet beaches is to assume beach evaporation is equal to lake evaporation.

Salinity can have a major effect on the rates of evaporation from both tailings and from ponded water (Newson and Fahey, 1998). Salinities above that of sea water may reduce evaporation significantly. More importantly, the formation of a salt crust on the tailings surface will create a barrier which slows further drying of the beach.

Water recovery is improved by minimising the free water surface area on a tailings dam, which reduces evaporation loss. In some cases it may be strategic to maximise evaporation in order to remove contaminated water as part of an environmental management plan. This would require maximising the tailings pond area and/or frequent wetting of beaches with thin layers, and/or by using a separate evaporation pond.

5.7 Water Recovery

Excess water within the tailings dam is either removed by evaporation or collected for recycle to the process plant, depending on environmental and process considerations. In some cases water quality may allow direct discharge to the environment, possibly including the need for treatment.

Recovery is usually achieved by a pump or gravity system. Floating pump stations allow flexibility of operation with water level changes being easily accommodated. However, minimum operating depths may be in the order of 1m to 2m, hence necessitating more water in the decant than may be desired. Pump sizing may need to cope with volumes accumulated in severe flood events. Floating gravity decants or siphon decants can also be developed if sufficient head is available.

Fixed decant structures are commonly used. These usually comprise concrete or steel tower structures with controllable outlets at various levels. They often have permeable materials such as rockfill surrounding them to improve water clarity and give a large area for water entry. The draw off level can be adjusted to suit requirements of the pond. A tailings discharge plan is required to control the beach shapes so as to maintain the position of the pond around the tower.

Pipes through the embankment have been the cause of internal erosion failures under tailings dam embankments. If this type of outlet pipe is provided, particular care is needed in design and construction to reduce the risk of this type of failure.

The draw-off system needs to allow the formation of adequate pondage to permit settlement of solids before the water is removed. A shroud over the outlet is also common to prevent floating debris or scum being carried over.

The structural design of tower decants should take into account the potential down-drag forces applied to the structure by consolidation settlement of the tailings, seismic loading and other risks during operation. The design should take into account consideration of how the structure will be decommissioned on dam closure.

5.8 Seepage

5.8.1 General

Seepage from tailings dams will potentially develop through the embankments, foundations and floor of the impoundment. The amount of seepage loss will depend on the permeability of the various materials and will be greatly influenced by the permeability of the tailings themselves, which in many cases is quite low.

Seepage losses may not be significant in the overall water balance, but the environmental impact of contaminated seepage may be a significant factor.

Along with losses due to evaporation, seepage is one of the more difficult components to quantify accurately. Often this is taken as the component that closes the water balance, in other words, once the inputs and other outputs (losses) are quantified (or estimated), seepage losses are considered to be the component that balances the inputs and outputs. However this can seriously under or overestimate the seepage losses due to uncertainty in estimating other large water balance components.

Seepage assessment is necessary as part of detailed design to:

- define pore pressures/phreatic surfaces for use in stability analysis;
- evaluate restrictions on rate of rise, if any;
- determine potential impacts of seepage on the receiving environment; and
- allow design of drainage and collection systems.

It is desirable in most cases to attempt to quantify potential seepage losses before the tailings dam is constructed and this is where the role of seepage modelling is important.

The key driver of seepage is the elevation difference between the decant pond and the surrounding ground. If there were no water retained on, or within, the tailings dam, seepage would not be a concern. This is one of the primary perceived advantages of high density thickened tailings deposits where no decant pond exists on top of the storage. However, seepage from the associated balance pond needs to be considered. The height of a conventional tailing dam increases during its lifetime, thus continually increasing the elevation difference between the pond and the surrounding ground and hence the driving head causing seepage. When predicting likely seepage losses from a tailing dam it is therefore common to use the final height as the design condition for modelling. However, it can be useful to make predictions of likely seepage quantities at various times during the operational life of the tailing dam. In this way, predicted performance (such as drain flow rates) can be compared with actual performance, allowing for modifications to the predictions of performance at final height. It also allows for intervention at an early stage should actual performance be worse than the predicted performance. This proactive approach may also allow for taking advantage of an opportunity, should the actual performance be better than the predicted performance.

Seepage, as conventionally defined, is not the only mechanism responsible for the generation of pore water pressures within tailings impoundments. Normal loading consolidation (dissipation of excess pore pressure generated by undrained loading of the tailings material) and shear induced pore pressure are equally important mechanisms that should be considered in the analysis of pore pressure in tailings. The combination of seepage and consolidation pressures often culminates in non-hydrostatic conditions which need to be considered in the design.

If pore pressure is not properly considered, the potential for failure may be underestimated eg, stability during construction. A full range effective stress analysis can be undertaken considering consolidation and strength parameters (Vitharana & Terzaghi, 2005).

5.8.2 Predicting seepage quality and quantity

Estimates of likely seepage volumes are usually based on some form of modelling. This modelling utilises computer simulations and it is essential that accurate and realistic input parameters are obtained for these modelling exercises. It is also important to benchmark the output by comparing actual seepage against seepage predictions for various intermediate phases of a tailings dam construction, and not be restricted to the final geometry.

Once realistic input parameters, boundary conditions and model geometry have been determined, a seepage analysis can be used to estimate the direction and quantity of seepage from a tailing dam. It will usually be necessary to estimate seepage quality as well. In some cases it may be possible to base estimates of quality solely on the measured quality of decant water; however it is becoming increasingly necessary to predict the fate of contaminants (contained within the tailings seepage water) in the surrounding environment. Input from specialists such as geochemists and hydro-geologists may be required.

Seepage modelling can also be used to locate instrumentation designed to monitor the performance of a tailing dam during construction and operation. Modelling can help identify likely critical sections and locations within a tailing dam where instrumentation can provide maximum benefit.

5.8.3 Components of a seepage model

Any seepage model must include a realistic representation of the geometry of the problem being modelled, assignment of suitable parameters to the various materials present (in-situ soils, tailings, liners, etc.) and definition of appropriate boundary conditions.

Problem geometry: Representation of the tailings within a tailing dam and the foundation soil below a tailing dam as homogeneous and isotropic layers is often unacceptably simplistic. In particular, the foundation soil may be complex, with the existence of paleo-channels, fractures, fissures or layers of differing material. It is essential to conduct sufficient site characterisation to ensure a realistic representation of the subsurface has been established.

Material properties: For a seepage analysis, the key parameter is the saturated hydraulic conductivity. Some materials (eg segregating tailings placed sub-aerially) might exhibit anisotropic hydraulic conductivity values. Saturated/unsaturated modelling would involve the potential variation of hydraulic conductivity with degree of saturation in material above the fully saturated zone. Transient seepage analyses would require data on hydraulic conductivity, porosity and/or volumetric water content. The hydraulic properties of tailings are dependent on the void ratio achieved in practice, and potential layering and cracking within the deposit.

5.8.4 Monitoring and verification

All tailings dams require some form of instrumentation. Piezometers are used for measuring pore water pressures. Most conventional piezometers can only measure positive pore pressures which occur below the phreatic surface. The phreatic surface starts at the decant pond, and the slope of this surface towards the perimeter of the tailings dam depends on the hydraulic properties of the tailings and underlying soils as well as any drainage layers or liners that might have been incorporated into the tailings dam. If the flow is predominantly vertical (bottom draining) the pore water pressures underneath the phreatic surface are generally less than hydrostatic. In contrast, when dealing with high rates of rise and/or very soft tailings, generation of excess pore water pressures can create higher than hydrostatic conditions below the phreatic surface. Capturing of true and realistic pore water pressure distributions within a tailings dam is crucial for any seepage modelling exercise.

If a sufficient number of piezometers are installed the shape of the phreatic surface and underlying pressures can be determined. This information can be used to verify design assumptions, modelling predictions and as input to stability analyses. Instrumentation can also be used to provide trigger levels that would indicate unsafe conditions due to increased pore water pressures above safe values.

Regular piezometer monitoring enables the performance of a tailings dam to be evaluated on an ongoing basis.

Drains and/or drainage layers may be built into the dam during construction to keep the phreatic surface a suitable distance away from the downstream face. The design of suitable drainage is described in ICOLD Bulletin No 97, “Tailings Dams Design of Drainage”. Instrumentation of tailings dams is discussed in ICOLD Bulletin 104 - “Monitoring of Tailings Dams”.

5.8.5 Predicting impact on groundwater

Once the potential quantity and quality of seepage water has been estimated, the potential impact on groundwater can be predicted. Before considering potential impacts, it is essential to accurately characterise and quantify the background (existing) conditions. Information required includes depth to the water table(s), any significant aquifer(s), amount and quality of the groundwater and the transmissivity of the ground. Information can be obtained from records or sampling of existing bores, other geological and geotechnical drilling carried out on the site, and specific hydrogeological investigations. A hydrogeological investigation can include simple monitoring bores to measure water levels, “down-hole” tests carried out to assess formation permeability, pump testing and water quality testing.

5.8.6 Environmental Assimilative Capacity

Where seepage studies indicate a potential problem, it may be necessary to model the actual movement of contaminants in the environment.

Contaminants in groundwater may be subject to attenuation by various natural processes including decay, biological and/or chemical breakdown, retardation/absorption, dispersion and dilution. Flow through unsaturated zones, in particular if the soils or weathered rocks have high clay content, is particularly important in this regard. Cyanide and metals absorption characteristics can be measured for soils using laboratory scale tests. For rocks, some form of in-ground tracer type tests may be preferred.

Groundwater seepage velocities are often slow and the actual mass of contaminant transported may be small. Where seepage emerges into existing streams or other water bodies, the assessment of potential effects should be based on the diluted concentrations. Threshold concentrations in the receiving water that are acceptable are set by regulatory authorities.

5.8.7 Design Measures to Minimise Seepage

Rather than having to implement retrospective water management strategies such as installing seepage cut-off trenches or interception bores, implementation of certain key principles during the design and operation phases can minimise seepage problems. Maximisation of solar drying, minimisation of water content of tailings and minimising the volume (and areal extent) of ponded water are fundamental considerations.

5.8.8 Lining of TSFs

All foundation soils will allow some seepage. However, the rate of seepage may be so slow and the assimilative capacity of the environment so large that the impacts of the leakage are small. A risk based approach to seepage losses would quantify the magnitude of this potential impact.

Methods to limit or manage foundation seepage include cut-offs, interception trenches or wells, grouting, and collection sumps/dams below points of seepage. Cut-offs are useful in areas where preferential seepage zones of higher permeability exist within the foundations.

Naturally occurring clay under impoundment areas can be left in place or improved by added compaction to constitute a liner, or if necessary, additional clay may be imported. Natural soils may also be improved by the addition of bentonite. Natural clays often have relatively high permeability due to fissures, root holes etc. hence the requirement for re-working and compaction.

In some circumstances it is not necessary to control the seepage from the base of a TSF, such as when the tailings liquor is benign, or when the local groundwater is unfit for animal or human consumption (e.g. hypersaline). At the other extreme, however, there might be situations where leakage of even very small concentrations of a particular contaminant might be unacceptable, such as certain radioactive constituents.

Synthetic liners are an option in lieu of or in conjunction with clay. When considering the potential need for an engineered lining system, such as a geomembrane or a composite liner, it is necessary to quantify the benefit of such a solution. The tailings material itself may have a very low permeability, particularly the tailings at the base of the TSF where consolidation has reduced void ratios and thus hydraulic conductivities. Furthermore, it is often the case that the more weathered or oxidised ore at the top of the deposit is mined and processed first, giving a layer of more clayey tailings across the base of the impoundment facility.

Consideration of an engineered lining system should also consider the implications of underdrainage, when all seepage through the tailings would have to be collected and managed within drainage structures. Otherwise there is the risk of rapid build-up of excess pore water pressures (as downward drainage into the sub-surface is limited, potentially leading to low density and low strength tailings.

Liners may consist of a number of materials including:

- compacted clay;
- natural soils mixed with bentonite or similar additives;
- bitumen seal;
- Poly Vinyl Chloride (PVC) or similar liners;
- High Density Poly-Ethylene (HDPE), Linear Low Density Poly-Ethylene (LLDPE), butyl or similar geosynthetic liners; and
- bentonite layers of patent design such as geo-composite liners (GCL).

Some clays flocculate in the presence of high salinity water and have higher permeability than indicated by laboratory results using fresh water.

Each of these should be researched for the possibility of damage, compatibility with the retained tailings, and for their longevity. It is noted for example, that synthetic liner materials can lose plasticiser content when in contact with clay and potentially become brittle. The liners will be subject to a full hydrostatic pressure unless drainage systems are built on top. In such circumstances small tears and incomplete seams can lead to significant seepage, depending on the permeability of the tailings. Most synthetic liners have an inherent permeability due to the likelihood of minor imperfections in the manufacturing process, and assigned values are often used in design.

Where the control of seepage is crucial a double liner (or composite liner) system may be used. In its simplest form two liners are placed in contact with each other on the basis that the probability of faults occurring in each liner at the same location is very remote. A typical situation would be a plastic (or geosynthetic) liner placed over a compacted clay liner.

In some situations the two liners may be separated by a drainage medium such as sand which contains collector pipes which will collect any seepage through the first liner into a monitoring system. Since this drainage layer will almost invariably be at atmospheric pressure, the hydraulic gradient across the lower liner is then very low and can therefore be assumed to control seepage below the second liner to minimal levels. However, the use of drainage systems should take into account the risks that a drain can act as a conduit to preferentially direct seepage to any defects in the underlying liner.

The long-term life of a synthetic liner system needs to be carefully considered if there is a need for permanent sealing of foundations in the post-closure phase. It is likely that synthetic liners cannot be relied on for performance in excess of 100 years and possibly their life expectancy could be much shorter.

5.9 Drains and Filters

Drainage is one factor affecting seepage and stability that can be addressed in the design.

A drainage system must have the following features:

- a filter to prevent loss of particles from the dam or foundation;
- a drainage layer to convey the water from the filter; and
- outlets to exit water from the drainage layer.

The drains and drainage layers have to be large enough and extend far enough within the embankment to reduce pore pressures as required. They must be completely surrounded by filter material so as to prevent any fine particles from being carried away with the drained water, which could lead to failure by piping. Further information is in ICOLD Bulletin No. 97, Tailings Dams - Design of Drainage.

Filters must be properly designed e.g. use methods described by Fell et al. 2005, and constructed of clean, free draining, non-plastic sand and gravel. Geotextile filters in contact with tailings may clog and should only be used after consideration of this aspect.

The design life of a filter in a tailings dam environment needs particular consideration in relation to the post-closure period if there is a risk of chemical precipitation or reaction that may change filter properties. It is likely that a filter cannot be relied on to perform its function into the post-closure phase if AMD seepage is occurring, or could possibly develop leading to blockage or cementation of filters. In this case, design may need to consider alternative means to protect a tailings dam from the risk of piping. This could include:

- provide conservatively sized filters;
- avoid materials prone to piping; and
- design for very low hydraulic gradients.

Particular care is needed to protect filters and drains during first filling where highly mobile tailings flows could lead to damage.

6.0 Design – Embankment

The objective of tailings storage embankment design is to ensure that the structures are able to withstand the potential loading conditions that could be expected during their lifetime to the extent that the risk of failure is acceptably low.

6.1 Stability Analysis

6.1.1 Stability Evaluations

Stability evaluations of tailings dams differ from those for conventional dams in the following respects:

- tailings dam embankment zones may be thinner and smaller, especially for the upstream method of construction and are typically constructed in stages over many years;
- upstream construction relies on the strength of the tailings which can vary with time due to consolidation and potential liquefaction; and
- the pore pressures within the tailings are a combination of seepage pressures and consolidation pressures which generally culminate in non-hydrostatic conditions requiring specialised modelling techniques.

6.1.2 Methods of Stability Analyses

The analysis of stability of tailings dam embankments is usually carried out using limit equilibrium procedures. Some of these procedures consider all of the conditions of static equilibrium (force and moment equilibrium) while others consider only some of them. Those procedures that have reasonable side force assumptions and that explicitly satisfy moment equilibrium are recommended, such as Bishop (1955), Morgenstern and Price (1965), Spencer (1967), Chen and Morgenstern (1983), and Sarma (1973).

In some cases (if the required data are available) a finite element/difference method is used where stability is marginal or where it is necessary to predict deformations and/or pore pressures in unusual situations. This is directly relevant to upstream construction where the material is susceptible to strain softening and where there is potential for liquefaction.

The method of analysis should be determined by experienced practitioners guided by a risk-assessment process.

6.1.3 Loading Conditions

Before starting stability analyses, clear understanding needs to be developed about the loading conditions. Each loading condition represents a physical condition or scenario that needs to be analysed with specific types of material strengths. Different types of shear strengths (drained or undrained), even for the same material, may be needed for different loading conditions.

In addition it may be necessary to consider the contractive and dilative state of materials. The contractive versus dilative behaviour could be evaluated through laboratory tests, such as consolidated undrained triaxial tests with pore water pressure measurements, and/or field tests, such as cone penetration tests with pore water pressure measurements.

The following loading conditions should be considered for tailings dam analyses:

6.1.3.1 Drained condition

This loading condition assumes that the excess pore pressures caused by loading (or unloading) have dissipated due to a slow rate of construction or sufficient time after construction, and the shear-induced pore pressures are also zero due to a slow rate of shearing during failure. In essence, this loading condition represents the long-term stability of a tailings dam under steady-state conditions, with no rapid change in phreatic surface or geometry (either loading or excavation).

For this loading condition, all materials are characterised with effective stress drained shear strength. The physical conditions/scenarios that this loading condition may represent include:

- long-term static stability of the ultimate design height embankment; and
- long-term post closure stability of a TSF.

This loading condition should not be used to evaluate:

- stability during construction, where geometry and/

- or pore water pressures are changing;
- stability of saturated contractive materials;
- stability of new construction over existing slopes;
- stability of renewed deposition over old impoundments;
- slope stability with toe excavation; and
- post-seismic stability where the seismic event is small enough to preclude liquefaction but large enough to induce undrained conditions.

For these latter scenarios the short-term undrained loading condition needs to be evaluated as described below.

6.1.3.2 Undrained condition

The undrained or partially drained loading condition represents the stability of an embankment where loading and/or failure occurs rapidly enough that there is not enough time for drainage of induced excess pore water pressures, or where pore pressures are developed due to the contractive nature of the tailings and/or embankment and foundation materials. Some drainage may occur in the field but it is difficult to predict how much and where along the shear surface it will occur. To guard against this uncertainty, the standard practice is to check the stability of such materials using the undrained strength envelope. Materials for which undrained strength is of particular importance include saturated contractive tailings and soft foundation clay layers. Coarse grained, free draining materials and dilative materials, which are not expected to sustain any excess pore water pressures, are adequately characterised with effective stress drained shear strength parameters.

Static liquefaction is another important slope failure mechanism whose potential needs be evaluated as part of the undrained loading condition. As defined by Fell et al. (2007), static liquefaction occurs at relatively low stresses and is characterised by large pore pressure development and a brittle stress-strain response, resulting in close to zero effective stresses. Further details on static liquefaction can be obtained from Fell et al. (2007) and Duncan and Wright (2005).

6.1.4 Shear Strength Characterisation

The level of site investigations, including field and laboratory testing, should be compatible with the level of design and the associated analyses.

Effective stress (drained) shear strength parameters may be estimated from consolidated drained (CD) triaxial tests, consolidated direct simple shear tests or consolidated undrained (CU) triaxial tests with pore water pressure measurement.

Consolidated undrained shear strength should be derived in accordance with the Undrained Strength Analysis (USA) approach of Ladd (1991). This approach is recommended for all saturated contractive materials. The crux of the USA approach is that the undrained shear strength is a function of the pre-shear/pre-loading effective consolidation stress. This approach is also commonly called the Su/σ'v approach.

For situations where the undrained strength is estimated to be higher than the drained strength, undrained strength should be capped at the drained strength to avoid reliance on negative pore water pressures. In other words, undrained shear strength values higher than the drained shear strength values should generally be avoided.

For horizontal or near horizontal shear planes, direct shear or direct simple shear type shear strength should be used (instead of the triaxial shear strength) to account for possible anisotropy in shear strength.

The use of total strength parameters is not recommended because total stresses do not directly account for the pore water pressures, and for tailings dams the use of total strength parameters may give misleading results. Material strengths, both drained and undrained, are a function of effective stresses and not of total stresses.

6.1.5 Earthquake Considerations

Most tailings comprise fine sand, gravel, ash or filter cake, which are placed in a relatively loose state. Beaches or stacks formed from these materials often appear solid, however it is important to consider whether such apparently solid material may liquefy under either static or dynamic loading conditions. If liquefaction does occur, the strength of the liquefied portions of the tailings is significantly reduced and can lead to failure. The topic of liquefaction is complex and a useful reference is Idriss and Boulanger (2008).

The design of a tailings dam for earthquake or blast-induced vibration, should take into consideration:

- the level of seismic activity that may occur at the site appropriate for design during operations;
- the level of seismic activity that needs to be considered for closure design;
- the potential for amplification or dampening of the

firm ground acceleration by foundation and/or embankment materials;

the ability of the proposed tailings dam to survive predicted earthquake loadings;

the potential for liquefaction of the saturated tailings on an elevated beach or in the storage; and

the potential for liquefaction of foundation layers.

The assessment of seismic hazard can be made from a history of the earthquakes that have occurred in the vicinity of the storage. Reference may be made to Australian Standard AS 1170.4-1993, however this does not cover the wide range of earthquake probabilities relevant to dam designs.

High and Significant Consequence Category tailings dams should use specific site information and the assistance of seismology specialists. Estimates of ground motion parameters from past earthquakes can be calculated for a specific site.

The designer requires information on both the Operating Basis Earthquake (OBE) and the Maximum Design Earthquake (MDE) for dam design (refer ANCOLD Guideline for Design of Dams for Earthquakes, 1998). Dams should remain serviceable under the OBE. OBE is generally expected to cause limited damage/deformations that could be repaired without significantly disrupting operations. Under the MDE, damage could be more extensive and may disrupt operations, but the structural integrity of the dam needs to be maintained and uncontrolled release of tailings/water should not occur.

When considering the MDE, the concept of Maximum Credible Earthquake (MCE) is often used. The MCE is calculated deterministically and is taken as the maximum theoretical earthquake associated with known or inferred faults in proximity of the site. Therefore the MCE technically does not have a return period associated with it, and is the maximum earthquake that could ever occur at the site. Earthquake events for 1:10,000 AEP or greater generally begin to approach the MCE event. For closure the MCE should be used for design but taking into account expected long term properties of the tailings. This could include lowered phreatic surface and increased strength from consolidation and possibly chemical bonding.

Recommended design earthquake loadings are presented in Table 7.

Well compacted embankment dams constructed from clayey fill or rockfill are generally resistant to earthquake shaking, although provision must be made for crest settlements and displacements resulting from the earthquake, including liquefaction of foundation layers. These can be estimated so that a suitable freeboard can be maintained at all times to avoid the risk of overtopping.

Hydraulically placed sand fills are particularly susceptible to liquefaction or slope instability under earthquake conditions unless compacted to an acceptable relative density. The required density depends on grading and grain shape and can be determined by laboratory tests, to which a safety margin is usually added.

Several tailings dams using upstream construction have failed by liquefaction.

Upstream construction dams require particularly careful design and detailing to withstand earthquakes. They should use internal drainage and suitably shaped starter dams to reduce the length of a potential failure surface that could pass through the retained tailings.

Note that tailings as placed are usually stratified, so underdrains may not result in complete drainage of the tailings and liquefaction may occur under moderate earthquakes.

6.1.5.1 Seismic Loading

Analysis of dams for seismic loading is a specialist area and should only be undertaken by experienced persons. Reference should be made to ANCOLD Guidelines on Design of Dams for Earthquake. This field is rapidly evolving and designers and operators need to ensure that they use the most up to date methods. Of particular note, pseudo-static analysis as a screening tool for earthquake stability is now not

Table 7 Recommended Design Earthquake Loadings (AEP)

Dam Failure Consequence Category	Operations phase		Post Closure
	OBE	MDE	
Low	1:50	1:100	MCE
Significant	1:100	1:1000	MCE
High/Extreme	1:1000	1:10000	MCE

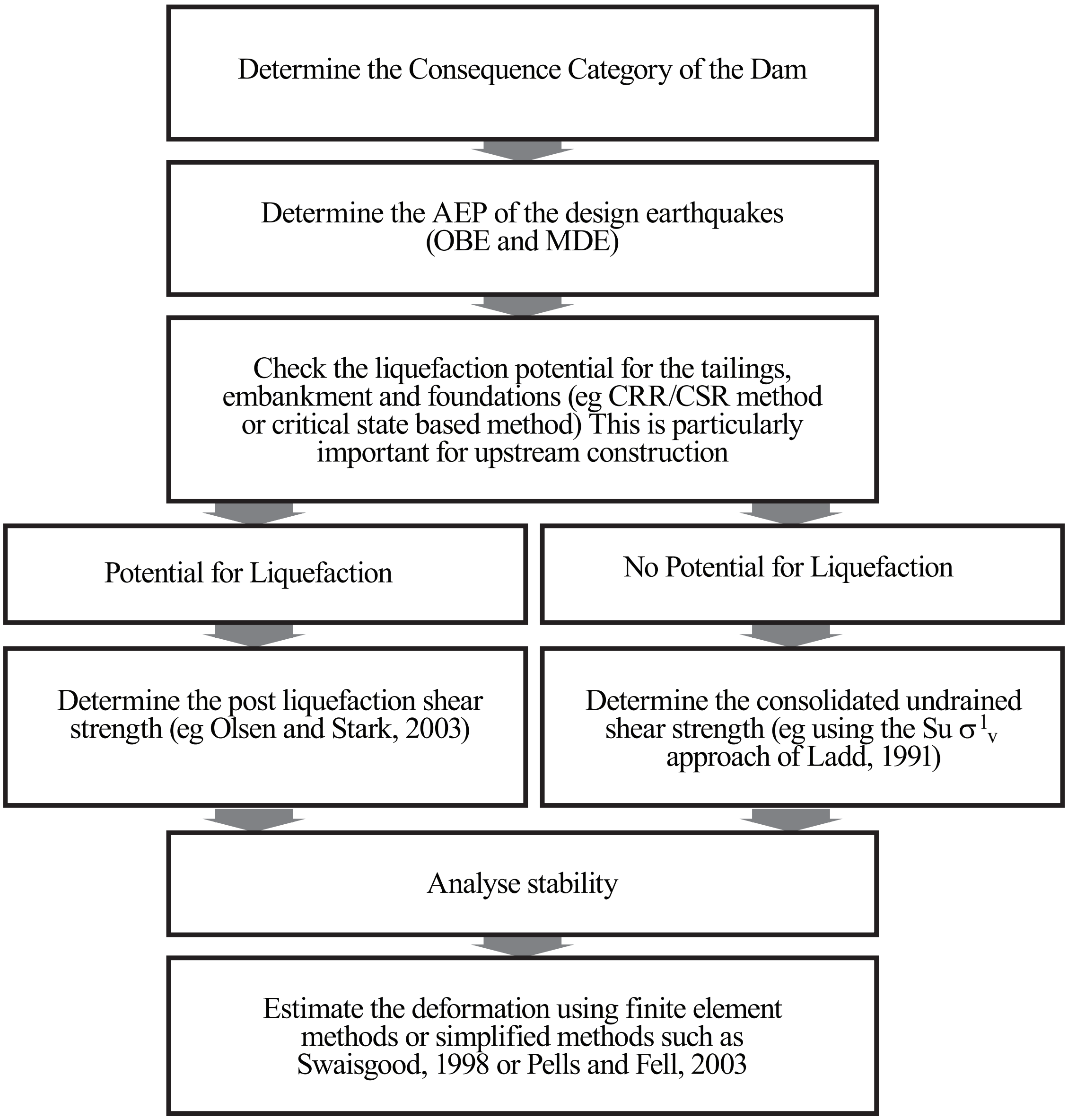
recommended. Instead a process as outlined in Figure 6 should be followed. Key aspects of this are the use of simplified deformation analyses such as Swaisgood (1998) and Pells and Fell (2002, 2003) to obtain estimation of the deformation of a dam following earthquake shaking.

6.1.5.2 Post-seismic Condition

Following an earthquake, the stability of a slope may be diminished because cyclic loading has reduced the shear strength of the material – this is especially true for tailings. The reductions in shear strength are generally treated differently depending on whether or not liquefaction occurs.

The first step in evaluating strength loss is to determine if the material will liquefy. The procedures for doing this are semi-empirical, based on consideration of particle size grading, the degree of saturation, results of field tests and case histories. Four different field tests are generally considered suitable for measuring soil resistance to liquefaction: (1) cone penetration tests, (2) Standard Penetration tests, (3) shear-wave

Figure 6 Flow sheet for seismic stability analysis



velocity measurements, and (4) for gravelly sites, the Becker penetration test. Various correlations have been developed that relate the results from these tests to the resistance of the material against liquefaction, measured as cyclic resistance ratio (CRR). The CRR values are then compared with the seismically induced cyclic stress ratio (CSR) to determine if liquefaction will occur. CSR values could be estimated from the simplified procedure of Seed and Idriss (1982) or could be calculated using a more rigorous site response analysis approach, such as that implemented in the SHAKE computer program.

An alternative approach would be to use critical state based liquefaction assessment (Jefferies and Been, 2006).

If liquefaction is expected, reduced values of the undrained residual or post liquefaction shear strengths are estimated. If a material is not expected to liquefy it is still possible that pore water pressures will increase in the material and its shear strength may be reduced. The reduction in shear strength is generally related to the factor of safety against liquefaction, which is defined as CRR divided by CSR.

Once the post-seismic shear strengths have been determined, a conventional static slope stability analysis is performed to estimate the post-seismic stability of the structure. This analysis is considered to be applicable to conditions after the earthquake has ceased, and no additional acceleration forces are applied in the analysis.

Liquefaction assessment is a specialised area that requires expert knowledge. Susceptibility of materials to liquefaction is not only dependent upon the CRR/CSR values but also on many other material characteristics such as particle size gradations, Atterberg limits, etc. Guidance on liquefaction assessment and post-seismic stability can be obtained from Duncan and Wright (2005), Fell et al. (2005), Youd et al, (2001) and Seed and Boulanger (2008).

6.1.6 Acceptable Factors of Safety and deformation

There are no "rules" for acceptable factors of safety, as they need to account for the consequences of failure and the uncertainty in material properties and subsurface conditions. Table 8 shows the ANCOLD recommended factors of safety for tailings dams under various loading conditions.

Acceptable deformations should be determined in relation to the potential impact on the serviceability of the dam. Deformations should not reduce freeboards to unacceptable levels or result in the potential disruption of the filter with large shear movements. This could lead to delayed failure after an earthquake.

When presenting results, mode of failure (shape and location of the potential slip surface) and the internal stratigraphy of the section should be identified in addition to the calculated minimum factor of safety.

Table 8 Recommended factors of safety

Loading Condition (Note 1)	Recommended Minimum for Tailings Dams	Shear strength to be used for evaluation
Long-term drained	1.5	Effective Strength
Short-term undrained (potential loss of containment)	1.5	Consolidated Undrained Strength
Short-term undrained (no potential loss of containment)	1.3	Consolidated Undrained Strength
Post-seismic	1.0 -1.2 (Note 2)	Post Seismic Shear Strength (Note 3)

Note 1 See Section 6.1.3 for description of loading conditions

Note 2 To be related to the confidence in selection of residual shear strength. 1.0 may be adequate for use with lower bound results.

Note 3 Cyclically reduced undrained/drained shear strength and/or liquefied residual shear strength for potentially liquefiable materials.

6.1.7 Additional Points to Consider

The following points are made specifically in reference to the use of limit equilibrium methods to analyse the stability of tailings dams.

In the majority of applications, non-circular failure surfaces may need to be considered.

Critical failure surfaces are defined as those which give the lowest factor of safety, and which would likely cause significant damage if sliding occurred. Shallow failure surfaces are often identified by computer analyses using automatic search routines as giving the minimum factor of safety but do not lead to the critical breaching of the dam.

Situations which can lead to an overestimation of factor of safety can usually be related to the assumptions made regarding shear strength and pore pressures, not to problems in the analysis itself, e.g.:

- incorrect assessment of location of phreatic surface and pore water pressure conditions;
- anisotropic conditions in the fill or tailings, giving relatively high horizontal permeability and elevated phreatic surface levels;
- non-recognition of bedding plane shears or landslip surfaces in the foundation;
- non-recognition of fissuring in the soil/rock foundation;
- 'liquefaction' under earthquake loading, leading to loss of shear strength; and
- static liquefaction as stress conditions change e.g. by upstream construction where failure occurs at stresses less than given by effective stress parameters. This occurs when the loose tailings generate positive pore pressures during shearing.

Recent advances in the area of numerical modelling have made it possible to calculate the factor of safety of a slope using finite element/difference techniques (Dawson and Roth, 1999; Dawson et al. 2000). The major advantage of using finite element/difference methodology is that trial shear surfaces are not required to locate the most critical shear surface. This is an expert area requiring special skills, judgment and experience other than mathematical expertise.

6.1.8 Progressive Failure

Consideration should be given to the risk of progressive failure (Potts et al, 1990), where, for example, the slip surface passes through high plasticity clay which exhibits brittle or strain softening behaviour as experienced at Aznalcóllar dam (Gens and Alonso 2006).Progressive failure, associated with large slip surfaces, with a near vertical face/scarp within the embankment is a critical case. Such slip surfaces may not directly indicate potential loss of containment, but subsequent progressive failures of the vertical scarp may.

6.1.9 Reliability and Sensitivity Analyses

Reliability calculations are used to estimate the statistical reliability of the calculated factor of safety considering the inherent uncertainties in the input parameters. This method provides a means of evaluating the combined effects of uncertainties and a means of distinguishing between conditions where uncertainties are particularly high or low. Reliability calculations could be performed using probability based statistical techniques such as those described by Duncan (2000). This may be useful in decision making.

It is good practice that analyses are carried out to assess the sensitivity of the factor of safety to assumptions on shear strength, pore pressures and geometry of sliding, and that the embankment is designed to be stable within a range of assumptions. Seepage analyses should be reviewed in light of stability analyses to ensure the potential range of the critical pore pressures has been evaluated.

6.2 Settlement

Tailings densities are low when deposited, but will increase under the effects of surface drying or from consolidation under self-weight, the weight imposed by ongoing deposition or the weight of a capping layer.

Consolidation rates may be quite slow, sometimes taking many years, particularly for fine grained, clayey tailings. Traditional consolidation models used in geomechanics may not correctly simulate early behaviour, and use can be made of Finite Strain Theory and finite element modelling.

As the material consolidates, the permeability also reduces with the lowest layers being most dense and having the lowest permeability. This restricts downwards flow necessitating much of the consolidation water to move upwards through a longer distance than consolidation of normal soils. This in turn causes a slower consolidation than might be expected. Detailed analyses take into account the changing characteristics of the tailings as they consolidate.

The consolidation of tailings may result in settlements of many metres in some cases.

The effects of such settlement on the embankment or any structures near or within the tailings are to be considered carefully. For example, upstream construction may be built partly on an existing earthen embankment and partly on tailings, causing ongoing differential settlement. This can lead to cracking of the embankment both longitudinally and laterally, the effects of which should be considered in stability analyses.

Similarly, the settlement of tailings around any embedded decant tower, causeway or pipe system can be quite significant, leading to down-drag loads which can damage such systems. Monitoring equipment embedded in the tailings must also be capable of tolerating such settlements.

Settlement may continue for many years after the placement of tailings has been finalised. This will mean that surface drainage on a rehabilitated upper surface will change with time and may cause ponding if sufficient allowance or ongoing maintenance has not been provided.

The consolidation causing this settlement may also continue to release water and any associated salts from within tailings for a considerable time after mine closure.

Settlement can be caused by evaporation from the tailings surface which, apart from shrinkage in the drying layer, will lower the groundwater level and increase the effective stresses on deeper tailings and thus initiate further consolidation.

6.3 Durability of Construction Materials

The durability of all construction materials must be considered in the design of tailings dams intended to safely retain tailings into the long-term post-closure phase. Examples of materials that should be avoided in tailings dam construction could include:

- rip-rap or armour rock subject to break-down by weathering;
- rockfill containing sulphides that could be prone to oxidation, breakdown and release of acid drainage;
- drain material that may react with the process solution; and
- synthetic materials such as geotextile and pipes that do not have proven long-term performance.

6.4 Design Report

The design report describes the basis of the design, including the design concept/philosophy and all design parameters such as the geotechnical properties of the tailings and construction materials, the site meteorological conditions (rainfall, evaporation, wind, etc.) and the key performance criteria. The design report is critically important in determining the safety controls, operating procedures and maintenance programs that need to be implemented for the successful operation of the facility.

The design report also provides easy and quick reference for details in the event of an emergency, the assessment and evaluation of an operational need to modify operation or design, or the need for a back-analysis of an issue arising.

A typical Table of Contents for a Design Report is presented in Appendix A.

6.5 Third-Party Reviews

As a prudent and proven risk management/control approach, third-party reviews are encouraged at different stages of design and operation of TSFs. These reviews should be treated separately from the annual reviews of the facility, and should be carried out by an independent party different to the designer.

7.0 Construction

The objective of construction is to create a safe and stable tailings storage that conforms to the design intent, meets regulatory commitments and meets the intended tailings and water management requirements.

7.1 Introduction

The integrity of a tailings embankment is as critical as for any water dam. Assuming a sound design, the success or failure of a tailings embankment will depend heavily on the manner in which it is constructed. Construction management, technical supervision and quality assurance/quality control (QA/QC) are essential for the successful construction of a tailings dam and ancillary works.

The requirements for successful construction management of a tailings dam are as set out below, together with other construction related issues.

These requirements apply equally to initial construction and any subsequent stages or raises.

7.2 Supervision and Documentation

7.2.1 General

The responsibilities for technical direction and documentation of the works need to be fully defined prior to the commencement of construction. The preferred arrangements are set out in the following sections.

7.2.2 Designer

The Designer is responsible for the design, documentation and specification of the tailings dam construction works. The specification should include definition of the required QA/QC operations and the appropriate means of dealing with non-conformance.

It is highly desirable that the Designer should be closely involved in construction. It is preferable that the Designer should also be the Responsible Engineer (see below), but where this is not the case, the Responsible Engineer should have a defined relationship to the Designer to allow ongoing interaction to ensure the design intent is achieved and that any potential changes to site conditions and/or potential design considerations are communicated to and acted upon by the Designer.

7.2.3 Responsible Engineer

The Responsible Engineer is the engineer responsible for supervision during construction and for certification of the construction works.

The usual regulatory requirement for construction certification is that the works have been executed in accordance with the design intent. It follows that all design changes required during construction must be approved by the Designer, and documented either by notes or revisions to construction drawings.

The Responsible Engineer is responsible for the technical direction of the work and should certify that the tailings dam has been constructed in conformance with the design and specifications.

If not personally on site during all of the construction period, the Responsible Engineer should be represented by an Engineer's Representative or Resident Engineer who will carry out the technical direction of the work under the direction of the Responsible Engineer. Technical direction comprises interpretation of the design and specifications and review of site conditions and materials to ensure that the intent of the design is implemented. Site conditions often vary from those assumed during the design and it is important that these variations are recognised, accommodated and documented during construction. Construction inspector(s), reporting to the Responsible Engineer or Resident Engineer should be used when the complexity or importance of the work warrants it.

Visual inspection of works can be significantly more effective than random sampling and testing in maintaining the quality of workmanship and supervision by experienced personnel is recommended practice.

7.2.4 Quality Control/Quality Assurance

Quality Assurance (QA) comprises management of the design, construction and operation process to ensure that the systems in place are capable of delivering the quality objectives of a project. Quality Control (QC) comprises inspection of the work and testing of materials prior to incorporation in the Works to verify compliance with the specifications. This work comprises testing of potential borrow areas, filter materials, concrete aggregates etc., inspection of membrane liners, pumps, pipelines etc. during or soon after manufacture and prior to installation or incorporation into the works.

The QC work is usually carried out by the Responsible Engineer or an independent testing company who reports to the Responsible Engineer. Irrespective of the size of the project, as a minimum, earthworks should be subject to geotechnical testing. Test methods should be in accordance with the methods set out in AS 1289, Methods of Testing Soils for Engineering Purposes. Whilst not strictly applicable to embankment dams, further guidance on the practicalities of earthworks testing is provided in AS 3798-2007 Guidelines on Earthworks for Commercial and Residential Developments.

A **Site Inspection Manual** that presents QA methodology and the types and frequency of QA/QC test work, inspection, recording and reporting requirements, in accordance to the construction specification, should be prepared, maintained and amended when required. The Manual should include a site organisation chart showing lines of communication and responsibilities for the construction management team. The manual should include protocols for acceptance and rejection of components of the work, re-work and re-testing requirements. A Table of Contents for a Site Inspection Manual is provided in Appendix B.

7.2.5 Construction Site Management

There are several ways in which the construction of a tailings dam can be delivered. These include:

- Tailings dam constructed by owner using mine equipment or by direct hire;
- Tailings dam constructed by contractor; and
- Tailings dam constructed by combination of contractor and owner.

It is not unusual for the initial stage of a tailings dam to be constructed by a contractor and subsequent stages to be constructed by the mine. The management system required for the successful construction of the tailings dam will depend on who is carrying out the work.

An appropriate management structure for a tailings dam constructed by a contractor is shown in Figure 7.

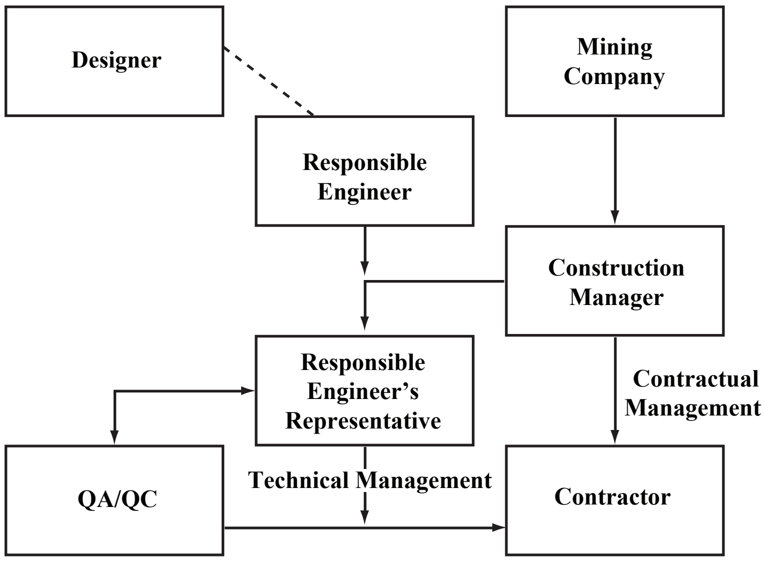


Figure 7 Management structure for contractor constructed tailings dam

The size of this management team depends on the size and level of complexity of the construction project. The team could be as small as one person who provides technical direction, carries out QA/QC inspections and field testing and provides contract management. This is only possible if the project is small in scope. A large tailings dam development may require a significant team comprising a Resident Engineer, project engineers and inspectors, and a site laboratory for materials testing. A separate construction management team may be required comprising an owner's representative, contract manager, quantity surveyors and cost control personnel.

An appropriate management structure for an owner constructed facility is shown in Figure 8.

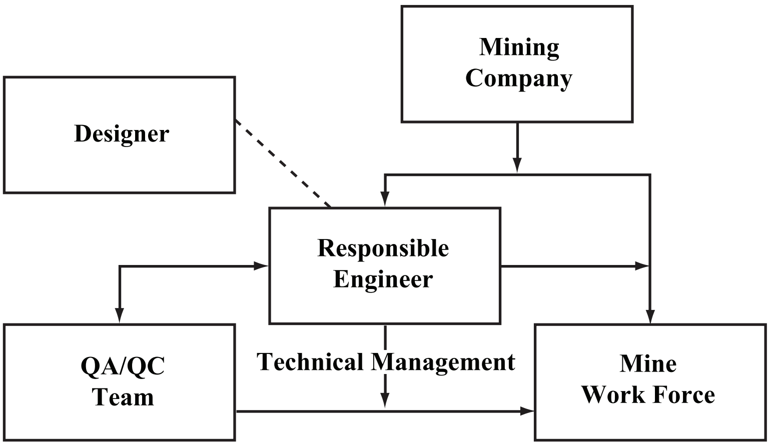


Figure 8 Management Structure for Owner Constructed TSF

The main difference in this case is that the mine is both the owner and constructor of the tailings dam as well as the client of the engineer. The lines of authority to ensure that the technical requirements of the tailings dam construction are met need to be established and recorded in the Site Inspection Manual. Again, the size of the team depends on the size and complexity of the construction project. Projects where both contractor and owner are involved in the construction will require elements of both management structures.

The most important requirement is technical direction and supervision to ensure that the tailings dam is constructed according to the design intent of the Designer.

7.3 Storage Preparation

7.3.1 Clearing and Stripping

Preparation of the storage area should be covered in the design specification and/or drawings.

The extent of storage preparation required will generally be site specific and dependent on a number of factors relating to the extent of vegetation and the necessity to control seepage through the floor of the storage. The following considerations may apply:

Where the removal of trees from the storage area is likely to cause instability of the surrounding land, tree removal may not be appropriate, otherwise all trees and large bushes within the area for storage should be removed. The removal of these may be carried out by dozing or felling depending on the extent and nature of the vegetation. Vegetation and felled trees not suitable for timber or other use may be disposed of in accordance with local regulations. Alternatively they can be chipped or stockpiled for use during rehabilitation. Where soils within the storage have been identified as suitable for use in rehabilitation (or topsoiling) these should be stripped after the removal of the vegetation.

As the usefulness of organic rich soils can deteriorate with stockpiling, the advice of the local soil conservation department or other suitably experienced advice should be sought on the most appropriate methods of storing the soil to minimise degradation.

Where a design requires special treatment of the storage floor to reduce the permeability, particular attention should be given to preventing the subsequent desiccation and cracking of the treated soils. Where broad scale preventative measures are not possible the work should be carried out progressively ahead of the tailings as it covers the floor of the storage.

7.3.2 Springs and Permeable Ground

Features such as springs that may rise within the basin of a storage should be identified. An appropriate measure for addressing such occurrences would include depressurising the ground water and placing a sealing layer over the spring. The depressurising may cease once there is sufficient weight on top to hold down the seal. Where groundwater drains are considered an option, it may be appropriate to isolate them from the tailings with an impermeable or low permeability cover to minimise the contamination of the groundwater by tailings water. This can ensure that the groundwater collected by the isolated groundwater drains will meet release standards.

Where permeable features such as faults or shear zones have been identified, measures must be taken to minimise potential seepage from these. Appropriate measures would include the blanketing of the areas with low permeability fill and/or the installation of drainage.

7.3.3 Preparation for Liners

Facilities that store hazardous tailings containing cyanide, radio-nuclides etc. may require a continuous membrane basin liner or multiple liner, refer 5.8.8. The success of membrane liners relies on the care taken in preparation of the bedding layers and in the QA/QC programmes for installation. Liners can be punctured by sharp rock particles in the bedding layer beneath the liner or in the over liner material. Protective layers of geotextile can be used to protect liners from puncture. The geotextile-membrane liner interface can be a plane of weakness and care must be taken during construction to prevent slip failures. Compound liners require that the membrane liner be placed in direct contact with a low permeability soil liner. This combination can result in a significant reduction in potential leakage. This relies on continuous contact and excessive wrinkles in the membrane liner can make this less effective.

7.4 Foundation Preparation

Foundation preparation for embankments should be covered in the design specification and/or drawings.

The foundations for embankments should be prepared with equal care and diligence as for any conventional water holding dam. The prepared foundation should be inspected by a qualified geotechnical engineer or engineering geologist and if necessary should be mapped. The Responsible Engineer should confirm by verification testing that the geotechnical conditions encountered are consistent with the design assumptions.

The strength of the foundation materials needs to be confirmed as meeting design assumptions. In dry climates where saturated clays are rare, this is generally not difficult to achieve. Where saturated clays occur, consideration must be given to stability during construction. Rates of construction need to consider the dissipation of pore pressures as the dam is built and stability analyses with pore pressure predictions should be carried out to determine an acceptable safe rate of construction (refer Section 6.1). Having determined acceptable construction pore pressures, instrumentation must be installed as the work proceeds to enable the actual pore pressures to be monitored.

Where the foundations contain permeable layers of sands, gravels or alluvial, the question of seepage control must be addressed (refer Section 5.8). Cut-off trenches or under drainage collection systems may be required, depending on the type of tailings dam, the nature of the tailings water, the topography and the ground water regime. Loose layers of saturated sands are potentially liquefiable and if encountered may need to be removed or treated in situ.

Where the foundations consist of rock, seepage may commence along steep rock faces or in narrow joints where good compaction is difficult. Concentrated seepage through rock joints may also initiate internal erosion in the embankment materials. This is normally solved by reshaping such features, filling local features with concrete, slush grouting of jointed ground and/or the construction of filter blankets.

Seepage through deep seated joints can be restricted by grouting or by collecting it with a controlled under drainage system. The local site conditions and nature of the rock will generally be the deciding factors in determining the most suitable action.

7.5 Instrumentation

Instrumentation is placed to monitor response of the tailings dam to construction and operation. Instrumentation can be delicate, and relies on accurate installation to the specifications of the instrument manufacturer and the Designer. In cases where multiple installations are required, particular attention must be given to correct labelling and identification of the output points. The instruments require protection during construction from earthmoving machinery etc. Particular care is required to protect existing instrumentation and monitoring equipment during staged construction or construction of embankment raises.

Instrumentation should be specified by the Designer and baseline instruments need to be in-place at least 6 months prior to construction.

Electronic equipment will also need to be shielded from induced electric current from lightning strikes.

7.6 Source of Materials

A variety of materials may be utilised for construction of tailings dams. The material available for use in embankment construction is likely to vary throughout the life of the storage. Evaluation and testing to characterise the material properties is part of the normal design process.

Natural site materials may be available, including typical soils and rock, similar to those which would be used in conventional embankments. However, the need to produce cost effective designs often requires consideration of the use of materials which would be considered marginal for a water dam.

It is often desirable to locate borrow pits for natural materials within the storage area. If this is done, consideration should be given to the influence of the borrow pit on seepage from the storage.

When the tailings are discharged into borrow pits, they can be expected to fill rapidly with little time for drying or consolidation. The persistent high water content of these tailings will inhibit the desiccation and consolidation of tailings deposited over these borrow areas. Borrow pits should be located far enough from the embankment to ensure that the desiccation of tailings is not inhibited where stability is dependent on the strength of the tailings. Borrow pits should be developed to uniform floor grades to avoid isolated ponding.

It may be necessary to import critical components from off-site sources (e.g. sands or gravels for filter/ drainage zones). The cost implications of this will need careful consideration.

Significant quantities of mine waste are generated from open-cut operations. In many cases, pre-stripping of the ore-body may be scheduled for the same time as construction of the starter embankment, and waste will be available. In other cases it may be necessary to construct the starter embankment with natural materials, with waste only becoming available for subsequent raises.

In some cases, the use of the mine fleet to place overburden waste material directly at the embankment site can be more economic than the use of local materials. The following considerations apply:

- mining is usually on a large scale, and selection of particular materials will be difficult;
- wider crest widths or zone widths are likely to be required to suit large equipment;
- the inclusion of coarse and permeable material is a distinct possibility;
- placement and compaction of thin lifts, or narrow zones will not be practicable or possible; and
- it is more difficult to achieve face slopes other than the natural angle of repose of the dumped material.

On the other hand, there is usually no shortage of material, and the incremental cost of placement may be very low compared to conventional earthworks. Where mine waste is used for embankment construction, weathered oxide waste generally provides a more favourable construction material. In many instances a rock waste that could be a suitable construction material will be precluded from use because of its chemistry. Where any mine waste is used for embankment construction it should be tested to ensure that it is not potentially acid forming.

7.7 Use of Tailings for Construction

7.7.1 Perimeter Embankments

If the design calls for the use of tailings as the main construction material to construct perimeter embankments (or dykes) for the tailings dam, it is important to ensure that the excavation of the tailings from within the basin does not compromise the integrity of the tailings dam. When tailings are excavated from a trench adjacent to the perimeter, this can fill with water during wet weather or lead to extension of the decant pond excessively close to the embankment and lead to potential for piping failure. Also, rapid filling of the trench with tailings can result in deposits of low strength, under-consolidated tailings in the structural zone of the tailings dam embankment. This can lead to instability, excessive seepage through the downstream face of the embankment and possibly piping failures. Tailings should therefore be excavated in thin layers from the tailings beach while maintaining drainage away from the perimeter to the supernatant pond or excavated from areas remote from the perimeter and hauled into place. Excavated trenches should be of limited depth (<0.5m) and compartmentalised to limit lateral flow, leading to slimes being deposited away from the discharge area. Tailings placed in trenches should be allowed to dry before placing materials over the top.

If the moisture content of the excavated tailings is too high to permit compaction to the required density, the tailings can be processed using techniques such as mud farming where specialised machinery is used to dry the tailings prior to excavation. Temporary stockpiling of tailings can also be used to allow drying to occur. Alternatively other materials may be mixed with tailings to control moisture content.

Where tailings is used for construction, the downstream face of each stage must be dressed progressively with a suitable material such as mine waste or topsoil and re-vegetated to prevent erosion.

If tailings are used as the filter medium or the dam is zoned with tailings, the particle size distributions should be checked for internal stability (Sherrard et al, 1989 and Kenney et al, 1985).

7.7.2 Hydrocyclones

Hydrocyclones have been used for the production of construction materials for tailings embankments where the tailings contains a high fraction of coarse material or where a clean separation of the tailings can be achieved.

The use of hydrocyclones is more difficult for fine graded tailings (i.e. containing a high proportion of silt sizes and below), and separation is not likely to be fully efficient in slurries containing significant proportions of clay fines (as from oxide ores).

Effective hydrocyclone separation of a tailings material is assisted by a low slurry density in the feed. Where water resources are restricted, a high slurry feed density will require small diameter hydrocyclones and high operating pressures to achieve cyclone efficiency. For efficient construction, the underflow must be free draining, able to stand at the required angle of repose when deposited, and capable of being compacted.

Hydrocyclones can be used in a fixed location to generate material for mechanical placement. The cyclone underflow is stockpiled to drain then handled and placed in a manner appropriate to its properties. The cyclone overflow is disposed of as a slurry. In some cases cyclone underflow may be piped from a fixed cyclone station by pumping or gravity flow.

Hydrocyclones can also be individual units located in the embankment construction area, so that the underflow is deposited and drained in its final location without double handling. This involves periodic relocation of units and pipelines, and must always take account of the need to deliver the cyclone overflow to the storage area without causing erosion of the underflow deposit. In general this may be accomplished with small diameter cyclones, although larger skid mounted cyclones with delivery pipelines are common.

Hydrocyclone performance is affected by changes in feed pressure, feed pulp density, and by wear of the hydrocyclone components. The underflow deposit is usually uniformly graded and is susceptible to erosion, and cyclone malfunction can result in rapid erosion of the deposit. Incorrectly separated or placed tailings can be highly susceptible to liquefaction. For these reasons constant supervision of the operation is required.

A generous freeboard is usually maintained between the crest of the embankment being built and the beach formed by the cyclone overflow.

Design considerations include:

- location of cyclones;
- number and size of cyclones;
- number of cycloning stages required;
- quantity and availability of dilution water; and
- quantity and availability of sand that can be produced compared to requirements.

Cyclones embankments are typically raised by centreline or downstream methods. Additional information on the operation and construction of tailings embankments using hydrocyclones is contained in ICOLD 101 and ICOLD 106.

7.8 Staged Construction

The use of the downstream method of staged embankment raises requires large quantities of materials for embankment construction. Factors that may influence such a choice would include the need for a water retaining dam, a rapid rate of rise in a narrow valley situation and seismic loadings. In addition the downstream method may be necessary for the early stages of development when the rate of rise is high and before the tailings has attained sufficient strength to permit other forms of construction. The downstream method (refer to Section 3.7) also provides a convenient arrangement where the waste dump can be integrated with the tailings dam.

Other forms of staged construction are centreline and upstream (refer to Section 3.7). These methods require progressively less quantities of embankment fill material compared with downstream construction, but have an increasing reliance on the strength of the tailings to provide stability.

For the centreline method, the strength of the tailings at the time of construction is not as significant as it is for the upstream method. Generally only a small portion of the upstream shoulder is placed on the tailings surface. If the surface is too soft to support construction equipment, material can be dozed from the crest of the embankment until a sufficient depth has been achieved over the tailings to support the equipment. In instances where the tailings is very soft, it can be displaced by this method, requiring a suitable geotextile to be laid on the surface of the tailings to assist in the placement.

Compaction of the material initially placed on the tailings will generally not be possible. This coupled with the low strength of the tailings can be expected to result in settlement with consequent formation of longitudinal cracks on the upstream face and crest. Providing account of this has been included in the design, it should not present more than a temporary construction issue. Despite this, the extent of any cracking and settlement during construction should be noted and reported to the designer for confirmation that it is within acceptable limits.

The use of the upstream construction method is dependent on the formation of wide, well consolidated and drained/desiccated tailings beaches on which the greater portion of a staged embankment is placed. Construction by this method requires the tailings to have adequate strength to support mechanical equipment and the weight of the embankment without large settlements. Under these conditions the embankment material can generally be placed and compacted directly on the surface of the tailings beach.

If adverse weather conditions, unexpected changes in ore type or increased rates of production lead to soft tailings beaches, the design will need to be modified to provide access for construction and to accommodate the ongoing settlements from consolidation.

Appropriate construction measures on soft tailings include the provision of a drainage layer over the footprint area on the tailings surface. The use of geotextiles in conjunction with the drainage layer will generally provide a significant improvement in the construction conditions.

During staged construction on soft tailings attention must be paid to stability in the upstream direction. If the tailings have poor consolidation characteristics, it may be necessary to restrict the rate at which the embankment is constructed to ensure that pore pressures within the tailings do not increase to a point where failure can occur.

Areas of soft tailings and any design changes made during the construction of a stage should be accurately documented. This information is critical to ensure that the future design and investigation take full account of the changes.

Mud farming techniques, where low pressure swamp buggies, ‘amphi-rollers’ or swamp dozers are used to break up surface tailings crust and provide drainage channels, can be used to improve the foundations for upstream stages.

Variation in conditions cannot be predicted at the initial design stage and changes should be regarded as normal and an integral part of ongoing design and development. The possibility for changes should however be recognised at the initial design stage so that the integrity of the design can be achieved for any potential changes.

7.9 Commissioning

The objectives of the commissioning phase are to:

- confirm that all components are functioning according to the specifications prior to placing tailings;
- make safe and protect the works which may be damaged during the early placement of tailings, and in particular;
  - covering and protection of exposed drainage system components from the effects of wind or erosion by stormwater;
  - protection of exposed drainage system components from the effects of damage or blocking by tailings;
  - protection of the underdrains from damage by construction equipment;
  - prevent initial tailings flow from eroding embankments, drains, liners, etc.; and
- confirm the tailings properties/behaviour and dam/tailings facility behaviour against the design specifications.

7.10 As Built Drawings and Construction Report

Construction and commissioning records, including field and laboratory testing, should be kept to provide documentation of compliance with the design drawings and specifications. Deviations from the drawings or specifications should be documented in "as-built" records. A final surface survey is required as part of the "as-built" drawings.

These records are also essential for ongoing management of the tailings dam. The construction records together with monitoring data form the basis of the design of subsequent stages.

The records should be collated and presented in a Construction Report prepared at the end of construction of the starter facility and after the completion of each stage.

"As-built" drawings should be filed in records or archive, and be readily available to operational personnel, together with investigation and design reports. These need to be kept accessible during the life of the tailings dam and passed on to subsequent owners post-closure.

A typical Table of Contents for a Construction Report is presented in Appendix C.

8.0 Operation

The objective of the operations phase of a tailings dam is to safely store the tailings in a manner to minimise risks to the operations and the environment during mining and closure. An important aspect of this is the management of changes during operations so that the storage remains in compliance with design and regulatory requirements.

To achieve this objective, operational constraints need to be identified and incorporated into operational procedures.

8.1 Management and Training

Operation of tailings dams should be in accordance with approved procedures, signed off by regulators where required, and regularly reviewed and modified if necessary to improve tailings management or reflect changes in conditions.

An Operations, Maintenance and Surveillance Manual (refer to ANCOLD Dams Safety Management Guidelines-2003) should be produced prior to commencement of tailings placement, outlining all designer requirements for operation, maintenance and dam safety surveillance that must be met to ensure the ongoing safety and effective operation of the tailings dam facility. A Dam Safety Emergency Plan (DSEP) should also be produced (see Section 8.6).

The owner should ensure that the tailings dam is operated by an appropriately experienced team with a proven track record in the execution of works of a similar nature and magnitude. For EXTREME, HIGH and SIGNIFICANT Consequence Category dams, the team should include a professionally qualified civil or geotechnical engineer. Operators should be appropriately trained for their roles with regular refresher training.

It is most important that the owner and management of an organisation owning a tailings dam are aware of the consequences of failure of the dam, and their legal responsibilities to ensure that proper and adequate attention is given to the management of risks. It is the owner's responsibility to ensure that adequate funds and resources are provided to allow staff to establish and maintain the required level of rigor in operating and maintaining the facility.

8.2 Operations Plan

The objective of the operational phase of a tailings dam is to develop the storage in such a manner as to ensure that the tailings facility is:

- maintained in a safe and stable state and in accordance with prescribed risk management specifications;
- operated in accordance with the requirements of the Design Report and Operations, Maintenance and Surveillance (OMS) Manual, including periodic updates, and within the constraints of industry norms of good practice;
- operated in accordance with legal requirements;
- operated to achieve prescribed environmental objectives; and
- operated in accordance with the closure plan and intended use after closure.

The tailings facility should be operated in order to achieve the following objectives:

- to control distribution of the tailings in order to achieve the required geometric shape of the deposit, to maintain the water pool within the specified position and to ensure that segregation does not compromise the structural integrity of the deposit;
- to control the deposition cycle in order to ensure that settlement and drying of tailings conforms with the design intent;
- to control the level and position of the water pool in order to maintain a specified water cover or maintain freeboard to prevent the risk of overtopping (see Sect. 8.4);

to control the flow and discharge of storm water which accumulates on the storage in such a way as to prevent damage;

to control access so that only those persons authorised to gain access for the purposes of operation and supervisory management can do so;

to optimise the recycle of water from the storage where appropriate. Discharge of water to the environment should not be permitted unless specifically allowed in the design and subject to water quality requirements;

to keep uncontaminated water separate from contaminated water; and

to control dust during windy conditions by more frequent deposition to create maximum area of wet beaches and by control of traffic in the area.

8.3 Operations, Maintenance and Surveillance Manual

An Operation, Maintenance and Surveillance (OMS) Manual should be completed, normally prior to commissioning of a tailings dam. The Manual should cover design intent, predicted behaviour of tailings, daily operations and inspections, water management procedures, criteria for mechanical and electrical works (including pumps), surveillance, maintenance and reporting requirements. Operational Management Plans within the OMS Manual should specifically highlight all designer requirements for operation and response actions that must be met to ensure the ongoing safety of the dam.

The OMS Manual should specify all requirements for operators and the minimum level of operator training with alternatives (e.g. consultant assistance) whenever these operator requirements cannot be met.

OMS Manuals for tailings dams should be updated at least every two years with the whole tailings facility management strategy reviewed to see if there are better ways of achieving the facility's objectives.

The OMS Manual should include maintenance requirements. The Manual should be updated prior to closure to include care and maintenance requirements during closure.

8.4 Monitoring and Surveillance

The operational procedures for the tailings facility should include provisions for surveillance (i.e. regular inspection, monitoring and evaluation) and documentation thereof. Conditions can develop during operations which, if not detected early, could lead to loss of containment or unsuitable conditions for undertaking plans for extension or closure of the facility. Accordingly, owners should meet in full the provisions of Chapter 5 of the ANCOLD "Guidelines on Dam Safety Management- 2003". These guidelines recommend that owners undertake comprehensive inspections on initial dam filling, and thence on a five yearly basis, with intermediate audit inspections undertaken usually on an annual basis. These requirements are summarised in Table 9 and Table 10.

In ensuring effective surveillance of tailings dams, the owners are required to select suitable operational staff and arrange for their training in the areas of dam safety management with regular refresher courses to keep operators up to date with current practices. As part of that training, operators should be capable of recognising abnormal conditions and circumstances that could affect the safety of their dams and be able to institute appropriate actions including when to call for more expert assistance.

Routine inspection and monitoring of the dam by trained staff should be carried out in accordance with the designer's requirements (usually aligning with Table 5.3 of ANCOLD-2003 as modified by regulatory requirements). The items that need to be monitored and the relevant associated instrumentation should be designated by the dam designer to enable a suitable coverage of the aspects that affect the ongoing safety and operational performance of the facility.

Ongoing recording of inspection findings, monitoring instrument readings, and any incidents is essential for all tailings dams. Attention is drawn to ICOLD (1996) no.104, "Monitoring on Tailings Dams" which deals with the monitoring of tailings dams during construction and operation.

Table 9 Dam safety inspections levels

Type of Inspection	Personnel	Purpose
Comprehensive	Dams Engineer and Specialist (where relevant)	The identification of deficiencies by a thorough onsite inspection; by evaluating data; and by applying current criteria and prevailing knowledge. Equipment should be test operated to identify deficiencies.
Intermediate	Dams Engineer	The identification of deficiencies by visual examination of the dam and review of surveillance data against prevailing knowledge. Equipment is not necessarily operated.
Routine	Operations personnel / inspector	The identification and reporting of deficiencies by field and operating personnel as part of their duties at the dam.
Special	Dams Engineer and Specialist	The examination of a particular feature of a dam for some special reason (e.g. after earthquakes, heavy floods, rapid draw down).
Emergency	Dams Engineers	The examination of a particular feature of a dam which has been identified as having a possible deficiency or which has been subject to abnormal conditions.

Table 10 Frequency of Inspection

DAM FAILURE CONSEQUENCE CATEGORY	INSPECTION TYPE			
	Comprehensive	Intermediate	Routine	Special
EXTREME OR HIGH A, B or C	After first year of operation, then 2 yearly	Annual	Daily to 3 times/ Week	As required
SIGNIFICANT	After first year of operation , then 5 yearly	Annual	Twice Weekly to Weekly	As required
LOW		On first filling then 5 yearly	Monthly	As required

Records should be kept in an accessible, secure repository and in an organised form covering:

- Groundwater monitoring with special emphasis on the environmental impacts of the tailings dam on groundwater (e.g. geochemical processes);
- Surface drainage and seepage monitoring, both visual observations and seepage measurement are required as a minimum, with chemical analysis also of value (e.g. acid drainage generation);
- Capacity monitoring (tailings, process water, water recovery, evaporation);
- Tailings monitoring (e.g. beach development, drainage, density, desiccation);
- Monitoring of instrumentation and instrumentation readings;
- Monitoring of equipment and pipework;
- Monitoring of dam movements, stresses, cracking and seepage;
- Inspection reports (i.e. times, dates, observations);
- Incident reports (i.e. time date, nature, actions); and
- Annual audit.

Monitoring of seepage is essential even when every reasonable effort has been made to minimise it. If sufficient seepage occurs so that it is detectable, it will be necessary to assess the impact on the environment and in some situations to take action to recover the lost tailings liquor to limit the environmental impact.

Monitoring of the facility's performance is also imperative as a facility is usually designed for particular tailings characteristics. Deviations from these typical characteristics, (i.e. grading, slurry density, chemical constituents) could influence the operating procedures and the facility performance. Therefore, tailings characteristics should be checked at periods not exceeding 6 months. Overall filling rates, densities, beach shapes, water recovery etc. should be formally evaluated at 12 month intervals, and significant variations referred to the designer.

Formal technical reviews/audits should take place at regular intervals. The audits should be undertaken by appropriately skilled personnel and should be formally recorded. Audits should include consideration of dam safety. A suitable approach is described in ANCOLD, 2003.

Effective management techniques are required to ensure that the outcome of the inspections, monitoring and audits are referred to the designers, constructors, operators and regulators as relevant. Any necessary changes should be confirmed as having been carried out. A typical Table of Contents for an Inspection Report is presented in Appendix D.

8.5 Embankment Raising

Tailings dams are often designed to have containment embankments progressively raised during operation. Such raisings should not increase the risk of operating the dam and need to take into account prevailing weather conditions during raising (flood risks, wet weather) and geotechnical parameters. Flood handling capabilities of tailings dams are particularly crucial for their long-term safe operation so need to be kept well maintained at all times, including during raising. The interaction of construction work with tailings discharge needs to be coordinated to ensure there is no conflict which may increase the risk of tailings spill.

While upstream and centre lift tailings dams can be a cheaper method of construction, they require the highest level of design input, operator skill and owner diligence in order to maintain their stability. They also need to be subject to strict design and operational constraints to ensure their ongoing safety with the following critical operational issues highlighted for the consideration of dam owners and their designers:

- a seepage flow net analysis detailing all assumptions should be undertaken to specify trigger piezometric levels, which signal "unsafe" phreatic surfaces and these should be regularly checked against actual piezometric levels and operating pond levels;
- tailings discharge requirements for safe operation of the dam should be established, targeting the required density for construction and stability;
- a safe maximum rate of rise of the dam should be determined, based on a total stress stability analysis; and
- incorporate additional monitoring aimed at fully understanding the pore pressures being developed in the dam.

8.6 Dam Safety Emergency Plan

A Dam Safety Emergency Plan (DSEP), in conjunction with appropriate emergency authority planning, should be prepared for tailings dams where any persons, infrastructure or environmental values could be at risk should the dam collapse or fail (see Chapter 8 of the ANCOLD, 2003). The DSEP should include an appropriate dam break study with the conservative assumption of liquid tailings flow in the event of dam failure unless a more sophisticated analysis of water and/or tailings flow can be justified. DSEP's are to be updated annually and tested at regular intervals.

8.7 Maintenance

The principle in determining maintenance priorities is to attend to all items that affect the structural integrity first, followed by environmental items and then by conventional maintenance (see ANCOLD 2003 etc.). For example, a wash-away of a perimeter wall that compromises the freeboard would need to be repaired urgently, as would a burst slurry delivery pipeline. Conversely, the gradual siltation of a stormwater drain would need less urgent attention.

Spillages can occur in the operation of tailings dams. The first principle should be to prevent spillages through disciplined operation and maintenance. The second principle should be to incorporate a surrounding ditch or catch area so that the area affected by a spillage is minimised. Particularly sensitive environmental areas, e.g. stream crossings, should be protected from spillages. When spillages do occur, clean-up operations should be prompt and thorough.

8.8 Security

All access ways, and in particular those likely to be in use during adverse climatic conditions, are to be made safe for the operating personnel to negotiate in the course of their duties. Access to dangerous areas should be limited by appropriate barriers and signs and through communication and training.

The possibility of theft and malicious damage should be considered. The management system should thus take into account the possible loss of equipment or damage to the facility. Provision should be made to ensure that the integrity of the storage is not compromised under these potential circumstances.

9.0 Closure

Sustainable closure is the target set at commencement of planning for a tailings dam and is subject to review throughout the construction and operation phases. ANCOLD have adopted 1000 years as a notional post-closure life for the purpose of focussing design and operational considerations.

9.1 Sustainable Closure

These Guidelines have introduced aspects of closure throughout the various sections, highlighting the important principle of designing, constructing and operating a tailings dam with an aim to an eventual closure strategy that will allow a safe and stable structure to remain following the completion of mining operations. Post-closure, a tailings dam must be able to cope with potential conditions to be encountered over the extended period determined as the design life, potentially of 1000 years or longer.

The following more specific principles apply to the successful achievement of sustainable design and post closure performance (ICOLD, 2011, draft):

- the main objective of mine closure should be the long-term stabilisation of physical, chemical, ecological and social conditions of the tailings dam within a reasonable time scale to prevent any ongoing degradation;
- the closed facility should not require ongoing maintenance and expenditure other than normally required for similar land use;
- the closed facility should not pose a risk to human health and safety;
- the closed facility should not pose an unacceptable environmental risk; and
- the facility is left with an appropriate and sustainable land use and water use that meets stakeholder and community objectives and supports a sustainable ecology

9.2 Closure Plan

Decommissioning and rehabilitation options should be evaluated early in the life of the project. A Closure Plan should be prepared, and costed, as part of the initial project development and included in economic, social and environmental analysis of the project viability. The Closure Plan should then be kept live and regularly reviewed and updated as the project develops through design, construction, operation and potential changes in scale and direction (i.e. Integrated Life-Cycle Management). The Closure Plan should address:

- closure objectives, strategy and context (including climatic regime, policy; performance objectives, criteria and indicators);
- required monitoring information, data collection, analysis and records management;
- specific issues (including geochemistry of tailings and entrained water, salinity, radioactivity, future land use, etc.);
- implementation and management of closure stages (active, passive and self-sustaining), including monitoring and audits to ensure systematic risk reduction; and
- the potential for and the procedures to be followed in the event of early closure.

9.3 Closure Options

Closure options need to be reviewed on a case by case basis as there are likely to be specific issues to be addressed in each case. Some considerations include:

- landform reconstruction options will be influenced by climate;
- water management approach will be driven by climatic regime and should consider possible climate change;
- a water or saturated soil cover might be appropriate in a wet climate to maintain the tailings saturation when required to prevent oxidation and the production of contaminants in seepage;
- a rainfall shedding cover may be appropriate in a wet climate to minimise infiltration and ongoing seepage with an appropriately sized spillway;

a store/release cover might be appropriate in a moderate or dry climate, possibly including a sealing layer;

allowing the development of an evaporative crust may be appropriate in a dry climate, in which any infiltration into the desiccated tailings will re-evaporate, without reliance on vegetation. Special attention is required for dust control; and

stakeholder engagement is essential.

9.4 Closure Issues

Issues to be addressed in the Closure Plan include:

final landform and its relationship to embankments and storage geometry;

earthworks plan and staging;

materials handling and stockpiling;

temporary works;

physical and chemical stability of the tailings facility and durability of control structures;

cover types for tailings;

consequences of extreme environmental conditions (e.g. drought, flood, fire, earthquake);

access control;

structural integrity;

geotechnical stability;

on-going settlement;

erosional stability, including sedimentation and its influence on drainage;

surface drainage works (noting that these concentrate flows, making them difficult to sustain without rigorous design, construction and ongoing maintenance);

surface treatment to minimise erosion (via rock cover and/or vegetation), while sustaining vegetation; and

monitoring and audit requirements for the closure process and aftercare.

9.5 Progressive Closure

The achievement of closure is likely to take an extended time, during which varying degrees of intervention and maintenance will be required. For this reason, progressive closure of partial areas of the site is recommended, to demonstrate and develop effective methods and to potentially reduce the risks of unexpected issues delaying final closure.

9.6 Mine Completion

Mine Completion is the goal of mine closure where mining lease ownership can be released and responsibility accepted by the next land user. Mine completion will require confirmation that agreed performance targets have been achieved. This is likely to require a period of active management and monitoring over an agreed time-frame during which the required performance can be demonstrated.

10.0 References

Other Relevant ANCOLD Guidelines

- Guidelines on Assessment of the Consequences of Dam Failure (2000), revision due 2012
- Guidelines on Risk Assessment (2003)
- Guidelines on Dam Safety Management (2003)
- Guidelines on Selection of Acceptable Flood Capacity for Dams (2000)
- Guidelines for the Design of Dams for Earthquake (1998), revision due 2012
- Guidelines on Dam Instrumentation and Monitoring (1983)

This ANCOLD Guideline for Tailings Dams is written to include aspects arising from the nature and variety of climatic conditions in Australia and nearby countries. However, the following international guidelines prepared by ICOLD are also relevant:

- No. 45 Manual on Tailings Dams and Dumps
- No. 74 A Guide to Tailings Dam Safety
- No. 97 Tailings Dams - Design of Drainage (1994)
- No. 98 Tailings Dams and Seismicity (1995)
- No. 101 Tailings Dams Transport, Placement and Decantation (1995)
- No. 103 Tailings Dams and Environment (1996)
- No. 104 Monitoring of Tailings Dams (1996)
- No. 106 A Guide to Tailings Dams and Impoundments (1996)
- No 121 Tailings Dams Risk of Dangerous Occurrences Lessons learnt from Practical Experiences (2001)
- Draft Bulletin on Sustainable Design and Post-Closure Performance of Tailings Dams, (2011)

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