Evaluation of

Safety of Tailings Dams

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PREFACE

As recently as 40–50 years ago, the majority of tailings dams were constructed based on the long-time experience of miners, thus employing an empirical design method with little engineering input. It wasn't until the 1960s that tailings dams were designed based largely on engineering principles and analyses. At that time, still relatively little attention was paid to designing with respect to potential environmental impacts.

The potential for environmental impacts and health hazards associated with tailings dam operations has long been recognised and, in this regard, a very significant progress was made throughout the 1970s and the early 1980s in the area of radionuclide and cyanide contamination. The late 1980s through the early 1990s became the 'acid mine drainage' epoch.

The vulnerability of upstream tailings dams to failure under earthquake loads was strongly realised by the mid-1960s and, by the early 1970s, the foundations for analysing the liquefaction potential and seismic stability of tailings dams were laid down. The late 1980s through the early 1990s were particularly fruitful in further advancing the methodology for investigating the seismic stability of tailings dams.

In the 1960s and 1970s, most tailings dams were designed according to the 'state-of-the-art' developments in geotechnical engineering, however, still little attention was paid to the actual length of the service life of a typical tailings dam. In those years, a one- or two-page design 'closure plan' typically included some general statements as to the intent of draining the tailings pond, vegetating tailings surface, and providing a permanent spillway. By the 1980s, the long closure phase characteristic of tailings dams received the deserved attention.

In the early days, tailings dams were commonly designed by engineers who specialised in the general practice of geotechnical engineering. At some prior to the early 1970s, it seems, the discipline of tailings dam engineering was born. Today, tailings dam engineering requires much more than the application of geotechnical engineering principles. Some rudimentary understanding of the fundamentals of environmental sciences, geochemistry and contaminant hydrogeology, hydrology and seismicity, regulatory and social issues, *etc.*, as well as a strong focus on tailings (rather than conventional) dams are required from tailings dam engineers. Tailings dam engineering has become a multi-discipline specialisation in which geotechnical engineering still plays the most prominent, although not necessarily prevailing role.

As recently as 20 or 30 years ago, legislative requirements pertaining to the design, construction, operation and closure of tailings dams were quite general, limited in scope, not well defined or non-existent. Today, many jurisdictions have technically advanced regulations and/or guidelines, which specifically target tailings dams.

As recently as 20 or 30 years ago, a failure of tailings dam, which did not result in loss of life or extensive property damage, was seen as an unfortunate yet forgivable event. Today, no failure of tailings dam can be pondered acceptable even if all consequences of failure, including environmental impacts, are negligible. It can reasonably be assumed that the media would be there the following day, and the damage to the owner's reputation could be severe, regardless of the merits.

We thus have witnessed a tremendous progress in tailings dam engineering and the way we perceive tailings dams, occurring over a very short time (which is particularly short when compared to the service life of a typical tailings dam). Such rapid progress also means that we have to struggle somewhat when adapting to the new situations. Notwithstanding the lessons to be learned, past failures of tailings dams must also be seen from this perspective. There is nothing wrong with the mining industry, contrary to the recent media and Internet reports.

Maciej B. Szymanski

Mississauga, Canada
January, 1999

CONTENTS

1 GENERAL

1.1 INTRODUCTION

This Document has been prepared with the purpose of presenting a consistent approach to tailings dam safety evaluations, which is based on consequence classifications of tailings dams and other considerations specific to tailings dams. The term 'safety evaluation', as used herein, encompasses all instances when the safety of tailings dam is evaluated, including the design stage.

Some discussions presented herein are also relevant to evaluating the safety of other (than tailings) dams operated at mine sites. These may include clean or contaminated water management dams, runoff/watercourse diversion dams, sedimentation, sludge or polishing pond dams, *etc*. Additional or different dam safety evaluation requirements, as compared with those outlined in this Document, may apply to any of such dams.

An emphasis is put on environmental impacts that could result from tailings dam failure. Incorporating a clearly defined approach to evaluating such impacts into the tailings dam safety evaluation process is advocated herein in response to several phenomena that have occurred in recent years:

- increased awareness of environmental impacts that could result from a failure of tailings dam;
- increased costs of tailings dam failure (production losses, environmental clean-up cost, *etc.*, including the damage to owner's reputation and all the resulting consequences);
- increased liabilities to which dam owners and engineers are exposed;
- increase in the size of tailings dams and, therefore, the consequences of potential dam failures;
- increased regulatory pressures, with legislations which specifically target tailings dams;
- recent failures of tailings dams which resulted in significant environmental impacts;
- maturing of tailings dam engineering in the area of environmental protection requirements.

An emphasis is also put on the tailings dam closure phase, although no specific section in this regard is provided (except for a commentary). One of the fundamental premises underlying the recommended approach to dam safety evaluations is that a tailings dam should be as safe during the production phase as after the cessation of mine operation.

Following the approach to tailings dam safety evaluations outlined in this Document should allow for constructing and operating tailings dams with a reasonable degree of confidence as to the various aspects of dam safety. This would be accomplished by employing an approach developed specifically for tailings dams. Furthermore, following a uniform approach to evaluating the safety of tailings dams would also allow for applying the experience from various mine sites in a more systematic manner, whether with reference to mine sites operated by the same owner or otherwise.

Although operated tailings dams are significantly safer today than these were two decades ago, introducing further improvements to their safety will often be possible. Such improvements can be accomplished by following a sufficiently comprehensive dam safety evaluation program, which allows for both identifying potential deficiencies in existing dam structures and/or operating procedures, as well as implementing appropriate corrective measures. The purpose of this Document is to describe such a program. It provides a framework within which improvements to tailings dam safety can be realised. It also provides a framework based on which safety requirements for new tailings dams can be established.

Whenever a recommendation is made in this Document, it refers to a minimum requirement unless explicitly stated otherwise. As with any other document of this type, caution, experience and sound judgement are required when contemplating the use of any of the recommendations stated herein. In fact, this Document is intended as a proposal rather than guideline and the word ‘recommended’, as used herein, may have to be interpreted as ‘proposed’, depending solely on the reader.

This Document is intended for engineers, regulators and other professionals involved in tailings dam safety evaluations. It is also intended for tailings dam operators who should always be aware of the rationale underlying the recommendations made by engineers with regard to tailings dam safety.

Some of the views expressed throughout this Document may be bias since these were partly shaped by the author’s experience. Thus it needs be said that the author’s experience is limited, with few exceptions, to North and South American mine sites, with the majority of experience gained from projects across Canada. Except for one of each: graphite, potash, sulphur, molybdenum and rare earth projects, two coal, two iron and several uranium projects, the author’s experience is limited to base metal and gold mining operations. During the last decade, the author has spent about equal time working on projects involving the design of new tailings and contaminated water storage dams, and projects involving tailings dam closure. Acidic drainage, cyanide and other contamination of site waters, including contaminated water management systems, always represented the key design issues on those projects. The influence of this experience will be apparent throughout the Document.

1.2 TO THE READER

To Tailings Dam Engineer:

If you are a recent graduate, chances are you will not be able to appreciate the significance of some tailings dam safety aspects discussed herein, even if you graduated as the 'number one' in civil/geotechnical engineering and have the necessary (limited) knowledge of the fundamentals of conventional dam engineering, mining, hydrogeology, geochemistry, environmental sciences, process engineering, *etc*. In addition to your degree, you may need a few years of experience in tailings dam engineering to be able to appreciate all dam safety aspects addressed in this Document.

[On the positive note, if you re-read the preceding paragraph from another perspective, you will see how much fun you will have in the years to come.]

If you are an experienced tailings dam engineer, reading this Document will be easy. Chances are you will be critical of some of its contents and this is the way it should be. If reading this Document helps you clarify or improve (no matter how little) the tailings dam safety evaluation program that you have had in mind, you will make the time that I spent on writing this Document truly worthwhile.

To Tailings Dam Operator:

If you are a tailings dam operator, meaning the site person responsible for tailings disposal operation, chances are you will not have adequate background to appreciate all technical details discussed in this Document. You may have a background in metallurgy, mining or environmental sciences, while few sections of this book have been written for engineers with background in tailings dam engineering. These you will easily recognise. They refer to some detailed analyses, the understanding of which is of no practical importance to *the understanding of the overall tailings dam safety evaluation process*, which is the principal subject of this book. I do not expect you to appreciate, for instance, the details of tailings liquefaction, flood or undrained strength stability analyses. And yet, this book has also been written for you. I strongly believe that you will benefit from reading it. How much you will benefit depends on how much effort you are willing to put into the reading.

Skip, without regrets, all paragraphs that you are not comfortable with. You will not lose much. You still will be able to grasp all the things that are essential to your involvement in tailings dam safety evaluations. If you are curious about the technical details, your tailings dam engineer will be pleased given the opportunity to explain these to you (I could not do it here without at least doubling the size of this book).

If you decide to go for a minimum, you should read Sections 1, 2, 6.2–6.4, 7, 8 and 9, as well as study Tables 1 and 6, neglecting the fine print under the tables, however, scanning the accompanying text to appreciate their significance. Somehow I think you will go beyond the minimum.

To Regulator:

If you are a regulator involved in tailings dam safety evaluations, you will need to realise that it is not likely that a document of this type, which would cover all conceivable site and region specific conditions and situations, will ever be written. You will also need to remember that this Document is not intended as a guideline. It is up to you to write a relevant guideline or policy. If reading this Document helps you organise your thoughts while preparing such a guideline or policy, or examining a tailings dam project, then I will feel rewarded.

To All Readers:

You will find that few thoughts on tailings dam safety evaluations are somewhat scattered throughout the text, and you might not like it. This I could have corrected rather easily (I am quite skilful with word processing) and yet haven't done so. The reason for this is that having a tailings dam safety aspect completely treated in one, well-marked section would not be appropriate here. This would be inconsistent with the intent of this Document, which is intended neither as a handbook (where you go to a specific section to select a pipe size) nor textbook (where you first review the principles of soils mechanics, then the properties of tailings materials, fundamentals of hydrology and hydrogeology, types of tailings dams, field exploration program, design of runoff management systems, *etc.*). It is intended as a practical document for those who have already seen a tailings dam or two, and may wonder about dam safety while relocating a tailings discharge pipeline, designing a tailings dam, or discussing the need for conducting a risk analysis or dam safety review.

Perhaps this Document can best be viewed as a 'study book'. As such, it should be read in its entirety, skipping the parts that may appear 'too technical'. These would primarily be included in Section 10 and several sections of the Commentary (Appendix A).

Some tailings dam safety aspects discussed in this Document may be controversial, for instance, the issue of potential loss of life in the case of new tailings dams, the water cover, the consequence classification in terms of environmental impacts, or the stability assessment of upstream dams. In respect to such aspects, it is essential to evaluate the practical consequences of the recommendations made herein, prior to agreeing with or rejecting any of such recommendations. The Commentary has been specifically designed to aid such evaluations.

To Steven G. Vick:

Many thanks for reviewing this book. This was a very kind and a very helpful review. I particularly appreciate your willingness to share thoughts on dam safety. I think that the presentation of many topics is significantly better now, improved upon in response to your comments. I have studied these comments carefully and believe that in the most essential case where we have somewhat different views (the use of experience from inactive upstream tailings dams), I err on a conservative side. Looking forward to meeting you one day in person.

1.3 PURPOSE AND CONTENTS OF THE DOCUMENT

This Document has been prepared to accommodate the engineering perspective. Its primary purpose is to recommend:

- a complete safety evaluation program for tailings dams, and
- the most fundamental safety requirements for tailings dams

as well as discuss the rationale underlying these recommendations. The rationale is discussed throughout the main text and elaborated on in the Commentary (Appendix A).

The various instances when a tailings dam safety evaluation is conducted are identified in Section 1.4. These instances form a base for the grouping of tailings dam safety evaluation requirements discussed in Sections 7 through 10. The two fundamental types of tailings dam failures are identified in Section 3, and the consequence classifications for tailings dams are discussed in Section 4. The characteristics of typical tailings dam operating phases, outlined in Section 5, are taken into consideration in assigning appropriate dam safety evaluation requirements. The most common components of tailings dam safety evaluation are discussed in Section 6.

Tailings dam safety is addressed in ICOLD Bulletin 74 titled '<u>Tailings Dam Safety. Guidelines</u>' (1989). As opposite to the ICOLD guidelines in which selected requirements pertaining to the overall aspect of tailings dams safety are outlined, the attention is focused in this Document on a complete tailings dam safety evaluation program and associated requirements.

1.4 TAILINGS DAM SAFETY EVALUATION PROGRAM

There are six instances when a tailings dam safety evaluation is conducted. These include:

I dam surveillance (DS);
II dam safety inspection (DSI);
III dam safety review (DSR);
IV initial design of dam;
V designing for stage-raise of dam;
VI designing for dam closure;

Components I through VI constitute a complete *tailings dam safety evaluation program* (Figure 1).

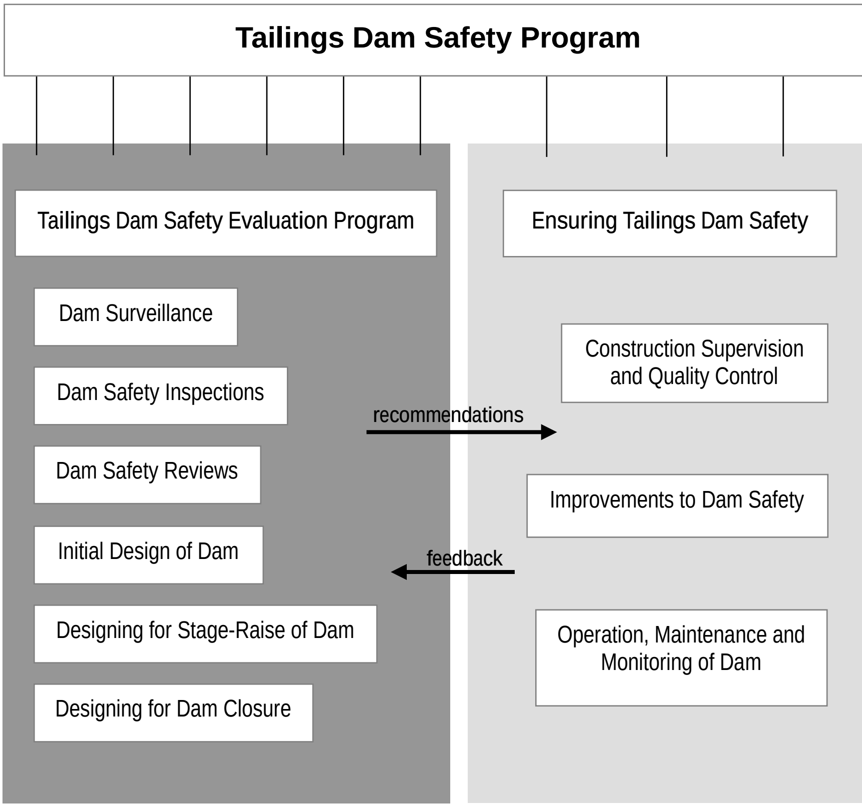


Figure 1
Components of Tailings Dam Safety Program

Tailings dam safety evaluation program starts at the initial design stage, after final selections of the dam site and the type of dam have been made. This typically corresponds to the feasibility design level at which a tailings dam comes into existence, albeit still on computer screens and design briefs only, and the site-specific conditions relevant to dam safety become largely known (design levels are discussed in Section 10.1).

Except for some ‘small’ tailings dams the failure of which would result in negligible consequences, as well as the very few other dams that can be retrofitted for closure to the conditions which would permit the dams to be left unattended, the implementation of this program will take hundreds of years.

Besides evaluating the safety of tailings dams, the following conditions pertaining to dam safety must also be satisfied (these refer to ensuring rather than evaluating dam safety):

VII adequate construction supervision and quality control must be provided;

VIII where necessary, improvements to dam safety must implemented;

IX tailings dam must be operated and closed out in accordance with the design requirements, including the implementation of appropriate monitoring and maintenance programs.

Components I through IX constitute a complete *tailings dam safety program* (Figure 1). In the majority of cases, the owner assumes the responsibility for components I and IX. Components II through VIII are typically attended by the tailings dam engineer, with input from the owner. Where component VIII relates to tailings dam operating requirements, the owner implements improvements to dam safety, often following a recommendation made by the engineer.

The primary purpose of this Document is to address the tailings dam safety evaluation components (I through VI), however, some discussions pertaining to components VII, VIII and IX are also included throughout the text. Dam safety requirements relating to components I, II and III are discussed in Sections 7, 8 and 9, respectively. Selected design requirements for tailings dams (components IV, V and VI) are discussed in Section 10.

1.5 EXPERIENCE FROM CONVENTIONAL DAM ENGINEERING

It is often said when comparing tailings dams with conventional (*e.g.*, hydroelectric, irrigation, flood control or water supply) dams that the primary purpose of a tailings dam is to contain solids, and this represents the principal difference between these two types of dams. While this is somewhat true, little can be gained from this statement when applying the experience available from conventional dam engineering to the evaluation of safety of tailings dams. For instance, considering potential failure of a dam in the downstream direction, a typical low permeability tailings dam essentially works in the same manner as a conventional embankment type dam of similar design, regardless of stored solids, and yet it may be significantly different in other dam safety aspects.

The differences between tailings and conventional dams are very substantial (these are discussed in Appendix A–I), and as such, must not be overlooked when applying the conventional dam experience to tailings dams. Perhaps the most illustrative example in this regard is the fact that the actual performance of typical tailings dam, in terms of its physical stability under normal loading conditions, cannot be fully evaluated until the last stage-raise is constructed, tailings are deposited to their final configuration, and the tailings pond reaches, and maintains for a period of time, its highest normal operating level. This would only be possible near the end of mining operation. Prior to that, a false sense of security could develop when observing satisfactory dam performance over the years. In the case of conventional dams, the same level evaluation can be performed shortly after the construction (*i.e.*, upon the completion of initial filling).

It is therefore imperative to recognise and take into consideration the numerous differences between the tailings and conventional dams, whenever relying on the methods and/or experience available from conventional dam engineering.

The above discussion implies that having a dam safety evaluation document prepared specifically for tailings dams is necessary, if only to avoid potential errors or omissions that might occur when using the experience available from conventional dam engineering. It will also be seen from the contents of this Document that the evaluations of tailings dams must typically account for significantly more complex safety aspects, as compared with the evaluations of conventional dams.

1.6 APPROACH TO TAILINGS DAM SAFETY EVALUATIONS

The approach to evaluating tailings dam safety outlined in this Document is based, in part, on the consequence classification method. This means that the safety evaluation requirements are designated based on a consequence classification category that must be established for each tailings dam (each dam has to be classified with respect to the consequences of hypothetical failure). The use of a consequence-based classification for evaluating dam safety is in agreement with the approach endorsed by many conventional dam safety organisations and regulatory agencies responsible for setting up dam safety standards. This method is also well suited for tailings dams when addressing the potential for structural failure of dam with respect to environmental impacts and other consequences of failure.

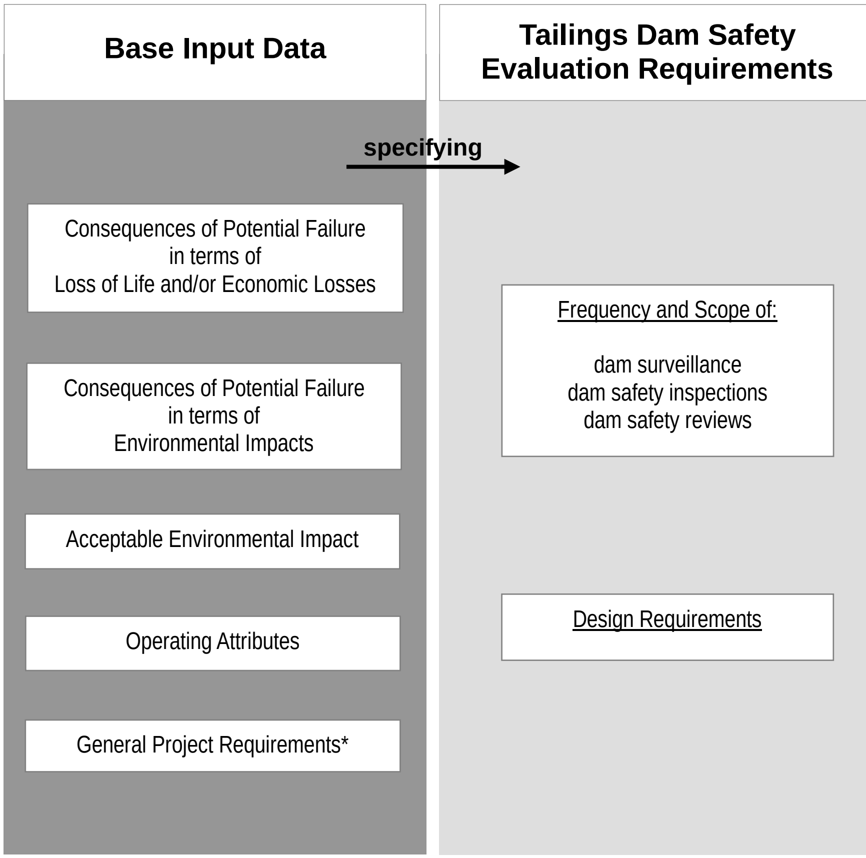
The recommended approach to the selection of tailings dam safety evaluation requirements is outlined on Figure 2. In more detail, this approach is discussed in Sections 3, 4 and 5.

Exception to the conventional approach is the recommended use of two independent consequence classifications for the purpose of selecting dam safety evaluation requirements:

- consequence classification in terms of potential loss of life and economic losses;
- consequence classification in terms of potential environmental impacts.

For the same purpose, consideration is also given to:

- environmental impacts that may be occurring as a result of tailings dam operation on a continuos or intermittent basis;
- safety related tailings dam operating conditions that vary with the dam operating phase.



* 'General project requirements' may include owner's specific objectives, regulatory requirements, etc. (see Section 10.5).

Figure 2
Selection of Tailings Dam Safety Evaluation Requirements

A consequence classification in terms of potential environmental impacts for tailings dams, referred to as the *impact classification*, is introduced in Section 4.2. This classification and a consequence classification in terms of potential loss of life and economic losses (LLEL) form a base of the recommended approach to evaluating the safety of tailings dams, together with other 'base input data' identified on Figure 2. The consequence classification in terms of potential loss of life and/or economic losses is termed the *LLEL classification*.

Evaluation of tailings dam safety from the perspective of environmental impacts, which may be occurring as a result of dam operation on a continuous or intermittent basis, is based on an *acceptable environmental impact.*

Tailings dam safety evaluation requirements are discussed taking into consideration the safety related operating conditions (the *operating attributes*), which vary with the dam operating phase.

Selection of another approach to evaluating tailings dam safety may be necessary in some cases. Legislation in force or some specifics of existing or planned tailings dam operation are the primary factors that could indicate the necessity or advantage of selecting another approach or safety requirement. This Document could then be used as a 'starting point'.

The five thoughts that have led to the preparation of this Document can be summarised as follows:

- The use of experience and/or methods available from the conventional dam engineering for evaluating the safety of tailings dams requires a very careful consideration. Otherwise, it may lead to selecting an improper approach or safety requirement not only because tailings dams are different from conventional dams but, also, because they are more complex.
- It would be best if a consistent approach to tailings dam safety evaluations is followed throughout the mining community (always subject to site-specific considerations). Otherwise, chances are that different tailings dams will be subject to different dam safety evaluation standards, which necessarily means that some tailings dams will be less safe than others.
- For the majority of tailings dams, potential environmental impacts represent by far the most essential safety concern and these should be addressed in a well-defined manner.
- Some conditions directly relevant to dam safety vary throughout the service life of tailings dam to such a degree that these must be explicitly accounted for when specifying dam safety evaluation requirements.
- Designing for tailings dam closure should be carried out to the same standards as designing for tailings disposal (*i.e.*, mine production) phase, to the extent practically possible.

The approach to tailings dams safety evaluations recommended herein is not new, except perhaps for few elements and some specific recommendations. This approach or, at least, the majority of its components have been incorporated into tailings dam safety evaluations by many engineers. The purpose of this Document is to outline this approach in an organised manner and discuss the rationale underlying specific recommendations.

The rationale underlying the various recommendations made with respect to tailings dam safety is intensively discussed throughout the Document, and much of the Commentary is focused on such discussions. The intent here is to explain in detail the reasons based on which the recommendations have been developed. This should help the Reader when contemplating the acceptance of recommendations stated herein, particularly where there is no general agreement on the treatment of a tailings dam safety aspect.

1.7 MOST ESSENTIAL READING

There are hundreds of technical publications addressing various aspects of tailings dams safety, and few tailings dam operators or regulators, or even practising engineers will have the time necessary to take full advantage of the available information, keeping in mind that each of the published findings or recommendations needs be critically reviewed as well as compared and weighted against other publications, and the experience of the tailings dam engineer, operator or regulator.

Nevertheless, there are a number of both comprehensive and issue-specific technical publications of particular importance to tailings dam safety. The most essential among comprehensive publications is still the fundamental book by Steven G. Vick titled 'Planning, Design, and Analysis of Tailings Dams', originally published in 1983 and later reprinted (BiTech Publishers Ltd, 1990).

The ICOLD publications on tailings dams, which invariably include very sound although, in isolated cases, somewhat bias reviews and recommendations, include Bulletins 45, 74, 97, 98, 99, 101, 103, 104 and 106. These publications address the various aspects of design, construction, analysis and safety of tailings dams.

ICOLD Bulletin 106 titled 'A Guide to Tailings Dams and Impoundments – Design, Construction, Use and Rehabilitation' (1996), which replaces Bulletin 45, is perhaps the most comprehensive of the ICOLD documents. It contains a review of the modern practices used in the design and construction of tailings dams.

ICOLD Bulletin 103 titled 'Tailings Dams and Environment. Review and Recommendations' (1996) is of particular relevance to this Document since it puts a strong emphasis on both the environmental and closure aspects of tailings dams safety.

ICOLD Bulletin 74 titled 'Tailings Dams Safety. Guidelines' (1989) specifically addresses tailings dam safety. It complements ICOLD Bulletin 59 titled 'Dams Safety Guidelines' (1987), which addresses the safety of conventional dams, including embankment dams.

USCOLD Committee on Tailings Dams published an important summary document on past failures and other incidents relating to the performance of tailings dams, in 'Tailings Dam Incidents' (1994).

Of the technical literature on conventional dams, the two reports titled 'Safety of Existing Dams – Evaluation and Improvement', National Academy Press, Washington D.C., 1983 and 'Safety of Dams – Flood and Earthquake Criteria', National Academy Press, Washington D.C., 1985 include very comprehensive reviews of the approach and methods used in the conventional dam engineering, as well as the underlying rationale.

Other references are quoted throughout this Document when addressing specific tailings dam safety aspects.

1.8 ABBREVIATIONS AND SELECTED DEFINITIONS

The following are the abbreviations and definitions of selected terms used throughout the Document:

DS	-	dam surveillance
DSI	-	dam safety inspection
DSR	-	dam safety review
CCC	-	consequence classification category
PMF	-	probable maximum flood
PMP	-	probable maximum precipitation
IDF	-	inflow design flood
EDF	-	environmental design flood
MNL	-	maximum normal tailings pond operating level
MPL	-	maximum permissible tailings pond operating level
MCE	-	maximum credible earthquake
MDE	-	maximum design earthquake
AEP	-	annual exceedance probability
RP	-	return period
DI	-	design interval
PEDDI	-	probability of exceedance during design interval [%]
AMD	-	acid mine drainage
RMS	-	runoff management system (refers to the entire mine site)
SCF	-	seepage collection facility operated d/s of tailings dam
WTP	-	water treatment plant

Type I and Type II failures:

Type I and Type II failures refer to structural and performance failures of tailings dams, respectively; in the former case, the failure of tailings dam may result in either environmental impact or loss of life and/or economic losses, or both, while in the latter case, the dam failure may result in environmental impact and, in some cases, health hazard – Table 1

LLEL classification:

classification of dams based on the consequences of potential structural failure of dam in terms of loss of life and/or economic losses, adapted from the conventional dam engineering – Table 2

determinant:

term used to identify a component of environmental impact, with a 'class of determinant' defining the relative weight (severity) of the component – Table 3 impact classification:

classification of tailings dams based on the consequences of potential structural failure of dam in terms of environmental impacts, developed specifically for tailings dams – Table 4

group category:

a consequence group category (Group A or B), which combines the CCCs resulting from the LLEL and impact classifications, defined for the purpose of designating DS/DSI/DSR requirements – Table 5

tailings dam operating phase:

period in the service life of tailings dam during which a characteristic set of operating attributes relevant to dam safety does not significantly change – Table 6

tailings dam safety evaluation requirements:

these include the scopes and frequencies of DS, DSIs and DSRs, as well as the design criteria and other design requirements addressed with reference to typical tailings dam safety evaluation components – Table 7

2 SPECIAL REQUIREMENTS

2.1 PERSONNEL

Except for dam surveillance (DS), the responsibility for each tailings dam safety evaluation should be assumed by a senior professional engineer, whose work should be subject to review by a qualified principal of the organisation carrying out the evaluation.

A dam safety inspection (DSI) may also be carried out by a junior professional engineer under the direction of a senior engineer, provided that the dam was previously inspected by the senior engineer.

The rationale underlying this recommendation is that conducting a DSI typically represents a 'one-time shot' and there would be no opportunity to rectify omissions. Similar recommendation applies to conducting a field inspection/site reconnaissance for the purpose of dam safety review (DSR) or dam design.

When conducting a DSI, there should be no restrictions as to the origin of the engineer in the sense that he/she can be either a retained consulting engineer or engineer employed by the owner. However, conducting a DSI by an owner's employee who resides at the site may have shortcomings since he/she may overlook the obvious and/or might not have the benefit of the 'know-how' and experience available from engineering consulting firms specialising in tailings dams.

DSR should be conducted by a small team of retained tailings dam engineers and other specialists (few, if any, mine owners would have on staff a team of specialists with the training and experience adequate to undertake a DSR).

When conducting a DSR, it would be best if the principal reviewer is not an employee of the engineering firm responsible for the original design and construction of the dam. This would allow for bringing in additional experience and a 'fresh look'. However, a person who participated in the original design and construction of the dam should be included as a member of the review team for the purpose of each DSR, wherever practically possible. His role would be to ensure that all pertinent information is available to the review team (some tailings dams have a long and complex history of design and construction).

It should be recommended to the owner that an owner's representative be a member of the review team. This would ensure that any need for a change to the scope of DSR that may be identified while conducting the review (*e.g.*, the need to carry out an engineering analysis or field investigation) is well understood by the owner. This would also ensure that the owner is well familiar with the detailed aspects of tailings dam safety.

An owner's representative experienced in operating tailings dams should also actively participate in each tailings dam design project. This would allow for better understanding of the safety-related dam operating requirements. As Mr. Vern Coffin of Noranda, after being around tailings dams for some 40 years, remarked on more than one occasion, the designs might turn out to be deficient unless the future operating conditions are well understood at the design stage ("you guys design the dams but it is us, the operators, who will have to operate them"). The importance of designing for practical ('user-friendly') tailings dam operating requirements cannot be overemphasised.

On major tailings dam design projects, it will be beneficial to form a 'design review board' consisting of highly experienced tailings dam engineers independent of the engineering firm responsible for the designs. The primary role of review board would be to ascertain that no 'fatal flaws' exist in respect to the proposed designs, the designs are adequate to meet the project objectives and the state-of-the-art developments in tailings dam engineering have been used *and* properly interpreted.

DS should be implemented by site personnel with guidance provided by the tailings dam engineer.

Site personnel responsible for dam surveillance should have suitable training relevant to tailings dam safety evaluations, including also understanding of the rationale underlying the surveillance requirements.

2.2 BATTERY LIMITS

Unless specifically requested by the owner otherwise, there should be no battery limits with respect to the scope of tailings dam safety evaluation.

The tailings dam safety evaluation program recommended herein is more extensive than those pertaining to the 'conventional' concept of dam safety (*i.e.*, the potential for structural failure of dam), particularly with respect to potential environmental impacts. There may be a reluctance on the owner's part to release environmental monitoring data to the engineer.

If judged necessary or beneficial, the engineer should request the owner's permission to review data and/or inspect facilities which are not directly relevant to the conventional concept of dam safety when carrying out a DSI, DSR or dam design. Such data/facilities may include, for instance, water quality monitoring records or the capacity and efficiency of water treatment plant (WTP). If judged necessary or beneficial, the engineer should also request the owner's permission to take samples for testing of water quality, tailings, dam construction materials, *etc*. (field testing of pH and conductivity may have to be performed as a matter of routine in conjunction with a DSI or DSR).

Nevertheless, the owner may request the engineer to limit a tailings dam evaluation to the conventional aspect of dam safety. The engineer should then inform the owner as to the potential for environmental impact, where applicable.

2.3 CONSTRUCTION SUPERVISION AND QUALITY CONTROL

Adequate construction supervision and quality control should be provided, on a full time basis, on all tailings dam construction projects where common dam construction techniques involving foundation preparation, fill placement and compaction, or geosynthetic installation, are used. These services should be provided by qualified personnel, with background in geotechnical or civil engineering and experience in tailings dam construction. The construction supervision and quality control effort should be commensurate with the complexity of dam design and/or construction. Periodic site visits by the design engineer should become a part of the construction quality control.

Some tailings dams are constructed on a 'continuous' basis over the entire mine production phase. Other (typically embankment type) tailings dams are constructed in several stages, with design adjustments often introduced during the production phase. In all cases, the record keeping and generation of detailed as-built information are essential.

The construction supervision and quality control services are usually provided by an engineering firm on projects involving downstream tailings dams constructed of borrow materials and raised in one or more stages. Keeping detailed construction records and preparation of as-built reports should be the responsibility of the engineering firm.

In the case of a typical upstream tailings dam, providing these services by an engineering firm on a continuous basis would be too expensive, and is not really necessary since the firm would be able to offer little in terms of construction supervision and quality control on a daily basis. In this case, a construction manual should be prepared by the design engineer for use by the tailings dam operator, outlining in detail the tailings deposition plan, step-berm construction requirements, plan for rotating slurry discharge locations, tailings pond management requirements, restrictions on the minimum width of tailings beach, sampling plan for tailings gradation testing, survey requirements, *etc.* Construction manual should become a part of the tailings dam operations manual (Section 7.1). Periodic site visits by the design engineer would be required to check the conformance of construction with the design requirements. These visits might have to be made in addition to conducting DSIs (discussed in Section 8). During foundation preparation or drainage blanket construction works, construction supervision and quality control should be provided on a full time basis.

For centreline and downstream tailings dams constructed using the hydraulic fill method, the construction supervision by an engineering firm may have to be provided on an intermittent basis. Similar to upstream tailings dams, preparation of a construction manual would be required, and the foundation preparation or drainage system construction works should be supervised on a full time basis.

Some owners may prefer to carry out construction supervision and quality control with their own forces. The design engineer may endorse such an arrangement only if he/she is satisfied that the owner's personnel are fully qualified to carry out the work. Even then, it needs be clearly understood that the engineering firm will not be able to assume the full responsibility for this aspect of tailings dam safety. Under such an arrangement, keeping detailed construction records and the preparation of as-built reports would be the responsibility of the owner.

In general, providing construction supervision and quality control by mine personnel is not preferred. This is because it is rare that an engineer or technician employed by the owner would have the training and experience comparable to those of an engineering firm specialising in the design and construction of tailings dams. Moreover, it cannot be excluded that, being an employee of the owner, the site person responsible for construction supervision and quality control would be influenced by the priorities set up with respect to mine production rather than the quality of construction.

The foundation preparation works should be carried out under the supervision of a geotechnical engineer. In this regard, it needs be realised that these works represent a continuation of geotechnical exploration program carried out for the purpose of tailings dam design. Design adjustments introduced based on the observations made during dam foundation preparation are common, and constitute a part of the design process.

Design adjustments must be approved by the design engineer. Implementation of design adjustments approved by the field engineer only would not be acceptable, except for emergencies.

2.4 ENVIRONMENTAL STUDIES

Carrying out an environmental study may be required in conjunction with conducting a DSR or dam design.

Evaluation of baseline or current environmental conditions, or conducting environmental impact assessment (EIA), should be carried out by an environmental scientist with input by the tailings dam engineer.

Engineer's input is essential to the prediction or evaluation of the performance of tailings dam in terms of potential or actual environmental impacts. For instance, the engineer may have to predict the rate of contaminant loadings that would be reporting to the receiver(s), or the size of the area downstream of tailings dam that would be inundated by water and/or tailings solids in the case of dam failure. In other words, the engineer's responsibility would be to define the sources of potential impacts, the pathways, the constituents of potential releases and their magnitudes, as well as the components of the downstream environment that could be affected.

In assessing future conditions downstream of tailings dam, the environmental scientist will often be required to determine an acceptable environmental impact. This determination is necessary for dam safety evaluation purposes, as discussed later in this Document.

2.5 GEOCHEMICAL STUDIES

Similar to environmental studies, a geochemical investigation must constitute an integral part of each tailings dam design project. In many cases, the results of geochemical investigation will form a base for evaluating potential environmental impacts and, consequently, the design of tailings dam. This design aspect has been very significantly advanced over some 30 years in the area of radionuclide and cyanide related contamination and, more recently, the AMD contamination. U.S. Nuclear Regulatory Commission, Canadian National Uranium and Mine Environment Neutral Drainage (MEND) programs as well as other programs and technical conferences resulted in numerous publications directly related to this aspect of tailings dam safety. A comprehensive review of current practices in the area of the geochemistry of mine site waters, with an emphasis on AMD, is provided in the book by K.A. Morin and M. Hutt ('Environmental Geochemistry of Minesite Drainage – Practical Theory and Case Studies', MDAG Publishing, 1997).

Tailings dam engineer will often require input from a geochemist throughout the entire tailings dam design process. In this regard, there are some general issues that need be given special attention. Firstly, the geochemical aspects of tailings dam design are strongly specific to mine sites (and as complex as a tailings dam itself) and significant experience from *mining* projects should be expected from the geochemist. This is still a rare speciality although, it seems, many people without training in geochemistry can nowadays interpret the results of acid base accounting or kinetic testing, which is a 'slippery road'. Secondly, both the geochemist and, particularly, the tailings dam engineer must realise that an *accurate* prediction of future site waters contamination will not be possible in the majority of cases (more so with respect to seepage than overland runoff). This must be taken into consideration when designing a tailings dam. Thirdly, in some cases, it will not be practically possible to complete the geochemical investigation during the initial design stage, and conducting some confirmatory work might be required during the productions phase. This could involve updating geochemical database and the resulting predictions (this is somewhat similar to the design of upstream tailings dam: an on-going input during construction will often be required from the designer).

Input into the designs from an experienced geochemist can be crucial at some tailings dam projects. The classic case is where the engineer, based on the results of acid based accounting testing which indicate a low of ratio of neutralisation to acid generation potentials, concludes that designing for water cover represents the preferred closure option. A geochemist, on the other hand, might show that the contamination of site waters would not be severe. He/she might also suggest other, safer and more economic (than a water cover) solutions to the potential problem. Another classic case is declaring a 'no-problem' situation with respect to AMD because there is sufficient and easily available neutralisation potential. A geochemist, on the other hand, might show that significant contaminant leaching under neutral pHs would occur.

In the case of new mine, the geochemical investigation must start at the outset of the project. The results of examination and testing of the rock (ore and waste rock) samples obtained from the exploration drilling and surface sampling will form a base for the pre-conceptual and conceptual (pre-feasibility) level designs. If required, further geochemical information would be obtained from the testing of pilot plant tailings and, possibly, proposed dam construction materials. Throughout the designs process, the geochemical study may have to be further advanced, and a specific field and laboratory investigation program designed and carried out. This could involve obtaining additional rock, overburden, groundwater and surface water samples, conducting acid base accounting and kinetic testing, mineralogical and petrographic evaluations, geochemical modelling, evaluation of attenuation capacity of dam materials and subsurface strata, *etc*. At the same time, the quality of mill process and mine water as well as other streams that would be reporting/routed to the tailings pond will have to be evaluated. It is only after the geochemical and process water quality predictions are made, the tailings dam designs, which must also incorporate designing for closure, may be finalised. On some projects, the results of geochemical evaluations may dictate the selection of dam site and/or type of dam.

In the case of existing tailings dams with advanced contamination of tailings impoundment waters, the approach to geochemical evaluations may be somewhat different. Besides the geochemical studies mentioned in the preceding paragraph, surface water and groundwater quality surveys will typically form a key design background aspect. The importance of setting up a problem-focused, comprehensive and sufficiently long survey program (contamination of site waters may vary with seasons, weather conditions, *etc*.), as well as the necessity to examine and address each sampling location on both the individual and the overall site basis, cannot be overemphasised.

2.6 TAILINGS DAM MANAGEMENT

Tailings dams are discussed in this Document from the technical perspective. The management of tailings disposal facilities in the sense of managing requirements and management responsibilities, is outside of the scope of this Document. These issues are addressed in a recent publication by the Mining Association of Canada (September, 1998), titled '<u>A Guide to the Management of Tailings Facilities</u>'.

Some practical aspects concerning the management of tailings dams need be emphasised here. As illustrated on Figure 1, there are nine components of tailings dam safety program, and *each* of these components requires quality control that should be provided by the owner. The owner should exercise quality control to ensure that dam surveillance, safety inspections and safety reviews are carried out according to the specified requirements, a qualified consulting engineering firm is selected, the design dam operating procedures are adhered to, *etc*. This quality control aspect refers to the day-to-day tailings dam safety program and appropriate 'management controls' must be set and exercised throughout the service life of tailings dam.

Invariably, the owner will also have to make decisions that fall outside of the day-to-day tailings dam safety program. These may relate, for instance, to the need for carrying out a problem-focused DSR (Section 9) or risk analysis (Appendix A–VIII). These may also relate to the selection of dam safety requirements with respect to potential losses to the owner (Appendix A–IV) or design criteria more stringent than some minimum acceptable criteria (Section 10.9 and Appendix A–XII.7). Again, adequate management controls must be set to allow for appropriate making of such decisions.

Notwithstanding the importance of management controls that need be set at the 'high' (corporate) and the 'low' (tailings area foreman/supervisor) levels, it is the 'intermediate' (say, mill superintendent/mine manager) level at which, in the author's view, the responsibility of the chief quality controller should be assumed. The experience shows that at this level, the time devoted to tailings facility operation is often, albeit not always, surprisingly humble when considering the resulting short and long term liabilities, as compared to those associated with the mill, mine or plant operation. This is perhaps a carry-over from the old times when a tailings disposal operation was viewed a less important part of mining project, as compared with the mill, mine or plant operation. Needless to say, this view is no longer affordable.

The experience also shows that, in some cases, there is either too much or too little reliance on the services provided by the retained tailings dam engineer. An adequate balance needs be found in this regard to get the best out of the perspective, knowledge and experience of both the tailings dam operator and the engineer.

3 TAILINGS DAM FAILURES

3.1 CONSEQUENCES OF TAILINGS DAM FAILURE

The consequence classification method (often referred to as the 'hazard classification' method), which is widely used in the conventional dam engineering, is also well suited for tailings dams when addressing the consequences of potential structural failure of dam (primarily, dam breach). These consequences, relevant to both conventional and tailings dams, are summarised on Figure 3.

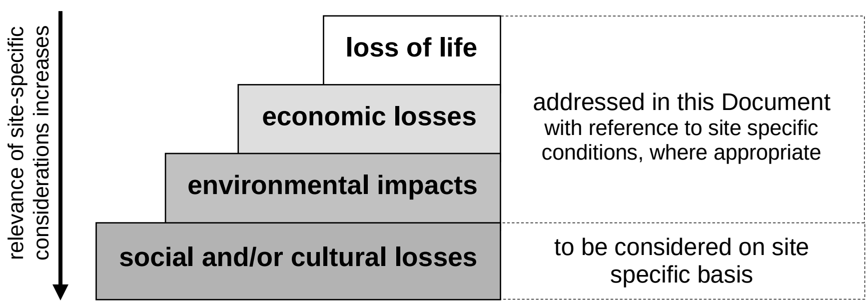


Figure 3
Consequences of Potential Dam Failure

The consequence classification method is used for designating appropriate dam safety evaluation requirements. This method offers a uniform approach to the day-to-day dam safety evaluations that can be used in the majority of situations, always taking into account the dam/site specific conditions.

Consistent with the consequence classification method, the more severe consequences of hypothetical dam failure, the more stringent dam safety evaluation requirements must be selected with regard to both the allowable probability of failure and the effort required to conduct dam safety evaluations throughout the service life of the dam. In general, more stringent dam safety evaluation requirements also mean that the construction and operation of tailings dam will be more expensive, all other factors being equal.

Some discussions on this method are presented in Appendix A–VIII and Appendix A–XVIII under the 'Type I failure – external cause' heading.

At present, there seems to be no alternative to the consequence classification method and the safety evaluations of tailings dams, as related to potential structural failure of dam, have to be carried out based on this method (and other 'base input data' identified on Figure 2).

As indicated on Figure 3, the relevance of site-specific considerations generally varies depending on the type of the consequence of dam failure. For instance, while the 'weight' of a certain number of lives lost must be taken independent of site-specific conditions, the 'weight' of social and/or cultural losses may be strongly site specific. It is essential to notice that environmental impacts are placed relatively high on the site-specific scale. This will be taken into consideration when discussing the consequence classification of tailings dams in terms of environmental impacts (Section 4.2).

3.2 TAILINGS DAM FAILURES – ENVIRONMENTAL IMPACTS

Environmental impacts which may occur immediately following a structural failure of tailings dam and persist over either short or long time, or may occur on an intermittent basis, or the onset of which may be expected to occur in future on a single-event, intermittent or continuous basis, have to be taken into consideration for the purpose of evaluating the safety of tailings dam with respect to the consequences of potential failure.

One of the most significant differences between evaluating the safety of tailings dams in terms of environmental impacts and loss of life and/or economic losses, is the possibility of dam failure occurring without any damage to dam structure that has to be accounted for in the former case. Thus the potential failure of tailings dam with respect to environmental impacts may involve either a structural failure (Type I) or the failure of dam performance (Type II), as outlined in Table 1.

[Note that the terms 'dam failure' in terms of environmental impacts and 'non-compliance' condition are not considered the same, as discussed in Appendix A–V.1.]

The distinction between the structural and performance failures of tailings dams has long been made and accounted for by tailings dam engineers. This is summarised in ICOLD Bulletin 74 where the safety of tailings dams is divided into two items: 'structural stability of dam' and 'environmental safety'. In principle, these items correspond to the Type I and Type II failures, respectively (the terminology used in the ICOLD bulletin may be somewhat confusing since the concept of 'structural stability of dam' must also incorporate the potential for environmental impacts).

Groundwater contamination that may result from either Type I or Type II failure requires special attention. With respect to potential Type I failure, groundwater contamination might result from the release of tailings pond water entering a downstream aquifer or the release of reactive tailings generating contamination which eventually reaches a groundwater flow system.

Table 1

Types of Tailings Dam Failures

(environmental impacts' perspective)

TYPE OF FAILURE	CONTAMINANT RELEASE PATHWAY	RELEASED CONTAMINANT[1]	POSSIBLE CAUSE OF FAILURE (EXAMPLES)[2]
Type I structural failure[3]	· dam breach · top of dam[4]	· **contaminated water** · **solids** · **dam construction materials**	· seismic event or blasting effect · high runoff event (overtopping) · foundation/dam over-stressing · excess pore pressures · slope saturation by infiltration · internal erosion · plugging of d/s slope/filter zone · excessive settlement · freezing of d/s toe of dam · failure of embedded structure · inadequate spillway structure · deterioration of dam construction materials · slope erosion by seepage or overland runoff
Type II performance failure[5,6]	· overflow spillway, decant structure, *etc.* · emergency spillway[7]	· **contaminated water** (supernatant discharge)	· high/low runoff event · change in pond water chemistry · inadequate pumping capacity · error in tailings pond operation
		· **solids** (suspended in water)	· inadequate tailings deposition · high runoff event · high wind event
	· dam · dam foundations · dam slope	· **contaminated water** (seepage or tailings slope overland runoff by-passing dam site and seepage collection facility, if existing)	· low runoff event · change in pond water chemistry · raise in hydraulic head · advancement of contaminated groundwater plume · consumption of attenuation capacity · deterioration of low permeability zone · onset of net acidity generation in dam materials
		· **solids** (rockfill dam)	· inadequate tailings deposition · raise in hydraulic head/ inadequate filter zone
		· **solids** (dam shell constructed of tailings)	· inadequate slope erosion protection (erosion may result from overland runoff, seepage or wind action)
special case: failure of water cover	· overflow spillway · dam · dam foundations	· **contaminated water** (released as seepage or spillway discharge)	· low runoff event · deterioration of low permeability zone · initial flooding

Notes to Table 1:

[1] ‘Solids’ may include reactive or chemically inert tailings, sludge and other contaminants in particulate form contained by tailings dam.

[2] ‘Deterioration of low permeability zone’ has been included under the performance rather than structural failure assuming that no dam breach or significant structural damage would result from deterioration.

Notes to Table 1 (continued):

[3] In the context of this table, structural failure of tailings dam refers to potential environmental impacts. A structural failure of dam must also be considered with respect to potential loss of life and/or economic losses, as well as social/cultural losses.

[4] Since typical tailings dams are susceptible to structural (breach) failure as a result of overtopping, this mode of failure is defined as a Type I failure in the sense of the release of contamination, even though some tailings dams have been overtopped without significant structural damage.

[5] Performance failure is considered from the perspective of potential environmental impacts. A tailings dam may also fail in terms of its performance, without damage to dam structure and without causing significant environmental impacts, from the perspective of economic losses to the owner. For instance, excessive seepage may result in a negative tailings pond water balance as related to process water supply.

[6] Contamination of the surrounding environment by wind-blown tailings is not addressed here since this has no relevance to tailings dam performance, except where the source of tailings is a slope of tailings dam. Similar remarks apply to contamination generated in radioactive (uranium) tailings, except where the tailings pond water exiting as seepage or decant discharge is contaminated with the products of radioactive decay.

[7] Release of contaminated water during a flood in excess of EDF needs not constitute a dam failure (as discussed in Section 10.7 and Appendix A–XIV).

With respect to potential Type II failure, groundwater contamination could be associated, for instance, with seepage bypassing a tailings dam site. In many cases, however, significant groundwater contamination would be associated with the performance of tailings impoundment as a whole rather than tailings dam itself. As pointed out later in Section 6.4, applying common sense and practical approach is necessary to decide if, in those cases, the potential for groundwater contamination should be addressed in conjunction with the tailings dam safety evaluation program.

When considering a Type I failure (primarily, dam breach), the tailings dam safety evaluation requirements with respect to potential environmental impacts will be of the same kind as those with respect to potential loss of life and/or economic losses (*e.g.*, a design flood criterion), and the more stringent requirements must prevail. For instance, while a 1 in 1,000 years design flood might be considered acceptable when addressing potential environmental impacts, selecting a PMF as the design flood could be necessary because of the potential for loss of life.

When examining potential Type II failure, a different kind of dam safety requirement or safety aspect will often have to be considered as compared with potential Type I failure. For example, design events such as a low flow condition in the receiver or the onset of net acidity generation may have to be considered when addressing potential Type II failure. These kinds of events would not be relevant to potential Type I failure (barring such specific dam safety issues as clogging of filters due to chemical precipitation caused by AMD).

In some cases, the same kind of design event may be relevant to both potential Type I and Type II failures. For instance, extreme flood may affect the physical stability of dam by raising the tailings pond level (potential for Type I failure) and cause the release of contaminated tailings pond water through an emergency spillway (potential for Type II failure). Nevertheless, the approaches to selecting appropriate dam safety requirements still would be different, dependent on the type of failure as discussed in the following paragraphs.

The most fundamental difference between the Type I and Type II failures results from the fact that in the latter case, a tailings dam may continue to function satisfactorily, after failing, as a tailings/water retention structure. An important consequence of this is that a tailings dam may fail in the sense of Type II failure on an intermittent, often statistically regular basis. The most typical of such failures would involve intermittent releases of contaminated water through emergency spillway or a low flow condition periodically occurring in the receiver impacted by contaminated seepage. Thus a safety evaluation of tailings dam may have to account not only for the potential occurrence of Type II failure but, also, the frequency of such occurrences.

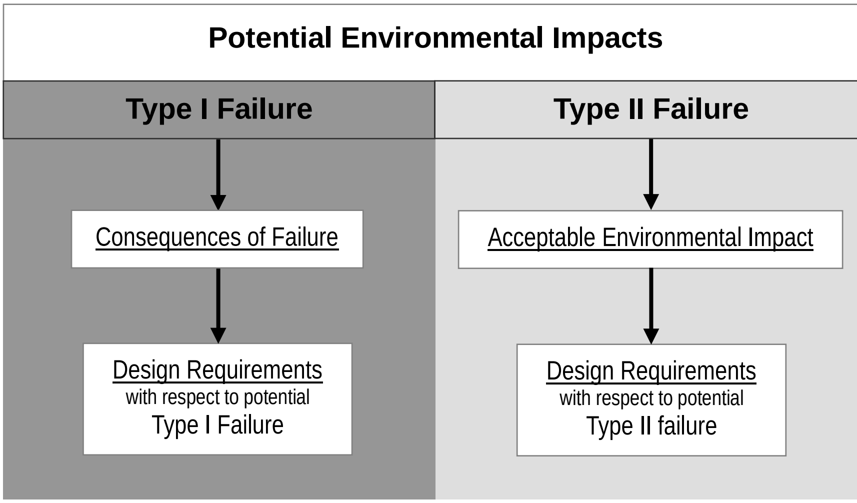
As stated in Section 3.1, the selection of tailings dam safety evaluation requirements with respect to potential Type I (structural) failure should be based on the *consequence classification method*. This means that the required margin of dam safety, the scope and frequency of dam surveillance, safety inspections, safety reviews and, in some cases, the operating effort, must be specified based on the consequences of potential dam failure (and other base input data illustrated on Figure 2).

Selecting tailings dam safety evaluation requirements with respect to potential Type II failure cannot be based on the consequence classification method. This is because the release of contamination through the Type II pathways indicated in Table 1 could be occurring during the life of tailings dam on a continuos or intermittent basis, without causing an adverse environmental impact, which means that the actual impact would be equal to, or less than an *acceptable environmental impact* (the concept of acceptable environmental impact is discussed, from the design perspective, in Appendix A–V.2).

The difference between these two approaches to tailings dam safety evaluations is best seen when considering the design of tailings dams (Figure 4). The design objective with respect to potential Type II failure is to ensure that the *resulting environmental impact is always acceptable*, according to some environmental design criteria. The design objective with respect to potential Type I failure is *to prevent a sudden release of contamination*, with reference to the consequences of structural failure of dam. Therefore, the approach to the design of tailings dams with respect to potential environmental impacts can be summarised as (see Appendix A–II for further discussion in this regard):

> For the purpose of designing a tailings dam with respect to environmental impacts, the selection of design requirements relevant to potential Type I failure should be made based on the consequence classification method. When considering potential Type II failure, this selection should be made based on an acceptable environmental impact.

The design approach outlined on Figure 4 with respect to potential Type II failure has been commonly followed by tailings dam engineers.



For illustration purposes, other input data relevant to selecting design requirements (see Figure 2) are neglected.

Figure 4
Selection of Design Requirements for Tailings Dams
(environmental impacts' perspective)

The design approach with respect to potential Type I failure has often been different. The design criteria were usually selected based on local practice, experience and judgement (sometimes with a reference to design criteria used in the conventional dam engineering) rather than a consequence classification of *tailings dams* derived based on relatively unbiased premises. As a result, passing experience from one site to another was rather difficult, and the selection of tailings dam safety evaluation requirements was influenced by the personal dispositions of the engineer and the regulator, thus resulting in a certain unpredictability of the eventual outcome of dam safety evaluation. Although a complete avoidance of these dispositions will probably be never possible, making the tailings dam safety evaluation process more uniform throughout the mining community and, consequently, having a wide pool of experience available would, in the end, benefit both the mine owners and the public.

4 CONSEQUENCE CLASSIFICATIONS OF TAILINGS DAMS

4.1 LOSS OF LIFE AND ECONOMIC LOSSES

A consequence-based classification developed for conventional dams may be used for classifying tailings dams with respect to potential loss of life and/or economic losses.

A number of consequence-based classifications of dams are available. With few exceptions, these classifications were developed for evaluating the safety of hydroelectric, flood control, water supply, irrigation and similar uncontaminated water retention dams, rather than tailings dams. In spite of this, a consequence-based classification of conventional dams may also be used for evaluating the safety of tailings dams in terms of *potential loss of life and economic losses*. The rationale here is that the significance of hazards resulting from dam operation should be taken independent of the type of industry.

[As recommended in Section 4.3, evaluating the safety of tailings dams in terms of *potential environmental impacts* should not be based on a consequence-based classification of conventional dams. This is not to say that the significance of such impacts should be considered dependent on the type of industry. The rationale here is that potential environmental impacts should be considered separately from potential loss of life (Appendix A–III.4).]

The classification of dams recommended by the Canadian Dam Safety Association (CDSA) in '<u>Dam Safety Guidelines</u>' (CDSA, 1995), referred to as the loss of life and economic losses (the LLEL) classification, is adapted herein for the purpose of classifying tailings dams. Another consequence-based classification of conventional dams could also have been chosen. The CDSA classification has been selected because it reflects well the generally accepted approach to evaluating dam safety (except as pointed out below). It also has some advantages from the tailings dams perspective, as discussed in Appendix A–III.1. A summary of the CDSA classification is presented in Table 2.

According to the CDSA guidelines, potential losses to the owner's property and operation (*e.g.*, loss of dam or power generation) are to be included under 'economic losses' for the purpose of dam classification. This is not a common approach, and is not recommended herein (see discussion in Appendix A–IV).

Contrary to the restriction stated in the CDSA guidelines, the LLEL classification may also be used for designing *new* tailings dams, except where potential environmental impacts are addressed (Sections 4.2 and 4.3). CDSA restricts its use to evaluating the safety of existing dams.

Table 2

Consequence Classification of Dams *, **

CONSEQUENCE CATEGORY	POTENTIAL INCREMENTAL CONSEQUENCES OF FAILURE[a]	
	LOSS OF LIFE	ECONOMIC, SOCIAL, ENVIRONMENTAL
Very High	Large increase expected[b]	Excessive increase in social, economic and/or environmental losses.
High	Some increase expected[b]	Substantial increase in social, economic and/or environmental losses.
Low	No increase expected	Low social, economic and/or environmental losses.
Very Low	No increase	Small dams with minimal social, economic and/or environmental losses. Losses generally limited to the owner's property; damages to other property are acceptable to society.

Notes to Table 2:

[a] Incremental to the impacts which would occur under the same natural conditions (flood, earthquake or other event) but without failure of the dam. The type of consequence (e.g., loss of life, or economic losses) with the highest rating determines which category is assigned to the structure.

[b] The loss-of-life criteria which separate the High and Very High categories may be based on risks which are acceptable or tolerable to society, taken to be 0.001 lives per year for each dam. Consistent with this tolerable societal risk, the minimum criteria for a Very High Consequence dam (PMF and MCE) should result in an annual probability of failure less than 1/100,000.

* This table should be read in conjunction with 'Dam Safety Guidelines' (CDSA, 1995).

** For the purpose of tailings dam safety evaluations, the references to 'environmental losses' made in this classification should be disregarded (see Section 4.3). Although 'social losses' are accounted for in this classification, it is recommended that such losses be considered on a site-specific basis (see Figure 3 in Section 3.1).

4.2 ENVIRONMENTAL IMPACTS

Each tailings dam should be classified with respect to reasonably foreseeable consequences of potential Type I failure in terms of environmental impacts, wherever such impacts are judged non-negligible.

There are a number of determinants that can be used to evaluate the environmental consequences of potential failure of tailings dam. A set of such determinants selected for the purpose of this Document is presented in Table 3. Each determinant has been divided into three classes to reflect its relative severity. Judgement will have to be exercised with reference to the examples given in Table 3 when assigning a determinant class.

Table 3
Selected Determinants for Establishing Consequence Categories in Terms of Potential Environmental Impacts for Tailings Dams

DETERMINANT	RELATIVE RATING	CLASS	EXAMPLES OF ENVIRONMENTAL IMPACTS
A Amount of Impact	large	**A3**	municipal water intake, large amount of biota impacted or large area affected
	moderate	**A2**	
	small	**A1**	few household water intakes, few fish or small area affected
D Duration of Impact	very long	**D3**	hundreds of years – reactive tailings released or slowly recharging aquifer affected
	long	**D2**	years – benthic communities and/or sediment impacted
	short	**D1**	weeks/months – contaminated water released with no long-lasting damage to downstream environment
S Sensitivity of Downstream Environment	very sensitive	**S3**	exceptional value of fish resources, agricultural land use or downstream receiver/aquifer used for domestic water supply
	sensitive	**S2**	
	not very sensitive	**S1**	remote site, small stream or isolated lake with aquatic life of no distinct value
P Public Perception	strong	**P3**	special interest groups involved (lands claimed by aboriginal people or proximity to wilderness park)
	typical	**P2**	no special interest groups, interest of local communities (*e.g.*, municipal water supply or agricultural water use)
	not significant	**P1**	little interest from parties other than regulatory agencies

A consequence classification for tailings dams in terms of potential environmental impacts (the impact classification) has been derived based on the set of the four determinants identified in Table 3. This classification is presented in Table 4.

Table 4
Consequence Classification of Tailings Dams in Terms of Potential Environmental Impacts[1,2]

CONSEQUENCE CLASSIFICATION CATEGORY	POTENTIAL CONSEQUENCES OF FAILURE	CLASSIFYING DETERMINANT GROUPS
High	Severe environmental impact	**I** any combination of two class '3' determinants, except for P3 ***example: A3 + S3*** **II** any combination of a class '3' determinant with one or more determinants in class '2', except for P3 ***example: A3 + (D2 and/or S2)***
Significant	Moderate, or perceived moderate to severe environmental impact	**III** any combination of a class '3' determinant with all other determinants in class '1', except that P2 may be substituted for P1 ***example: D3 + A1 + S1 + P1/P2*** **IV** P3 with any combination of other determinants except as indicated under the High category ***example: A1 + D2 + S2 + P3*** **V** any combination of class '2' and class '1' determinants except as indicated under the Low category ***example: A2 + D2 + S1 + P1***
Low	Low environmental impact	**VI** all determinants in class '1' except that P2 may be substituted for P1 ***i.e., A1 + D1 + S1 + P1/P2***

Notes to Table 4:

[1] Since the significance of the public perception determinant (P) cannot be judged based on either scientific, economic or engineering principles, its weight with regard to classifying a tailings dam may have to be negotiated between the stakeholders.

Notes to Table 4 (continued):

[2] The impact classification is not intended for situations where a tailings dam failure would result in health hazard. References to 'water intake' and 'domestic water supply' made in Table 3 are meant to reflect a potential resource loss rather than health hazard. Where potential for health hazard exists, it should be considered on a site-specific basis.

> Until a generally acceptable consequence classification of tailings dams in terms of potential environmental impacts becomes available, tailings dams may be classified in accordance with the impact classification.

A consequence classification category (CCC) in terms of potential environmental impacts should be established or reviewed/revised in co-operation with professionals other than engineers (*e.g.*, aquatic biologist, terrestrial or water resource scientist).

Where environmental impacts associated with sources other than potential failure of the tailings dam being evaluated are examined, the concept of 'incremental losses', which is commonly used in the conventional dam engineering, needs not apply. This is because environmental impacts will have to be usually addressed in terms of cumulative rather than incremental impacts.

The recommended impact classification outlines a *general framework* within which a typical tailings dam can be classified. It is not intended as a substitute for the experience of the engineer or environmental scientist evaluating the safety of dam, or for the regulatory requirements applicable at the site. Where appropriate, consideration should be given to establishing another set of determinants that may be more suitable with respect to specific conditions of the site and the type of environmental impact being investigated.

Adjustments to the classification recommended in Table 4 may be required in order to account for the specifics of regional environments. This is because the significance of specific environmental impacts may vary from region to region. Considering, for instance, the impact on groundwater quality, its significance would likely be different when addressing a site located in northern Canada, mid-west United States or South America's Altiplano. Any adjustments to the classification presented in Table 4 would also necessitate an examination of the safety evaluation requirements discussed Sections 7 through 10, which are recommended with reference to this table. If necessary, adjustments to these requirements should be made consistent with the intent of this Document.

The impact classification has been designed to provide for a flexibility in assigning appropriate CCCs for tailings dams so that site-specific conditions can always be accounted for. This relates to the fundamental requirement associated with (any) classification of dams in terms of environmental impacts:

> Since a single, distinct denominator adequate for quantifying potential environmental impacts that would result from the failure of *any* tailings dam (such as a number of lives lost or the monetary value of damages to developed properties) does not exist, site-specific conditions must always be carefully considered when classifying a tailings dam.

The clean-up, habitat restoration and similar works, which would have to be carried out following tailings dam failure, are not relevant in the context of tailings dam classification. These works relate to the owner's potential economic losses and cannot be accounted for within the framework of the consequence classification method. In this regard, a tailings dam needs not be classified (see Appendix A–III.3 for relevant discussion).

In developing the impact classification, the primary objective was to derive a simple classification which is: (i) suitable for evaluating the safety of tailings dams, including the selection of design criteria, (ii) consistent with the current dam engineering practice, and (iii) founded on the principles that can readily be understood by the owner, the engineer, the non-specialist regulator and the public.

Throughout this Document, the impact classification is used for:

- In combination with the LLEL classification, recommending the scope and frequency of DS, DSIs and DSRs (Sections 7, 8 and 9).
- Recommending the flood and earthquake design criteria pertaining to potential structural (Type I) failure of tailings dam as well as some other design requirements (Section 10).

As stated at the beginning of this section, the impact classification is intended for addressing potential Type I failure. Although similar considerations would be involved when addressing potential Type II failure (*e.g.*, sensitivity of the receiver or the duration of impact), in this case the design criteria should be selected based on an acceptable environmental impact rather than impact classification, as discussed in Section 3.2 and Appendix A–II.

Further commentary on the impact classification is presented in Appendices A–III.2 - A–III.4.

4.3 APPLICABILITY OF CONSEQUENCE CLASSIFICATIONS

A tailings dam can be classified based on the LLEL classification only if the consequences of potential Type I failure are limited to loss of life or economic losses, or both, and potential environmental impacts are negligible.

When selecting tailings dam safety evaluation requirements with respect to potential loss of life and/or economic losses, it needs be realised that some safety aspects specific to tailings dams are not accounted for in the guidelines developed for conventional dams. Therefore, even if potential environmental impacts are negligible, the safety evaluation requirements stated in those guidelines may have to be adjusted or revised. This has been taken into consideration, where appropriate, in recommending the safety evaluation requirements for tailings dams discussed later in this Document.

For tailings dams, the consequences of potential Type I failure in terms of environmental impacts should be considered *separately* from the consequences of failure in terms of loss of life and/or economic losses. Where potential environmental impacts that would result from tailings dam failure are judged non-negligible, the impact classification should be used in addition to the LLEL classification.

Consequently, the references to environmental losses included in the LLEL classification (Table 2) should be disregarded when classifying a tailings dam, except where potential environmental impacts can be expressed in monetary terms ('tangible' losses). Environmental impacts may then be considered as economic losses, consistent with the approach accepted in the conventional dam engineering.

It follows that CCCs resulting from both classifications will have to be determined for each tailings dam where potential environmental impacts are non-negligible. The CCCs resulting from the two classifications *must not* be compared unless a correlation between these categories is established with a specific purpose, and checked against the consequences of its intended use. [Such a correlation is introduced in the following subsection.]

Tailings dam safety evaluation requirements resulting from the two classifications *must* be compared and the more stringent requirement selected, wherever the same type of requirement is considered (*e.g.*, a design flood criterion).

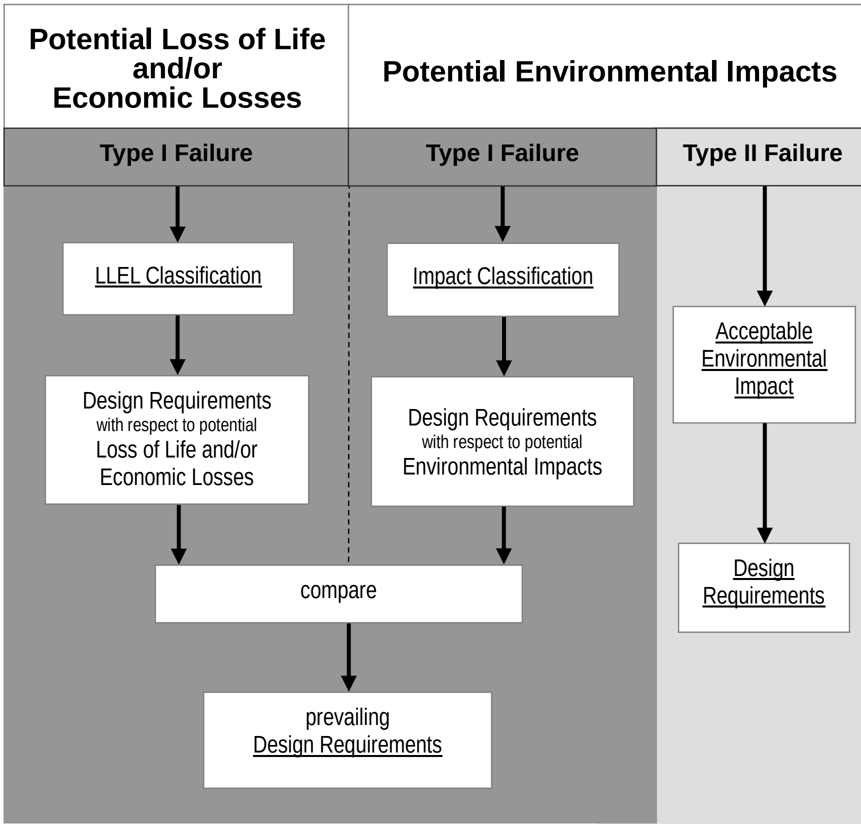
The recommended process for selecting design requirements for tailings dams is illustrated on Figure 5, which also incorporates the process previously outlined on Figure 4.

4.4 A CORRELATION BETWEEN CONSEQUENCE CATEGORIES

For the purpose of tailings dam safety evaluations, it is convenient to establish a correlation between the CCCs in terms of potential environmental impacts and loss of life and/or economic losses. Such a correlation is introduced herein to simplify the designation of DS/DSI/DSR requirements (*i.e.*, the amount of effort required for evaluating the safety of dam throughout its service life). This correlation *is not* intended for specifying design requirements.

With regard to DS/DSI/DSR requirements, it is considered reasonable to define a correlation between the CCCs in terms of potential environmental impacts and loss of life and/or economic losses by drawing a boundary line between the High and Low categories of the LLEL classification and the High and Significant categories of the impact classification, as illustrated in Table 5. The intended use of the correlation is illustrated on Figure 6.

With reference to Table 5, if *either* of the consequence classifications stipulates the Group A category, the dam should be classified in this category. This also means that if *both* consequence classifications stipulate the Group B category, the dam should be classified in the Group B category.



For illustration purposes, other input data that may be relevant to selecting design requirements (Figure 2) are neglected.

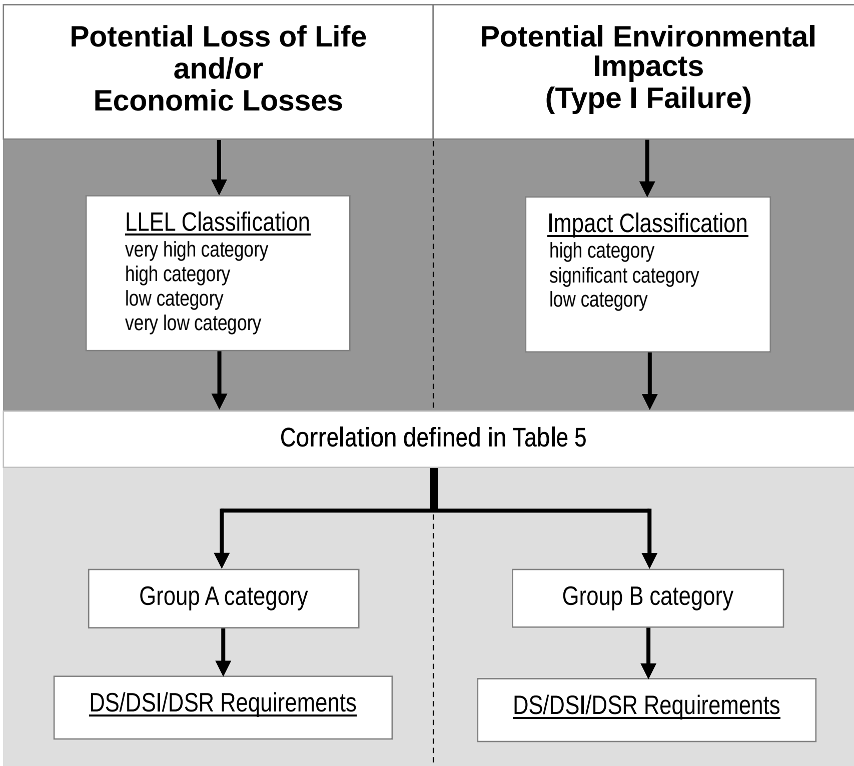
Figure 5
Selection of Design Requirements for Tailings Dams

Table 5
A Correlation between LLEL and Impact Classifications

LLEL CLASSIFICATION	IMPACT CLASSIFICATION	GROUP CATEGORY
Very High High	High	**A**
Low Very Low	Significant Low	**B**

possibility of loss of life → (Very High / High)

boundary line (between A and B)



For illustration purposes, other base input data relevant to selecting DS/DSI/DSR requirements (Figure 2) are neglected.

Figure 6
Selection of DS/DSI/DSR Requirements for Tailings Dams

It follows from Figure 6 that the correlation defined in Table 5 allows for introducing a remarkable simplification into the process of selecting DS/DSI/DSR requirements. This simplification is not only convenient but, also, necessary for practical reasons. Designating DS/DSI/DSR requirements for each of the seven CCCs resulting from the two consequence classifications would neither be practical nor is really necessary.

As emphasised in Table 5, the potential for loss of life constitutes a base of the correlation. However, the potential for loss of life needs not exist for tailings dam to be classified in the Group A category. If a dam is classified in the Very High or High category (LLEL classification), then it must be classified in the Group A category even if the Very High or High category has been designated based on the 'economic losses' criterion only.

A commentary on the Table 5 correlation is presented in Appendix A–VI.

5 TAILINGS DAM OPERATING PHASES

Typical tailings dam operating phases are identified in Table 6. The operating attributes (i) to (ix) represent some of the most essential tailings dam operating aspects, which are directly relevant to tailings dam safety. For instance, while during the production phase the potential for operating errors is significant, adequate dam surveillance can easily be accomplished on a day-to-day basis. On the contrary, during the closure phase there is no potential for operating errors (the dam is no longer operated) while carrying out dam surveillance on an on-going basis would not be viable in typical cases. In general, the set of attributes identified in Table 6 will be different for each of the tailings dam operating phases.

The attribute (ix) is distinctly different from the remaining attributes. It refers to the *length* of an operating phase rather than some physical or operating conditions characteristic of each phase. The significance of this attribute is discussed in Section 10.6 and Appendix A–X.

Where appropriate, the operating attributes characteristic of a tailings dam operating phase must be taken into consideration for the purpose of specifying dam safety evaluation requirements.

Table 6 is not intended for identifying a complete set of operating attributes relevant to tailings dam safety, and it will often be necessary to consider other operating characteristics, which are more site-specific. [For instance, while during Phase 4 no pipelines or decant structures built into the dam would be operated, such facilities are often operated during Phase 1. Another example of an operating attribute is a flood warning system, which must be provided where the potential for loss of life resulting from dam failure exists.] The purpose of presenting Table 6 is to define typical tailings dam operating phases rather than a complete set of safety related attributes.

Evaluation of tailings dam safety carried out at any current or imminent* operating phase must be conducted taking into consideration the anticipated dam safety requirements pertinent to all future phases. The level of detail to which future safety requirements need be addressed should be commensurate with the anticipated activities at the mine site and the time period(s) between the current or imminent phase and future phase(s).

* The term ‘imminent’ refers to the next operating phase for which a tailings dam safety evaluation is being performed.

Any improvements to dam structure or operating procedures that may be recommended following a DSI or DSR should be compatible, to the extent practically possible, with the anticipated dam safety requirements pertinent to future operating phase(s).

Table 6
Typical Tailings Dam Operating Phases
(for tailings dams containing contaminated water)[1]

OPERATING ATTRIBUTES	OPERATING PHASE					
	1 Production		**2** Transition[2]		**3** Long Term Treatment	**4** Closure[6]
	1A dam raised in stages[3]	**1B** dam raised in one stage	**2A** overland runoff treated[4]	**2B** seepage treated[4,5]		
(i) Configuration of Tailings Deposit/Impoundment	varies	varies	possible changes in future	final	possible changes in future	final
(i) Dam in Final Configuration (retrofitted for closure)	no	no (possible 'yes')	no (possible 'yes')	yes	no (possible 'yes')	yes
(iii) Opportunity for Dam Surveillance (by site personnel)	continuous	continuous	periodic or continuous	periodic or continuous	periodic or continuous	none
(iv) Potential for Operating Errors	significant	significant	moderate	none	moderate	none
(v) Potential for Improvements to Dam Structure	very good	some	some	poor	some	poor
(vi) Different. Head / Stresses in Dam & Foundation Increase	yes	yes (possible 'no')	no	no	no	no
(vii) O/F Spillway Operating (pond level uncontrolled)	no	no	no	yes	no	yes
(viii) Degree of Contamination in Tailings Pond & Seepage	often increases, may reach steady state		decreases, may temporarily increase in seepage		decreases, may tempor. increase	negligible
(ix) Duration of Phase (typical 'design interval')	(1-10)[7]	5 to 30	1 to 5	5 to 50	(50 to 200)[8]	500 to 1000

Notes to Table 6:

[1] For tailings dams which do not contain contaminated water, some of the operating phases indicated in this table would not apply. See text for relevant discussion.

[2] Phase 2 refers to the post mining stage where contamination is trapped in tailings deposit, tailings pond and/or groundwater and no new contamination is generated (*e.g.*, the case of residual cyanide or ammonia contamination), as opposite to Phase 3 where contamination is generated in the long term (typically, AMD generation). Phase 3 may also apply to the case where contamination is generated in tailings dam construction materials only, while tailings solids are chemically inert.

Notes to Table 6 (continued):

[3] Some tailings dams may be raised on a continuous basis.

[4] Both overland runoff and seepage may be treated during Phase 2. Phases 2A and 2B are distinguished to emphasise the difference in typical lengths of time (phase durations) required for tailings pond water and seepage to become sufficiently clean for direct release to the environment. Phase 2A is essentially an extension Phase 1 except that significant changes to the tailings pond water balance and site personnel will typically take place following the cessation of tailings disposal operation.

[5] From the perspective of tailings dam structure, Phase 2B is essentially equivalent to Phase 4, except for the presence of site operators and the responsibility for dam safety (province/territory/state would typically become the dam owner during Phase 4 only). Retrofitting of dam to its final configuration in preparation for Phase 4 may, in some cases, be delayed until seepage collection and treatment is completed to defer the expenditure.

[6] During Phase 4, tailings dams are no longer operated. This also applies to Phase 2 where overland runoff is not treated (Phase 2B).

[7] The duration range given for Phase 1A refers to typical stage-raise durations. Typical phase durations are the same as for Phase 1B.

[8] 'Guess' estimate. The actual length of Phase 3 may be of critical importance when selecting the tailings impoundment closure option (Appendix A–XI.4).

The operating phases identified in Table 6 need not be applicable to all existing or planned tailings dam operations. However, all or some of these phases would be applicable to the majority of current tailings dams.

Less common tailings disposal operations involving some sorts of 'tailings dams', such as dry-stacking or deposition of filtered tailings, might require revisions to Table 6, particularly with respect to the 'spillway' attribute.

The layout of Table 6 refers to a typical tailings dam which contains contaminated water. This table is also intended to apply to the situations where only a small or intermittent tailings pond exists (common dam safety evaluation requirements would also apply to these situations).

Phase 1 incorporates tailings dam construction, and may also incorporate the retrofitting of dam for closure. Phases 2 and 3 may incorporate the retrofitting of dam for closure. During Phase 4, tailings dam is at its final configuration, fully retrofitted for closure.

Phase 1 may also incorporate a start-up phase. The significance of this phase would often be related to the storage of mill start-up water. However, the start up phase may also involve other essential dam operation aspects, for instance, the formation of initial tailings beach.

For dams which contain contaminated water but do not contain tailings (*e.g.*, seepage collection pond or contaminated runoff management dams), only Phases 1B and 2 would apply. Such a dam would be breached or removed upon the cessation of mine operation. At that time, the dam might still contain sludge and/or contamination stored in dam materials/subsurface strata. Hence, a transition period could be necessary before the final decommissioning of dam takes place.

For tailings dams which do not contain significantly contaminated water (*i.e.*, tailings pond water is suitable for direct discharge to the environment), only Phases 1 and 4 would typically apply. A decant structure/spillway would usually be operated during the production phase subject to climatic conditions, recycle water requirements and, in some cases, a controlled discharge scheme specified based on some environmental discharge criteria (such a scheme can relate to the dilution available in downstream receiver(s), passive treatment in tailings pond implemented to enhance the natural degradation of cyanide, thio-salts oxidation, *etc*.).

Where tailings solids do not currently generate significant contamination but are expected to generate such contamination in future (typically, as a result of the onset of net acidity generation), some of the operating phases identified in Table 6 may or may not apply. This would primarily depend on the timing of the onset of net acidity generation, the closure scheme and the degree of contamination in tailings impoundment resulting from other sources. Phase 2 would apply in this case regardless of net acidity generation if the process related contamination has been significant and/or dissolution of precipitants causes excessive contamination of tailings impoundment waters (seepage or overland runoff).

Only Phase 1 would apply to a tailings dam designed to cease operating as a dam structure in future, as the tailings impoundment is expanded downstream.

It follows that there is a variety of operating phase combinations and one might conclude that defining typical operating phases for tailings dams is not very practical. This, however, is not the case. The fact is that each of the phases identified in Table 6 has its own characteristics directly relevant to the actual degree of tailings dam safety and safety evaluation requirements. Further discussion in this regard is presented in Appendix A–VII.

[The concepts of 'temporary suspension' and 'state of inactivity' with respect to mine operations have sometimes been used by regulatory agencies for defining the safety requirements for mine sites. From the perspective of tailings dam safety, these mine 'operating' states should be accounted for by identifying appropriate dam operating attributes applicable to any of such states.]

In addition to the dam operating attributes, both the consequence classification categories and acceptable environmental impact, including also general project requirements, must be taken into consideration when specifying safety evaluation requirements for tailings dams. This is illustrated on Figure 2, which outlines a summary of the discussions presented in Sections 3 through 5.

The approach outlined on Figure 2 is illustrated in more detail on Figure 7. The intent of presenting this figure is to indicate which of the base input data will *most significantly* influence the selection of a specific set of tailings dam safety evaluation requirements. Other, less pronounced relations between the base input data and safety evaluation requirements exist.

The distinction between the 'external' and 'internal' causes of tailings dam failure indicated on Figure 7 has been made based on the review of 'possible causes of failure' outlined in Table 1. This distinction allows for emphasising the special meaning of the 'duration of phase' attribute (ix), discussed in Section 10.6 and Appendix A–X.

Tailings Dam Safety Evaluation Requirements			Base Input Data				
			Consequence Classification Categories	Acceptable Environmental Impact	Operating Attributes		General Project Requirements
					(i) – (viii)	(ix)	
DS/DSI/DSR Requirements			✓		✓		✓
Design Requirements	Type I Failure	Cause of Failure: External *e.g.*, flood, earthquake or avalanche event	✓			✓	✓
		Cause of Failure: Internal *e.g.*, internal or slope erosion, foundation or decant failure					✓
	Type II Failure	Cause of Failure: External *e.g.*, flood or low flow condition in the receiver		✓		✓	✓
		Cause of Failure: Internal *e.g.*, change in water chemistry of grout curtain failure					✓

Figure 7
Selection of Tailings Dam Safety Evaluation Requirements from Base Input Data

In general, nothing should influence the selection of tailings dam safety evaluation requirements with respect to potential 'Type I failure – internal cause' and 'Type II failure – internal cause'. Such requirements may include a safety factor, filter design criterion, tailings beach formation technique, employing appropriate method of engineering analysis, adequate geotechnical exploration program or specification for foundation preparation, *etc*. In other words, appropriate engineering design principles, methods and standards must be employed, regardless of the consequence classification category or an operating attribute.

As indicated on Figure 7, each set of safety evaluation requirements may depend on general project requirements (discussed in Section 10.5). This is understandable since, for instance, a regulatory policy or owner's objective may necessitate the selection of a more stringent requirement than could otherwise be allowed for.

A general discussion on tailings dam failures with reference to Figure 7 is presented in Appendix A–XVIII.

6 TAILINGS DAM SAFETY EVALUATION COMPONENTS

The six instances when a tailings dam safety evaluation is conducted have been identified in Section 1.4. The most common components of tailings dam safety evaluations are briefly discussed in the three following subsections. Other components may have to be considered, depending on the specifics of tailings impoundment design and operation.

6.1 CONSEQUENCE CLASSIFICATION CATEGORIES

The CCCs for a new tailings dam should be determined at the initial design stage, based on a *detailed* assessment of the consequences of potential Type I failure.

The first opportunity to examine CCCs for an existing tailings dam will be at the time of next DSI, DSR or designing for stage-raise/closure of the dam.

If no CCCs for existing tailings dam are determined by the time of next DSI, the dam should be classified, on a *preliminary* basis, in conjunction with the DSI. If no CCCs are determined by the time of next safety evaluation involving a DSR or designing for stage-raise/closure of the dam, the dam should be classified based on a *detailed* assessment of the consequences of potential failure at the time of the evaluation.

Input from other professionals (*e.g.*, aquatic biologist or terrestrial resource scientist) will be required to determine a CCC in terms of potential environmental impacts based on a detailed assessment of the consequences of dam failure. When determining a CCC on a preliminary basis, this input would not be required if there is a “clear-cut” case. [A “clear-cut” case could be declared, for instance, where a major dam containing sulphidic tailings is located immediately upstream of a world-famous salmon river or a small tailings dam containing chemically inert tailings and relatively uncontaminated water is situated in a remote area of no distinct environmental, historical or resource value.]

The CCCs should be reviewed, on a *preliminary* basis, at the time of each DSI. A *detailed* review of CCCs will be required in conjunction with conducting a DSR or designing for stage-raise/closure of the dam.

Revisions to CCCs may be required because some conditions downstream of the dam have changed. Other factors that could indicate the need to revise a CCC include, for instance, significant changes in tailings pond water chemistry, ore composition/tailings properties, size of the dam, size and location of tailings pond, or another dam constructed upstream of the tailings dam being evaluated.

6.2 GENERAL AREA OF TAILINGS DAM SITE

Although some of the safety evaluation components discussed in this subsection are not directly related to tailings dam structure, their examination will be required wherever they affect or may affect the dam design, performance or operating requirements.

Review of Legislative Requirements

[May relate to tailings dam design and/or operating requirements.]

All relevant legislative requirements applicable to the tailings dam site should be identified and reviewed in conjunction with carrying out a DSR or dam design. This task should also include the examination of written and/or unwritten policies followed by the regulatory agencies.

A critical review of legislative requirements will be particularly essential in countries/jurisdictions where such requirements are either not well defined or, if applied, would result in dam safety standards inferior to the generally accepted modern standards. Setting up more stringent requirements may then be necessary to ensure that the tailings dam is designed and constructed in accordance with modern practices, and the owner is protected against future changes in legislative requirements that can reasonably be foreseen at the time of dam safety evaluation.

In some cases, a critical review of regulatory requirements may reveal that a requirement is unreasonably stringent with respect to the site specific conditions.

Hydrologic, Seismic and Other External Load Data

[Relate to tailings dam design and operating requirements.]

Meteorological/hydrologic and seismic conditions at the tailings dam site must be determined at the initial design stage. The results of these determinations should be reviewed and, if required, updated when conducting a DSR or designing for stage-raise/closure of the dam.

Other external load data that may have to be investigated include wind or avalanche conditions, stability of tailings impoundment (‘reservoir’) slopes, permafrost, *etc*.

Properties of Dam and Dam Foundation Materials

[Relate primarily to tailings dam design and performance; may affect operating requirements.]

Subsurface conditions, including geotechnical and hydrogeological properties of dam and dam foundation materials, are investigated at the initial design stage. In some cases, additional investigation may have to be carried out for the purpose of conducting a DSR or designing for stage-raise/closure of the dam.

The scope of dam foundation investigation may vary depending on the purpose(s) of the dam and other site-specific conditions. While investigating physical-mechanical parameters and hydraulic conductivities of subsurface soil/rock strata, local and regional geologic-tectonic setting as well as groundwater physical conditions would be necessary for virtually all tailings dams, other types of investigations may be required to address some project specifics. These may include the evaluation of liquefaction potential of dam and/or dam foundation materials, geochemistry and attenuation capacity of subsurface strata and/or dam construction materials, the extent and the degree of contamination of an existing groundwater plume, solubility of soil/rock foundations, *etc.* These aspects should be investigated at the initial-design stage, however, it may also happen that the need to conduct a specific investigation becomes apparent only during the dam operation.

For some existing tailings dams (particularly old or abandoned dams), adequate information on subsurface conditions and/or composition and properties of dam materials might not be available. Carrying out relevant investigation may be necessary for the purpose of conducting a DSR or designing for stage-raise/closure of the dam.

Environmental Conditions

[Relate to tailings dam design and/or operating requirements; may relate to dam performance.]

Environmental studies conducted at the initial design stage will typically include the determination of baseline conditions and environmental impact assessment. Evaluation of current environmental conditions may have to be carried out in conjunction with a DSR or designing for stage-raise/closure of the dam, or as an assignment separate from dam safety evaluations carried out to fulfil a regulatory requirement.

The most common environmental conditions that would have to be investigated include meteorology, hydrology and geology of the site, surficial soils, aquatic and terrestrial habitats, the quality and use of surface water and groundwater, land use in the general dam area, air quality, socio-economics, public perception as well as the examination of developed properties situated downstream and upstream of the dam. Information on these conditions should be reviewed when conducting a DSR or designing for stage-raise/closure of the dam and, if necessary, updated. The existing environmental impacts, if any, should be quantified.

Public perception may present an essential tailings dam design and/or operating aspect. It may vary significantly with time in response to a variety of happenings. This aspect may have to be reviewed for the purpose of conducting a DSR or designing for stage-raise/closure of the dam.

Review of Design, As-built and Monitoring Data

[May relate to tailings dam design, performance monitoring and/or operating requirements.]

Review of background information on the design of tailings dam, including also the information on as-built conditions, is an essential part of each DSI and DSR as well as designing for stage-raise/closure of tailings dam. Identifying relevant information gaps is one of the primary tasks that needs be carried out in conjunction with tailings dam safety evaluations.

Similarly, a review of the monitoring data on dam performance should be included in tailings dam safety evaluations, carried out with the primary purpose of identifying 'unsafe' trends.

Engineering Analyses and Designs

[Relate to tailings dam design, performance and operating requirements.]

Engineering analyses conducted for the purpose of tailings dam design may include the development of tailings deposition plan, deriving water balance and flood routing, liquefaction potential and dam stability analyses, settlement and other deformation analyses, groundwater flow (seepage) modelling, establishing filter design requirements and sizing of filter zones, geochemical and contaminant loadings analyses, *etc*. Tailings dam designs are developed based on the results of these analyses.

At the initial design stage, the selection of dam site and dam type as well as planning for future stage-raises of the dam are included in the engineering analyses. The selection of dam site, dam type and dam construction materials is often made at the conclusion of the pre-feasibility design level (design levels are discussed in Section 10.1).

Detailed designs for tailings dams are developed at the initial design stage and immediately prior to each stage-raise and closure of the dam. In the latter case, the conceptual or feasibility level designs would have been developed at the initial design stage. However, the results of dam safety evaluation carried out at the time of designing for stage-raise/closure of the dam may indicate that those designs need be updated or revised.

In some cases, carrying out engineering analyses and design work may also be required following a DSI or DSR recommendation.

Where new design input data become available (*e.g.*, from mining exploration, past construction observations, new field/laboratory investigations, monitoring of dam performance, enlargement to meteorological or seismic database, or technical publications), these must be accounted for when developing the detailed designs for stage-raise/closure of the dam.

The original methods of engineering analyses should be reviewed and, where necessary, the analyses repeated using the state-of-the-art methods when carrying out a DSR. Engineering analyses using the original methods may have to be repeated for the purpose of DSR or designing for stage-raise/closure of the dam as a result of having either expanded or updated design input data (*e.g.*, seismic database).

As part of DSR or designing for stage-raise of the dam, the tailings deposition plan and schedule for future dam raises should be reviewed and, if necessary, updated or revised.

Dam Structure

[Relates to tailings dam performance; may affect operating requirements and future designs.]

A typical tailings dam comprises zoned or homogeneous structure constructed of earthfill, rockfill or tailings, sometimes including geosynthetics. Tailings dams can be constructed as low permeability (*e.g.*, central or upstream low permeability core with grout curtain), pervious (*e.g.*, 'upstream') or highly pervious (*e.g.*, rockfill with upstream filter zones) structures.

Some tailings dams have very complex structures comprising a variety of materials and irregular zones. This is particularly applicable to older dams constructed over many years, by different owners, with objectives varying in response to new regulatory requirements, new/improved tailings disposal or construction methods, mill process alterations, *etc.*

In the case of upstream and centreline tailings dams constructed entirely or in part of tailings, the dam structure is not well defined on the upstream side and includes a portion of the tailings deposit. Consequently, the tailings deposit becomes a part of dam structure when considering seepage flows, potential for shear failure, liquefaction, internal erosion, development of excess porewater pressures or sinkholes, settlement, *etc.* Hence, this part of tailings deposit must be subject to dam safety evaluation as well. Even for downstream tailings dams, the tailings deposit may have to be subject to a safety evaluation, for instance, where the liquefaction of tailings immediately upstream of the dam would exert a significant, additional force on the dam, or the tailings deposit is designed to form a low permeability zone.

Visual inspection of tailings dam structure is required for the purpose of each safety evaluation carried out after the initial construction.

Field investigation of an existing dam structure in terms of its physical composition may be required as part of a safety evaluation, particularly at older tailings dams where no as-built information is available. Such an investigation may also be required where a specific dam safety aspect needs be addressed (*e.g.*, clogging of a filter zone, change in phreatic surface location, or an unexpected degree of dam seepage contamination).

Tailings dams may incorporate elements built into dam structure which might no longer be active and sometimes forgotten. Abandoned decants and tailings pipes are common. Such elements are directly relevant to tailings dam safety and must be subject to safety evaluation, wherever practically possible.

Discharge Facilities

[Relate to tailings dam design and operating requirements; may affect dam performance.]

Examination of the conditions of existing discharge facility should be a part of each tailings dam safety evaluation (there may be more than one discharge facility associated with a tailings impoundment). The adequacy of existing discharge facility should be confirmed at the time of DSR and designing for stage-raise/closure of the dam.

Where a component of discharge facility is built into dam structure (*e.g.*, embedded decant pipe), potential failure of this component must be considered in relation to potential failure of the dam. [Availability of detailed designs for eventual plugging of decant pipe should be checked in conjunction with conducting a DSI, DSR or dam design.]

Similarly, where the discharge facility incorporates a pipeline (*e.g.*, siphon or water return pipeline) installed over, or build into the dam, potential failure of the pipeline must be considered in relation to the stability of dam structure.

Where the discharge facility is in the form of a pump barge or pumphouse, possible break-downs of this facility and the possibility of power failure will have to be accounted for when evaluating the safety of tailings dam.

Seepage Collection Facilities

[Relate to tailings dam design and performance; may affect operating requirements.]

A seepage collection facility (SCF) may comprise a (seepage and local overland runoff) collection pond and dam, ditch, horizontal drains, subsurface/toe drain or another arrangement. There may be more than one SCF associated with a tailings dam.

From the perspective of intercepting contaminated seepage, SCF should be considered a component of tailings dam in the sense that its design and performance are directly linked to the design and performance of tailings dam. Therefore, an assessment of SCF conditions and performance will be required for the purpose of conducting tailings dam safety evaluation, as related to its ability to intercept and collect contaminated seepage.

Where the SCF is in the form of a collection pond contained by dam, this dam should be considered a structure separate from the tailings dam from the perspective of its structural stability and the ability to retain water. A separate evaluation of the SCF dam should be carried out, typically at the time of tailings dam safety evaluation.

Where the SCF is in the form of a drain or another arrangement the failure of which could affect the structural stability of tailings dam, the drain should be considered a part of the tailings dam structure.

Dam Instrumentation

[Relates to monitoring of dam performance; may affect operating requirements and future designs.]

Typical instrumentation of tailings dam includes piezometers and/or monitoring wells installed downstream or upstream of the dam, or within the dam structure. It may also include inclinometers, settlement plates, flow weirs and survey monuments. For dams located in highly seismic areas, the instrumentation may include seismographs.

Determining tailings dam instrumentation requirements is part of the design work. Instrumentation readings should preferably be taken by the site personnel, if present, with the interpretation and evaluation of the results provided by the tailings dam engineer. The site personnel should have a suitable training in reading dam instrumentation.

Upstream of Dam

[Relates to operating requirements; may affect tailings dam design and/or performance.]

Evaluation of the operating procedures/facilities implemented/located upstream of tailings dam should form a part of dam safety evaluation as far as these procedures/facilities may affect the dam safety. These may include the tailings disposal method, tailings pond operating levels, tailings pond size and location, upstream diversions, *etc.*

The intent of this part of tailings dam safety evaluation is to confirm that the actual operations upstream of tailings dam are in accordance with the design assumptions or, with respect to the initial design stage, to ensure that appropriate operating procedures are specified consistent with dam safety requirements. For instance, an inappropriate tailings disposal method could result in tailings solids overflowing a dam or discharging through spillway/decant structure, reduction in the depth of spillway approach channel, inadequate distribution of (coarse and fine) tailings, *etc.*

A review of the current and/or expected degree of contamination upstream of tailings dam may be required when evaluating the dam safety. For the purpose of DSR or dam design, investigation of the actual and/or potential sources of contamination situated within the dam watershed, or elsewhere within the mine site may be necessary. This could involve a mineralogical evaluation of tailings, ore or waste rock materials, carrying out acid base accounting or leachate tests, geochemical modelling, contaminant loadings analysis, seep survey, examination of mine site facilities containing other contaminant sources, *etc.*

Special evaluations of the conditions upstream of tailings dam may be required where the dam supports a water cover designed to prevent/impede AMD and/or reduce the rate of radiation, or a dry cover is provided over the tailings deposit.

Runoff Management System

[Relates to tailings dam design and operating requirements; may affect dam performance.]

In general, runoff management system (RMS) at a mine site involves intercepting, collecting, routing, temporary storage, recycling, treatment and discharge of overland runoff and/or groundwater. The concept of RMS, as used herein, refers to the entire mine site and includes the management of process, mine, domestic, mill site or waste rock dump/yard/road runoff, and other waters.

Management of tailings pond often represents a component of RMS. In this case, RMS directly relates to the operation of tailings dam and should be examined in conjunction with each DSR or dam design. The rationale here is that the engineer responsible for dam safety evaluation will need to confirm that the design tailings pond storage capacities and operating levels are also adequate from the perspective of the entire RMS, and the degree of tailings pond water contamination would yield no surprises.

Evaluation of the performance of WTP, where such a plant is a component of RMS, would not be included in tailings dam safety evaluations. However, the knowledge of WTP influent quality, operating schedule and the capacity of WTP would be necessary for evaluating tailings dam safety, wherever the WTP influent stream represents a component of the tailings impoundment water balance. Information on the quality of WTP effluent would be required for evaluating the potential for Type II failure where tailings dam seepage and/or overflow report, or would report to the same receiver as the WTP effluent.

Similarly, evaluation of the components of RMS located outside of the tailings dam watershed (*e.g.*, mine workings and mine water pumping facility, or a waste rock dump watershed) would not be included in tailings dam safety evaluation. However, the knowledge of relevant pumping capacities would be required when deriving the tailings impoundment water balance or conducting flood routing computations.

The above represents an essential consideration. It means that the indirect components of tailings pond water balance would not be evaluated under the tailings dam safety evaluation program and the associated requirements taken ‘for granted’.

It would be best if the designs of RMS and tailings impoundment are carried out under the same project. Should these designs be handled under different projects, the tailings dam engineer would typically need the following information generated from the RMS design project:

- overall site water balance presented, as a minimum, on a monthly basis;
- stream flows routed to and/or discharging from the tailings pond, preferably on a daily basis, under normal and extreme flood/draught conditions;
- chemistries of the various streams reporting to tailings pond (may vary with time and/or seasons);
- the intended use of tailings pond for partial or complete passive treatment, including the associated design criteria, where applicable;

- capacity of WTP, including operating schedule and discharge constraints, if any;
- environmental design criteria for tailings pond water discharge (overflow discharge and/or dam seepage).

This information would be used for setting up the design criteria for tailings dam, deriving tailings pond water balance, developing dam raising schedule, establishing adequate tailings pond operating levels, designing seepage reduction measures, *etc*., as well as for conducting DSRs.

Downstream of Dam

[Relates to tailings dam performance; may affect operating requirements and future designs.]

The pre-mine conditions downstream of tailings dam would be determined at the initial design stage, under the environmental baseline study. Where the potential for a Type II failure exists, inspection of the conditions downstream of tailings dam, *i.e.*, beyond the area immediately adjacent to the downstream toe of the dam, should be incorporated into each DSI, DSR and designing for stage-raise/closure of the dam.

Past Performance and Failures of Dam

[Relate to tailings dam performance; may affect operating requirements and future designs.]

For the purpose of conducting a DSI, DSR or designing for stage-raise/closure, having information on the past performance of tailings dam is essential. This could be available from the field inspection, instrumentation readings or discussions with the site personnel. Particularly valuable information would be that related to the dam performance under maximum past loading conditions or deterioration forces (maximum tailings pond level, peak flow, earthquake, extreme rainfall and/or snowmelt, *etc*.).

Observations of the conditions downstream of tailings dam as well as relevant information obtained from the owner may allow for determining if the dam failed in the recent or distant past in the sense of Type II failure. It may also be necessary to determine if the dam has ever failed in the sense of Type I failure. For instance, tailings deposited downstream of dam or vegetation kills may be indicative of past failures, either in the sense of Type I or Type II failure.

Compliance with Regulatory Requirements

[Relates to tailings dam performance; may affect operating requirements and future designs.]

A review of the flow and water quality data with respect to regulatory compliance may be necessary in conjunction with carrying out a DSI, DSR or designing for stage-raise/closure. In most cases, the owner would conduct such reviews on an 'on-going' basis (the engineer should be kept updated on the results of these reviews). Nevertheless, the engineer still may have to review the data searching for trends or examining parameters which are not subject to the on-going reviews, even though he/she is not a qualified water quality specialist (input from a water quality specialist would be required in many cases).

Other (than water quality) compliance aspects relating to tailings dam safety may include, for instance, dam operating requirements such as maintaining a minimum freeboard or the schedule and rates of tailings pond water discharge. These should be reviewed by the engineer as well.

Preparation/Reviews of Tailings Dam Operations Manual

[Relates to tailings dam surveillance and conformance of operating procedures with the design assumptions; may relate to dam construction requirements.]

A tailings dam operations manual should be prepared at the initial design stage and reviewed in conjunction with conducting a DSR or designing for stage-raise/closure of the dam. It should also be reviewed and, if necessary, updated or revised whenever a significant change to the tailings dam operating conditions is planned.

The contents of tailings dam operations manual will be strongly site-specific. Typical tailings dam safety aspects that should be addressed in the operations manuals are discussed in Section 7.1.

Spill Control Measures – Pipelines

The performance of spill control measures associated with pipelines would not typically relate to the performance of tailings dam. If a contaminated water pipeline is installed over, or built into the dam structure, it should be addressed under the 'Dam Structure' component. If such a pipeline is located within the tailings dam watershed, the pipeline performance may have to be addressed under the 'Upstream of Dam' component.

Spill control measures represent an essential part of the environmental protection program and the owner may consider advantageous to incorporate a safety evaluation of spill control measures into the tailings dam safety evaluation program (failure of a contaminated water pipeline may result in an impact similar to Type II failure).

6.3 OTHER DAMS

Another dam (*e.g.*, an internal water/tailings retention dam or runoff/watercourse diversion dam) may exist upstream of the *tailings dam* for which a safety evaluation is carried out.

Where another dam exists upstream of tailings dam and its failure could affect the tailings dam performance, a separate safety evaluation of the other dam should be carried out concurrently with the tailings dam safety evaluation.

The consequences of potential failure of the tailings dam should be determined taking into consideration potential failure of the other dam. A failure of the tailings dam could occur as a result of a failure of the other dam due to a flood or earthquake event less severe than the design event selected for the tailings dam, where a failure of the other dam was not considered in the tailings dam design. Such a failure could also result from an independent cause/event, for instance, a foundation failure or static liquefaction at the other dam.

Failure of a dam located upstream of the tailings dam could result in a sudden release of water, liquefied tailings, or both, thus placing an additional load on the tailings dam (potential for Type I failure). It might also result in an unacceptable release of tailings pond water and/or tailings solids via spillway/decant structure (potential for Type II failure).

In some cases, the failure of tailings dam being evaluated could result in a failure of an internal dam. Where applicable, this should be taken into consideration when examining the consequences of potential failure of tailings dam.

Similar remarks apply to runoff/watercourse diversion ditches or pipelines situated upstream of tailings dam.

6.4 SAFETY EVALUATION COMPONENTS – SUMMARY

The typical components of tailings dam safety evaluation are summarised in Table 7. Some of these components need not apply to all tailings dams.

The level of detail to which a component of dam safety evaluation should be addressed may vary depending whether the evaluation is carried out for the purpose of DS, DSI, DSR or dam design.

It follows from Table 7 that similar sets of safety evaluation components need be addressed when conducting a DSR and designing for stage-raise/closure of tailings dam. Designing for stage-raise/closure is considered equivalent to a 'DSR + the detailed design work'. If a DSR was carried out recently, no tailings dam safety evaluation would be required in conjunction with designing for stage-raise/closure. Conversely, there would be no need to carry out a DSR if the dam was recently designed for stage-raise or closure (see also Section 9.2).

The overall objectives of DSR and designing for stage-raise/closure of tailings dam are different. While a DSR is conducted with the primary objective of addressing tailings dam safety with respect to the *current* operating stage/phase, designing for stage-raise/closure is carried out with respect to the *next* operating stage/phase. From another perspective: while the purpose of a DSR is to ascertain that an existing tailings dam has adequate margin of safety, designing for stage-raise/closure is carried out with the purpose of 'moving' a dam into the next operating stage/phase.

Table 7
Components of Tailings Dam Safety Evaluations

COMPONENT	DS	DSI	DSR	DESIGNING FOR	
				new dam	raise/closure
Establishing CCCs		✓ [1]	✓ [2]	✓ [3]	✓[2]
Review of CCCs Established Previously		✓ [1]	✓[4]	n/a	✓[4]
Review of Legislative Requirements			✓	✓	✓
Hydrologic, Seismic & Other External Load Data			Review [5]	✓	review [5]
Properties of Dam and Dam Foundation Materials			Review [5]	✓	review [5]
Environmental Conditions			Review [5]	✓	review [5]
Review of Design, As-built and Monitoring Data		limited	✓	n/a	✓
Engineering Analyses and Designs			Review[6]	✓	review[7]
Dam Structure	✓	✓	✓	incl. in design	✓
Discharge Facilities	✓	✓	✓	incl. in design	✓
Seepage Collection Facilities	limited	limited	✓	incl. in design	✓
Dam Instrumentation[8]	✓	limited	✓	incl. in design	✓
Upstream of Dam	limited	limited	✓	✓	✓
Runoff Management System			✓	✓[9]	✓
Downstream of Dam		✓	✓	baseline	✓
Past Performance and Failures of Dam		✓	✓	n/a	✓
Compliance with Regulatory Requirements		limited	✓	incl. in design	✓
Preparation/Review of Dam Operations Manual		limited	✓[10]	✓	✓[10]
Other Dams	✓	✓	✓	✓[9]	✓

Notes to Table 7:

[1] On a preliminary basis.

[2] If required, based on detailed assessment of the consequences of failure.

[3] Based on detailed assessment of the consequences of failure.

[4] Revision to CCCs may be required based on detailed assessment of the consequences of failure.

[5] Upon review, field investigation and/or obtaining additional design information may be required.

[6] Upon review, analyses may have to be repeated using updated methods and/or design input data.

[7] Prior to construction, a review of the designs will be required with reference to the results of dam safety evaluation even if the detailed designs for stage raise/closure of the dam were developed earlier, *e.g.*, at the initial design stage.

[8] Reading and on-going evaluation of working conditions as well as maintenance of dam instrumentation should be the responsibility of site personnel. The engineer conducting a DSI should observe the working conditions only. Carrying out a DSR or dam design should involve confirmation of the adequacy of dam instrumentation.

[9] Designing for these components is often included in the tailings dam design project. If not, such designs must be completed and available for evaluating tailings dam safety at the design stage.

[10] Review and updating, if necessary, are required.

The components of tailings dam safety evaluations summarised in Table 7 are not meant to be exhaustive. Depending on site-specific conditions, other components may have to be added.

A certain difficulty might arise when delineating an appropriate ‘boundary’ for tailings dam safety evaluations. Few engineers would disagree that a failure of grout curtain, as related to the release of contamination via seepage, is directly related to tailings dam safety. On the other hand, a failure of plastic liner at a location away from the dam where the entire impoundment is lined, resulting in a significant contamination of groundwater, might be difficult for some engineers to accept as a ‘tailings dam failure’, even if the flowpath extends under the dam. In this regard, common sense and practical approach need be applied when delineating an appropriate ‘boundary’ for tailings dam safety evaluations at each site.

6.5 MONITORING OF TAILINGS DAM PERFORMANCE

Monitoring requirements for tailings dams are discussed in depth in ICOLD Bulletin 104 titled ‘Monitoring of Tailings Dams’ (1996). Typical dam instrumentation is described, for instance, in ‘Embankment Dam Instrumentation Manual’, United States Department of the Interior, Bureau of Reclamation, 1987.

Monitoring of tailings dam may be carried out for various purposes. Most commonly, dam monitoring is carried out with the purpose of identifying unsafe conditions/trends (‘warning signs’), confirming the design predictions and/or assumptions, or evaluating the actual performance of dam. The purpose of each component of the monitoring program should be clearly stated in the tailings dam operations manual (Section 7.1).

From the perspective of potential Type II failure, the results of monitoring of downstream receiver(s) may have to be analysed when evaluating the performance of tailings dam. Data on water quality in the receiver(s) will often be available from the background and compliance locations, however, these might not be sufficient for evaluating the safety/performance of tailings dam and additional sampling location(s) may have to be established.

Monitoring database should be updated and frequently reviewed by the site personnel. The tailings dam engineer should assist the site personnel in setting up the review requirements. The database should be kept in a spreadsheet or similar format, which permits an immediate analysis of trends. The results of monitoring should be plotted against time scale and other reference data (*e.g.*, piezometric against tailings pond levels, inclinometer data against dam height and tailings pond level, flows against precipitation and temperature, or water quality in downstream wells against tailings pond water quality and levels).

Frequency of the reviews will depend on the type of data and the purpose of monitoring, and should be specified by the tailings dam engineer. Typically, the frequency should not be less than on a quarterly basis. The reviews should be recorded and a copy of each record submitted to the engineer, who should also analyse the data in conjunction with each DSI.

In case of an unusual reading, the engineer should immediately be informed. It should be up to the engineer to define 'unusual' readings. For this purpose, he/she would often require input from an environmental scientist and/or geochemist.

6.6 SCOPES AND FREQUENCIES OF DS, DSIS AND DSRS

In the following three sections, recommendations are given with respect to the scopes and frequencies of DS, DSIs and DSRs.

The recommendations on the scopes of DS, DSIs and DSRs are rather generic. An effort has been made to provide a reasonably comprehensive outline of DS/DSI/DSR requirements, nevertheless, these must be set up in detail on a site-specific basis.

The recommendations on the frequencies of DS, DSIs and DSRs are intended to reflect reasonable minimum requirements. Other than common sense, experience and the understanding of how a tailings dam 'works', there is little rationale based on which the frequency of DS, DSIs or DSRs can be specified.

A frequency may be specified based on a day/night shift and this reflects the need for an 'on-going' surveillance of tailings dam. If a frequency is specified on a weekly basis, it does not mean that there is something special about 7 days from the perspective of tailings dam performance. Weekly frequency refers to a certain convenience and implementation rigour associated with the weekly routine (on Tuesdays I have the safety meetings, while on Thursdays I must walk the dam). On the other hand, there may be something special about the 365-day period underlying the annual inspection requirement. This has to do with the seasons and associated 'seasonal' loads on the dam (in some climates, the concept of seasonal loads might not apply well). Finally, 'every several years' (say, every 5–15 years) frequency would be associated with a time period during which: (i) long term dam performance record becomes available, (ii) meteorological, hydrologic or seismic database could be significantly enlarged, (iii) significant progress in the tailings dam engineering and/or associated sciences can be expected, and (iv) changes in regulatory requirements could be anticipated.

7 SURVEILLANCE OF TAILINGS DAMS

7.1 SCOPE

The intent of DS is to make ‘on-going’ observations relating to the conditions and performance of tailings dam structure and associated facilities (tailings pond discharge and diversion structures, pipelines, dam instrumentation, *etc.*), as well as tailings disposal and tailings pond management operations, so that any changes to dam conditions or performance, or a hazardous condition can be identified and promptly addressed.

Surveillance of tailings dam should be carried out by the mine personnel, whenever present at the site. The owner should be made aware of the importance of site personnel contributions to dam safety.

Detailed scope and frequency of DS walk-overs should be discussed between the tailings dam engineer and the owner. The engineer should make relevant recommendations, including developing a DS program or specifying revisions to existing program (if necessary). Conducting a simplified risk analysis for existing tailings dam in the from of a workshop may be useful to determine the necessary scope and frequency of DS walk-overs (Appendix A–VIII), particularly for dams where complex operating procedures are implemented.

DS program should be outlined in a *tailings dam operations manual* comprising one or more independent ‘sections’, with each page/figure having clearly marked revision date. As a minimum, the manual should contain information on:

- organisational matters relating to the responsibility for dam safety and management, including the administration/updating of the manual;
- detailed scope and frequency of DS walk-overs, including the underlying rationale and the format of surveillance reports;
- outline of tailings deposition plan, including its relevance to dam safety, immediate objectives and closure design (closure plan) requirements;
- design tailings pond operating levels and their relevance to dam safety;
- potential modes of dam failure and relevant warning signs, if any;
- emergency action plan in case of an incident that affected, or could affect dam safety (partial slope failure, unusually high tailings pond level, *etc.*);
- emergency response plan in case of dam breach;
- dam instrumentation, including the purpose(s) of monitoring;

- definitions of 'unusual' instrument readings, loading and other events;
- dam safety aspects that need be monitored but cannot be addressed by walk-overs or dam instrumentation readings (*e.g.*, monitoring of weather conditions or environmental monitoring);
- other dam operating requirements and a list of fundamental design criteria (*e.g.*, routine maintenance of dam, schedule for dam raising, the use of stoplogs in decant structure, start-up time for seasonal water treatment, minimum tailings beach width, flood design criteria, critical phreatic surface location, or maximum permissible excess pore pressures).

A tailings dam operations manual should also include:

- a complete list of engineering and environmental reports as well as other documents relevant to the design, construction, monitoring, maintenance, safety improvements, safety inspections and reviews, surveillance, permitting and performance of tailings dam;
- construction manual in case of dam constructed by mine forces (design drawings, specifications and supervision/quality control requirements).

It follows that the approach advocated herein is to incorporate both dam surveillance and operating requirements (dam safety aspects I and IX identified in Section 1.4) into one tailings dam operations manual. This would allow for the person directly responsible for dam surveillance having a more comprehensive understanding of dam safety, for which another person may be ultimately responsible (*e.g.*, mill superintendent or environmental supervisor). Each new person responsible for dam surveillance should become thoroughly familiar with the relevant parts of tailings dam operations manual, as well as become aware of the importance of dam surveillance.

In setting up a DS program, it needs be recognised that the personnel directly responsible for conducting DS will not typically have the training and experience of a tailings dam engineer (often, a person with background in mining, milling, plant engineering or environmental sciences is made responsible for dam surveillance). Care must be exercised when preparing a tailings dam operations manual to ensure that the personnel responsible for dam surveillance know not only what to do but, also, why it needs be done.

Frequent visual inspections of tailings dam and associated facilities, including diversion facilities (where existing), form the base of dam surveillance.

Under typical conditions, dam surveillance would involve a walk-over to observe potential changes to dam structure. These may include, for instance, evidence of slope deformation, crest settlement, cracking, slope and/or toe erosion, condition of rip-rap, dam seepage in terms of quantity, discoloration and clarity, including also a visual inspection of discharge facility(ies). [In 1997, a tailings dam was overtopped in southern Spain following a heavy rain, most likely as a result of partial blockage of emergency spillway.]

DS should also include inspecting the tailings disposal and tailings pond management operations, including making observations of the tailings pond level and active beach configuration as well as the location of tailings slurry discharge. [In 1996 in Eastern Canada, a tailings beach was permitted to raise, unnoticed, to the top of an internal dam containing large pond, and the flow of tailings slurry overtopped the dam.]

Site-specific conditions must carefully be considered when specifying the frequency of DS walk-overs. For instance, this frequency may have to be increased during the spring freshet (*e.g.*, in Canada) or rainy season (in the tropics). When freezing of tailings pond or ice formation/snow accumulation may result in a hazardous condition, the spillway/decant structure surveillance frequency may have to be increased in winter. [In 1989 in Quebec, a section of internal tailings dam and associated overflow spillway were washed-out as a result of ice blockage of the spillway inlet, which occurred following a temporary suspension of tailings slurry discharge (and dam surveillance).]

An overflow spillway and/or decant structure should be inspected by site personnel *during* each heavy rainfall and spring freshet where the potential for brush/debris accumulation or erosion exists. Under Canadian and similar conditions, a tailings pond spillway or runoff/watercourse diversion facility may have to be frequently inspected in areas of beaver activity. [The well publicised 1990 failure of the Matachewan tailings dam in Ontario was the result of a beaver constructed dam.]

Special attention should be paid to pipelines and other structures laid over or embedded in dam structure, noting that tailings pond water may be corrosive. [In 1993, a CSP decant pipe embedded in tailings dam failed at a mine site in Ontario, resulting in a critical condition. The pipe failed because the tailings pond 'turned acid' upon the suspension of mill operation.]

Where blasting can affect a component of tailings disposal facility (*e.g.*, dam structure, tailings deposit or discharge facility), dam surveillance may have to include the monitoring of ground accelerations.

Where underground workings are located under the tailings dam, DS may have to involve monitoring of both blasting effects and the mining progress. [In 1991 at a mine site in Quebec, a sedimentation pond dam failed, and a large pond was emptied, as a result of a blast in the underground workings advanced under the dam.]

Special considerations may have to apply to the monitoring of dam seepage where the potential for clogging of filter zone or internal erosion exists (these types of considerations should be addressed in close co-operation with the tailings dam engineer).

Monitoring of weather conditions (*e.g.*, cumulative depth of precipitation or depth of snowpack) should be carried out in conjunction with carrying out DS for many tailings dams.

DS should also include reading the dam instrumentation (piezometers, flow weirs, monitoring wells, *etc.*) and observing its working conditions. The frequency of readings should be specified by the tailings dam engineer. The results should be compiled, preferably in the format that would facilitate interpretation of trends, reviewed on a regular basis and made available to the tailings dam engineer (see Section 6.5).

Any unusual occurrences relevant to tailings dam physical and/or operating conditions noted in conjunction with DS (or otherwise) should immediately be reported to the tailings dam engineer.

The requirements for records keeping, schedule, scope, frequency of walk-overs, emergency action plan, communication with the engineer, *etc.*, relevant to tailings dam surveillance and operation should be reviewed from time to time, as a minimum at the time of each DSR and designing for stage-raise/closure of the dam.

The DS requirements stated above are not intended to be complete or generally applicable. These requirements, similar to the requirements of any other component of tailings dam safety evaluation program, are strongly site-specific and it will be up to the tailings dam engineer to specify adequate requirements for each tailings dam.

7.2 FREQUENCY

DS may be carried out on either regular or irregular basis, depending on the dam operating phase.

During the production phase (Phase 1), regular surveillance of tailings dam can easily be accomplished and should be implemented. The primary objective of DS during this phase is to observe possible changes in the performance of tailings dam and discharge structure conditions, and confirm that the tailings disposal operation and pond water management are in accordance with the design requirements. Additional dam surveillance walk-overs should be conducted following any unusual event, as well as during any unusual activities in the dam area that could affect dam performance (*e.g.*, during construction in the dam area or blasting in nearby mine workings).

As a ‘rule of thumb’, weekly or biweekly DS walk-overs should be carried out during the production phase for a typical tailings dam classified in the Group A or B category, respectively, under normal operating and weather conditions. More frequent walk-overs would be required during dam construction (*e.g.*, when a step-berm is being constructed for the raising of upstream tailings dam).

The above requirements refer to ‘formal’ DS walk-overs, which should be documented. Additional tailings site surveillance may have to be performed on a more frequent basis, for instance, where active pipelines are located over easily erodible dam crest and/or slope (these should be inspected *at least* once during each day and night shift), tailings pond level is frequently regulated using stop-logs, or tailings pond discharge rate is controlled based on pH and/or other parameters.

Daily walk-overs during Phase 1 may be required where particularly hazardous conditions exist (*e.g.*, at upstream tailings dam where significant slope erosion is taking place, large and frequent fluctuations in tailings pond level occur, the pond is close to the crest of dam, or the level of active tailings beach is close to a maximum design elevation). The scope of daily surveillance, if required, should be kept to a minimum, with the 'formal' surveillance conducted on a less frequent basis.

During Phases 2A and 3, tailings pond still is operated and its level typically regulated. The primary objective of dam surveillance during these phases is to confirm that the tailings pond is operated in accordance with the design requirements, no dam deformation or erosion has occurred, and the emergency/overflow discharge structure as well as dam instrumentation are in good working conditions. During these phases, the frequency of walk-overs may be less than during the production phase.

Where the WTP operating personnel or site security are present at the site during Phases 2A or 3, or where the site is located close to a populated area, regular dam surveillance may easily be accomplished and should be implemented (the surveillance personnel should be familiar with the relevant parts of tailings dam operations manual).

Where no operating/site security personnel are present at the site on a continuos basis during Phase 2A or 3, the frequency of DS walk-overs should be specified consistent with the WTP operating/maintenance schedule. Supplementary dam surveillance walk-overs may be required, particularly for tailings dams in the Group A category (these would be *necessary* where the potential for loss of life exists). The need for, the scope and the frequency of supplementary walk-overs should be identified/specified by the tailings dam engineer.

Fully automated WTPs are becoming common. Where such a plant is operated from a distant location ('operating centre') during Phase 2A or 3, direct DS should be implemented in conjunction with the inspection/maintenance of the WTP. Remote DS, which may involve remote monitoring of tailings pond levels and a surveillance camera showing the spillway, both sending information to the operating centre, should then be implemented, particularly for tailings dams classified in the Group A category.

For tailings dams during Phase 2B, DS should be conducted, as a minimum, in conjunction with the operation and maintenance of the SCF/WTP, even if the tailings dam is retrofitted for closure, that is, the tailings pond is no longer operated and permanent spillway(s) have been provided. For dams in the Group A category, remote DS and/or additional direct DS may be required (see the preceding paragraphs).

The DS requirements discussed above would not apply to tailings dams during Phase 4. During this phase, the responsibility for dam safety would be taken over by a regulatory agency. The dam safety evaluation program would consist of DSIs and DSRs. Tailings dam walk-overs or remote surveillance, where required, would then become a part of the DSI program.

7.3 REPORTING

Records of DS observations should be kept at the mine site and made available to the tailings dam engineer on a regular basis (as a minimum, immediately prior to each DSI). These records should be in the form of standard surveillance reports such as, although significantly less comprehensive than the sample forms for DSI reporting attached in Appendix B.

Where the tailings dam walk-overs are conducted by site security personnel (typically at nights and during weekends), these should be recorded in a log book.

Any maintenance or safety improvement works relating to dam structure or an associated facility, or a change in dam operating procedure proposed based on DS observations, should be reported to the tailings dam engineer whose role would be to review, design for (if required) and approve such works or changes.

8 TAILINGS DAM SAFETY INSPECTIONS

8.1 SCOPE

The primary purpose of DSIs is to evaluate, on a regular basis, the current and past performance of tailings dam and observe potential deficiencies in the dam conditions, performance or operation. This evaluation should be based on detailed observations made by the engineer at the dam site and the information on dam performance, operating and other relevant conditions obtained from the owner.

Each DSI should include making recommendations as to the improvements to tailings dam safety, if such are required, and future dam safety evaluations.

The scope of DSI that would apply to a typical tailings dam is outlined in Table 7 and elaborated on in this subsection. This scope will depend on the dam operating phase. The following discussion focuses on the production phase. For other operating phases, the scope of DSI could be less intensive.

Consequence Classification Categories

The CCCs should be known to the engineer conducting a DSI, including also the background (rationale) to determining the CCCs. This is essential to making problem-focused observations. For instance, if the receiving environment is sensitive and a potential for Type II failure exists (this would be identified in the background to the relevant CCC), then particular attention may have to be paid to the quality and quantity of dam seepage or the rate and frequency of supernatant discharge, as well as possible evidence of environmental impacts downstream of the dam.

See Section 6.1 for other DSI requirements with respect to CCCs.

Design and As-built Information and Monitoring Data

Immediately prior to conducting a DSI, the engineer should review all relevant background information with a particular emphasis on the design drawings and specifications, DSR reports, as-built information, past monitoring results (including a review of trends), previous DSI reports and dam surveillance records. This review is intended to ensure that the engineer has 'fresh in mind' the specifics of the dam. For instance, the presence of a fault zone identified in the as-built report would allow for carrying out problem-focused observations at the dam toe, while the location of a distinct construction material zone could explain deformations or seepage observed at the dam slope.

A detailed review of the design rationale, design criteria, design input data or the methods of engineering analyses would not typically be required for the purpose of conducting a DSI.

Dam Structure

Detailed visual observations made at the tailings dam structure and associated facilities form a base of DSI.

The inspection of dam structure should involve making visual observations at the dam crest, downstream and (the visible part of) upstream slope, abutments, downstream toe area including seepage collection ditch/drain or stabilising berm, if existing. This part of DSI primarily relates to the structural integrity of tailings dam and should involve observing the evidence of slope, crest or toe erosion, cracks, settlement, bulging and other deformations, daylighting of phreatic surface, plugging of slope materials and/or filters by chemical precipitation, seepages including seepage clarity and rate, current and past freeboards or tailings beach widths, adequacy of the dam to retain solids, performance and conditions of decant structure(s) built into the dam and/or pipelines embedded into or laid over the dam, vegetation and other dam-specific or unusual occurrences.

The various structures that may have been built into the dam should be given special attention, particularly if their use has been discontinued.

Signs of seepage discoloration and/or chemical precipitation should be observed as a matter of routine. In some cases, testing of water quality may be required, including field determinations of pH and conductivity. In more isolated cases, sampling and testing of dam construction and/or tailings materials may be necessary to address actual or potential acid generation or contaminant leaching at neutral pHs.

Inspection of pipelines (*e.g.*, tailings slurry discharge, seepage return, mine water or water recycle pipeline) should be included in the DSI where such a pipeline is build into, or installed over the dam, or a pipeline break would result in discharging clean or contaminated water into the tailings pond (where practical, installation of flowmeters designed to shut off the flow in the case of pipeline failure should be considered).

Discharge Facilities

Tailings pond discharge facility(ies) separate from dam structure may include an overflow spillway, emergency spillway, pump barge, pumphouse, siphon pipe or another arrangement. These should be visually inspected as to their current and expected (future) performance, structural integrity, sedimentation, corrosion, resistance to ice forces, actual or potential flow obstructions, and maintenance and surveillance procedures.

Unless requested by the owner, a detailed inspection of pump barge or pumphouse operated at the tailings impoundment should be excluded from the scope of DSI since the relevant expertise would not typically be available from the tailings dam engineer.

Seepage Collection Facilities

The inspection of SCF, where existing, should include visual observations relevant to its ability to intercept and collect contaminated seepage.

Where the SCF comprises an overland runoff/seepage retention dam, a separate inspection of this dam should be conducted, similar to the tailings dam inspection. Other components of the SCF (*e.g.*, emergency spillway) should then be subject to inspection as well.

Dam Instrumentation

Each DSI should include the inspection of dam instrumentation. This should be limited to visual observations of each instrument conditions. Taking instrument readings in order to check its performance and operating conditions, or to obtain monitoring data should not be included in the scope of DSI unless specifically requested by the owner. Relevant recommendations should be provided in the DSI report if there are reasons to suspect that an installation is not in good working condition.

Upstream of Dam

This part of DSI should be based on the observations made in the general tailings impoundment area and the information provided by the owner. As stated in Section 6.2, the intent of this part of DSI is to confirm that the actual operating procedures implemented upstream of the dam are in accordance with the design requirements. As a minimum, these procedures should include the tailings pond operating practice (*i.e.*, tailings pond operating levels) and the tailings disposal operation (*i.e.*, tailings beach formation as it may affect the size and location of the tailings pond).

A particular attention should be paid to the changes that occurred in tailings pond and tailings deposit configurations since the last DSI, which could affect the performance of discharge facility or the stability of dam. At some sites, the size and/or location of tailings pond may vary relatively quickly (most typically, at upstream tailings dams). In these cases, information obtained from the owner on the past tailings pond locations should be obtained and analysed with respect to dam safety.

Although a review of the runoff management system would not be a part of DSI, changes to the tailings impoundment water balance that may have occurred in the past should be identified at the time of DSI based on information provided by the owner. These may involve (significant) changes to the mine water discharge rate, mill feed rate, process water quality, water treatment rate and schedule, *etc.* If any of such changes has occurred, it should be recommended in the DSI report that the adequacy of the tailings pond management system is confirmed.

All runoff/watercourse diversion facilities located upstream of tailings dam should be subject to inspection in conjunction with each DSI.

While conducting a DSI, the engineer should discuss with the owner the short and long term objectives of dam raising and tailings deposit formation. The DSI report may have to include pertinent recommendations.

For typical upstream tailings dams, the scope of DSI (and the frequency of DSIs) will have to be more intensive as compared with tailings dams raised in one or more stages. The step-berm raising technique, the beach length and beach slope, the schedule for moving tailings discharge location, the degree of tailings desiccation (where applicable), the quality and distribution of beach materials, *etc.*, should be reviewed in detail in conjunction with each DSI. This review would constitute a crucial assignment. An inadequate quality of a portion of a beach or any other non-homogeneity built into the dam might result later in excessive deformation of dam structure or, in the extreme case, dam failure.

Special observations may have to be made where the tailings dam supports a water cover designed to prevent/impede AMD or reduce the rate of radiation.

It needs be clearly understood that the safe operation of tailings dam is the responsibility of the owner and not the engineer, although the operating procedures should be specified by the engineer in co-operation with the site personnel.

Downstream of Dam

Where the potential for environmental impact resulting from a Type II failure exists, a walk-over inspection beyond the downstream toe of the dam will be required as part of each DSI.

Unless specially arranged for, no expertise to evaluate impacts to the downstream environment would be provided for the purpose of conducting a DSI. Nevertheless, relevant observations should be made by the engineer downstream of the dam (*e.g.*, observations relating to water quality and flow rates, chemical precipitants, discoloration, vegetation kills, erosion of discharge ditch or receiving stream channel, polishing pond performance, spilled tailings, or the pH of runoff streams). The premise here is that the engineer, familiar with the design objectives and potential Type II failure modes, may observe some evidence of environmental impact while conducting the field work and bring it to the attention of the owner.

If requested/agreed by the owner, the engineer should arrange for another professional to evaluate actual environmental impacts.

Past Performance and Failures of Dam

Of particular importance to conducting a DSI will be the owner's supplied information on the performance of dam/discharge structure under maximum past load conditions (*e.g.*, largest flood in terms of peak flows, maximum past tailings pond level or closest distance between the tailings pond and the crest of dam, highest tailings pond contamination, heaviest rainfall as related to slope erosion and runoff pattern, largest earthquake, *etc.*).

It should also be determined and recorded in conjunction with each DSI if the dam failed in the past in the sense of either Type I or Type II failure. This determination should be made based on visual observations at the dam structure and downstream of the dam, supported by relevant information obtained from the owner.

If not recorded previously, the DSI report should include information on past failure(s) of the dam, if such failures have occurred, including also a brief description of the corrective works/actions.

Compliance with Regulatory Requirements

As part of DSI work, the engineer should review the information on compliance with regulatory requirements as it relates to dam performance.

Should non-compliance occurrence(s) resulting from dam performance happened in the past and be also expected to happen in future, the engineer should develop recommendations on possible improvements to dam performance, or recommend to the owner conducting a problem-focused DSR. These recommendations should be included in the DSI report.

Other Dams

Inspection of other dams, the failure of which could affect the performance of the tailings dam being inspected, should be incorporated into each DSI. The scope for inspection of any such dam should be established separately, taking into account the relation to the tailings dam and other site-specific conditions.

8.2 FREQUENCY

The frequency of DSIs should be established for each tailings dam taking into consideration the type of dam, applicable CCCs, dam operating phase and the surveillance commitment.

For tailings dams classified in the Group A category, DSIs should be conducted, as a minimum, on an annual basis. DSIs may have to be conducted more frequently where particularly hazardous conditions exist and/or particularly demanding tailings impoundment operating procedures are implemented.

For tailings dams classified in the Group B category, judgement should be used to define the frequency of DSIs with reference to dam surveillance commitment, CCCs, dam operating phase and the type of dam. Similar to Group A category dams, more frequent DSIs would be required for Group B category dams where particularly hazardous conditions exist and/or particularly demanding operating procedures are implemented.

For the majority of active mines, conducting dam safety inspections on an annual basis may have to be implemented also for Group B category dams, especially if the CCCs place the dam in the upper range of this category. The rationale here is that even if relatively low consequence categories apply, a structural failure of tailings dam would likely result in a temporary shut down of the mine operation, the cost of which would be many times higher than the cumulative cost of annual inspections.

DSIs for tailings dams constructed on a continuous basis may have to be conducted more frequently than for dams raised every several years, all other factors being equal. As pointed out in Section 2.3, periodic site visits by the design engineer would be required in the case of upstream tailings dams, and conducting DSIs in conjunction with these visits could easily be accomplished.

A DSI may also have to be conducted immediately following a Type II failure, depending on the specifics of failure. For instance, if the failure occurred as a result of extreme high or low flow event, carrying out a DSI focused on the resulting environmental impact and relevant improvements to dam safety could be required. On the other hand, if the failure occurred under a typical runoff condition, conducting a DSR focused on the review of runoff management system, contaminated seepage rates, *etc.*, might be necessary, unless the failure was caused by an operating error.

Where no on-going dam surveillance is implemented in the case of a remote, inactive mine, it should be recommended that DSIs be carried out, as a minimum, two times a year for tailings dams classified in the Group A category, assuming that a remote dam surveillance system is available (for many sites, one of the two annual DSIs should be conducted *early* during spring freshet or rainy season). For Group B category dams, carrying out a DSI on an annual basis may be required.

Regardless of the group category or dam operating phase, a DSI should be conducted immediately after each extreme load event. Should any signs of distress resulting from the event be observed at dam structure or elsewhere, conducting a complete or problem-focused DSR would be required.

The DSI requirements stated in this subsection can be relaxed for tailings dams classified in the Low category in terms of potential environmental impacts *and* the Low category in term of potential loss of life and/or economic losses.

8.3 REPORTING

The results of DSI should be tabulated and supported by a sketch showing the locations of photographs taken, seepage and crack/settlement locations, *etc.* Estimated seepage rates, dimensions of cracks, *etc.*, should also be documented. Videotaping while making site observations would be advantageous.

No format of a DSI report is suggested to ensure that an ample opportunity for addressing site-specific conditions exists. In general, a DSI report should include a brief summary of findings, supported by standardised forms (see examples attached in Appendix B), photographic record, sketches, tabulated results of testing (if conducted), *etc.* Each report should contain clearly identified conclusions and recommendations.

In conjunction with DSI, the engineer should check and acknowledge in the DSI report that sufficiently comprehensive and updated dam design, as-built and monitoring information ('documentation') is available not only from the engineer's office but, also, at the site. Should this not be the case, the engineer should recommend that the documentation be made available at the site at all times (this would not apply to closed out or abandoned mine sites).

As a minimum, DSI conclusions should incorporate the results of:

- evaluation of dam structure conditions;
- evaluation of the conditions of associated facilities (*e.g.*, spillway);
- evaluation of dam surveillance practice;
- evaluation of tailings pond operating procedures;
- evaluation of tailings disposal practice;
- evaluation of dam monitoring and documenting practices.

As a minimum, DSI recommendations should include:

- recommendations/confirmation regarding appropriate CCCs;
- recommendations/confirmation regarding the scope/frequency of DSIs;
- recommendations/confirmation regarding DS program;
- recommendations regarding dam maintenance works, if required.

Where necessary, additional design study, safety evaluation, monitoring or dam safety improvement works should be recommended in the DSI report. Any corrective works that are recommended should be compatible with the safety requirements applicable to future dam operating phases, where applicable.

Date for conducting the next DSR should also be recommended or confirmed. If requested by the owner, recommendation on the scope of work for the next DSR should be included in the DSI report.

9 TAILINGS DAM SAFETY REVIEWS

9.1 SCOPE

The objectives of conducting a DSR are to ascertain that a tailings dam has adequate margin of safety, as determined based on the current engineering practice and updated design input data, its performance and operation are in agreement with the design requirements, and the condition of the dam is satisfactory. Future performance of the dam needs be considered until the end of the current operating phase for the purpose of each DSR, taking also into consideration future phase requirements (Section 5).

The design requirements, some of which are discussed in Section 10, must be accounted for when conducting a DSR.

With regard to the production phase, the need for conducting DSRs strongly relates to the dynamics of tailings dam operation. In general, the need for conducting DSRs results from the fact that a tailings dam is designed to last a very long time, and it cannot be assumed that the design principles, criteria, methods or input data used for the purpose of the original analyses and designs would be acceptable throughout the entire service life of tailings dam. Furthermore, the developments downstream of the dam, which will take place during its long service life, would necessitate conducting dam safety reviews as well.

Typical DSR components have been identified in Table 7. In more detail, a DSR should include carrying out a DSI in accordance with the requirements of Section 8, and the review of:

- legislative requirements and regulatory policies applicable to the design, construction, operation and closure of tailings dam, including also the regulatory permit(s) under which the dam is operated;
- the owner's short- and long-term objectives (*e.g.*, preferred schedule for dam raising, planned increase in the mill production rate, expected use of tailings for underground backfill or planned custom milling);
- applicable CCCs (if not available, determining CCCs for the first time would be required);
- as-built data and design background information, including also new design data that may have become available since the last design stage or DSR (*e.g.*, additional information on subsurface conditions in the dam area or the results of environmental evaluation conducted to meet a regulatory requirement);
- dam monitoring data (*e.g.*, settlement, phreatic surface levels, discharge and seepage rates, or water quality records);

- tailings impoundment operating records (*e.g.*, quality and quantity of processed ore and mill process water, tailings discharge locations or tailings impoundment water balance);
- past and future (expected) performance of the dam in terms of stability, deterioration of dam materials and associated facilities, seepage rates, ability to buffer runoff, *etc.*, with reference to the design assumptions;
- geochemical and environmental conditions as related to the past and future (expected) dam performance;
- mine site runoff management system;
- tailings deposition plan;
- closure plan;
- design criteria;
- input data used in the past for the design purposes (*e.g.*, data on meteorological and hydrologic, seismic, dam material and dam foundation conditions, phreatic surface location, pore pressures, properties of tailings beach materials or seepage rates and quality);
- past methods of engineering analyses (stability, liquefaction, seepage, contaminant loadings and other analyses);
- degree of conservatism built into the analyses, designs and construction;
- dam surveillance and maintenance practice;
- operating and/or design requirements pertaining to future dam operating phases, including the closure phase;
- the adequacy of past DSIs;
- the adequacy of dam instrumentation;
- tailings disposal capital and operating costs;
- tailings dam operations manual.

The results of any of the above reviews may trigger the need for conducting an additional engineering analysis, field and/or laboratory investigation, environmental evaluation, updating design input data or revision to the tailings dam operations manual.

Should the results of DSR indicate an unsafe condition, appropriate recommendations should be developed as to the best course of action required to alleviate the safety concern. If a high cost of the most obvious corrective works is expected, it may be best to conduct a risk analysis, designed to find an optimal solution (see Appendix A–VIII). Recommendations may also be made regarding the necessary changes to dam operating procedures, for instance, changes to the tailings pond water management, dam construction technique, tailings slurry density or discharge method.

Many tailings dams constructed prior to the 1980s were designed without much consideration given to the issue of contaminant generation. The designs and/or dam operating requirements had to be later adjusted to meet the current environmental and other standards, whether in conjunction with the continuing operation of tailings dam or in preparation for the closure phase. One of the DSR objectives is to identify the need for such adjustments.

The engineering effort associated with carrying out a DSR should not be very intensive, particularly for newer dams or dams which were subject to DSRs previously. It will primarily depend on the comprehensiveness and quality of the available design, performance, operating and as-built information. For older dams where such information is sparse and/or of poor quality, this effort could be substantial at the time of the first DSR. In extreme cases, the engineering cost of conducting a DSR could be in the order of, although lower than the engineering cost associated with a new tailings dam project. On the other hand, the investigation of tailings dam failure could be significantly more expensive than the cumulative cost of all DSRs.

The owner should be kept informed on the DSR findings on an on-going basis. It would be best for an owner's representative to participate in each DSR as a member of the review team (Section 2.1).

A 'routine' DSR is not intended to address immediate tailings dam safety concerns. The frequencies of DSRs recommended in the following subsection are not sufficient for this purpose. Immediate dam safety concerns must be addressed in conjunction DS and DSIs, which are carried out much more frequently.

Nevertheless, a problem-focused DSR, outside of the 'routine' DSR program, may have to be carried out to address a specific dam safety concern. As pointed out in Section 8.2, conducting a problem-focused DSR could be necessary where evidence of distress has been observed following an extreme load event. Other safety concerns that might have to be addressed by conducting a problem-focused DSR include an increase in seepage contamination, structural integrity of decant structure built into the dam, properties of tailings beach, occurrences of a non-compliance condition, *etc.*

9.2 FREQUENCY

The frequency of DSRs for tailings dams should be determined based on the dam operating phase, CCCs, dam raising schedule (where applicable), tailings impoundment filling rate and other site-specific conditions.

The frequencies of DSRs recommended in the guidelines developed for conventional dams need not be appropriate for tailings dams, even for embankment type tailings dams with negligible potential for environmental impacts.

The following recommendations are made taking into account the dynamics of typical tailings dam operation. Note that during Phase 1, DSRs need not be conducted at regular time intervals. This may depend on the schedule for stage-raises of the dam.

Regardless of any other considerations, for tailings dams in the Group A category where no DSR has ever been conducted, carrying out a DSR as soon as possible should be recommended at the time of next DSI, unless the dam was designed and constructed less than about 4-5 years prior to the DSI and no problems with the past or current performance of the dam have been identified.

Regardless of any other considerations, a DSR should be carried out where significant changes to the tailings dam operating conditions have occurred (*e.g.*, tailings impoundment operating practice or tailings pond water chemistry has changed), or significant changes in dam performance have been observed. In these cases, the scope of DSR may be focused on the relevant dam operation, performance or design aspect.

Tailings Dams Raised on a Continuous Basis

For tailings dams raised on a continuous basis, DSRs should be conducted at reasonably regular intervals, with the frequency commensurate with the CCCs, dam operating phase and the rate of dam raising (Phase 1). For such dams, the frequency of carrying out DSRs should not be less than 5–10 years for dams classified in the Group A category, and 5–15 years for Group B category dams, with higher frequencies applicable to Phase 1 and relatively fast dam raising, and lower frequencies applicable to Phases 2, 3 and, particularly, Phase 4.

As pointed out in Section 8.1 under the ‘Upstream of Dam’ heading, for upstream tailings dams more effort will have to be put into conducting DSIs, as compared with dams raised in one or more stages. In a way, for a typical upstream tailings dam, a part of DSR work should be done under the DSI mandate. The same may have to apply to other dams raised on a continuos basis.

Tailings Dams Raised in One or More Stages

As pointed out in Section 6.4, designing for stage-raise of tailings dam should always incorporate a DSR, even if the detailed designs were developed previously, for instance, at the initial design stage.

As a ‘rule of thumb’ for tailings dams classified in the Group A category, the time between consecutive DSRs should not exceed 5 years during the production phase.

[This recommendation is rather stringent as compared with similar recommendations developed for conventional dams. The rationale here is that, with few exceptions, the operation of tailings dam is a dynamic process involving significant changes to the dam operating regime occurring within short time periods (increase in the hydraulic head, increased stresses in the dam and dam foundations, change in the tailings pond size and/or configuration, etc.).]

For tailings dams in the Group A category during Phases 2, 3 and 4, the frequency of DSRs should be determined based on site-specific conditions, with an emphasis on the actual dam performance as well as the actual surveillance, inspection and monitoring commitments. The frequency of DSRs should not be greater than 15 years. This time limit is recommended based on the expected progress in the dam engineering and environmental sciences or geochemistry, enlargements to the design background information (*e.g.*, hydrologic or seismic database), *etc.*, rather than the expected changes to dam performance. Nevertheless, possible changes in dam performance may have to be accounted for when setting up the time for conducting the next DSR (*i.e.*, where potential changes to the phreatic surface location could result from chemical precipitation in a filter zone or potential for an increase in the rate of contaminant loadings bypassing the dam site exits).

For tailings dams classified in the Group B category, judgement should be used in arriving at the recommendation on the need to conduct a *complete* (‘fully blown’) DSR. For dams in this category, carrying out a complete DSR might not be necessary if *all* of the following conditions are met:

- the dam has been engineered and adequate design and as-built information exits;
- preliminary review of the design and as-built information indicates that the dam was designed and constructed in accordance with reasonably modern standards;
- preliminary review of the design input parameters (*e.g.*, flood characteristics or peak ground acceleration) indicates that these parameters are within a reasonable range for the given site;
- there are no discernible reasons to review the consequence classification category(ies);
- strict adherence to the specified DS, DSI, monitoring and operating requirements is followed;
- adequate tailings dam operations manual exists; and
- no significant problems with dam performance have been identified from the DSIs and DS.

A *preliminary* review of the design and as-built information, and the records of past performance of the dam could then be sufficient.

For tailings dams in the Group B category, the frequency of either complete or preliminary DSRs should be between 5 and 15 years depending on the dam operating phase, with higher frequencies applicable to the production phase and lower frequencies applicable to Phases 2, 3 and 4.

It follows from the preceding recommendations and the discussion presented in Section 6.4 that for tailings dams raised during the production phase at approximately 5-year intervals or less, there would be no need to carry out a DSR separate from the dam safety evaluation conducted in conjunction with developing/reviewing the detailed designs for stage-raises of the dam.

Each tailings dam should be subject to a DSR at the time of designing for closure, except where the dam is classified in the Low category in terms of potential environmental impacts, the potential for a Type II failure is not significant, *and* the dam is classified in the Very Low category in terms of loss of life and economic losses. Note that future developments downstream of the dam should be taken into consideration to the extent reasonably possible.

9.3 REPORTING

An engineering report should be issued following each DSR. The report should document all findings of the review, including the review conclusions, and provide recommendations regarding possible improvements to the dam operation, monitoring, maintenance, inspection and/or surveillance programs. The necessary remedial works, if any, should be outlined in the report in detail, however, the associated designs would not typically be included under the DSR mandate.

The report should also include a complete list of the reviewed documents, the associated DSI report as well as the details of all field or laboratory investigations, engineering analyses and other evaluations, *etc.*, that may have been carried out for the purpose of the DSR.

10 DESIGN OF TAILINGS DAMS

A non-engineer involved in a tailings dam project sometimes rests assured when learning that the dam is “designed for the PMP”. There seems to be some fascination with tailings dam design aspects among those who do not really understand the overall question of dam safety. Other aspects, such as dam surveillance or construction supervision, seem to be given a lesser weight.

It needs be said that no best, sophisticated design work or the most stringent design criteria will cover for possible omissions in the construction supervision or quality control, operation, surveillance, safety inspections or reviews, or the lack of specific experience in tailings dams. And no one of these dam safety aspects can be said is more important than another. This is, basically, a compilation of the remarks made by many distinguished conventional dam engineers. Those remarks apply to tailings dams as well, and even more so considering the dynamics of a typical tailings dam operation.

Since this Document is not intended as a design manual, only selected tailings dam design aspects are addressed herein. In this selection, an attempt has been made to provide a brief overview of the design process and combine the design issues which are not extensively addressed in available publications with those which, in the author’s opinion, require some input from the perspective of tailings dam safety evaluations. The design and construction aspects of tailings dams are addressed in detail in Steven G. Vick’s ‘Planning, Design, and Analysis of Tailings Dams’, BiTech Publishers Ltd, 1990, ICOLD Bulletins 45, 97, 101 and 106, and other publications.

General issues relevant to tailings dams design, such as the quality of design drawings and technical specifications, construction contract, design review process, or reporting on and storage of the design and as-built information, are not discussed herein. It is emphasised, however, that these issues *are* directly related to dam safety and should be given strict attention regardless of the ‘magnitude’ of the tailings dam project.

10.1 DESIGN LEVELS

Although the terminology varies somewhat among tailings dam engineers, the most common design levels can be summarised as follows:

Pre-conceptual
This design level is based on a site reconnaissance, air photographs, small scale topographic maps and some knowledge of the site conditions (surficial lithology,

geologic-tectonic, seismic, hydrogeologic, meteorological, hydrologic, land use and environmental) on a regional scale. Engineer's general familiarity with the conditions of the dam site area and/or similar sites/projects may become a source of additional design information.

The mill and mine operating requirements are defined to the first approximation only. Some information on the subsurface conditions and geochemical properties of tailings and waste rock may be obtained from the mining exploration program.

In some cases, the final selection of tailings dam site may have to be made at this design level. If so, this selection should be made with direct input from a tailings dam engineer.

Only an order of magnitude cost of tailings dam construction can be estimated at this level.

Conceptual

Conceptual designs are based on a preliminary site investigation, which may include testpitting, limited topographic surveys, general survey of potential borrow areas, *etc*. 1:5,000 topographic maps (or better) are often used at this level. The knowledge of site conditions may be obtained from the regulatory agencies, neighbouring projects, technical publications, monitoring stations or small scale maps (surficial soils, hydrologic, geologic-tectonic, seismic, *etc*.).

Data on the mine production rate and mill process are often, albeit not always, reasonably ‘final’. However, other design input data such as the properties of tailings, mill water balance, mine or make-up water rates are still rather approximate. At this level, a reasonably safe assumption on the potential use of mine waste materials for tailings dam construction can often be made.

Two or more tailings dam design options are typically considered at this level. A design report is prepared presenting the design concepts, a comparison of alternative options and associated (capital and operating) costs, including also a recommendation on the preferred option in terms of dam site, dam type and the choice of dam construction materials. This may well be the most important recommendation made with respect to future design, construction, operation and closure of tailings dam.

The critical importance of this recommendation is that it is intended to support a decision on the construction of a complex structure that will have to serve for hundreds of years, designed to contain materials the release of which could result in significant economic and/or environmental impacts and, in some cases, loss of life. An error made at this stage could result later in very high and unexpected costs, particularly if an ‘unworkable’ site is recommended and the recommendation accepted.

Cost of dam construction can be estimated with an accuracy of not better than about 25-35%.

[The pre-conceptual and conceptual design levels are often referred to as the ‘pre-feasibility’ design level.]

Feasibility

The final selection of the dam site and the type of dam is often made prior to the feasibility design level however, in some cases, still more than one option may be considered.

The designs are developed based on a large scale topographic map (typically prepared from an air photo survey) as well as supplementary ground surveys, subsurface investigations involving geotechnical and hydrogeologic drilling, laboratory testing, geophysical investigation, site-specific seismic and meteorological evaluations, hydrologic evaluation including stream flow measurements, geochemical testing and analyses, and detailed engineering analyses. Tailings sample will often be available for geotechnical and geochemical testing from the pilot plant. Environmental baseline study and the EIA, prepared in parallel with the engineering analyses and designs would be completed, and the source(s) of dam construction materials identified and tested at this level.

The feasibility design level is advanced either immediately prior to or, in some cases, following the production decision. Feasibility of the design concept, including the viability of tailings impoundment closure option(s), must be fully confirmed at this level. An engineering design report is issued following the completion of feasibility designs.

Cost of dam construction can be estimated with an accuracy of not better than about 15-25%.

Detailed

Designs are further developed based on detailed topographic (ground) survey of dam site and supplementary field investigations that may be required to finalise the construction quantities and/or design details. Additional engineering analyses may have to be carried out in support of developing the design details. Technical specifications and construction drawings are prepared and a construction contract document is issued.

Cost of dam construction can be estimated with an accuracy of not better than about 10-15%.

These design levels would typically apply to a new mine project. For new tailings dams planned at an existing mine site, designing at the pre-conceptual and conceptual levels may not be necessary. The pre-conceptual and feasibility design levels need not apply to the re-construction of an existing dam (*e.g.*, where originally unanticipated dam raise is planned, re-construction of the dam is required to improve dam safety, or the dam is to be retrofitted in preparation for closure).

10.2 DESIGN STAGES

Three design stages generally apply to tailings dams:

- initial design stage
- designing for stage-raise
- designing for closure

Design work may also be carried out where improvements to dam safety are required. This may follow a DSI or DSR recommendation.

For upstream tailings dams raised on a continuos basis, detailed designs for the entire production phase should be developed at the initial design stage. These designs may still be modified during the production phase or at closure, however, changes to the original dam configuration would likely be costly.

For downstream tailings dams constructed in stages, the initial design stage should involve developing detailed designs for the first stage-raise (*i.e.*, for the starter dam) and feasibility level designs for future stage-raises. This means that the detailed designs for future stage-raises would be developed immediately prior to each stage-raise construction. This is a preferable approach since the results of dam safety evaluations conducted prior to each stage-raise may indicate an advantage or need for introducing some design adjustments.

Designing for tailings dam closure should be advanced at the initial design stage to the conceptual or, at the most, feasibility design level. Nevertheless, the viability of the closure concept must be fully confirmed at this stage. [As pointed out previously, it is necessary to take into consideration future conditions in the dam site area that can reasonably be predicted at the design stage.]

It follows that there would be some flexibility left with regard to the design details pertaining to future stage-raises and closure of tailings dam. The rationale here is that the best designs developed at the initial design stage might not necessarily be best at the end of the mine operation (say, 25 years into the future), when the actual tailings dam and/or tailings impoundment conditions or regulatory requirements will have changed from those originally assumed, or new closure technologies become available. Similar comment applies to future stage-raises of tailings dams.

10.3 DESIGN CONSERVATISM

As a general rule, an increased degree of design conservatism could be justified where:

- the potential consequences of tailings dam failure increase;
- the design information is poor (*e.g.*, where no reliable as-built information exists), or a design database (*e.g.*, meteorological or seismic) is limited;
- designing for a long operating phase is carried out (Phases 3 and 4);

- understanding of a design aspect is limited or some inherent uncertainties exist (*e.g.*, when evaluating the potential for tailings liquefaction).

Applying weighty conservatism to the selection of each of the design input parameters, interpretation of each of the engineering analyses and, later, to the design details should be avoided as this may lead to a 'pyramid of conservatism' (see Appendix A–IX for further discussion in this regard).

10.4 SITE SPECIFIC CONDITIONS

The most typical site-specific conditions, which must be considered in conjunction with tailings dam design project, include:

- legislative requirements, including relevant policies followed by regulatory agencies;
- owner's cash flow and other restrictions or policies, if any;
- plan regarding the management of other mine wastes;
- relevant details of the current or planned mine site operation plan;
- mill process, including mill/mine water balance and production rates;
- proven and possible ore reserves;
- existing/planned design layout of the mine site, including mine workings;
- ore and (often) waste rock mineralogy;
- actual or expected properties of tailings (geotechnical, hydrogeological and geochemical);
- actual or expected quality of mill, mine and other site waters, or the resultant quality of tailings pond water;
- treated water quality, where applicable;
- climate;
- local and regional physiographic and geologic-tectonic conditions;
- hydrologic, seismic and other external load data;
- dam foundation conditions;
- hydrogeologic conditions in the general area of dam site;
- design and as-built information as well as past performance data in the case of existing dam;
- availability of dam construction materials;
- environmental conditions, including public perception and future (predicted) land uses;
- appropriate CCCs (to be determined or confirmed, as required, at each design stage);

- information on the performance of other tailings dams in the general site area, if available.

Providing recommendations on the scope of investigation and the level of detail necessary to generate adequate information on site-specific conditions of tailings dam is outside of the scope of this Document.

10.5 OVERVIEW OF DESIGN CRITERIA

Design criteria used for tailings dam projects can be broadly divided into three groups:

- general project requirements
- engineering design criteria
- environmental design criteria

The first group would include the owner's objectives (*e.g.*, preferred walk-away closure scenario, dam construction by mine forces rather than an outside contractor, cash flow restrictions, or an allowance for potential increase in ore reserves), regulatory requirements/policies, intended tailings dam function (*e.g.*, temporary storage of process water and/or contaminated runoff, passive treatment, sludge storage), mine/mill operating requirements, *etc.*, as well as any other condition pertaining to dam construction or operation that might influence the selection of design criteria and/or other dam safety evaluation requirements.

When setting up the general project requirements, it is essential to take into consideration the design objectives pertaining to the *entire* mine site, with regard to the mine production and the following dam operating phase(s). For instance, should waste rock dump runoff and/or mine water were to be treated in the long term (after mine closure), it could be economically beneficial to allow for the long term treatment of tailings impoundment runoff as well (if required) and, then, developing appropriate dam designs would be necessary. Conversely, should no treatment of (other) site waters be required but significant AMD generation in tailings be expected, it might be preferable to design for underwater tailings disposal and the tailings dam would have to be designed to allow for implementing such a scenario.

Common engineering design criteria (*e.g.*, design flood and earthquake events, freeboard or a safety factor) would be included in the second group, derived primarily with respect to potential Type I failure.

Environmental design criteria would be those set up from the receiving environment perspective (*e.g.*, maximum contaminant levels permitted in a receiver, the size of initial mixing zone, or the identification of receiver(s) that must remain unaffected). These would relate to potential Type II failure.

According to Figure 2, general project requirements represent a component of the ‘base input data’, while (engineering and environmental) design criteria are included under the ‘tailings dam safety evaluation requirements’. This is consistent with the consequence classification method. For instance, while a CCC, being a rationale for selecting a design criterion, would be included under the left side of Figure 2, the resulting flood or earthquake design criterion would be included under the tailings dam safety evaluation requirements.

10.6 DESIGN INTERVALS

As discussed in detail in Appendix A–X, it is preferable that probabilistic flood and earthquake design criteria for tailings dams are selected based on the *probability of exceedance during design interval* (PEDDI) rather than *annual exceedance probability* (AEP), wherever the *design interval* (DI) can be estimated (‘design interval’ is sometimes referred to as the ‘exposure period’). The relationship between PEDDI, AEP and DI is given by the equation:

$$\text{PEDDI} = [\, 1 - (\, 1 - \text{AEP}\,)^{\text{DI}} \,] \times 100\%$$

AEP describes the probability of a design event (typically, flood or earthquake) being exceeded in any given year. AEP is a reciprocal of the corresponding return period (RP). For instance, a design flood with AEP = 0.001 means that the probability of a more severe (than the design) flood occurring in any given year is 1/1000. This corresponds to a design flood with RP = 1,000 years (flood with a return period of 1,000 years would be expected to occur, on the average, once every 1,000 years). From the above equation, the probability that an event with AEP = 0.001 will be exceeded during a design interval lasting, say, 100 years (DI = 100 years) is 9.5%, that is, the corresponding PEDDI = 9.5%. If the length of design interval is assumed to be 1 year, then PEDDI = AEP×100%.

The design interval is defined for the purpose of this Document as an entire time period during which neither the CCCs nor the tailings dam operating attributes are subject to significant changes. This means that a tailings dam during each design interval remains essentially ‘the same’ with respect to the potential for Type I failure. In general, the design interval should be taken as the duration of the current or imminent (*i.e.*, designed for) tailings dam operating phase. Typical phase durations are indicated in Table 6.

Selecting probabilistic design criteria based on PEDDI means that the extreme design loads are selected with explicit reference to the design interval. The design interval needs be specified or confirmed at each design stage.

Consistent with the provisions of Section 5, dam safety requirements anticipated with respect to future operating phases must be taken into consideration when selecting the design interval and appraising the consequences of the selection.

As discussed later in this section, selecting probabilistic flood and earthquake design criteria based on PEEDI is recommended with respect to the impact classification requirements. With regard to the LLEL classification, the recommended criteria will have been adapted from a guideline developed for conventional dams, in which no designs intervals are explicitly accounted for. Nevertheless, the need for considering the design intervals with respect to the LLEL classification requirements is emphasised in the ensuing discussions, wherever appropriate.

In general, the design intervals should correspond to the durations of Phases 1, 2, 3 an 4, with the following exceptions:

(i) where a distinct change in the CCCs is expected to occur during the following *stage-raise* interval, the duration of the current (or imminent) stage should be taken as the design interval;

(ii) where the designs are developed with the purpose of incorporating one or more operating phases beyond the current (or imminent) phase, the design interval should include these phases;

(iii) short-term operating phases such as Phase 2A or, in some cases, Phase 2B, should be incorporated into the preceding (*i.e.*, the production) phase for the purpose of selecting the design interval;

(iv) where Phase 2B is expected to last a relatively long time, the design interval should be selected as that corresponding to the Phase 4 duration, subject to note [5] under Table 6;

(v) where information on the original designs is poor and the first DSR is conducted, the design interval may have to be taken as that corresponding to the time period between the time of conducting the DSR and the end of the current operating phase, except as allowed for under (i) and (ii) above.

Because of general familiarity with the ‘return period’ concept, both PEDDI values and return periods are used for the discussion purposes throughout this Document. Whenever a return period (a reciprocal of AEP) is referred to with respect to the impact classification requirements, it is assumed that it has been computed from PEDDI and DI.

10.7 HYDROLOGIC DESIGN CRITERIA

Maximum Normal and Maximum Permissible Pond Levels

The *maximum normal pond operating level* (MNL) and the *maximum permissible pond operating level* (MPL) are defined with reference to the expected, most critical conditions in the tailings impoundment. These conditions will typically occur at the end of a stage operation, that is, immediately prior to either the next stage-raise or closure of the dam. For tailings dams constructed on a continuous basis, these levels continuously vary with raising of the dam crest.

Where tailings pond water discharge is not permitted under normal operating conditions, the MNL may be taken as that corresponding to the highest pond level expected to occur during a ‘wet' year or season with a return period in the range of 5 to 15 years (a sequence of years may have to modelled in some cases to determine the MNL). A MNL is used for selecting both the top of dam elevation with respect to normal operating conditions and the initial pond level for the IDF and EDF modelling (discussed later in this subsection). The same range of return periods for MNL may be considered in cases where the tailings pond discharge is regulated for the purpose of a controlled discharge scheme implemented according to some environmental criteria, passive treatment or process water supply requirements.

For the purpose of IDF or EDF modelling, the IDF or EDF design return period should be taken into consideration when selecting the design return period for the initial MNL. Where IDF or EDF corresponds to a PMF, a return period selected for the determination of the design MNL in the order of 5 years (on the ‘wet’ side) could be judged appropriate in most cases.

[The selection of initial pond level for modelling purposes must be ‘seasonally’ correct in the sense that the design MNL should be determined for the time of year when the design IDF or EDF can actually occur. For instance, while a 1 in 5-15 years MNL may be expected to occur in fall, a spring IDF or EDF could represent the critical design criterion. In other words, there would be only one MNL with respect to selecting the top of dam elevation while another (lower) MNL may have to be determined for the purpose of IDF or EDF modelling.]

The recommended above range of wet year return periods for determining the design MNL may be increased, but not excessively, for evaluating the seismic stability of tailings dam under the design earthquake load, with consideration given to the earthquake return period. The time period during which the MNL would be sustained in tailings pond needs be considered when deciding on the selection of the design MNL for seismic stability analysis.

Where there are no restrictions on tailings pond water discharge, the MNL corresponds to a nominal invert elevation of the discharge facility (overflow spillway, decant structure, *etc.*).

The MPL corresponds to the maximum pond level that would occur during the IDF, discounting the wind setup and wave runup. This pond level is used for selecting the top of dam elevation (*i.e.*, minimum permissible freeboard), accounting also for the wind setup and wave runup.

Where no discharge of tailings pond water is permitted under any circumstances, the MPL corresponds to the MNL plus the increase in the tailings pond level resulting from the maximum design hydrologic event (*e.g.*, a ‘severe’ sequence of wet months/years, PMP or PMP combined with snowmelt).

Inflow Design Flood

Inflow design flood (IDF) is considered with respect to potential Type I failure (Table 1). It is the largest flood that must be safely passed through the emergency or overflow spillway, or a decant structure, so that overtopping of the dam is prevented and sufficient freeboard exists, the tailings dam has an adequate margin of safety against shear failure during and following the flood, critical facilities associated with tailings dam are protected against structural failure or excessive erosion, and no ‘uncontrolled’ release of tailings pond water or tailings solids occurs.

The minimum flood design criteria recommended for designing of tailings dams with respect to potential Type I failure are presented in Tables 8 and 9. These two sets of criteria refer to the consequence categories resulting from the LLEL and impact classifications, respectively. The former criteria have been adapted from the ‘Dam Safety Guidelines’ (CDSA, 1995).

Table 8
Usual Minimum Design Criteria for Floods[1,2]
(LLEL Classification)

CONSEQUENCE CLASSIFICATION CATEGORY	INFLOW DESIGN FLOOD
Very High	PMF
High[3,4,5]	0.001 to PMF
Low	0.01 to 0.001

Notes to Table 8:

[1] Adapted from the CDSA guidelines with notes [3], [4] and [5] added. See the CDSA guidelines (CDSA, 1995) for related discussions.

[2] Probabilistic criteria are expressed in terms of AEP, which indicates the probability that the design flood would be exceeded in any given year.

[3] For existing tailings dams, PMF should always be selected as the IDF where an increase in loss of life is expected, unless shown unjustifiable from an ‘additional cost vs benefit’ analysis. This applies to relatively short operating phases (Phase 1, Phase 2 and, possibly, Phase 3).

[4] For existing tailings dams and operating phases lasting significantly more than 100 years (i.e., Phase 4 and, often, Phase 3), PMF must be selected as the IDF where an increase in loss of life is expected (the significance of the ‘100-year’ period is discussed in Section 10.9 and Appendix A–X).

[5] For new tailings dams, PMF should be selected as the IDF where the potential for loss of life exists, regardless of the phase.

In many cases it will be possible to satisfy design criteria more stringent than the minimum criteria recommended in Tables 8 and 9, at acceptable costs. This is because tailings dam watersheds are typically small and safe routing of higher peak flows can be accomplished by providing a relatively small enlargement to the spillway or discharge structure and/or freeboard, or a PMF volume can be stored. There are, however, some notable exceptions in this regard as pointed out in Appendix A–XIII.

Table 9
Minimum Design Criteria for Floods – Preliminary
(Impact Classification)

CONSEQUENCE CLASSIFICATION CATEGORY	INFLOW DESIGN FLOOD[1,2,3]
High	<2% to PMF
Significant	2% to 20%
Low	20%

Notes to Table 9:

[1] Probabilistic criteria are expressed in terms of PEDDI, which defines the probability that the design flood would be exceeded during the design interval. Design based on AEP rather than PEDDI may have to be carried out where the length of design interval cannot be established with a reasonable accuracy (Phase 3) or cannot be agreed upon/rationalised (Phase 4). This should be avoided, if possible. In general, the AEP values given in Table 8 are not considered adequate for applying to the corresponding CCCs established from the impact classification.

[2] Selection of a design PEDDI value between the limits shown may be based on the applicable determinant group (Table 4). For instance, ‘A3+D3+S3’ may become a rationale for selecting a PMF as the IDF regardless of the length of the design interval while for the High category established from group ‘A3+D2+S1+P1’, PEDDI = 2% may be considered adequate (see also Appendices A–III.2 and A–XII.4 for relevant discussions).

[3] The resulting return period for the IDF should not be less than 200 years regardless of the consequence category and the length of design interval.

Design flood events resulting from the criteria stated in Table 9 are presented in Table 10 in terms of return periods and PMF for selected design intervals (calculated using the equation given in Section 10.6).

Table 10
Minimum Design Floods (IDF) – Impact Classification
(in terms of return periods and PMF)[1]

CONSEQUENCE CLASSIFICATION CATEGORY	DESIGN INTERVAL [years]						
	10	20	50	100[2,4]	200[2,4]	500[3,4]	1,000[3,4]
High	**>500**	**>1,000**	**>2,500**	**>5,000**	**>10,000**	**PMF**	**PMF**

Significant	**500 to 200**	**1,000 to 200**	**2,500 to 250**	**5,000 to 500**	**10,000 to 1,000**	**PMF to 2,500**	**PMF to 5,000**
Low	**200**	**200**	**250**	**500**	**1,000**	**2,500**	**5,000**

Notes to Table 10:

[1] Derived from Table 9.

[2] Design intervals would typically apply to Phase 3.

[3] Design intervals would apply to Phase 4 or Phase 2B with tailings dam retrofitted for closure.

[4] For high return periods (*e.g.*, 5,000 or 10,000 years), selection of a PMF as the IDF should be considered.

In some cases, a PMF volume must be stored because of the potential for environmental impact, and IDF needs not be designed for (see discussion under the following ‘Environmental Design Flood’ heading). Nevertheless, an emergency spillway still should be provided.

Although the principles are essentially the same, designing for IDF in the case of tailings dams can be significantly different in details than in the case of conventional dams. This is because the size and land characteristics of tailings dam watershed as well as tailings pond operating requirements are usually significantly different from those typical of conventional dam watersheds and reservoir operations.

Some considerations relevant to the selection of flood design criteria are presented in Section 10.9 and a commentary on these criteria is included in Appendix A–XII.

Environmental Design Flood

Environmental design flood (EDF) is considered with respect to potential Type II failure (Table 1). It is the smallest flood, in terms of volume, during which a controlled discharge of contaminated tailings pond water is permitted so that the discharge results in an acceptable environmental impact (Appendix A–V.2).

In practice, EDF is assumed to be the largest flood, in terms of volume, that must be stored with another, somewhat larger flood selected to construct the discharge hydrograph necessary to estimate the impact on the downstream receiver(s). Under the larger flood, the release of contaminated water is proven to have an acceptable environmental impact, taking into consideration the expected frequency as well as the probability of occurrence of EDF during the design interval. [The flood storage capacity in tailings impoundment often varies during the production phase, with the most critical condition occurring immediately prior to the next stage/closure of the dam.]

In terms of generated runoff volume, EDF must be smaller than IDF. A flood with volume exceeding the design EDF volume is expected to occur on a statistically regular basis (this does not apply where PMF is selected as the EDF). The probability of this occurrence is computed with reference to the design interval.

In extreme but relatively frequent cases, a PMF volume is selected as the EDF (where, for instance, a multiple household water intake is located downstream of tailings dam containing contaminated water). In this case, there is no need to design for IDF.

A long sequence runoff event rather than a short term rainfall will have to be often selected as the EDF. Such an event may result from a sequence of rainfalls, rainfalls combined with snowmelt or snowmelt. In some cases, the EDF may correspond to a sequence of extreme wet and normal years.

Where the modelled EDF results from the combination of severe rainfall event and snowmelt, the snowpack and relevant temperature sequence may be selected as those corresponding to an event with return period of 5-10 years (on the 'wet' side), unless meteorological considerations indicate otherwise (note the recommendation on the initial pond level for EDF modelling stated earlier in this subsection). The reliability of hydrologic model needs be taken into consideration in the final selection of design snowmelt event.

A more detailed discussion on the determination of EDF is presented in Appendix A–XIV.

Low Flow Condition in the Receiver

Low flow condition in the receiver is considered with respect to potential Type II failure (Table 1). It is a critical low flow condition occurring in the receiving stream being impacted by either contaminated seepage or tailings pond overflow discharge, or both. During this occurrence, adequate water quality criteria still must be met in the stream, so that the resulting impact is acceptable.

Design return periods for the low flow events may vary depending on the sensitivity of the receiver, assimilative capacity of the receiving stream, water use, aquatic habitat downstream of the dam, *etc.*

In some jurisdictions, the 7Q20 or a similar concept is used with reference to specified water quality objectives ('7Q20' is a 7-day average low flow occurring, on the average, once in every 20 years). In this case, the acceptable environmental impact is 'pre-defined' since applying the 7Q20 criterion does not give any indication as to the environmental impact that would occur under stream flows lower than the 7Q20 (see also relevant discussions in Appendices A–II and A–V.2).

The design low flow condition is expected to occur on a statistically regular basis. The probability of this occurrence should be computed with reference to appropriate design interval, which may span more than one dam operating phase.

Low Flow Condition in Tailings Pond

Low flow condition in tailings pond is considered with respect to potential Type II failure in the 'special case' identified in Table 1. It refers to a critically low tailings pond inflow under which the water cover is reduced to a design minimum depth.

Various minimum water cover design depths have been considered, typically in the range of 0.01 to 0.5 m (the nominal water cover thickness with reference to the overflow spillway level has often been designed at 1 to 2 m). It needs be realised that the minimum design depth of water cover must be considered not only from the perspective of exposing tailings to air or the re-suspension of tailings solids but, also, from the standpoint of the reliability of the hydrologic and hydrogeologic (loss of seepage) models.

On a preliminary basis, the return period for the design low flow condition in tailings pond may be taken between 20 and 50 years, depending on the geochemical characteristics of the top tailings layer, degree of neutralisation potential left and the reactivity of tailings, the expected duration of the drought period, time of the year when this event is expected to occur, as well as the expected impact on the tailings pond and receiving water quality following the drought period. If the top tailings generate net acidity at the time of flooding, the above range of design return periods may have to be increased, depending on the expected impact. Although a detailed geochemical evaluation may be carried out in this regard, a conclusive prediction adequate for selecting the design return period may be difficult to arrive at (there are inherent inaccuracies associated with making such predictions). Hence, carrying out the designs based strictly on an acceptable environmental impact could be difficult in practice.

It is of interest to note that the *environmental design flood* and *low flow condition in the receiver* components of hydrologic designs for tailings dams refer to limited time periods, lasting only as long as the contamination is being generated and/or residual contamination is being flushed out. In the case of *low flow condition in tailings pond*, this design aspect refers to 'forever'.

10.8 EARTHQUAKE DESIGN CRITERIA

Maximum design earthquake (MDE) is considered with respect to potential Type I failure (Table 1). It is the earthquake that generates the maximum magnitude of ground motions at the dam site resulting in the largest seismic load or the most severe post-earthquake condition, which the dam must withstand without structural failure.

Permanent deformation of tailings dam structure due to MDE load is expected to occur. This may result in the necessity to retrofit the dam.

Potential failures of tailings dams that need be considered include those that would occur 'during' the earthquake or at some time after shaking (the 'liquefaction' failure), both as a result of earthquake generated loads.

The minimum earthquake design criteria recommended for designing of tailings dams with respect to potential Type I failure are presented in Tables 11 and 12. These two sets of criteria refer to the consequence categories resulting from the LLEL and impact classifications, respectively. The former criteria have been adapted from the 'Dam Safety Guidelines' (CDSA, 1995).

Table 11
Usual Minimum Design Criteria for Earthquake Loads[1,2]
(LLEL Classification)

CONSEQUENCE CLASSIFICATION CATEGORY	MAXIMUM DESIGN EARTHQUAKE	
	deterministically derived	probabilistically derived
Very High	MCE	0.0001
High[3,4,5]	50% to 100% MCE	0.001 – 0.0001
Low	–	0.01 – 0.001

Notes to Table 11:

[1] Adapted from the CDSA guidelines with notes [3], [4] and [5] added. See the CDSA guidelines (CDSA, 1995) for related discussions.

[2] Probabilistic criteria are expressed in terms of AEP, which indicates the probability that the design flood would be exceeded in any given year.

[3] For existing tailings dams, MCE or AEP=0.0001 should always be selected as the MDE where an increase in loss of life is expected, unless shown unjustifiable from an 'additional cost vs benefit' analysis. This applies to relatively short operating phases (Phase 1, Phase 2 and, possibly, Phase 3).

[4] For existing tailings dams and operating phases lasting significantly more than 100 years (i.e., Phase 4 and, often, Phase 3), MCE or AEP=0.0001 must be selected as the MDE where an increase in loss of life is expected (the significance of the '100-year' period is discussed in Section 10.9 and Appendix A–X).

[5] For new tailings dams, MCE or AEP=0.0001 should be selected as the MDE where the potential for loss of life exists, regardless of the phase.

Table 12
Minimum Design Criteria for Earthquakes – Preliminary
(Impact Classification)

CONSEQUENCE CLASSIFICATION CATEGORY	MAXIMUM DESIGN EARTHQUAKE[1,2,3]
High	<5% to MCE
Significant	5% to 20%[4]
Low	20%[4]

Notes to Table 12:

[1] Probabilistic criteria are expressed in terms of PEDDI, which defines the probability that the design earthquake would be exceeded during design interval. Design based on AEP rather than PEDDI may have to be carried out where the length of design interval cannot be established with a reasonable accuracy (Phase 3) or cannot be agreed upon/rationalised (Phase 4). This should be avoided, if possible. In general, the AEP values given in Table 11 are not considered adequate for applying to the CCCs established from the impact classification.

Notes to Table 12 (continued):

[2] Selection of a design PEDDI value between the limits shown may be based on the applicable determinant group (Table 4). For instance, 'A3+D3+S3' may become a rationale for selecting MCE as the MDE regardless of the length of the design interval while for the High category established from group 'A3+D2+S1+P1', PEDDI = 5% may be considered adequate (see also Appendices A–III.2 A–XII.4 for relevant discussion).

[3] The resulting return period for MDE should not be less than 200 years regardless of the consequence category and the length of design interval.

[4] For existing tailings dams with downstream slopes at their final configurations, the minimum PEDDI value applicable to the Low category and the lowest range of Significant category may be increased from 20% to 40% when designing for Phase 4, if substantiated based on a 'cost vs reduced risk' analysis.

Design earthquake events resulting from the criteria stated in Table 12 are presented in Table 13 in terms of return periods and MCE for selected design intervals (calculated using the equation given in Section 10.6).

Table 13
Minimum Design Earthquakes (MDE) – Impact Classification
(in terms of return periods and MCE)[1]

CONSEQUENCE CLASSIFICATION CATEGORY	DESIGN INTERVAL [years]						
	10	20	50	100[2,4]	200[2,4]	500[3,4]	1,000[3,4]
High	**>200**	**>400**	**>1,000**	**>2,000**	**>4,000**	**MCE**	**MCE**
Significant	**200**	**400 to 200**	**1,000 to 250**	**2,000 to 500**	**4,000 to 1,000**	**MCE To 2,500[5]**	**MCE to 5,000[5]**
Low	**200**	**200**	**250**	**500**	**1,000**	**2,500[5]**	**5,000[5]**

Notes to Table 13:

[1] Derived from Table 12.

[2] Design intervals would typically apply to Phase 3.

[3] Design intervals would apply to Phase 3, 4 or Phase 2B with tailings dam retrofitted for closure.

[4] For high return periods (*e.g.*, 2,000 or 5,000 years), the selection of MCE as the MDE should be considered.

[5] For PEDDI = 40% (see note [4], Table 12), the return periods of 1,000 and 2,000 years would apply to the design intervals of 500 and 1,000 years, respectively.

The design approach and analytical methods pertaining to earthquake generated loads are essentially the same for tailings dams as for conventional dams, except that the long design intervals associated with Phases 3 and 4, characteristic of tailings dams, must be taken into consideration. Comprehensive information on the methodologies used in earthquake engineering practice with respect to conventional dams is provided in '<u>Federal Guidelines for Earthquake Analyses and Design of Dams</u>', FEMA 65/March 1985, ICOLD Bulletin 46 titled '<u>Seismicity and Dam Design</u>', and other publications. ICOLD Bulletin 98 titled '<u>Tailings Dams and Seismicity</u>' specifically addresses seismic design analyses for tailings dams.

Earthquake design criteria selected for the tailings dam and associated discharge structure (*e.g.*, spillway), or any other tailings impoundment structure, should be the same wherever a failure or deformation of this structure due to earthquake load could result in the failure of tailings dam (design criteria selected for such a structure may be more stringent than the tailings dam criteria).

The operating basis earthquake (OBE) concept, which is often considered in the conventional dam engineering, has also been used for the design of tailings dams. The OBE concept does not seem to be well suited for tailings dams. In any case, since this concept cannot be related to the consequences of dam failure in the sense of either LLEL classification or impact classification (it relates to potential economic losses to the mine owner rather than potential environmental impacts, loss of life or damages to the downstream properties), no recommendations on the selection of OBE are presented in this Document.

Some considerations relevant to the selection of earthquake design criteria are presented in Section 10.9, and a commentary on these criteria is included in Appendix A–XII.

10.9 FLOOD AND EARTHQUAKE CRITERIA – APPLICATION

Summaries of the recommended flood and earthquake design criteria are presented in Tables 14 and 15 in terms of return periods and maximum possible events for selected design intervals.

The purpose of presenting Tables 14 and 15 must be well understood. These are not intended to compare, in any way, the consequences of potential dam failures in terms of environmental impacts and loss of life and/or economic losses. Such comparisons are neither practically possible nor necessary (see Appendix A–III.4). These two tables are merely intended to summarise the recommended flood and earthquake design criteria resulting from both the impact and LLEL classifications. The fact that the same terms are used for describing some consequence classification categories in both cases is coincidental.

Flood and Earthquake Criteria – LLEL Classification

The recommended 'usual minimum' flood and earthquake design criteria with respect to potential loss of life and/or economic losses have been adapted from a guideline developed for conventional dams and, as such, must be considered with caution.

Table 14
Summary of Flood Design Criteria Resulting From LLEL and Impact Classifications
(in terms of return periods [in years] or PMF, from Tables 8 and 9/10)

CONSEQUENCE CLASSIFICATION	CONSEQUENCE CLASSIFICATION CATEGORY	DESIGN INTERVAL [years]		
		20	100	500
Impact	High	1,000 – PMF	5,000 – PMF	PMF
	Significant	200 – 1,000	500 – 5,000	2,500 – PMF
	Low	200	500	2,500
LLEL	Very High	PMF		
	High	1,000 – PMF		
	Low	100 – 1,000		

Table 15
Summary of Earthquake Design Criteria Resulting From LLEL and Impact Classifications
(in terms of return periods [in years] or MCE, from Tables 11 and 12/13)

CONSEQUENCE CLASSIFICATION	CONSEQUENCE CLASSIFICATION CATEGORY	DESIGN INTERVAL [years]		
		20	100	500
Impact	High	400 – MCE	2,000 – MCE	MCE
	Significant	200 – 400	500 – 2,000	2,500 – MCE
	Low	200	500	2,500
LLEL	Very High	MCE		
	High	1,000 – 10,000 *or* 50% to 100% MCE		
	Low	100 – 1,000		

In particular, it is essential to note that the ranges of design criteria for the High and Low categories given in Tables 14 and 15 under the 'LLEL' headings, are not intended to relate to the various lengths of design intervals. These are intended for interpolating between the 'magnitudes' of the consequences of failure corresponding to the lower and upper limits of the categories, consistent with conventional dam engineering practice. Therefore, Tables 14 and 15 emphasise a significant shortcoming associated with the use of conventional dam engineering practice for designing of tailings dams: different probabilities of dam failure associated with different lengths of design intervals cannot be accounted for when using the conventional dam engineering approach (this shortcoming does not apply to the recommended design criteria resulting from the impact classification). This design aspect has to be taken into consideration when selecting appropriate flood and earthquake design criteria for tailings dams with respect to potential loss of life and/or economic losses.

The shortcoming mentioned in the preceding paragraph is perhaps best seen when comparing the duration of the closure phase taken at 500-1,000 years with the typical design interval applicable to conventional dams taken as 100 years (see Appendix A–X for relevant discussion). It is obvious that applying a design criterion (other than PMF or MCE) taken appropriate for conventional dams to designing for closure of tailings dam would be inappropriate and always on the 'wrong' side. Hence, notes [4] were added to Tables 8 and 11.

The above consideration is relevant to High category dams (LLEL classification) where the potential for loss of life is addressed. It may also be relevant to Low and High category dams when considering potential economic losses.

The rationale for adding notes [3] and [5] to tables 8 and 11 is discussed in Appendix A–XII.1.

Flood and Earthquake Criteria – Impact Classification

The minimum flood and earthquake design criteria recommended in Tables 9 and 12, are intended as being *reasonable* and *practically achievable*. Since much input from various professionals, mine owners, regulators and the public would be required to pass a relevant 'reasonability' test, these are termed '*preliminary*'. Regardless of any other considerations, these criteria may be used with confidence if the two following conditions are satisfied:

Condition 1: The selected design criteria offer a satisfactory level of protection against potential environmental impacts as judged and agreed upon by the stakeholders who may include the owner, the public, the regulatory agencies and the tailings dam engineer supported by environmental scientist.

Condition 2: An 'additional cost vs benefit' analysis indicates that providing a higher level of protection (a more stringent criterion) cannot reasonably be justified.

The necessity to satisfy Condition 1 is almost trivial.

Satisfying (explicitly) Condition 1 at each site would probably be necessary regardless of the above mentioned 'reasonability' test. This is because it is highly unlikely that the results of such a test would be conclusive and, if so, observed later by all the stakeholders at all sites.

Condition 2 is intended to ensure that tailings dams are designed using more stringent than the minimum design criteria (recommended in Tables 9 and 12), wherever the PMF or MCE need not apply and the project economics allows for implementing a more stringent criterion. This possibility should be investigated by the engineer with input from the owner (experience-based judgement or conducting a simple, rudimentary 'additional cost vs benefit' analysis would be sufficient in most cases). If considered potentially feasible, the engineer should develop a detailed rationale sufficient for the owner to make a learned decision in this regard. A commentary on Condition 2 is presented in Appendix A–XII.7.

The ranges of the recommended flood and earthquake criteria for tailings dams classified in the High category (impact classification) and short design intervals are relatively broad. This results from the difference between the recommended minimum PEDDI values for this category (2% and 5%, respectively) and the maximum possible events (PMF or MCE). With respect to tailings dams classified in the High category, Condition 2 requires that a consideration be given to selecting a maximum possible event as the design criterion, regardless of the length of design interval.

10.10 FREEBOARD

Freeboard requirements for tailings dams are strongly site specific and recommending generally applicable freeboard design criteria does not seem practically possible. In general, these requirements would be independent of the length of design interval. However, when selecting a design freeboard, other tailings dam operating attributes may have to be accounted for, together with the applicable CCCs and other site-specific considerations.

Freeboard requirements may vary from site to site, depending on the accuracy of the hydrologic model, tailings pond water quality, type of dam, method and rate of tailings deposition, location of tailings pond (adjacent to, or at a distance from the dam), WTP operating capacity and schedule as well as potential WTP breakdowns, requirements for passive treatment in tailings pond, existence of upstream 'internal' dams (often designed to withstand smaller than the tailings dam floods), reliability of upstream diversions, expected resistance of dam structure to deformations under single and/or repetitive seismic loads, *etc.*

For an embankment type dam with tailings pond located adjacent to the dam and the excess water discharging directly to the environment, the freeboard requirements are not different from those used in the conventional dam engineering, except that some of the factors listed in the preceding paragraph still have to be taken into consideration (*e.g.*, potential for failure of an internal dam or the tailings impoundment configuration varying with time). A comprehensive discussion of freeboard requirements for conventional dams is presented in 'Freeboard Criteria and Guidelines for Computing Freeboard Allowances for Storage Dams', U.S. Department of the Interior, Bureau of Reclamation, 1992.

For low permeability tailings dams where no tailings pond discharges are permitted under normal operating conditions, the freeboard requirements are more specific to tailings dams (most notably, the necessity to provide for a safe storage of EDF volume). In this case, it will be necessary to allow for appropriate wind setup above the maximum EDF pond level when selecting the top elevation of the low permeability zone. A 'safety factor' of 0.3 m may be considered reasonable in this respect, depending on the reliability of the hydrologic and wind velocity data.

For pervious tailings dams constructed of coarse tailings (typically, upstream tailings dams), the minimum freeboard will often have to be considered with reference to the design minimum width of tailings beach. In these cases, potential shear failure of the dam may be more critical than dam overtopping. Similar consideration could apply to a highly pervious dam constructed of rockfill, even though a filter zone may exist between the tailings deposit and dam structure. In this case, a minimum width of tailings beach may have to be specified for seepage control purposes.

Where a tailings dam is at its final height, it will often be possible to handle an insufficient freeboard by adjusting the site water management practice. This would not apply to Phases 2B and 4 during which the dam is no longer operated.

As a first approximation, freeboard requirements outlined in the following paragraphs may be considered. Approximate freeboard may have to be determined, for instance, at the conceptual design stage for the purpose of estimating the dam volume and associated construction costs. This could be particularly important in case of large tailings dam constructed of borrow materials.

Maximum Normal Pond Operating Level

For upstream tailings dams, a minimum width of tailings beach rather than freeboard will typically represent the governing criterion with respect to the allowable tailings pond levels. A minimum beach width of between 150 m and 450 m has often been found satisfactory for medium and high dams under normal operating conditions, although some dams have actually been operated with a tailings beach width of 50 m or less. Site-specific design considerations in this respect may include the margin of dam stability, the slope of tailings beach, flood storage requirements, precipitation and/or snowmelt conditions (this has to do with the raising of phreatic surface due to slope infiltration), allowable seepage losses, tailings gradation, susceptibility to slope erosion, site seismicity, etc.

As pointed out above, for highly pervious rockfill dams (with upstream filter zones and, possibly, upstream slope erosion protection), the minimum width of tailings beach will primarily depend on the allowable seepage losses.

For low permeability tailings dams classified in Very High category (LLEL classification) or High category (impact classification):

- where discharge of tailings pond water is permitted during normal operating conditions, the minimum freeboard may be assumed at 1.5 m or 2% of the dam largest height, whichever is greater;

- for tailings dams situated in areas of high seismicity, this freeboard depth may have to be increased when designing for Phase 4 and, possibly, Phase 3, depending on the expected resistance of dam structure to deformation (the dam will be subject to numerous earthquakes and resulting deformations during the long service life);
- where no discharge of tailings pond water is permitted under normal operating conditions, the minimum freeboard may be taken as 1.0 m above the allowance for storing the EDF volume;
- for dam sites where heavy tropical rains occur and the construction of large spillways for each stage-raise of tailings dam would be prohibitively expensive as well as for sites in arid and semi-arid climates, the approximate freeboards given above might not be adequate and should be determined on a site-specific basis.

For tailings dams classified in the lower consequence categories, the minimum freeboards indicated above may be reduced. However, a freeboard of less than 1.0 m should not be selected where tailings pond water discharge is permitted under normal conditions. Where no discharge of pond water is permitted under normal conditions (it is unlikely that this would apply to a Low category dam in terms of environmental impacts), the minimum freeboard should not be less than 0.5 m after the EDF volume is allowed for.

Maximum Permissible Pond Operating Level

For upstream tailings dams, the maximum permissible tailings pond level should be set in terms of minimum allowable width of tailings beach determined based on slope stability considerations (as noted previously, the phreatic surface under flood conditions may raise in response to both the change in tailings pond size and dam slope/beach infiltration).

Where tailings pond is located adjacent to the dam during Phase 4, the minimum freeboard for passing IDF may be assumed at 1.0, 0.6 or 0.3 m for dams classified in the Very High, High or Low category (LLEL classification), respectively. With respect to the impact classification, the same may be assumed for High, Significant or Low category dams. Experience from similar projects or a first approximation calculation would be required at the conceptual design level to 'guess-estimate' the IDF hydrograph. For other operating phases, these freeboards may be reduced, particularly where a PMF is selected as the IDF (assuming that PMF is determined with a reasonable degree of confidence).

The higher crest elevation of tailings dam, resulting from either the MNL or the MPL criterion, must be selected. Note that an 'additional' freeboard may be required to allow for having an emergency discharge spillway designed to stay permanently dry (Section 10.12).

10.11 FACTORS OF SAFETY IN DAM STABILITY ANALYSES

The stability of tailings dam under static loads is typically assessed based on the limit equilibrium method. Stability analyses are carried out, using either 'drained' or 'undrained' shear strength parameters, with reference to the design (specified) minimum acceptable factors of safety.

The safety factors commonly used in the drained strength analysis (often referred to as the 'effective stress analysis') are also recommended in Table 16, except that somewhat higher values are recommended for tailings dams retrofitted for closure. These safety factors are recommended with reference to dam stability analyses for which reasonably, but not overly conservative shear strength parameters and phreatic surface locations are selected (see Appendix A–XV.1).

Some proposed methods of tailings dam stability analyses have been designed to utilise other 'minimum acceptable' safety factors, particularly when using the undrained shear strength parameters (see, for instance, the proposal by Steve J. Poulos', 'Strength for Static and Dynamic Stability Analysis', Hydraulic Fill Structures, Geotechnical Special Publication No. 21, 1988).

Table 16
Minimum Safety for Stability Analyses under Static Loads[1,2,3]
(drained strength analysis)

TAILINGS POND LEVEL	DAM SLOPE	DAM CONFIGURATION			
		TEMPORARY to be raised in future	FINAL Not retrofitted for closure		FINAL retrofitted for closure
		Phase 1A	Phase 1B	Phases 2&3	Phases 2B&4
maximum permissible pond level (MPL)	downstream	1.5	1.5	1.5	1.6 – 1.8
most critical pond level	upstream[4]	1.3 – 1.5	1.3 – 1.5	1.5	1.6 – 1.8
most critical pond level (post-earthquake)	upstream[4]	1.1 – 1.2			
maximum normal pond level (MNL) (post-earthquake)	downstream	1.1 – 1.2			

Notes to Table 16:

[1] Safety factors higher than indicated may have to be selected where significant uncertainties with respect to the as-built conditions, seismologic database, subsurface conditions, etc., exist.

[2] Safety factors lower than those indicated may be justified in the stability analyses carried out assuming, e.g., a filter zone completely plugged with time and other extreme dam performance conditions. Evaluation of dam stability under such conditions would be particularly relevant to designing for long lasting phases, especially Phase 4.

[3] All other being factors equal, the indicated upper bound values could be considered for 'higher category' tailings dams while the lower bound values could be considered for dams classified in low categories (see Appendix A–IX for discussion on design conservatism).

[4] Likelihood of dam breach following a slope failure in the upstream direction should be taken into consideration when selecting an appropriate factor of safety.

The safety factors recommended in Table 16 are not intended for use in undrained strength analyses (see Appendix A–XV.2 for relevant discussion).

A pseudo-static analysis may be carried out for tailings dams where no potential for partial or complete liquefaction of dam and dam foundation materials exists (a 1/3 reduction factor with respect to the maximum peak ground acceleration is often used). Where this analysis is carried out to address potential failure in the downstream direction, the MNL may be assumed for the time that the MDE occurs (see Section 10.7). When addressing potential failure in the upstream direction, the most critical pond level below the MNL may have to be found and analysed. A minimum safety factor of 1.1–1.2 can then be selected for design purposes, consistent with the widely accepted practice.

[The primary purpose of conducting a pseudo-static analysis for tailings dam is to compute a 'screening value' safety factor. Depending on this value and other design data such as, for instance, the magnitude of design peak ground acceleration or freeboard depth, a dam deformation analysis may have to be carried out. Newark's type analysis is often used, however, carrying out a more sophisticated finite element analysis could be justified in the case of a 'major' tailings dam.]

A commentary on liquefaction potential and post-earthquake stability analyses is provided in Appendix A–XV.3.

10.12 DISCHARGE FACILITIES

A variety of outlet (or 'discharge') facilities are used at tailings dam sites, as discussed in Appendix A–XVI. Examination of the conditions of existing discharge facility(ies) is an integral part of each tailings dam safety evaluation. Evaluation of the capacity of discharge facility would be required in conjunction with conducting a DSR or dam design. This aspect of tailings dam safety needs be considered from the perspective of both passing the flows and/or controlling water storage volumes as well as the structural integrity of tailings dam, wherever a decant pipe or tunnel is passing through or under the dam.

Where a decant pipe or tunnel is designed to pass through or under the dam, the fundamental design requirement is that adequate *detailed* designs for eventual plugging of the decant structure be developed at the initial design stage, taking into consideration the potential deterioration/failure of the plug – decant structure system in the short and very long terms. Wherever practically possible, the construction of such structures should be avoided. Where such a structure is to be constructed, its potential failure prior to and after plugging needs be considered in relation to the potential failure of tailings dam.

Where no discharge of tailings pond water is permitted under normal operating conditions, the typical discharge arrangement comprises a pumping facility and an emergency discharge structure. Such a structure should be provided even if the tailings impoundment is designed to store a PMF volume.

Where the tailings dam is at its final configuration fully retrofitted for closure (Phase 4 and, most likely, Phase 2B), the discharge facility(ies) should be in the form of an open channel spillway. Emergency discharge facility during

Phases 1, 2A and 3 should also be in the form of an open channel spillway, wherever practically possible.

Where the presence of on-site personnel is not continuous and the tailings pond discharges on a continuous or near-continuous (as opposite to 'occasional') basis, an emergency spillway with the invert situated slightly above the maximum permissible pond level should be provided. This spillway would be designed to stay permanently dry (under all floods less severe than the IDF), except when, and if, the primary discharge facility fails as a result of plugging by brush, ice, beavers, *etc.* This consideration would be particularly important in the case of tailings dams classified in higher consequence categories.

As pointed out in Section 7.2, for remote sites where on-site personnel are not continuously present, having a remote monitoring of the tailings pond level and a surveillance camera showing the discharge structure would enhance tailings dam safety.

Design flows for discharge facility(ies) should be determined taking into consideration the reliability of the hydrologic model. A design conservatism may be justified when designing for Phase 4 (the severity of extreme hydrologic events, particularly where determined based on the probabilistic method, tends to increase with enlargements of hydrologic databases).

A commentary on discharge facilities is provided in Appendix A–XVI.

10.13 TAILINGS DAM CONSTRUCTION MATERIALS

The design aspects relating to tailings dam construction materials are addressed in ICOLD Bulletins 97, 103 and 106. The use of geosynthetics and acid generating mine wastes for tailings dam construction is briefly discussed in this subsection.

The use of geosynthetics for construction of tailings dams is often economically (and environmentally) attractive, and is acceptable as long as the eventual deterioration of such materials is accounted for. In this regard, the use geosynthetics needs be considered with caution.

The common example is a plastic liner built into, or installed over tailings dam structure, designed to function as a low permeability zone. Although well selected, designed and installed plastic liner would be expected to perform satisfactorily during Phases 1, 2 and perhaps even during Phase 3, there seems to be no proof available at this time that the liner would last, performing according to the design function, also during Phase 4 (*i.e.*, in the very long term).

Should the containment of actual or potential contamination were to depend on the performance of plastic liner during Phase 4, incorporating a liner in tailings dam design might or might not be acceptable. For instance, should residual contamination be trapped behind the dam, it could be argued in most cases that the contamination would be released extremely slowly during the long process of liner deterioration (the liner would not be expected to deteriorate 'overnight').

On the other hand, where a flooded deposit of acid generating tailings is to be contained by tailings dam, incorporating plastic liner into the dam design would not be acceptable unless it can be reasonably proven, from the results of hydrogeochemical and other analyses, that the release of contamination would be sufficiently slow to meet appropriate environmental design criteria, even after the complete deterioration of the liner (under some circumstances, it may be very likely that by the time of complete liner deterioration, the rate of contamination generated in tailings would be extremely slow).

Should the structural integrity of tailings dam were to depend on the performance of plastic liner during Phase 4, incorporating a liner into tailings dam design would not be acceptable. Defensive measures designed and implemented to ensure tailings dam safety upon complete deterioration of the liner could alleviate this concern.

Similar comments apply to the use of filter fabrics for tailings dams construction.

The use of *freshly* ground (tailings) or mined (waste rock) materials containing sulphides for tailings dam construction is primarily a question of the available neutralisation potential, expected rate of contaminant generation, economics during the production phase and closure design philosophy, as well as the long term safety of dam (note that some tailings and waste rock need not generate net acidity to become a source of significant contamination). Although it would be best to avoid the use of AMD generating materials for tailings dam construction, under some circumstances this option may still be viable, for instance, in arid climate or permafrost area, or where a ‘collect and treat’ operation is to be implemented at the site for reasons other than the generation of AMD in dam materials. An economic analysis could also indicate the advantage of using acid generating materials for dam construction, for instance, where no borrow materials are available in the site vicinity while (acid generating) waste rock is plentiful or some ‘ideal’ conditions for the construction of an upstream tailings dam exist. Long term treatment would then be a penalty.

Except for dams in arid climate or permafrost area, it seems that constructing a tailings dam of AMD generating materials based on purely economic considerations could be justified in few, exceptional cases only.

Nonetheless, the use of AMD generating materials for dam construction could be justified when considering the long term physical safety of tailings dam and the consequences of potential Type I failure. This could apply to the situation where a water cover represents the only practical option to prevent AMD generation in tailings, but is considered undesirable with respect to the long term safety of tailings dam (see relevant discussion in Appendix–XI.4). In this case, if AMD generation in tailings is permitted after mine closure, then the use of AMD generating materials (tailings or waste rock) for dam construction could be reasonable.

The use of *oxidised* mine waste materials for tailings dam construction, *i.e.* sulphide bearing materials that have been exposed to oxygen and water infiltration for a period of time prior to construction, whether generating acidic or neutral drainage, could lead in some cases to the potential for severe environmental impact. On one project, the use of oxidised tailings for dam construction resulted in more than two orders of magnitude increase in contaminant concentrations in groundwater, associated with the dissolution of salts and hydroxides that precipitated in the ‘in-situ’ tailings prior to construction. Similar, although less extreme increases were observed associated with re-working of waste rock containing sulphides. Hence, the use of oxidised mine waste materials for dam construction should generally be avoided.

APPENDICES

Appendix A
Commentary

Appendix B
Sample Tailings Dam Inspection Forms

Appendix A

Commentary

APPENDIX A – CONTENTS

I TAILINGS vs CONVENTIONAL DAMS

Some of the most fundamental differences between tailings and conventional (*e.g.*, hydroelectric, irrigation, flood control or water supply) dams, identified from the perspective of dam safety evaluation requirements, include:

- There is no need to design a conventional tailings dam to last for a very long time, say, hundreds of years or more. While a conventional dam can be assumed to cease functioning in the foreseeable future (*e.g.*, at the time of decommissioning a power plant), a typical tailings dam will have to function long after the mining operation ceases.
- Design intervals for tailings dams may vary from 1 year (stage-raise of dam) to 500 years or more (closure phase) while for conventional dams, the design interval is usually taken to be in the order of 100 years.
- At many modern tailings disposal operations one of the primary objectives is to operate a dam with the purpose of controlling the release of contamination, in addition to storing tailings and re-cycling process water. This is not typical of conventional dams where the primary objective is to operate uncontaminated water reservoirs.
- Consequently, while ensuring the physical stability of dam structure and appurtenances represents the most critical aspect of dam safety for conventional dams, for tailings dams containing contaminated water and/or reactive solids, the containment of actual or potential contamination typically represents an equally critical dam safety aspect, which is not relevant to conventional dams.
- In the majority of cases, tailings dam operating attributes vary significantly with time and the dam operating phase (*e.g.*, tailings pond water balance, hydraulic head or the opportunity to conduct dam surveillance on a frequent basis). This is not characteristic of conventional dams.
- Tailings dams are typically constructed in stages or on a continuous basis, over many years while conventional dams are constructed in one stage, over a relatively short time period. There are numerous consequences of this difference.

  For instance, the actual performance of a typical, stage-constructed tailings dam cannot be fully evaluated, in terms of its physical stability under normal loads, until the last stage of the dam is constructed, the impoundment immediately upstream of the dam is completely filled with tailings, and the tailings pond reaches and maintains, for a period of time, its highest normal operating level. This would only be possible at the end of mine operation. In the case of conventional dams, such an evaluation can be made shortly after construction (after the initial filling).

- For conventional dams, excessive seepage which does not endanger the safety of dam structure will not likely affect the downstream users, environment or properties while for tailings dams containing contaminated water, excessive seepage may result in environmental damage and, in some instances, may also become a health hazard.
- A tailings dam containing contaminated water may be operated without discharge and, in some cases, without a spillway or decant structure while the majority of conventional dams are designed to pass flows on a continuous or, at least, intermittent basis.
- While potential for contaminant generation in tailings dam construction materials (typically, in reactive waste rock or tailings) is characteristic of many tailings dams, it does not represent a significant safety aspect in the case of conventional dams.

  Climatic conditions may strongly influence the design of tailings dam not only from the perspective of flood or frost protection and similar criteria but, also, when selecting dam construction materials. Under permafrost or very dry climatic conditions, the use of reactive tailings or waste rock for tailings dam construction could be viable while in a wet climate, the use of such materials might be unacceptable or prohibitively expensive due to environmental constraints.
- Some tailings dams may be designed as pervious structures that need not retain a reservoir (tailings pond), or may need to retain a small pond only with large seepage flows permitted, contrary to conventional dams.
- A conventional dam usually intercepts runoff from a significantly larger watershed as compared with the majority of tailings dam watersheds. This represents an essential difference between tailings and conventional dams from the perspective of selecting appropriate hydrologic design techniques and criteria.
- For many tailings dams, the designer has to account for a combination of site-specific conditions such as a certain 'dam structure – pond water level – tailings beach' configuration and the degree of pond water contamination, both occurring at a time in future. Taking into account the inherent difficulties with predicting future contaminant levels and tailings deposit configurations (one has to be practical), it follows that the designer has to account for a combination of ‘events’ that may or may not occur during the service life of the dam. [This is similar to, but significantly more complex than designing for flood resulting from a combination of precipitation and snowmelt events that may or may not occur during the service life of the dam.]

  These types of design considerations would not be relevant to conventional dams which work, in principle, as ‘steady-state’ structures under normal loads. In contrast, tailings dams prior to mine closure work like ‘transient’, generally non-linear with respect to time systems (the time dependent parameters may include the hydraulic head, dam structure and foundation loads, degree of contamination, *etc.*).

The above discussion must not be seen as an overstatement of the complexity of tailings dams. To prove the point, consider one of the most typical tailings dam design assignments, which involves the prediction of contaminant loadings associated with dam seepage. The actual loading rate will depend at any point in time on the hydraulic head, attenuation capacity of tailings deposit as well as dam and dam foundation materials, the history of process water chemistry, current and past tailings pond configurations, hydraulic conductivity of tailings deposit, hydraulic conductivities of dam and dam foundation materials, geochemical reactions in tailings pond water and groundwater; and other factors.

The differences between tailings and conventional dams are well understood by tailings dam engineers. Nevertheless, it still happens that an author of publication on tailings dams refers the reader, without qualifications, to the conventional dam engineering when discussing an embankment type tailings dam. This may lead to confusion, at the best.

There are other, less technical differences between tailings and conventional dams that are relevant to evaluating dam safety. In contrast to tailings dams, conventional dams are usually owned and operated by a state, province, public utility company or a water resource authority. These dam operators typically have relatively large resources and a different kind of relationship with the public in the sense that the public is often a direct recipient of the benefits of dam operation. The value of these benefits is less subject to market fluctuations and competition, as compared with the value of the mining product. It follows that the approaches to dam safety evaluations taken by the owners of conventional and tailings dams could be different. Indeed, many hydroelectric companies permanently maintain on staff teams of highly experienced dam safety engineers, while it is rather rare today for a mine owner to maintain such a team. The mine owners rely more heavily on retained engineering firms. This may have both positive and negative effects. On one hand, having an outside engineer conducting dam safety evaluation may allow for a more objective evaluation and lesser ‘internal pressure’ to necessarily arrive at a least costly solution. On the other hand, some important information on tailings dam conditions may be lost as a new engineering firm is retained. [There are other, significant differences in the approaches to the construction and operation of dams, including the evaluation of safety of dams, taken by the owners of conventional and tailings dams.]

Construction and operation of tailings dam is sometimes considered to be an unprofitable, money draining part of the mine operation (an ‘unwanted burden’). This is an inappropriate view, which will bring benefits to neither the owner nor the public. The proper approach is to view tailings disposal as an intrinsic part of the mine operation, being part of the profit making, similar to the use of reagents, power, site security or the maintenance of mine access road. It is true that a tailings deposit, including the tailings dam, will represent a liability long after the mine operation and profit making cease. The only way to cope with such an unpleasant outlook is to incorporate this liability into the balance sheet as a day-to-day expense since day one (this is now routinely followed in Canada). Again, these types of considerations do not apply to conventional dams which, in principle, represent a liability only as long as the benefits are generated.

II TYPE I AND TYPE II FAILURES

As discussed in Section 3, the design of tailings dams with respect to potential Type I and Type II failures should be based on the two consequence classifications and acceptable environmental impact, respectively. The need to follow these two different design approaches is elaborated on in this section.

The basic design questions and methods pertaining to the Type I and Type II failures can be summarised as:

Type I failure: What would be the consequences of structural failure of tailings dam? The design criteria, and the resulting dam construction costs, are selected such that the risk of potential failure of dam is acceptable.

Type II failure: What would be the environmental impact resulting from tailings dam operation? The design criteria, and the resulting dam construction costs, are selected such that the impact associated with dam operation is acceptable.

The fundamental difference between these two design approaches is that during the service life of tailings dam, no release of contamination through the Type I pathways (Table 1) is expected to occur. On the contrary, the release of contamination through the Type II pathways, occurring either on a continuos or intermittent basis, is expected and permissible as long as the resulting impact is acceptable. In other words, if a tailings dam fails in the sense of Type I failure, *contamination is released*. If a tailings dam fails in the sense of Type II failure, *the contamination is released in excess of an acceptable level*, thus resulting in an unacceptable environmental impact ('acceptable environmental impact' is defined, from the design perspective, in Section V.2).

Consequently, from the perspective of potential Type II failure, there may be an *indefinite number* of environmental impacts, each more severe than the acceptable impact. When considering Type I failure, a *distinct* environmental impact resulting from potential dam breach can be (at least, in principle) defined and accounted for when selecting appropriate dam safety evaluation requirements.

The approach to dam design with respect to potential Type I failure, based on the consequence classification method, is well known. To illustrate the design approach based on acceptable environmental impact, the two most common design assignments pertaining to potential Type II failure are outlined below.

Where the potential consequences of occasional discharges of contaminated tailings pond water through an emergency spillway are examined, it is found that these discharges would result in an acceptable impact provided that sufficient dilution is available, and the discharge frequency and durations are tolerably short. Such discharges should then be permitted, unless they can be prevented at a reasonable cost. The relevant designs are therefore developed based on an acceptable environmental impact. The design objective is to prevent discharges when no sufficient dilution is available and/or the expected frequency/durations of discharge are not tolerable. This tailings dam safety aspect is handled by designing for 'environmental design flood' (Sections 10.7 and XIV).

Considering contaminated seepage bypassing tailings dam site and reporting to a receiving stream, the seepage would result in an acceptable impact provided that the stream flow is sufficiently high. Again, dam seepage in this case should be permitted if the stream flow is sufficiently high under most conditions. This tailings dam safety aspect is handled by designing for 'low flow condition in the receiver' (Section 10.7).

The above discussion implies that the concept of the consequence classification method cannot easily be adapted for the design of tailings dams with respect to potential Type II failure. This is perhaps unfortunate since the primary advantage of using the consequence classification method, that is, being able to use the same standards at various sites, is lost. In most cases, the design criteria relating to potential Type II failure have to be defined on a site-specific basis.

In some jurisdictions, acceptable environmental impact may be 'pre-defined' (see discussion on the 7Q20 flow criterion in Section 10.7 under the 'Low Flow Condition in the Receiver' heading). The advantage of having such pre-defined criterion is that no work needs be done to determine acceptable environmental impact. It should be noted, however, that these types of criteria are often very conservative (relatively high 'safety factors' are used to arrive at water quality objectives, which are meant to apply to a wide variety of conditions that may be encountered within the jurisdiction). Hence, it may be advantageous to carry out a special evaluation to determine appropriate design criteria based on site-specific considerations. Such criteria could be less stringent and yet acceptable.

In some jurisdictions, a limit on acceptable environmental impacts may also be set with respect to designing for EDF. In British Columbia, for instance, the acceptable environmental impact is limited with respect to the confinement of AMD contaminated waters by the requirement to use a 1 in 200 years flood as a minimum design criterion (W.A. Price and J.C. Errington, 'Guidelines for Metal Leaching and Acid Rock Drainage at Minesites', Ministry of Energy and Mines, August, 1998). As shown in the example discussed in Section XIV, the actual design criterion (the EDF) had to be selected far more stringent than the minimum allowable criterion on a tailings dam project in British Columbia.

Therefore, to avoid either overly conservatism or being non-conservative, acceptable environmental impact may have to be determined on a site-specific basis, with reference to the relevant regulatory requirements (if existing).

III CONSEQUENCE CLASSIFICATIONS

III.1 LELL Classification

The consequence classification in terms of potential loss of life and/or economic losses selected for the purpose of this Document is that recommended by the CDSA. As pointed out in Section 4.1, another consequence-based classification developed for conventional dams could have been selected, however, the CDSA classification has some advantages from the tailings dams perspective.

One of the reasons for choosing the CDSA classification is that it does not incorporate a dam height–impoundment storage parameter, contrary to many other conventional dam classifications. This parameter is not well suited for tailings dams and, based on conventional dam engineering practice, could not readily be applied to tailings dams where a sudden discharge of liquefied tailings mass rather than an amount of uncontaminated water often represents the key safety concern. Also, the flood and earthquake design criteria recommended by the CDSA (Tables 8 and 11) do not incorporate fractions of PMF and MCE (except for the alternative 50% to 100% MCE), the use of which is difficult to rationalise (see Section XII.1 under the 'Fractions of PMF and MCE' heading).

III.2 Impact Classification

Before discussing the impact classification introduced in Section 4.2, it needs be emphasised that this classification has been derived for a very specific purpose: to address the safety of tailings dams. As such, it must not be examined 'out of the context', *i.e.*, in separation from the other contents of this Document.

The impact classification in itself does not have any real meaning with regard to tailings dam safety. Although a tailings dam can be classified based on Tables 3 and 4 (Section 4.2), these tables do not contain any information as to the appropriate dam safety evaluation criteria, scope, standards, *etc*. It is only after such requirements are designated for each of the consequence classification categories (Sections 7 through 10), the merits of the proposed impact classification can be judged.

Table 3

Determinants identified in Table 3, on which the impact classification is based, indicate a fundamental difference between the consequence classifications in terms of potential environmental impacts and loss of life and/or economic losses. While in the latter case single, well-defined determinants exist (the number of lives lost and the monetary value of economic loss), specifying a single determinant with respect to potential environmental impacts does not seem to be practically possible.

The set up of Table 3 also indicates that specifying quantitative parameters (or 'measuring sticks') in order to differentiate between the determinant classes '1', '2' and '3' is not considered practical. Instead, largely qualitative examples are provided to guide the selection of an appropriate class based on experience and judgement, with reference to site-specific conditions. Such an approach obviously leaves room for ambiguities, however, it does not seem that this shortcoming could easily be overcome. It may be reasonably expected that if a number of people are asked to define those measuring sticks, one might get the same number of surprisingly different answers, even from environmental scientists working in different environmental settings.

In fact, this problem is common to practically all consequence classifications developed for conventional dams where the consequence categories are broadly defined, leaving room for ambiguities as well. This is because no measuring sticks can readily be provided with respect to the number of lives lost, or even the monetary value of economic losses.

A great number of measuring sticks would be required and appropriate relationships between the various types of environmental impacts established to make the impact classification more precise. This would likely make such a classification too complex for practical use. It is possible, however, to provide some measuring sticks with respect to specific environmental impacts, as discussed below.

Mr. Paul McKee of Beak International Incorporated, an environmental scientist with extensive experience in evaluating environmental impacts for mining and other projects, reviewed Table 3 and showed how the determinant classes could be quantified, primarily from the aquatic life perspective. This is presented in Table A-1.

A comparison of Tables 3 and A-1 indicates that Mr. McKee also included the 'Extent of Downstream Impact' as a separate determinant. In the context of Table 3, this determinant is included under the 'Amount of Impact' in order to keep the number of determinants to a minimum, thus simplifying the impact classification.

Similar to Table A-1, tables could be prepared to address environmental impacts relating to the contamination of groundwater, domestic water supply, terrestrial habitat, *etc*. The use of such 'multi-table' classification would be rather complex since the dam safety evaluation requirements would have to be designated separately with reference to each of these tables. This is because much difficulty would arise with deriving suitable correlations between, for instance, '>50% reduction in aquatic species' and the corresponding 'degree and extent of groundwater contamination'.

Table A-1
Selected Determinants for Establishing Consequence Categories in Terms of Potential Environmental Impacts for Tailings Dams

DETERMINANT	RELATIVE RATING	CLASS	EXAMPLES OF ENVIRONMENTAL IMPACTS
A Amount of Impact	large	A3	Discharge results in >50% reduction in total number or numbers of species of fish or invertebrates in receiving water[1]
	moderate	A2	Discharge results in 30-50% reduction in total number or numbers of species of fish and invertebrates in receiving water
	small	A1	Discharge results in reduction in total number or numbers of species of fish or invertebrates <30%
E Extent of Downstream Impact	large	E3	>30% loss of fish or invertebrate numbers or species extending downstream by at least two stream orders
	moderate	E2	>30% loss of fish or invertebrate numbers or species extending downstream by no more than one stream order
	small	E1	>30% loss of fish or invertebrate numbers or species not exceeding beyond the immediate mixing zone[2]
D Duration of Impact	very long	D3	Significant impacts[3] persist for decades beyond mine life or years beyond dam failure[4]
	long	D2	Significant impacts persist for less than one decade beyond mine life or less than one year beyond dam failure
	short	D1	Significant impacts do not occur or persist for more than approximately one year or less beyond mine life
S Sensitivity of Downstream Environment	very sensitive	S3	Downstream aquatic resources[5] support regular commercial, subsistence or sport harvest, involving multiple individual users annually <u>or</u> rare or endangered aquatic or semi-aquatic species or fish stocks are present <u>or</u> aquatic habitat is recognised as ecologically unique or important[6] at a regional scale <u>or</u> water used in domestic water supply
	sensitive	S2	Downstream aquatic resources support occasional commercial, subsistence or sport harvest involving few users <u>and</u> rare or endangered aquatic or semi-aquatic species or fish stocks are not present <u>and</u> aquatic habitats not recognised as regionally unique or important but may be of local importance[6]
	not very sensitive	S1	Downstream aquatic resources not known to be harvested; rare or endangered aquatic or semi-aquatic fish species or fish stocks not present; aquatic habitats not recognised as locally important
P Public Perception	strong	P3	Special interest groups involved (lands claimed by aboriginal people or proximity to wilderness park)
	typical	P2	No special interest groups, interest of local communities
	not significant	P1	Little interest from parties other than the regulators

Notes to Table A-1:

[1] Receiving water – surface water receiving a discharge, after immediate mixing (i.e., after cross-channel mixing is achieved or until discharge is diluted to 1% concentration, whichever is achieved first).
[2] Mixing zone – the zone of physical mixing of discharged water, as defined in note 1.
[3] Significant impacts – those defined as classes '3' or '2'.
[4] As defined in Table 1.
[5] Downstream aquatic resources – fish, shellfish or other aquatic resources occurring within the same watershed as the dam.
[6] Regionally unique or important habitats – habitats that are recognised as ecologically unique or important beyond the watershed of interest. For example, comparable aquatic features are generally not found within 50 km. Local importance is assigned to aquatic features unique or important at scales of 10 to 50 km.

For the purpose of this Document, the more general Table 3 is used to allow for having some flexibility in establishing appropriate CCC with respect to a variety of potential environmental impacts. The use of Table A-1 would certainly be beneficial as less judgement would be required (site-specific conditions still would have to be taken into consideration). In this case, the impact classification and the resulting tailings dam safety evaluation requirements stated in Sections 7-10 might have to be adjusted, consistent with the intent of this Document.

Table 4

The classification outlined in Table 4 stipulates that the 'strong' public perception determinant (P3) must not force the High category even if one of the other determinants is in class ‘3’. On the other hand, determinant P3 would force the Significant category even if all of the remaining determinants were in class ‘1’. This is considered a reasonable approach, subject to note [1] under Table 4.

The impact classification also stipulates that only one determinant of class ‘3’ (the most severe class) should not force the High category. This proposal may be evaluated by comparing the following determinant groups:

I	A3 + D3 + S3	*(High category)*
III	A3 + D1 + S1 / A1 + D3 + S1 / A1 + D1 + S3	*(Significant category)*

In general, it would be unreasonable to designate the same dam safety requirements to groups I and III. Nevertheless, the selection of a safety requirement resulting from the High category for tailings dam classified in group III could be justified under some circumstances. This could apply to a site where one of the three determinants is considered, for good reasons, of paramount importance. Conversely, selecting dam safety requirements associated with the Significant category for tailings dam classified in group I might also be judged reasonable under some circumstances.

The preceding paragraph emphasises an important simplification incorporated in the impact classification. It relates to the determinants A, D and S being given the same ‘weight’ (*e.g.*, A1 is given the same ‘weight’ as D1 or S1). Because of this simplification, the groupings of determinants shown in Table 4 (*e.g.*, A3 + D2 and/or S2) may seem indicative of a 'neat and simplistic' (or ‘mathematical’, to avoid the term 'engineering') approach taken to define appropriate determinant groups. This is certainly true, however, it also true that these groups have been defined to simplify the classification of tailings dams so that it can be used for practical purposes. And any simplification means that ‘imperfections’ must occur. This is common to all real-life classifications.

For these reasons, the impact classification is intended as a general framework (as pointed out in Section 4.2), which needs be critically examined in each case. Adjustments, as necessary, may have to be introduced and, if so, the resulting dam safety evaluation requirements might also have to be adjusted consistent with the intent of this Document.

In fact, within the framework of tailings dam safety evaluation process described in this Document, any consequence-based classification in terms of potential environmental impacts could be substituted for the impact classification provided that, for practical reasons, not more than three consequence categories (*e.g.*, Low, Significant and High – the terminology is not essential) are identified. Again, specific tailings dam safety evaluation requirements, which are discussed with reference to the impact classification throughout this Document, might have to then be adjusted.

III.3 Clean Up, Habitat Restoration and Similar Works

As indicated in Section 4.2, the clean-up, habitat restoration and similar works, which would have to be performed following a failure of tailings dam, are not relevant in the context of tailings dam classification. Such works relate to the owner’s economic losses (see Section IV), similar to the losses that would result from the temporary shutdown of mill/mine operation. In other words, potential environmental impacts are to be determined for the purpose of classifying a tailings dam without making allowances for clean-up, habitat restoration and similar works. This is consistent with the consequence classification method. Within this method, for instance, economic losses to the downstream properties are considered to be a consequence of potential dam failure, regardless of the dam owner reimbursing the owner of downstream property.

The opposite view, meaning that the cost of clean up of released tailings would not be high and thus the proposed designs were acceptable, was presented to a regulatory agency in Eastern Canada, several years ago. It would obviously be very attractive to the owners if lenient dam safety standards could be applied on the account of low clean up cost. In this Document, however, such an approach cannot be endorsed for four reasons. Firstly, it would be inconsistent with the consequence classification method. Secondly, a reasonably accurate estimation of clean up costs would not practically be possible in most cases where a potential dam breach is examined. Thirdly, the owner’s reputation could seriously suffer even if the clean up cost is low. Fourthly, these types of design ‘solutions’ should not be permitted if we are serious about tailings dam safety.

[It is of interest to note that the cost of environmental clean-up represents one of the aspects that make potential environmental impacts truly different from potential economic losses. A low cost environmental clean-up might, in some situations, prevent a severe impact (think, for instance, of the release of 5,000 tonnes of sulphidic tailings which, if not cleaned up, would contaminate a sensitive stream for hundreds of years). When considering economic losses to downstream properties, such a situation would not be possible.]

III.4 Is Impact Classification Really Needed?

Incorporating the impact classification into tailings dam safety evaluation process is consistent with using the LLEL classification. In fact, the impact classification can be thought of as that 'removed' from the LLEL classification by deleting the 'environmental losses' (see Table 2 in Section 4.1) and considering such losses separately.

[It seems that in the CDSA and similar classifications developed for conventional dams, the phrase 'environmental losses' is included because it obviously has to be there. However, little guidelines are usually provided on how to evaluate the magnitude of such losses. On the contrary, the loss of life and economic losses receive the deserved attention (see, *e.g.*, G.M. Salmon and G.R. von Hehn, 'Consequence Based Dam Safety Criteria for Floods and Earthquakes', International Workshop on Dam Safety Evaluation, 1993).]

Although revisions may be required to satisfactorily improve the proposed impact classification, the fact is that such a classification needs be introduced. Otherwise, no consistent approach to tailings dam safety evaluations could be developed with respect to potential Type I failure in terms of potential environmental impacts based on the consequence classification method, and there seems to be no currently available alternative method.

Yet, many tailings dams have been successfully designed in the past, and their safety adequately evaluated based on experience and judgement, without the use of an 'impact' classification developed for tailings dams. A significant shortcoming of this approach is that it is not well suited for predicting the eventual outcome of dam safety evaluation (which is essential to the owners' planning their operations). This is because the selection of dam safety evaluation requirements may be strongly influenced by the personal disposition of the engineer and the regulator, as pointed out in Section 3.2. Neither this approach is well suited for passing experience from one project to another or applying the same principles to various projects. In other words, as long as no consistent 'impact' classification is employed, it may reasonably be expected that different tailings dam safety evaluation requirements will be specified at various mine sites, thus resulting in some tailings dams being necessarily less safe than others.

One of the primary reasons for introducing the impact classification is the premise that potential environmental impacts should be considered separately from potential loss of life. A comparison of the consequences of potential dam failure in terms of environmental impacts and loss of life does not seem really possible. There is no (and, perhaps, there will never be) a generally acceptable rationale based on which such a comparison can be made. This is not necessarily a ‘matter of principle’ only but, also, the fact that there is no common denominator, which also relates to the fact that there are at least several types of environmental impacts while the number of lives lost represents a single, well defined quantifier. A similar argument applies to comparing potential environmental impacts and economic losses.

The alternative to having a separate impact classification would be to include potential environmental impacts in a consequence classification which addresses potential loss of life and economic losses, as recommended in typical guidelines for conventional dams. As pointed out above, the fundamental problem with this approach is that there seem to be no indications as to the environmental impact that would be comparable to, say, the loss of 100 lives. The approach advocated in this Document is that no such comparisons need be made in the first place. It is sufficient to develop a separate and independent consequence classification (with designated tailings dam safety evaluation requirements), designed to address potential environmental impacts and, what is equally important, taking into consideration the distinctive characteristics of environmental impacts relevant to tailings dam sites.

In summary, the advantages of introducing the impact classification are:

- there is no need to compare environmental impacts with loss of life and/or economic losses;
- evaluating the safety of various tailings dams can be carried out to more uniform standards;
- a classification developed specifically for tailings dams can be employed;
- there is less room for errors due to inadequate interpretations of (ambiguous in terms of potential environmental impacts) classifications developed for conventional dams.

IV LOSSES TO THE OWNER

When analysing a hypothetical Type I failure, potential losses to the owner's property and operation (*e.g.*, dam replacement cost or mine production losses) could be taken into account for the purpose of classifying a tailings dam. The owner's property would then be considered on an equal footing with the downstream properties. However, the consequence classification method is not really intended to account for potential losses to the owner's property, and these should be considered separately. In principle, this method is intended to account for potential losses to the downstream and, in some cases, upstream properties, potential loss of life, environmental impacts, losses to the community, *etc*.

The approach advocated herein is that it should be solely up to the mine owner to decide on the acceptable level of risk relating to his own losses and, in this regard, tailings dam safety needs not be considered within a consequence classification framework. The premise here is that it is the owner who carries the cost of risk, which also includes the cost of his own (potential) losses.

The CDSA approach, in which 'economic losses' are to include potential losses to the owner's property, for instance, generation outage or dam replacement costs, is uncommon. Typically, the consequence classifications of dams account for potential damages 'in the area downstream of the dam' (*e.g.*, the 1979 U.S. Corps of Engineers' classification). The NSW (New South Wales) Dam Safety Committee in their July, 1996 guidelines make it particularly clear when defining the consequences that need be considered for assigning dam hazard rating as: *"Loss or damage to property, not owned by the dam owner…."*.

[If potential losses to the owner's property are excluded for the purpose of classifying tailings dams, as advocated herein, a confusion might arise when selecting flood and earthquake design criteria recommended by the CDSA (Tables 8 and 11), wherever the governing consequence classification category is established from the consideration of potential economic losses. This confusion, however, may be escaped from by realising that the CDSA document does not provide any real guidelines as to the quantification of potential economic losses, which is also typical of virtually all other consequence classifications of dams, and 'common sense' judgement will have to be used in any case, whether incorporating potential losses to the owner's property or not.]

A mine owner may be willing to assume a relatively high risk with respect to his own losses if the potentials for loss of life, environmental impacts, economic damages to the downstream properties as well as social and cultural losses are negligible. Although this is obviously acceptable, it has to be recognised that even if the consequences of hypothetical dam failure are limited to the owner's property, the question of losses to the public still may have to be addressed. For instance, if shutting down the mine operation for a prolonged period of time would be necessary following a tailings dam failure, the loss of employment opportunity could be perceived as a public issue (a socio-economic loss).

Under some circumstances, the owner might not have much of a choice but to accept a greater risk with respect to tailings dam safety where the potential consequences of failure are limited to his own economic losses. This could particularly be relevant to some older tailings dams where retrofitting a dam to modern standards cannot be justified based on the economics of the mine operation. It may then be beneficial to both the owner and the public to continue the operation with a relatively higher risk of dam failure rather than to shut down the mine. This, however, should not relieve the owner from the obligation to retrofit the dam to appropriate standards upon mine closure (at that time, retrofitting the dam could be less demanding in terms of costs as the tailings disposal and tailings pond water management would be discontinued) .

For the purpose of classifying a tailings dam with respect to the consequences of potential failure, the estimation of economic losses should include, as a *separate* item, potential losses to the owner. Such losses may include the costs associated with shutting down the mine operation, dam repair or replacement cost, *etc*. The acceptable level of risk should be decided by the owner, and the resulting dam safety evaluation requirements compared with those resulting from other consequences of potential dam failure, if applicable (the more stringent requirements must prevail). The results of relevant risk analysis might permit the owner to make a rational decision in this regard, as discussed in Section VIII.

Other potential losses to the owner, such as reputation losses (with all the resulting consequences) are not addressed herein. The significance of such losses must, again, be decided upon by the owner.

Finally, it needs be pointed out that each owner carries a cost of risk (of potential dam failure), whether explicitly acknowledged or not. This can be considered an 'intrinsic loss', which cannot be avoided. All other factors being equal, the cost of carrying this risk will be reduced with an increased effort put into the tailings dam surveillance, safety inspections and reviews, design, construction, operation and maintenance.

In the review of this Document, Steven G. Vick defined the 'corporate' consequences of tailings dam failure, which are outside of the scope of this (rather technical) Document. These include:

- *loss of cash flow during mine shutdown (direct)*
- *continuing costs during mine shutdown (direct)*
- *dam repair and environmental restoration costs (direct)*
- *loss of market capitalization (stock price)*
- *class-action litigation exposure from environmental NGO's*
- *class-action litigation exposure from shareholders*
- *criminal indictment of operating personnel*
- *permitting roadblocks*

and, it seems, require no comments.

V ENVIRONMENTAL IMPACTS

V.1 Dam Failure and Non-Compliance

The term ‘dam failure’ with respect environmental impacts, as used in this Document, refers to *non-negligible environmental impacts* only and it should be used with caution. If, for instance, a regulatory water quality limit set for downstream receiver was exceeded as a result of tailings dam performance, it would not necessarily mean that a dam failure occurred. If the exceedance resulted in a negligible environmental impact, a condition of *non-compliance* rather than dam failure would have occurred.

To illustrate the distinction between ‘dam failure’ and ‘non-compliance’, consider a regulatory limit on downstream receiver’s water quality set at a compliance point, for instance, in terms of Zn at 0.03 mg/L. If during a short period of time Zn concentrations at this location reached, say, 0.05-0.10 mg/L level as a result of tailings dam performance, this exceedance of regulatory limit would not have resulted (under typical conditions) in a measurable impact on aquatic environment. In other words, the environmental impact would have been negligible and no dam failure would have occurred, while a non-compliance situation would have applied. If, on the other hand, Zn concentrations reached, say, 10 mg/L and the amount of impact (*e.g.*, in terms of fish kill) was significant, a dam failure would have occurred unless this had been allowed for at the design stage (as discussed in the following subsection).

It is possible, although highly unlikely in modern jurisdictions, that a failure of tailings dam in terms of environmental impacts could occur while being in compliance.

Regardless of the above considerations, it is reasonable to expect that frequent occurrences of a non-compliance condition would trigger the need to conduct a problem-focused dam safety review (Section 9).

V.2 Acceptable Environmental Impact

The concept of *acceptable environmental impact* (referred to in Sections 3, 10.7 and II), when viewed as a design criterion with respect to potential Type II failure, has a separate meaning. Such an impact needs not be negligible but merely allowed for in the design (and approved by the regulatory agency).

Referring to the example given in the preceding subsection, if Zn concentrations in the receiver were elevated as a result of the occurrence of a flood in excess of the design EDF (Section 10.7) and some fish were affected, the impact would not have been negligible. However, neither the condition of non-compliance nor dam failure would have occurred as long as the impact would have been in accordance with the design allowance, thus corresponding to, or being less than the acceptable environmental impact.

Similar considerations apply to designing for a low flow condition in the receiver (Section 10.7). If Zn concentrations were elevated above specified water quality objectives during stream flows lower than the design ‘low flow condition in the receiver’, the impact might not have been negligible and yet neither the condition of non-compliance nor dam failure would have occurred.

In determining acceptable environmental impact, the probability of the release of contamination needs be taken into consideration. An environmental impact expected to occur, say, on the average once every 20 years may have to be considered more severe than that the same impact expected to occur once every 200 years. The frequency of such occurrences, in turn, should be considered with reference to the finite time period (the design interval) during which a Type II failure could actually occur.

From another perspective, having a Zn concentration raised to, say, 5 mg/L for a certain period of time once every 100 years might be judged a lesser impact than having Zn concentration raised to 1 mg/L for the same period of time once every 10 years.

[All the examples given in this and the preceding subsections have been presented to illustrate concepts rather than meaningful situations.]

V.3 Potential and Actual Environmental Impacts

For the purpose of classifying a new or existing tailings dam, it is necessary to consider the consequences of potential Type I failure.

The evaluation of both *potential* and *actual* environmental impacts may be necessary when investigating the safety of tailings dam. The evaluation of actual impacts may be required where such impacts: (i) have been occurring or occurred prior to the construction of tailings dam (this could apply, for instance, to an ‘old mining camp’), (ii) are occurring as a result of the operation of another ‘close-by’ mine or industrial facility, or (iii) have been occurring as a result of the tailings dam performance (this could apply to an existing dam where a downstream receiver has been impacted, whether on a continuous or intermittent basis, for a period of time).

The impact classification presented in Section 4.2 has not been developed with the purpose of evaluating actual environmental impacts. Nevertheless, based on this classification one could attempt to evaluate the magnitude of actual impact, *i.e.*, determine if the impact has been low, significant or high, particularly with respect to a Type II failure (this should not be confused with establishing a CCC for tailings dam with respect to potential Type I failure, where potential environmental impacts are analysed to determine if the dam should be classified in the Low, Significant or High category for dam safety evaluation purposes). In this regard, it is emphasised that evaluating actual environmental impacts is outside of the scope of the tailings dam safety evaluation process addressed in this Document. The impact classification is not suitable for evaluating actual environmental impacts, unless such an impact is analysed as a case history following a well documented Type I failure of tailings dam.

VI CORRELATION BETWEEN CONSEQUENCE CATEGORIES

As discussed in Section III.4, making comparisons between potential environmental impacts and loss of life and/or economic losses is not really needed, and the impact classification has been introduced herein in order to avoid making such comparisons. On the other hand, a correlation between the impact and LLEL classifications has been defined in Section 4.4 (Table 5) to simplify the designation of DS/DSI/DSR requirements. This correlation does involve a comparison of the consequence categories resulting from both classifications. This represents an inconsistency in the recommended approach to tailings dam safety evaluations.

It is emphasised that the correlation between the LLEL and impacts classifications presented in Table 5 is intended for designating the required *effort* associated with conducting DS, DSIs and DSRs. This correlation is not intended to designate the required *margin of tailings dam safety* in the sense of selecting appropriate design criteria and other design requirements. In this regard, the author's opinion is that no comparison between the two consequence classifications should or needs be made.

To avoid the above inconsistency, each of the Sections 7, 8 and 9 could have been subdivided into two subsections, one addressing the DS/DSI/DSR requirements with respect to potential environmental impacts, and the other one with respect to potential loss of life and economic losses (defining the Group A and Group B categories would not be necessary). This approach was carefully considered but quickly abandoned. It would not make any practical sense to designate, for instance, appropriate frequency of DSIs for each of the seven CCCs included in both classifications (three CCCs resulting from the impact classification and four CCCs resulting from the LLEL classification).

Therefore, an inconsistency has been introduced into the recommended tailings dam safety evaluation process based on practical considerations. This inconsistency, although essential in principle, is not considered significant from the perspective of selecting appropriate DS/DSI/DSR requirements for tailings dams.

It seems that a boundary line such as that shown in Table 5 can be recommended based on a personal disposition only. With respect to the Table 5 correlation, the recommended boundary line is based on the author's belief that, for the purpose of designating an appropriate amount of effort to be put into conducting DS, DSIs and DSRs, the High category resulting from the LLEL classification (which may be associated with the potential for loss of life) should require a greater effort, as compared with the Significant category in terms of potential environmental impacts.

VII TAILINGS DAM OPERATING PHASES

A brief discussion on the relevance of the tailings dam operating attributes and phases (Table 6) to tailings dam safety evaluations is provided in this section.

Four tailings dam operating phases are identified in Table 6. As pointed out in Section 5, not all of these phases need apply to each tailings dam. Furthermore, site-specific conditions and operating requirements may indicate the need to identify other essential to dam safety phases and/or operating attributes.

The tailings dam operating Phases 2A, 2B and 3 correspond to the single 'rehabilitation' phase identified in ICOLD Bulletins 74 and 103. Distinguishing between these three phases is necessary from the perspective of both contamination of tailings pond water and/or seepage, and the expected phase durations. In particular, while Phase 2A and 2B relate to the treatment of residual contamination only, contamination of site waters is actively generated during Phase 3.

It needs be pointed out that Phase 2A and/or Phase 2B may also apply to the situation where a cover over the tailings deposit is to be provided upon the cessation of tailings disposal operation. Under this closure option, the duration of Phase 2B may be critical from the economics standpoint. In general, the longer Phase 2B is predicted, the more attractive would be allowing for Phase 3 (rather than a cover), in which case the tailings dam would have to be operated in the long term.

The operating risk varies as the potential for operating errors and the opportunity for tailings dam surveillance vary with the dam operating phase. For instance, although no potential for operating errors will exist during Phase 4 when tailings dam is no longer operated, a remote dam may be seen during this phase once a year only (in fact, it cannot be excluded that some tailings dams will be forgotten in the long term). The operating risk represents an essential safety aspect that has to be accounted for when specifying dam safety evaluation requirements (*e.g.*, spillway or decant structure design, freeboard-storage volume criteria, or the frequency of DSIs).

A CCC appropriate for tailings dam may change as a result of changes in the dam configuration or tailings basin conditions (*e.g.*, increase in the dam height or increase in the degree of contamination of tailings pond water) during all tailings dam operating phases, except for Phase 4. The most significant of such changes would typically be associated with the production phase. Revisions to CCCs and the resulting dam safety evaluation requirements may be necessary when an operating phase changes.

During each of the tailings dam operating phases, the CCCs may change when some conditions downstream of the dam change as a result of new property development.

Tailings dam physical conditions are subject to changes during Phase 1 (increasing differential head, tailings pond location, available storage volume, formation of tailings beach, increase in dam height, *etc.*). During the two other phases when tailings pond is still operated (Phases 2A and 3), as well as during Phases 2B and 4, no such changes would be expected to occur. This needs be accounted for when specifying DS/DSI/DSR requirements.

The degree of contamination of tailings pond water, tailings porewater and groundwater may be subject to significant changes during any of the tailings dam operating phases, except for Phase 4 when tailings dam reaches a 'steady state'. This needs be taken into consideration when evaluating the safety of tailings dam in terms of potential environmental impacts and health hazards.

During Phases 1B, 2 and 3 when a tailings dam is at its final height, the dam may or may not be retrofitted for closure. This is one of the key aspects that needs be taken into consideration when conducting a tailings dam safety evaluation or specifying safety evaluation requirements.

Tailings dam operating conditions do not change during Phases 2B and 4, with the tailings impoundment runoff discharging on an intermittent basis or continuously through an overflow spillway. If a permanent tailings pond exists, its level is not operated during these phases and varies only in response to runoff conditions. In some cases, no tailings pond discharge will occur during these phases (*i.e.*, in the case of a highly pervious dam and/or arid climate). In terms of DS and DSR requirements, these two operating phases will be least demanding. On the other hand, the spillway design criteria may have to be more stringent than in the case of other operating phases.

The overflow spillway attribute referred to in Table 6 requires additional explanation. Firstly, an 'overflow spillway' may be in the form of an open channel, decant structure or another arrangement. Secondly, the spillway attribute refers to a tailings dam containing contaminated water where the WTP is fed from the tailings pond. Tailings pond discharge is then handled by a barge, pumphouse, siphon or another arrangement, routing the excess water to the mill and/or WTP. Where the WTP is located downstream of the dam, a controlled gravity discharge structure may be operated in addition to a discharge facility designed to feed the mill. Thirdly, an emergency spillway may or may not be provided at sites where a direct discharge of tailings pond water is not permitted. Some tailings dams are operated without any spillway, based on very conservative designs (this is not a preferable scenario – an emergency spillway still should be provided). Other tailings dams may be operated with a controlled decant structure discharging on an intermittent basis, according to some environmental restrictions. Finally, a spillway may be required during Phase 1, with no spillway required during Phase 4 (*e.g.*, at a tailings dam located in arid climate).

Evaluation of the adequacy of spillway represents one of the most crucial assignments of tailings dam safety evaluation. Careful attention needs be paid to the operating phase and operating attributes. From the perspective of having a spillway as 'maintenance-free' as possible, the most demanding is Phase 4, and other phases when the personnel are not continuously present at the site.

VIII RISK ANALYSIS

In general terms, risk analysis is a procedure designed to aid in decision-making. Its output includes a detailed background to understanding the liabilities associated with an industrial operation. As a method used for addressing the deficiencies of existing conventional dams and determining the associated risk levels, it has been intensively promoted in the technical literature for at least twenty years, particularly in conjunction with the 'national dam safety program' launched in the USA in the late 1970s. Detailed discussions of the risk analysis, as applicable to conventional dams, can be found, for example, in:

- '<u>Safety of Existing Dams – Evaluation and Improvement</u>', National Academy Press, Washington D.C., 1983;
- David S. Bowles, Loren R. Anderson and Terry F. Glower, '<u>Risk Assessment Approach to Dams Safety Criteria</u>', ASCE, Proceedings of 'Uncertainty in the Geologic Environment', 1996;
- Steven G. Vick and R.A. Stewart, '<u>Risk Analysis in Dam Safety Practice</u>', Proceedings of 'Uncertainty in the Geologic Environment', 1996.

Conducting risk analysis for a tailings dam could be, in some cases, even more beneficial than for conventional dams. This is for the greater complexity of tailings dams and tailings dam operations that may result in a number of potential failure modes and the sequences of events that could lead to a dam failure. Applications of risk analysis to tailings dams have been discussed in:

- Steven G. Vick, Gail M. Atkinson and Charles I. Wilmot, '<u>Risk Analysis for Seismic Design of Tailings Dams</u>', Journal of Geotechnical Engineering, ASCE, 1985;
- Dirk Van Zyl, Ian Miller, Victor Milligan and W. James Tilson, '<u>Probabilistic Risk Assessment For Tailings Impoundment Founded on Paleokarst</u>', Proceedings of 'Uncertainty in the Geologic Environment', 1996;
- Kelvin Dushinsky and Steven G. Vick, '<u>Evaluating Risk to the Environment from Mining Using Failure Modes and Effect Analysis</u>', Proceedings of 'Uncertainty in the Geologic Environment', 1996.

In the last reference, the application of Failure Modes and Effect Analysis (FMEA) is discussed. This method seems to be particularly well suited for setting up the scope of tailings dam surveillance.

Conducting a risk analysis is not a part of tailings dam safety evaluation program in the sense that it would not constitute a 'routine' assignment. Nevertheless, conducting a risk analysis could be useful in the following situations:

- When evaluating potential tailings dam sites and/or dam types at the conceptual design level. The objective here would be to identify the best option based on a detailed analysis of the potential modes of dam failure, the probabilities and the resulting consequences of failure, the risks and the associated confidence levels, with reference to the corresponding capital and operating costs.

  As pointed out in Section 1.4, the conceptual design level is not included in the tailings dam safety evaluation program, and conducting a risk analysis at this level would actually be done prior to the start-up of the program. Nevertheless, having the results of risk analysis conducted for the tailings dam option that would later be selected could be advantageous throughout the following dam safety evaluation program.
- When setting up the scope of DS and determining the amount and distribution of effort adequate for carrying out a well-focused DS for existing tailings dam (Section 7.1). Performing FMEA or a similar analysis in the form of a well documented workshop held at the site and attended by the dam operators, tailings dam engineer, owner's management representative and other professionals, as required, could be useful, especially at the sites where complex dam operating procedures are implemented. This could be carried out after the tailings dam operation is advanced so that site-specific operating conditions are well understood. The objective here would be to identify the potential modes and corresponding probabilities of dam failure/incident, the sequences of events that could lead to failure or incident, the consequences of potential failures and associated risks, with the ultimate purpose of defining problem-focused DS requirements as well as possible improvements to dam operating procedures.
- As a follow up to a DSR finding (Section 9.1). If the results of DSR indicate an inadequate margin of tailings dam safety, conducting a risk analysis could be considered where a very high, perhaps prohibitive cost of the corrective works is anticipated. At this point, the corrective works would be defined with reference to generally acceptable safety standards, determined, for instance, from the consequence classification method. The objective of further analysis would be to arrive at alternative solutions in terms of risks and the associated costs of corrective works, with the ultimate purpose of providing a firm, detailed rationale for making the decision on selection of the most cost-effective scenario. In this analysis, the generally acceptable dam safety standards may or may not be adhered to.

  [The 'alternative solutions' might include alternative approaches to tailings disposal, designed to lessen the risk associated with the existing operation. For instance, developing a new tailings disposal site, changing the method of tailings slurry discharge or the chemistry of the slurry, or using a part of tailings for underground backfill might be considered.]
- When evaluating potential losses to the owner (Section IV). Where potential failure of tailings dam would be expected to result in an economic loss to the owner's property only, conducting a risk analysis might pro-

vide a background for the owner to make a learned decision regarding the amount of risk that he is willing to accept. The objective here would be to arrive at the annual cost of risk that the owner is presently carrying* and, if necessary, to evaluate the means to reduce this cost. For this purpose, conducting a simplified risk analysis would likely be sufficient. The analysis would involve estimating the probability of failure(s) and the resulting costs (of production losses, clean-up, dam repairs/replacement, *etc.*). Then, if the cost of carrying the risk is deemed too high, the corrective works that could be implemented to reduce either the probability of dam failure or the failure cost, or both, would be determined together with the associated implementation costs.

* The owner might want to know the annual cost of risk regardless if the consequences of potential dam failure are limited to his own economic losses or not.

It follows that employing risk analysis as a method of addressing the safety of tailings dam could be justified in a variety of situations. It is emphasised, however, that there should be a specific reason to carry out such an analysis (and not just because several tailings dams have recently failed and the owner is rightly concerned – in this case conducting a DSR rather than risk analysis should be considered).

Risk analysis should not be confused with the consequence classification method. As pointed out in Section 3.1, the consequence classification method offers a uniform approach to the 'day-to-day' dam safety evaluations that can be used in the majority of situations. It is intended to account for the consequences of hypothetical dam failure rather than the risk of failure. The strength of this method is that it is suitable for defining some minimum dam safety standards that are deemed generally acceptable. These are defined based on a consequence (or 'hazard') rating. The risk analysis, on the other hand, offers a formalised approach to arriving at detailed rationale for making decisions pertaining to dam safety, based on considerations which are very strongly site specific and involve an analysis of both the likelihood of dam failure and the existing or proposed defensive measures, in addition to the consequences of potential failure.

It is perhaps best to think of the risk analysis as a 'highly organised judgement' method, which is well suited for addressing tailings dam safety where there is a specific reason to do so, with the purpose of arriving at conclusions that may or may not conform to the generally acceptable dam safety standards or evaluation procedures. On the contrary, there are no specific reasons to implement the tailings dam safety evaluation program based on the consequence classification method and other considerations outlined in this Document. It just has to be done.

Finally, it needs be emphasised that conducting a risk analysis will require a significant amount of judgement. Hence, involvement of highly experienced engineers and scientists should be considered.

On more than one occasion, the author witnessed a confusion between the consequence classification method and risk analysis. To appreciate the difference between *these two concepts, the following relations between the risk, consequence of dam failure (or 'hazard'), probability (or 'likelihood') of occurrence, and defensive measures (or 'safeguards') may be examined:*

$$Risk = Consequence \times Probability$$

$$Risk = \frac{Consequence}{Defensive\ Measures}$$

When examining these relations, it needs be realised that the 'consequence' is fixed (constant) for a given dam, under given conditions. For instance, when a hypothetical dam failure is analysed, the resulting environmental impact remains unchanged, regardless of the probability of occurrence or defensive measures (these would be assumed to fail).

The first of these relations is self-explanatory. Of interest here is that this relation shows that the consequence classification method implicitly incorporates the consideration of risk. Based on the 'magnitude' of a consequence of failure, for instance, a flood with a certain probability of occurrence is selected, without explicit consideration given to the risk of failure.

The second relation indicates that the risk can be reduced by implementing some defensive measures. These may include, for instance, additional freeboard, a higher safety factor, better compaction of dam materials, retrofitting the dam, or a stringent dam safety evaluation program. Nevertheless, the consequence (hazard) would not change.

Consider, for instance, an unsecured ventilation shaft (open to surface). There would be a consequence (hazard) relating to the potential for loss of life. In a heavily populated area (higher 'probability'), the risk of life lost would be higher as compared with a remote area (lower 'probability'), with the consequence (= life lost) being the same. If a warning sign is posted (a defensive measure), the risk would be reduced, however, the consequence still would be the same. If the shaft is fenced (a 'bigger' defensive measure), the risk would be further reduced, with the consequence still remaining the same. The consequence would be reduced to zero if the shaft is (properly) backfilled and, then, the risk would be reduced to zero as well.

IX DESIGN CONSERVATISM

There are no explicit rules as to the degree of conservatism that should be built into tailings dam designs, and this will depend on the experience and the disposition of the engineer. It seems, however, that some general rules in this regard may be defined using the following examples:

- Considering consequence classification categories: few engineers would be able to resist applying a greater conservatism to the design of tailings dam classified in a high consequence category as compared with a low category dam. This is considered a reasonable practice.
- Flood routing computations: if intensive and reliable flow monitoring data are available for the hydrologic model calibration, then a lesser degree of conservatism would be justified as compared with the case where the hydrologic model is constructed from a meteorological database with little site specific data available for calibration.
- Determining statistical floods: if, say, a 50-year database is available, then a lesser degree of conservatism would be required than in the case of a 20-year database when designing for a 1 in 500 years flood.
- Predicting future contaminated loadings associated with dam seepage: in this assignment, the degree of applied conservatism may have to be substantial since some inherent uncertainties relating to accurate predictions of contaminant generation rates and attenuation capacities, as well as hydrogeological and geochemical modelling, exist.
- Conducting an inundation study of the release of liquefied tailings mass: similar to the preceding example, the degree of conservatism may have to be substantial since the currently available methods to carry out such a study are rather approximate (where the potential for loss of life is investigated, the degree of conservatism *must* be high).
- Selecting design peak ground acceleration: if significant conservatism was applied to the selection of MDE moment magnitude, then applying significant conservatism to the selection of associated parameters (*e.g.*, the attenuation relationship, design accelerogram or material properties) might not be appropriate.

A typical tailings dam is designed to last a very long time and, looking into the past, one may reasonably expect that future dam safety requirements will become more stringent than those considered acceptable today. Although it is not possible to design for the future (*i.e.*, unknown) dam safety requirements, it is possible to expect that, for instance, today's regulatory limit on a metal concentration in the receiver may be reduced tomorrow. It is also possible that a design input parameter, such as peak ground acceleration, may be revised tomorrow to a different value.

This is one of the most difficult aspects of tailings dams design that has appeared on many projects as a result of changes in the regulatory requirements relating to receiving water quality, better understanding of tailings dam behaviour under seismic loads, *etc*. This issue could perhaps be addressed by increasing the degree of design conservatism, however, it may also be possible to develop designs that are sufficiently flexible so that future improvements to dam safety, if required, can be implemented at reasonable costs. Both the owner and the engineer need recognise that the construction and operation of a tailings dam is a dynamic process, and making necessary changes to dam structure and/or operation will often be possible prior to the final retrofitting of dam for closure. Hence, building into the designs an excessive conservatism ‘up the front’ might not represent the best approach from the perspective of project economics.

Some tailings dam design engineers are very conservative as evidenced by the conservatism applied to each of the design parameters and design analysis. For instance, significant conservatism has been applied to the selection of design input parameters at various levels of analysis as well as the interpretations of the analysis results and, later, to the selection of safety factors and design details. Such an approach may lead to a pyramid of conservatism resulting in excessive dam construction and/or operating costs. It should be avoided, unless the resulting incremental costs are acceptable.

The above discussion is not intended to imply that a ‘lowest cost’ or ‘risky’ approach is advocated herein with respect to tailings dam safety. It is intended to indicate that a thorough analysis of the degree of conservatism and the potential for a ‘pyramid effect’ is necessary.

X DESIGN INTERVALS

For selecting the probabilistic flood and earthquake design criteria with respect to potential environmental impacts, the use of probability of exceedance during design interval (PEDDI) is recommended (Section 10.6, and Tables 9 and 12). [Steven G. Vick in 'Planning, Design, and Analysis of Tailings Dams', BiTech Publishers Ltd, 1990, uses the term 'failure probability' to express the same measure.] This approach is in contrast to conventional dam engineering practice, where such criteria are commonly specified in terms of annual exceedance probability (AEP).

The advantage of the recommended approach is that it incorporates an explicit reference to the characteristics of tailings dam operation specific to each design interval, which typically corresponds to a dam operating phase ('design interval' is defined in Section 10.6). Hence, it allows for taking into consideration the dynamics of a tailings dam operation. Albeit this advantage seems obvious, it happens that the design engineer selects a probabilistic design criterion for tailings dam based on AEP without really considering the length of design interval, often with reference to a guideline developed for conventional dams.

In the conventional dam engineering practice, it is customary to select a design earthquake or flood event based on either AEP or probable maximum event (PMF or MCE). When selecting a design event based on the probabilistic method, this approach seems justified since most conventional dams are designed for a similar service life, typically taken in the order of 100 years, and only one operating phase exists. Thus the risk associated with dam operation can be generalised from the perspective of specifying probabilistic design criteria, without explicit reference to the design interval. Consequently, specifying an AEP as a design criterion is sufficient, keeping in mind that a given AEP indicates the probability of exceedance of the design event about 100 times lower than the probability of its exceedance during the service life of the dam.

Tailings dams are more complex than conventional dams and generalisations of this type are not easy to make. Consider, for instance, the selection of a design event for three tailings dams, all classified in the same CCC, with the scheduled production phase lengths of 10, 20 and 50 years. By the end of each mine operation, the tailings pond is to be drained and the dam retrofitted for closure. Hence, these time periods can be rationalised as appropriate design intervals. Assuming a design event with AEP of, say, 0.002 as the design criterion, it follows that the probabilities of this event being exceeded prior to closure (the PEDDI values) would be about 2.0%, 3.9% and 9.5%, respectively. While the first of these probabilities might be judged acceptable, the third one might not.

A fundamental difference between conventional and tailings dams is that, in the former case, one operating phase and one generally assumed design interval exist while, in the latter case, there is more than one operating phase and no single, generally applicable design interval can be defined.

The problem with using AEP for dam design purposes is that it represents, in fact, a mathematical concept in the sense that it refers to an artificial time period from the perspective of specifying design criteria, being a 365-day interval. On the contrary, PEDDI refers to the design interval, that is, to a time period during which *tailings dam exists under given conditions* (the CCCs + the operating attributes), which are directly relevant to dam safety.

One of the fundamental considerations that underlies the recommended approach to selecting design criteria with respect to potential environmental impacts is that, for tailings dams, a CCC may vary with the operating phases to the extent that selecting one set of design criteria for all operating phases could be overly conservative. It is obvious that the most stringent criterion would have to be selected, if only one criterion is allowed for.

In fact, different CCCs may also apply to various stages of the production phase. For instance, breach failure of a 5 m high starter dam, containing an adjacent, relatively small tailings pond, could have substantially less severe consequences than breach failure of the same dam raised later to, say, 30 m in height, and having a significantly larger tailings pond as well as sulphidic tailings deposited against the dam. A similar comment would apply to a tailings dam where the tailings pond is drained and the residual porewater contamination is flushed out prior to the closure phase: the consequences of potential failure during this phase could be significantly less severe than the consequences of failure during the production phase.

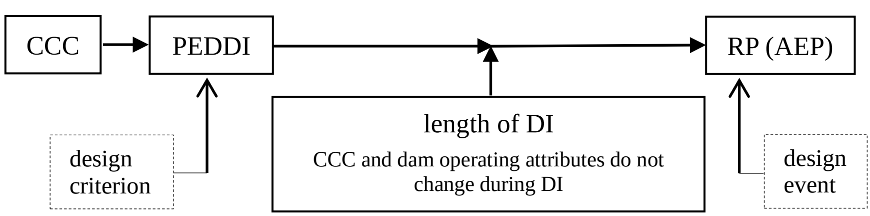
The explicit use of PEDDI may allow for savings in tailings dam construction costs. The case of the 5 m high starter dam referred to above is a good example in this regard. Why would the 5 m high dam classified, say, in the Low category need be constructed to the same standards as the 30 m high dam classified in the High category? Although often reasonable and practical, specifying the same design criteria for these two stages is not really necessary, consistent with the consequence classification method (Section 3.1).

The above discussion may seem to be an issue of semantics only since knowing the design interval, the corresponding PEDDI value can be calculated from AEP (see the equation given in Section 10.6). However, this is not the case since common attempts to apply the well established practice of conventional dam engineering to tailings dams may, and sometimes do lead to confusion.

In 1996, the author was retained by a provincial ministry in Eastern Canada to review the proposed flood design criterion for an existing tailings dam containing acid generating tailings. A 12-year production phase was specified and the tailings deposit was to be permanently flooded upon mine closure. The consultant selected a 1,000-year flood for the design of a diversion dam – tailings dam spillway system. As stated by the consultant, this selection was made based on the CDSA guidelines (which are intended for conventional dams). According to the proposal, the design flood was to apply to both the production and closure phases. It followed that the probability of exceedance of the design flood during the production phase was 1.2% (which could be judged acceptable) while for the assumed 200-year closure phase, this probability was 18% (which was not acceptable). In the author's opinion, three errors were made, all resulting from the use of a guideline developed for conventional dams. Firstly, the same flood was selected for *both the production and closure phases, for which the CCCs were correctly assumed the same (the CDSA guidelines do not contain any provisions that would allow for taking into consideration design intervals of various lengths). Secondly, the consultant's interpretation of the CDSA consequence classification resulted in a design flood too low with respect to the closure phase (the CDSA guidelines were not intended to apply to the situation were a tailings mass, capable of generating very significant toxicity in the long term, enters a major river system as a result of dam failure). Thirdly, the selected length of design interval for closure (200 years) was not adequate for this type of dam (the CDSA guidelines do not address designing for dam closure phase).*

The recommended use of PEDDI for selecting flood and earthquake design criteria means that the acceptable probability of potential tailings dam failure (the PEDDI value) should be established by considering the hazard associated with dam operation (= consequence of potential failure, which determines the CCC), and this probability should be taken *independent of the hazard duration*. [See Section XI.1 for relevant discussion with respect to the closure phase.]

The process of selecting the magnitude of design event based on the recommended approach is illustrated on the following diagram.



From the perspective of tailings dam construction costs, the recommended approach means that, in relative terms, the costs associated with the production phase (shorter DI resulting in lower RP) will generally be lower, while the costs associated with the closure phase (longer DI resulting in higher RP) will be higher, all other factors being equal. From the perspective of environmental protection, this approach means that a consistent level of protection can practically be assured throughout the entire service life of tailings dam (Section XI.1).

It is plausible that the design of tailings dams based on PEDDI rather than AEP would also be more acceptable to the mine owners, owners of downstream properties and the public. The owner of downstream property or the user of downstream receiver, for instance, might be less interested in the probability of dam failing in any given year but might rather want to know what is the probability of dam failure during the entire mine operating period, and beyond.

It is essential to note that while designing for the production phase, the durations of all future stage-raise intervals, where applicable, must be included in the design interval if no significant changes to the CCC are expected. Consider, for instance, a tailings dam to be stage-raised every 5 years over a 20-year production phase, with no significant changes to the CCC anticipated over the entire phase. Taking PEDDI at 2% as being acceptable, the extreme design event with a return period of 250 years might then be selected if a 5-year design interval is assumed. This would be inappropriate since the selection of the design event should be made based on the 20-year design interval, with the resulting minimum return period of 1,000 years.

Another example of relevance to the preceding discussion is the last stage-raise of tailings dam or dam constructed in one stage, with no changes to the CCCs expected in future. The question may appear if these dams should be designed and constructed sufficient for Phase 4, thus incorporating the most stringent design requirements (*e.g.*, design flood or 'maintenance-free' spillway). This might be best but not necessarily most economical approach. Regardless of the economics, the approach advocated in this Document is that designing of tailings dams should be carried out with reference to both the CCCs *and* the dam operating attributes applicable to an operating phase, the duration of which determines the design interval. In this particular case, the operating attributes would change upon the cessation of mine operation (Phase 1) and, where applicable, the cessation of transition phase (Phase 2) or long term treatment (Phase 3). Therefore, these two dams need not be necessarily designed and constructed sufficient for Phase 4, however, the future dam safety requirements pertaining to Phase 4 must be accounted for (Section 5).

XI DESIGNING FOR TAILINGS DAM CLOSURE

In principle, there should be no difference in tailings dam safety margins under operating and closure conditions where the designs are based on the consequence classification method. In some cases, these margins may 'automatically' increase upon mine closure, for instance, where the tailings pond has been permanently drained. Conversely, retrofitting a tailings dam may be required upon mine closure to ensure that adequate safety margins are maintained, for instance, where permanent flooding of the tailings deposit is planned.

There seem to be no reasons to presume that a well designed and constructed tailings dam would not last hundreds of years (an excellent discussion in this regard is provided by Arthur D.M. Penman and Victor Milligan in '<u>Longevity of Embankment Dams – A Critical Review</u>', International Workshop on Dam Safety Evaluation, 1993). This, however, can only be assured if appropriate dam safety evaluation, monitoring and maintenance programs are implemented all throughout the long closure phase.

XI.1 Design Criteria – Environmental Impacts

The basic premise underlying the recommended flood and earthquake design criteria resulting from the impact classification (Tables 9 and 12) is that the level of protection assumed to be acceptable in future (*i.e.*, to the 'future generations') should be the same as that considered acceptable today. This is assured by selecting probabilistic design criteria based on PEDDI, which means that the same level of protection would apply to the production, transition or long term treatment phase, and the closure phase for tailings dam classified in a certain CCC. For instance, if during the mine production-transition phase lasting, say, 50 years, a 5% probability of exceeding the design event is judged acceptable, the same 5% probability should be applied with respect to Phase 4 lasting, say, 500 years (where the relevant CCC is not expected to change).

The above can be explained by considering the following example. Suppose that a tailings dam is designed for a certain PEDDI value, which determines a design flood with respect to the production phase. If a larger flood comes during this phase and the dam fails, then be it. We knew the risk, we allowed for it and accepted it. If the dam has not failed during the production phase, still there is a chance that it will fail during the closure phase. For the dam to fail during the closure phase, a much larger flood would be required if the same design PEDDI is assumed (since the design interval would be much longer). If such a flood comes and the dam fails, then be it. Our defence would be that during the production phase, which was much shorter than the closure phase, we had the same chance for dam failure to occur (due to a much less severe flood). We cannot be any fairer than that.

The alternative, widely accepted in the conventional dam engineering practice, would be to base the selection of probabilistic design criteria on AEP. In this case, if an AEP of 0.001 were judged acceptable for selecting a design event then, during the 50-year production-transition period, the probability of exceeding this event would be 5% while during the 500-year closure period, this probability would be 39%. Such an approach would not be very satisfactory if we are serious about designing for closure of tailings dams.

The recommended approach obviously places a burden on the mine owners. Yet, the author believes that the resulting costs would be manageable.

Based on experience, it can be concluded from the examination of Tables 10 and 13 that a consistent level of protection can *practically* be assured throughout the entire service life of tailings dam if the length of closure phase is selected between 500 and 1,000 years. There is no rationale for assuming this length of closure phase other than: (i) the 500–1,000 year period seems sufficiently conservative, (ii) the resulting level of protection can practically be met *and* be consistent with that considered reasonable with respect to the production phase, and (iii) the 500-1000 year period gets close to the 'geological time' (in terms of expected geomorphologic changes) designing for which, if possible at all, could hardly be justified.

XI.2 Increase in Dam Safety Margin with Time

Some authors of technical publications on tailings dams point out that the margin of tailings dam safety will increase upon the cessation of tailings impoundment operation. This would result from lowering phreatic surface levels, the 'ageing' of tailings used for dam construction, and/or dissipation of excess pore pressures (these considerations would not apply well to tailings dams constructed as low permeability or highly pervious (rockfill) structures of borrow materials). In this regard, it needs be noted that the resulting increase in dam safety margins primarily refers to the increase of dam resistance to failure *under seismic loading*, being but one possible cause of dam failure (Table 1). It has little bearing on, for instance, the potential for dam overtopping, increase in contaminant levels, or clogging of filters in the very long term.

An increase in dam safety margin after the cessation of production phase is sometimes mentioned with reference to the inactive upstream tailings dams that did not fail during the 1965 Chilean earthquake. Although such an increase may apply to many sites and some tailings zones, it must not be considered as a general rule since the climatic, geochemical and other site-specific conditions may render such an increase, if any, insignificant.

On a project in Eastern Canada and a project in California, where studies of tailings liquefaction potential were conducted, the results of SPT testing indicated some 'blow-counts' in the order of 1-2 in the permanently submerged 'slime' portions of the deposits, in spite of the fact that the tailings had been deposited between about 10 to 20 years prior to the investigations. Therefore, if an ageing process had actually occurred, it would likely have little effect on the resistance of tailings to liquefaction (in both cases the slimes *were located within the potential failure zones). This is consistent with the findings reported by Jorge H. Troncoso in 'Evaluation of Seismic Behavior of Hydraulic Fill Structures', Hydraulic Fill Structures, ASCE Speciality Publication No. 21. While analysing the effect of the severe March 3, 1985 Chilean Earthquake, J.H. Troncoso states: "Most tailings dams in a 150 km radius from the epicenter suffered liquefaction of the impounded slimes even when some of them were as old as 40 years.".*

On another project in Eastern Canada, a comprehensive evaluation of tailings liquefaction potential was performed for an existing upstream tailings dam, with respect to both the remaining life of the mine and the closure phase. The dam is constructed by spigotting of very fine tailings, with 100% passing the #200 sieve and 85% passing the #325 sieve. The average specific gravity of tailings is 4.1. The results of a hydrogeological-hydrologic analysis indicated that future lowering of phreatic surface in the dam slope area would be insignificant, even if the tailings deposit is regraded upon mine closure to shed off the runoff so that no water pond would be formed. This has to do with a relatively high infiltration rate (precipitation about 1100 mm/year, evapotranspiration in the order of 420 mm/year, and the overland runoff typical of un-vegetated soil surface) as well as the very fine tailings grind. Hence, 'after closure' improvements to dam stability on the account of either ageing of the potentially liquefiable (saturated) tailings comprising dam slope or substantial lowering of the phreatic surface could not be reasonably assumed. In other words, this is a rather 'unique' dam and a direct application of the experience available from observing the performance of other, more 'typical' upstream tailings dams to the analyses of this dam could not be justified. On the positive note, the dam has been constructed with very flat slopes (up to 5:1, horizontal:vertical), the design peak ground acceleration is 0.18g (design MCE, M_x=6.0), and the duration of significant ground shaking would not be expected to exceed 2-3 seconds (the dam site is 'unique' as well).

On the other hand, there seems to be firm evidence that the strength of unsaturated tailings may significantly increase in a relatively short time, at least at some sites (see, *e.g.*, J. Troncoso, K. Ishihara and R. Verdugo, 'Aging Effects on Cyclic Shear Strength of Tailings Materials', Proceedings of Ninth World Conference on Earthquake Engineering, Tokyo-Kyoto, 1988). When accounting for such an increase in designing for tailings dam closure, a question may appear: would the increase in the strength of tailings be partially lost as a result of deformations caused by repetitive earthquake loads and, if so, would the ageing process repeated itself after each of such deformations in the sense that the chemical precipitation and other factors be as 'active' in future as in the few decades after the tailings deposition? This and similar considerations indicate that making an allowance for future increase in the strength of tailings due to ageing has to be considered with caution, and always with due consideration given to site-specific conditions.

XI.3 The AMD Generation Issue

On many projects, actual or potential AMD generation in tailings and/or dam construction materials presents a significant, and often most challenging aspect that must be taken into consideration when designing for tailings dam closure. This directly relates to the long term safety of tailings dams.

In general, there are three basic design scenarios that can be considered to prevent/control AMD in the long term, in the order of increasing performance risk:

- Permanent neutralisation of the AMD source by adding/enhancing neutralisation potential (*e.g.*, by mixing-in finely crushed limestone with tailings, or sulphide removal during the entire Phase 1 or by the end of this phase); providing a *maintenance-free*, *e.g.*, thick saturated soil or organics cover, *etc*. If no significant residual contamination associated with process water and/or prior AMD generation occurs, and no significant leaching of contaminants at neutral pHs takes place, then Phase 4 would follow Phase 1, that is, neither of the Phases 2A, 2B or 3 would apply.

  In some cases, having the entire tailings deposit neutralised would not be necessary as it could be sufficient to neutralise a top tailings layer only. This has to do with oxygen gradients and the rates of advancements of the oxidation and sulphide depletion fronts, as well as the attenuation of contamination within the tailings mass where some neutralisation potential is available (at some 'massive sulphide' operations, this would not work if the tailings comprise 'pure' sulphides).
- Collect and treat AMD in the long term (Phase 3). Upon sulphides depletion or the contaminant generation rate becoming sufficiently low, Phase 4 would follow.
- Prevent/control AMD generation by providing a *water cover* or a thin, *dry cover* ('composite' soil, plastic liner), designed to reduce the flux of oxygen or infiltration, or both. Either Phase 2A or 2B, or both, would typically (although not necessarily) apply, and Phase 4 would involve maintaining the cover.

In 'mine closure' terms, these three scenarios correspond to the following closure options:

1 *'Walk-away'*, with the effort to be put into monitoring, technical inspections and maintenance of tailings dam dependent on the type of dam and other site-specific conditions.

2 Long term *'collect and treat'* operation with eventual *'walk-away'*. There will be a limited life span associated with AMD generation, upon which a 'walk-away' scenario similar to option 1 will be possible.

3 Forever *'maintenance and care'* of (water or dry) cover, in addition to monitoring, technical inspections and maintenance of the dam. A 'walk-away' scenario similar to option 1 above will never be possible.

All other factors equal, water cover would generally reduce the long term physical safety of tailings dam while a dry cover, designed to prevent/reduce infiltration, would comparatively increase dam safety. Thus from the tailings dam safety perspective, a dry cover would generally be preferred when considering the potential for Type I failure.

Although preventing AMD generation represents the most desirable closure option for many tailings impoundments and all reasonable effort should be put into achieving this goal, the fact is that adequate prevention of AMD generation in both short and long term is still a challenging aspect of designing for mine waste disposal. The fact also is that leaving reactive tailings under a (water or dry) cover throughout Phase 4 represents nothing else but leaving a ponderous problem for future generations to care for. Hence, making an allowance for Phase 3 could be considered reasonable in some cases.

The selection of tailings dam closure option with respect to potential or actual AMD contamination may strongly relate to tailings dam safety in the long term. This is discussed in the following subsection.

XI.4 Water Cover Option

Implementing the ‘collect and treat’ (Phase 3) rather than ‘water cover’ closure option, would typically lead to having a much safer tailings dam in terms of physical stability during Phase 4. This is particularly evident when comparing a pervious (*e.g.*, constructed of tailings) or highly pervious (*e.g.*, rockfill with upstream filter zones) tailings dam with an allowance for Phase 3, and a low permeability dam designed to support water cover.

Some confusion in this regard appeared in the late 1980s and early 1990s in Canada in conjunction with considerations given to the ‘collect and treat’ vs ‘water cover’ closure options for sites where tailings had the potential to generate significant AMD during closure phase. Some mine owners and regulators were under the impression that providing a permanent water cover supported by one or more tailings dams, which would relieve the owner and, potentially, the public from the obligation to treat the tailings impoundment runoff in the long term, was a highly desirable closure option: “we would not have those sludge generating treatment plants all over the place”. Besides significant technical and economic problems with flooding of some tailings deposits (particularly those where advanced oxidation has already taken place), this judgement was flawed since an implicit assumption was made that a flooded tailings impoundment would be essentially ‘care and maintenance’ free as long as an adequate spillway is provided to ensure the safety of tailings dam(s).

Such an assumption is obviously incorrect. Tailings dam safety inspections, safety reviews, and care and maintenance will be required ‘forever’ in the case of tailings dam supporting water cover, and these would typically be more extensive than in the case of tailings dam for which another closure option has been selected. For the water cover case, the amount of maintenance and care with respect to dam structure would not be significantly different from that required at any comparable (in terms of the consequences of potential failure) operated hydroelectric dam. This needs be well understood before the water cover option is selected. It also needs be understood that the implementation of some remedial works that could conceivably be required during the very long service life of tailings dam supporting water cover would be impossible, as opposite to hydroelectric (and other water storage) dams where the reservoirs can be temporarily drained.

Strangely enough, the terms 'perpetual' and 'forever' were used in those years while referring to the 'collect and treat' option which, in fact, has a limited life span during which significant AMD would be generated (Phase 3). By the end of this phase, a safer dam would typically be left as compared with the flooded tailings option. This is immediately obvious when comparing a potential breach failure of tailings dam supporting water cover with breach failure of a (pervious or highly pervious) dam where the upper and major portion of the tailings deposit stored next to the dam would be moist rather than submerged.

In this regard, it also needs be realised that the treatment technology, including the safety and reliability of a collection and treatment system, is probably better understood that the safety of tailings dams in the very long term. Hence, having "those sludge generating treatment plants all over the place" *for a hundred years or longer* may have to be weighted against having "those tailings dams containing liquefiable, reactive tailings all over the place" *forever*.

On the other hand, it has to be emphasised that should the expected length of Phase 3 become comparable to the length of Phase 4 (see Table 6), the water cover option could present a more desirable solution, particularly for smaller tailings dams located in areas of low seismicity and moderate floods.

The flooded tailings closure option seems to be particularly weak when considering large dams at sites situated in moderate to highly seismic areas (where the dam would be subject to an 'infinite' number of earthquakes) and/or sites where large instantaneous peak flows occur (where relatively intensive monitoring and maintenance of the spillway would be required). The same applies to the sites where a catastrophic slide or avalanche could occur at the tailings impoundment slopes during the long closure phase.

In 1998, the author was retained to review a proposal involving the construction of a 230 m high tailings dam designed to contain 500,000,000 tonnes of tailings, about half of which were expected to be acid generating. The dam site is situated in an area of steep mountain slopes and high seismicity, with heavy rainfalls occurring during the rainy season. The proposal called for the construction of a concrete-faced rockfill dam designed to support water cover during Phase 4 (this was the most unprecedented and brave proposal that the author has ever seen). Sufficient amount of limestone rockfill (waste rock) would be available at the site for dam construction. In this case, having a highly pervious tailings dam (rockfill with upstream filter zones) rather than a concrete-faced rockfill dam during Phase 4 would offer a very significant advantage with respect to the safety of dam in the very long term. Allowing for Phase 3 could then present a penalty, offset by the lower cost of the pervious dam construction (actually, in the author's opinion, it was not clear from the study results if making such an allowance was really necessary since only a limited geochemical evaluation had been conducted). In any case, the author argued that the advantage of having a much safer dam during Phase 4 represented a crucial argument that was overlooked in the proposal (a highly pervious rockfill dam was not included in the various options studied).

Under some conditions, however, designing for water cover could be viable. Consider, for instance, a tailings impoundment located in a gently sloping terrain (no occurrence of impoundment slope slides or avalanches would be expected), in an area of low seismicity and moderate floods, having one or more low to medium size tailings dams. If an overflow spillway excavated in rock away from the dams can be provided, with an additional emergency spillway also excavated in rock, the system could be considered reasonably safe from the long term performance standpoint. The tailings dams, however, would not be ‘care and maintenance’ free.

It needs be noted that the water cover option would not result in a significant reduction of the consequences of potential dam failure under most conditions, as compared with the production phase. In some cases, the consequences of potential failure might increase, as the release of tailings following dam breach could be more severe. As pointed out previously, other closure options might result in reducing the consequences of potential Type I failure, where tailings deposits become significantly less saturated during Phase 4.

One of the most essential design issues relating to the water cover option is the ‘low flow condition in tailings pond’ (Section 10.7). Although at some sites having an adequate water supply even in dry years would not present a problem, at many sites this might become an essential obstacle.

On a closure project in Ontario, the tailings impoundment was divided into three cells by constructing two internal dykes for flooding purposes in order to ‘accommodate’ the sloping tailings surface. As it turned out, the uppermost cell was not capable of maintaining water cover during dry seasons because of the seepage losses through the internal dyke (which was not constructed as designed, as discovered after the closure designs were completed) and a bedrock ridge (which was not properly grouted). These types of problems may occur because tailings dam watersheds are often small as compared with the water cover areas.

Providing a fine sand cover (say, 0.3 m thick) over the tailings deposit prior to flooding would often be beneficial for a number of reasons, particularly if the sand is mixed with lime. This would lessen the flush of contamination upon initial flooding as well as reduce the release of contamination whenever the tailings surface is exposed to air during a severe drought period. There are also other advantages that would result from providing such sand layer. [On projects where tailings are deposited under water during the production phase, providing a sand layer would result in fewer advantages.]

XI.5 Safety of Typical Dams – Type I Failure

A brief discussion on the most common types of tailings dams is presented below, with reference to the safety of dams during Phase 4 in terms of potential Type 1 failure, accounting for most typical site conditions.

- From the long term stability perspective, a compacted rockfill dam with wide upstream filter zones, relatively coarse (pervious) tailings deposit adjacent to the dam, overflow spillway excavated in rock with the tailings pond located well away from the dam and an emergency spillway with invert located above the MPL, would probably present the most desirable closure design for medium and large tailings dams, particularly in the areas of high seismicity and/or high flood events. This scenario could be especially attractive for open pit mines where large quantity of waste rock are available and no generation of significant contamination in tailings or waste rock is expected. Even if contaminant generation is expected to occur, this type of tailings dam with allowance for Phase 3 could still be attractive, keeping in mind that after Phase 3 is completed, a relatively safe dam would be left in place during Phase 4.

- Valley-based upstream tailings dams located in areas of low seismicity could also be attractive from the long term safety perspective, provided that permanent wide tailings beach is assured by the location/elevation of overflow spillway excavated away from the dam, an emergency spillway is constructed as in the preceding case, and the dam slope is provided with erosion protection, preferably in the form of fine, graded rockfill or similar cover, or a strong vegetation cover. [A suitable downstream filter drain and/or toe protection would be required in many cases.] The fact the a portion of dam would remain saturated with phreatic surface fluctuating in response to pond level changes and slope infiltration, the possibility of static liquefaction and strong susceptibility to failure from overtopping, make upstream dams less attractive in comparison with rockfill dams, particularly in the areas of high runoff events. An upstream tailings dam forming the entire tailings impoundment perimeter could be equally attractive in arid climates, where the potential for dam overtopping is negligible.
- Low permeability tailings dams are less attractive from the long term stability perspective since these will have to permanently support adjacent 'reservoirs', whether in the form of a pond confined by dam structure or an 'aquifer' within the tailings deposit.

The amount of 'care and maintenance' required during Phase 4 would generally increase between the highly pervious and low permeability dams.

At a seminar given to Canadian federal and provincial regulators in 1994 on the closure of uranium tailings dams, the author was asked if it was possible to retrofit a tailings dam so that it would last for a 1,000 years (Phase 4) maintenance free. For the majority of low permeability tailings dams in Canada the answer is 'no', regardless if the dam supports water cover or not, unless an 'unlimited' budget is available. However, for many pervious or highly pervious tailings dams, the care and maintenance commitment would not be very intensive. For some highly pervious tailings dams which are not capable of maintaining a tailings pond on a continuous basis (e.g., rockfill dams), or are regraded to shed the overland runoff (e.g., some upstream tailings dams), this commitment could be minimal.

XII FLOOD AND EARTHQUAKE DESIGN CRITERIA

XII.1 Loss of Life and/or Economic Losses

The recommended flood and earthquake design criteria pertaining to potential loss of life and economic losses (Tables 8 and 11) have been adapted from a guideline developed for conventional dams. The key rationale for adapting these criteria is that the value of life or downstream property should be taken independent of the type of industry. As stated in Section 10.9, caution has to be exercised when considering these criteria, particularly with regard to the long lasting tailings dam operating phases.

Additional requirements (recommendations) are stated in notes [5] and [3] to Tables 8 and 11, both relating to potential loss of life. The basis for these recommendations is discussed under the two following headings.

Loss of Life – New Tailings Dams

As indicated in notes [5] to Tables 8 and 11, giving consideration to a less stringent than PMF or MCE design criterion for new tailings dams is not recommended wherever the potential for loss of life exists, even for dams classified in the High category (LLEL classification). In addition to the 'matter of principle' and the unavoidable controversy of the issue, the rationale here is that, in the majority of cases, new tailings dams can be designed and constructed to withstand PMF and MCE at reasonable costs, where deemed necessary. To make this argument work, the mining industry as a whole rather than a specific project must be considered.

[Exceedance of either PMF or MCE is taken virtually impossible. This means that a dam designed to withstand PMF and MCE is considered to provide for the highest level of protection that can reasonably be required with respect to potential 'Type I failure – external cause' (see Figure 7), assuming that these events have been estimated with a sufficient degree of confidence).]

The *differential cost*, defined as the difference in the costs of construction of a tailings dam being able to withstand PMF and MCE and an 'equivalent' dam designed using some less stringent criteria, could be very high at some sites. In these cases, a risk analysis could conceivably be carried out where the potential for loss of life exists, with the purpose of justifying the selection of a less stringent (than PMF or MCE) design criterion. It is reasonable to assume that the public, including those at risk, would have to participate in conducting such an analysis. Hence, conducting the risk analysis could be long and expensive, thus delaying the project and increasing the project cost, or unsuccessful in the sense of justifying a less stringent criterion. This presents a practical argument, which indicates that there could be little advantage in considering less stringent than the PMF and MCE criteria where the potential for loss of life exists.

In the *rare cases* where the differential cost referred to in the preceding paragraph is *prohibitively* high, a new tailings dam would not be constructed if the recommendations stated in notes [5] to Tables 8 and 11 are followed. This should be acceptable to the mining industry as a whole, as suggested later in this subsection.

In many guidelines developed for conventional dams, some loss of life is taken acceptable for dams classified in an *intermediate* consequence category, which may also be termed ‘significant’, ‘moderate’ or ‘high’. For this category, flood design criteria less stringent than PMF are often, albeit not always, permitted. [In some cases, earthquake design criteria less stringent than MCE are also permitted for dams in this category.] The corresponding numbers of lives that could be lost may be defined in those guidelines as: “few (no urban developments and no more than a small number of inhabitable structures)” – U.S. Army Corps of Engineers; “some increase [in loss of life] expected” – CDSA (the 1995 CDSA guidelines address existing dams only); “loss of identifiable life is not expected, but the possibility recognised, or the loss of less than 10 non-identifiable lives is expected” – NSW Dam Safety Committee, *etc.*

In other guidelines for conventional dams, the rules for classifying a dam in the intermediate category are more vague, or using a less stringent than PMF criterion is not permitted where the potential for loss of life exists. For instance, Ontario Hydro defines the intermediate category in terms of loss of life as: “No increase [in the number of lives lost] expected. Typically no urban development and no more than a small number of habitable structures downstream inundated.” In ICOLD Bulletin 59, using a design flood less stringent than PMF is taken permissible if the following condition exists: “A permanent low downstream risk level that should at no time include any additional risk to human life in inhabited areas due to failure of the dam.” According to the U.S. Federal Energy Regulatory Commission (FERC), quoted from the ‘Safety of Dams, Flood and Earthquake Criteria’, National Academy Press, Washington, D.C., 1985: “If structural failure would not present a hazard to human life …. design flood of lesser magnitude than the probable maximum flood would be acceptable ….”.

In summary, a review of the guidelines and practices used in conventional dam engineering indicates that:

- there is no general consensus as to designing a dam for less than PMF and MCE where the potential for loss of life exists;
- where designing for less than PMF or MCE is permitted while the potential for loss of life exists, the maximum ‘acceptable’ number of lives lost could probably be generalised as, say, being in the order of 10 or 30;

This generalisation is not intended to conclude, in any way, on a typical, taken acceptable number of lives that could potentially be lost. It is intended to emphasise that the number of mine sites, where a design criterion less stringent than PMF or MCE could conceivably be considered if relying on conventional dam practice, would be limited. If relying on the U.S. Corps of Engineers views, the number of such sites would be further limited since PMF would have to be selected for any 'large' tailings dam, even if 'few' lives only could be lost. Furthermore, PMF would have to be selected for any site where "several houses or a residential development" (rather than "isolated farmhouses") exist downstream of the dam, even if 'few' lives only could be lost ('Safety of Existing Dams –Evaluation and Improvement', National Academy Press, Washington, D.C. 1983).

- there is no real rationale for accepting the possibility of any loss of life in the case of new dams which do not exist yet, and thus need not necessarily be built.

When referring to conventional dam engineering practice, it is of interest to examine the results of survey conducted by the North Carolina Dam Safety Program in 1980 and 1982 (the survey results, as quoted below, have been taken from the report titled 'Safety of Dams, Flood and Earthquake Criteria', National Academy Press, Washington, D.C., 1985). According to this report: "The results (heretofore unpublished) reflect an extremely wide range of opinions but indicate the following median opinions from the 46 individual respondents for quantifying the boundaries on hazard classes":

Hazard Classification	Mean Values of Opinions	
	Probable Loss of Life	Economic Loss[a]
High	1 or more[b]	Greater than $200,000
Significant	0	$30,000 to $200,000
Low	0	0 to $30,000

[a] Includes downstream damages, but not cost of dam or value of services provided by reservoir.
[b] Strong consensus that loss of one life defines high hazard.

These results imply that it is very likely that the note [5] recommendations would be acceptable to many, if not the significant majority of us.

In conventional dam engineering practice, an 'equivalent' dollar value is often indirectly placed on human life. Such equivalent dollar values have been considered taking into account the reasonable cost of saving one life, relevant court decisions, or losses 'acceptable to the society'. For instance, G.M. Salmon and G.R. von Hehn in 'Consequence Based Dam Safety Criteria for Floods and Earthquakes', International Workshop on Dam Safety Evaluation, 1993, place this value at $10,000,000 when considering "…risks normally accepted by society…".

Although no explicit attempt is made in this Document to separate potential loss of life from economic losses, in fact, adding notes [5] to Tables 8 and 11 effectively separates potential loss of life from economic and other losses, in terms of flood and earthquake design criteria for new tailings dams, as follows:

Number of Potential Lives Lost	Recommended Flood and Earthquake Design Criteria
1 or more*	PMF and MCE
0	Prevailing criteria resulting from consideration of economic losses, environmental impacts as well as social and cultural losses

* Downstream residents and occupants of regularly attended workplaces with significant exposure periods. Exposure periods and the number of persons exposed should be considered in other cases (*e.g.*, mine personnel maintaining SCF, occasional fisherman or passer-by need not be included).

In other words, for the purpose of selecting flood and earthquake design criteria for new tailings dams, no parallels of any kind between potential loss of life and economic losses need be drawn if relying on the note [5] recommendations.

The preceding discussion has been intended to show that the note [5] recommendations are not largely inconsistent with conventional dam engineering practice. No suggestion is made herein that these recommendations reflect the necessary or reasonable standards from the perspective of societal values. It is suggested, however, that endorsing these recommendations is desirable from the mining industry's perspective.

From the preceding discussion, the rationale underlying the note [5] recommendations can be summarised as:

- these recommendations can be met in the majority of cases at reasonable costs, and thus be acceptable to the mining industry as a whole;
- occurrences of the rare cases, in which a new tailings dam would not be constructed because of the prohibitively high differential cost, should also be acceptable since, from the mining industry's perspective, it seems that there is more to gain than lose by endorsing the recommended criteria, particularly when considering the public perception and potential liability issues;
- conducting a risk analysis with the purpose of justifying the selection of less stringent design criteria would likely be lengthy and costly, with the outcome of the analysis virtually impossible to predict;
- these recommendations are not largely inconsistent with the conventional dam engineering practice; and
- minimising controversies at the permitting stage is highly desirable.

The key question obviously appears: how many tailings dams would not be constructed as a result of endorsing the note [5] recommendations (*i.e.*, how rare the 'rare cases' would be)? It this regard, it needs be realised that all of the following conditions must simultaneously be met for a tailings dam not to be constructed *as a result of the note [5] recommendations*:

- potential for loss of life exists;

- only 'few' lives could potentially be lost;
- regulatory requirements do allow for selecting less stringent than PMF and/or MCE criteria, where 'few' lives could potentially be lost;
- the differential cost is prohibitively high from the perspective of the project economics;
- neither potential environmental impacts nor potential economic losses, including also potential social and/or cultural losses, require the use of PMF and/or MCE criteria;
- only the production phase is considered (with respect to the long lasting tailings dam operating phases, PMF and MCE would have to be selected where the potential for loss of life exists, as discussed in Section 10.9);
- the results of relevant risk analysis justify the selection of a less stringent than PMF or MCE criterion (although carrying out such an analysis needs not be mandatory, it can reasonably be assumed that it would have to be carried out at least in some cases).

On a recent new tailings dam project where the potential for loss of life was identified, the consultant proposed to use the more critical of either 50%PMF or a flood with AEP = 0.0001 (1 in 10,000 years flood) as a design criterion for the first 2-year stage of dam operation, with 100%PMF to be applied to both the remainder of the production phase and the closure phase (handling 100%PMF would be very expensive during the first stage). The argument made was that the exposure period (2 years) was very short, and thus the proposal was acceptable. Since a reference to the exposure period (design interval) was made, this proposal could be explained by the following reasoning, with reference to conventional dam engineering practice. Because 100%PMF is (often, albeit not always) considered necessary when the potential for loss of life exists, with a typical life of conventional dam taken as 100 years, and the probability of PMF occurrence in terms of AEP can be judged in the order of 0.0001 to 0.000001, say, 0.00001, the resulting PEDDI is 0.1% over the 100-year design interval. Hence, assuming PEDDI = 0.1% as being acceptable, the design flood with AEP = 0.0005 (1 in 2,000 years flood) would provide the same level of protection with respect to the 2-year design interval. Therefore, the proposal to use 1 in 10,000 years flood as the design criterion for the first stage of dam operation, which corresponds to PEDDI = 0.02%, could be judged acceptable and, in fact, conservative from the perspective of conventional dam engineering practice.

The above reasoning has two flaws. As stated previously, the rationale behind using PMF (or MCE) is that the exceedance of either PMF or MCE is taken virtually impossible, thus a reasonably highest level of protection can be provided, where deemed necessary. The probability of occurrence is not relevant in this context, which also means that giving consideration to the length of design interval is not appropriate in this situation (such a consideration could be given for the purpose of performing a risk analysis). Secondly, dividing a dam operating phase into arbitrary intervals for the purpose of deriving a PEDDI value is not appropriate since it would always result in non-conservative designs (the example given in the second last paragraph of Section X is relevant to this discussion as well). In this case, the 2-year interval was identified based on the economics rather than the consequences of potential dam failure and/or dam operating attributes.

Having said that, one cannot help but wonder if the consultant's proposal should be rejected based on the preceding arguments, regardless of any other circumstances. Per-

haps in this particular case, the proposal could be judged acceptable when examining all specifics of the project, for instance, changes in the impoundment storage capacity during the 2-year period, occurrence of rainy and dry seasons, probability of dam breach as a result of overtopping, reliable flood warning system, or some other defensive measures (these are the attributes of a risk analysis). In the author's view, however, accepting this proposal would also mean setting up a precedent for future, perhaps inadvertent abuses of the PMF and MCE concepts. To prevent such potential abuses, it is best to draw a line.

[Even if the note [5] recommendations were considered 'far too stringent' in respect to the initial 2-year stage operation, a mere statement that the exposure period is short, and thus designing for a flood/earthquake lesser than PMF/MCE is appropriate, should not be taken acceptable unless supported by the results of a risk analysis.]

It is worth noting that the above case cannot really be considered with reference to conventional dam engineering practice. This is because the concept of a 'first-stage' operation cannot be related to conventional dams. In this case, only the general principles used in conventional dam practice can be accounted for. In other words, we are largely 'on our own' in this case.

The note [5] recommendations could be controversial, chiefly because of the views of some conventional dam safety organisations/owners (most notably, the U.S. Corps of Engineers, or CDSA). As stated at the beginning of this Document, "….caution, experience and sound judgement are required when contemplating the use of any of the recommendations stated herein.". In this regard, it is essential to keep in mind that the note [5] recommendations *are* consistent with the views of other dam safety organisations (*e.g.*, ICOLD, FERC, or ICODS).

The preceding discussion has been presented with a reference to conventional dam engineering practice. For better or for worse, this practice must not be ignored when considering tailings dams. In this regard, it needs be realised that the approach, which permits the use of a less stringent than PMF criterion where the potential for the loss of 'few' lives only exits, was developed and gained significant acceptance at a certain time and under some specific circumstances. This happened, most notably, in conjunction with the 'national dam safety program' launched in the U.S. in 1977, when it was realised that many existing high hazard dams were not capable of passing full PMF. The enormously influential views of the U.S. Corps of Engineers still present an indisputable 'bible' for many dam safety organisations, owners and engineers. It is highly unlikely, however, that the U.S. Corps of Engineers in the late 1970s would have accounted for the interests of the mining industry of the late 1990s.

Loss of Life – Existing Tailings Dams

In the case of existing tailings dams, the situation is different. The risks are already there, and the question of the legacy of the 'old times' must not be ignored. This legacy is not different from the conventional dams, asbestos, DDTs, CFCs, leaded gasoline, sewage disposal, dangerous roads, substandard buildings, pharmaceutical and many other, similar legacies. All these legacies have two things in common: they were deemed acceptable not long ago and the society cannot afford to correct the resulting situations 'over-night'.

According to Tables 8 and 11, selecting a flood or earthquake design criterion less stringent than PMF or MCE, respectively, is taken acceptable for existing tailings dams classified in the High category, even if ‘some’ increase in the loss of life is expected (Table 2). As discussed earlier in this subsection, this is consistent with many (albeit not all) guidelines for conventional dams, endorsed by various dam safety organisations and regulatory agencies.

Selecting a less stringent (than PMF or MCE) criterion would only be permitted if the results of ‘additional cost vs benefit’ analysis indicate that retrofitting the dam to higher standards cannot reasonably be justified (notes [3] to Tables 8 and 11). Regardless of the results of such an analysis, the design criteria for existing tailings dams with respect to potential loss of life must not be selected less stringent than those considered acceptable for conventional dams.

‘Additional cost vs benefit’ analysis may be performed in the form of a risk analysis, in which other (than the consequences of failure) dam safety aspects are accounted for. These may include a dam operating attribute, a flood warning system, or another defensive measure that would reduce the risk of potential loss of life. In this case, the selection of flood or earthquake design criterion with respect to ‘Type I failure – external cause’ (Figure 7) may also depend on tailings dam operating attributes and other relevant factors, rather than the CCC only.

The above discussion does not apply to long lasting tailings dam operating phases, as indicated in notes [4] to Tables 8 and 11.

Fractions of PMF and MCE

In many guidelines developed for conventional dams, the selection of flood and earthquake criteria relies more heavily on the deterministic method by incorporating some fractions of PMF and/or MCE. A widely known example of this approach is the guideline for selecting flood design criteria prepared by the U.S. Army Corps of Engineers (‘National Program of Inspection of Nonfederal Dams, Final Report to Congress’, 1982).

It seems that using a fraction of PMF or MCE reflects a long time practice accepted in the conventional dam engineering rather than some rationale developed based on acceptable risk. As pointed out in Section III.1, the approach followed by the CDSA (Tables 8 and 11) is preferred since the probability of exceedance of the design event is known, except for the PMF and MCE (and the alternative ‘50% to 100%MCE’).

[Since hydrologic and seismic databases are continuously enlarged with time, the design criteria comprising a combination of probabilistic criteria with the full magnitudes of PMF and MCE are becoming more reliable.]

XII.2 Environmental Impacts

As discussed in Section XI.1, one of the basic premises underlying the recommended flood and earthquake probabilistic design criteria resulting from the impact classification (*i.e.*, the PEDDI values given in Tables 9 and 12) is that the level of protection assumed to be acceptable in future, should be the same as that considered acceptable today. Obviously, this statement must not be seen as a rationale underlying the recommended criteria but, rather, as an objective towards which the criteria have been developed.

There is no rationale underlying the recommended design criteria given in Tables 9 and 12 other than: (i) these are considered ‘reasonable’ and ‘practically achievable’ and (ii) generally consistent with the current tailings dam engineering practice although, it seems, more stringent with respect to the High category dams and the closure phase (as discussed later in this section). It is believed that in the majority of cases, these criteria can be met at reasonable costs, with respect to all tailings dam operating phases.

XII.3 Flood vs Earthquake Design Criteria – Impact Classification

A comparison of the flood and earthquake design criteria recommended in Tables 9 and 12 indicates that in terms of PEDDI, the probabilistic criteria for floods are ‘more stringent’ than for earthquakes at the boundary between the High category and the upper range of Significant category dams (PEDDI = 2% vs PEDDI = 5%). The reasons for this proposal can be summarised as follows:

- The upper bound criteria for High category dams, being the PMF and MCE, are in principle the same in the sense that both refer to some ‘maximum possible events’. Yet, these two criteria may be judged significantly different in terms of the probability of occurrence. Albeit both the PMP (with the resulting PMF) and MCE are derived based on the deterministic method from which no probability of occurrence can be deduced, the corresponding probabilities are taken to exist. In terms of AEP, these are typically taken in the order of 0.00001 and 0.0001 for the PMP and MCE, respectively. It follows that making comparisons between flood and earthquake design criteria in terms of the probability of occurrence needs not necessarily be meaningful.
- The consequences of occurrence of an event more severe than the design event need not be comparable for floods and earthquakes. There seems to be no evidence that a well designed and compacted tailings dam would fail even under a very strong earthquake. On the contrary, typical tailings dams are vulnerable to failure as a result of overtopping. Hence, the outcome of an event more severe than the design event may be judged to represent a higher hazard in the case of floods than earthquakes for many tailings dams. Consequently, an ‘additional’ protection seems to be warranted with respect to the flood design criterion (lower PEDDI value).
- The consequences of tailings dam failure due to flood in excess of the IDF need not be comparable to those resulting from failure of the same dam due to earthquake in excess of the MDE. Should a breach of tailings

dam occur due to flood, the consequences in terms of environmental impacts would likely be more severe than those resulting from dam breach due to earthquake, particularly for dams classified in the High category. The majority of such dams would be expected to contain sulphidic and/or radioactive tailings with potential to generate contamination in the long term. The consequences of the release of such tailings would likely be more severe under flood condition as the amount of released tailings and the extent of their deposition by flood waters would be greater, with some solids deposited high on the banks of the receiving stream. Although, in principle, this issue could be handled by selecting different CCCs with respect to floods and earthquakes, such a precision in establishing CCCs would not be very practical. Therefore, having an additional protection incorporated into the flood design criteria seems to be justified, at least for many tailings dams classified in the High category.

- Providing a relatively large spillway/high capacity decant structure would not be excessively expensive for typical tailings dams (with some exceptions, see Section XIII). In many cases, tailings dam drainage areas are small and handling extreme flood events can be accomplished at reasonable costs. The cost of a larger spillway construction would often be small as compared with the cost of tailings dam construction or, from another perspective, the unit cost of tailings disposal would not significantly increase by providing a larger spillway. On the other hand, constructing new and, particularly, re-constructing some of the existing tailings dams sufficient to resist a larger earthquake could be very expensive at many sites. In other words, some practical cost considerations have been incorporated into the recommended design criteria.

XII.4 The 'Highest' Environmental Impact

Examination of Tables 3 and 4 indicates that, from the perspective of designating flood and earthquake design criteria, the impact classification could have been formulated in a way that is more consistent with conventional dam engineering practice. For discussion purposes only, this is illustrated as follows:

CONSEQUENCE CLASSIFICATION CATEGORY	POTENTIAL CONSEQUENCES OF FAILURE	CLASSIFYING DETERMINANT GROUPS
The 'Highest'	The most severe environmental impact	the most severe combination of determinants, except for 'P3' *i.e., A3 + D3 + S3*
High	Severe environmental impact	as in Table 4, except as indicated under the 'highest' category
Significant	Moderate, or perceived moderate to severe, environmental impact	as in Table 4
Low	Low environmental impact	as in Table 4

It follows from this table that the High category defined in Table 4 has now been subdivided into two categories, thus distinguishing the 'most severe environmental impact' category. Based on this table, one would 'naturally' designate the most stringent flood and earthquake design criteria (PMF and MCE) to this category, with the remaining criteria as shown in Tables 9 and 12. This would indeed be quite consistent with the design approach recommended by the CDSA (Tables 8 and 11) and other conventional dam safety organisations.

Such an approach is not considered appropriate for tailings dams. The intent of recommending the design criteria resulting from impact classification is that PMF or MCE should be selected for all High category dams regardless of the length of design interval, unless Condition 2 stated in Section 10.9 applies.

On the other hand, the intent also is to provide for a reasonable approach to the selection of design criteria. Consider, for instance, the 'A3+D3+S3' determinant group and a production phase duration of 10 years. Selecting a 1 in 5,000 years or 1 in 2,000 years flood as the design criterion (assuming that these can be estimated with sufficient accuracy) would result in PEDDI values of 0.2% or 0.5%, respectively. Assuming that Condition 2 is satisfied, this range of PEDDIs could be considered acceptable even if the 'highest' CCC applies.

XII.5 The Low Environmental Impact

The minimum flood and earthquake design criteria recommended for the Low category dams (PEDDIs = 20%, see Tables 9 and 12) may seem lenient with respect to the production phase, particularly from the owner's perspective.

It needs be emphasised that the design criteria given in Tables 9 and 12 are not intended to account for potential losses to the owner. Owners would be expected to insist on selecting more stringent design criteria even though their tailings dams are classified in the Low category. Few owners, if any, would accept a 20% probability of tailings dam failing during the production phase since this would likely result in a significant economic loss to the mine operation as well as damage to the owner's reputation. In any case, Condition 2 stated in Section 10.9 should always apply.

On the other hand, examination of the design return periods given in Tables 10 and 13 indicates that the recommended design criteria for low category dams are rather stringent when applied to the closure phase.

XII.6 Selection of Probabilistic Design Criteria – Impact Classification

Consider the probabilistic earthquake design events presented in Table 13. Suppose that a tailings dam is classified in the Significant category with respect to both Phase 1 and Phase 4. The dam is to be constructed over foundation comprising loose saturated sand. Suppose further that it has been determined that the dam would fail if the sand deposit liquefies. Phase 1 is to last 20 years and the analysis shows that the sand deposit would not liquefy under earthquakes with return periods of up to 1,000 years. The design earthquake, according to Table 13, can be selected as a 1 in 200 – 400 years event. Can the sand deposit be left unexcavated? The answer is 'no' since selecting a design criterion (or conducting any other tailings dam safety evaluation) must meet the requirement stated in Section 5:

> "Evaluation of tailings dam safety carried out at any current or imminent operating phase must be conducted taking into consideration the anticipated dam safety requirements pertaining to all future phases."

In this case, the fact that the dam could fail under the 1,000-year earthquake would violate the safety requirement pertaining to (future) Phase 4. Selecting a 1 in 200 – 400 years earthquake as the Phase 1 design criterion would be acceptable provided that the dam is designed and constructed so that, after retrofitting the dam for closure, it would be able to withstand the load resulting from a MDE between the 1 in 2,500 years earthquake and MCE (Table 13).

The most typical issue underlying the selection of 1 in 200 – 400 years design earthquake for Phase 1 would relate to the dam deformation expected to occur due to earthquake load, and the resulting loss of freeboard. Assuming a less severe Phase 1 design earthquake could allow for having a steeper downstream slope in the case of tailings dam constructed in stages, prior to retrofitting the dam for closure.

The advantage of selecting less severe design events for Phase 1 could particularly apply to the flood design criteria on projects where providing a large spillway/decant structure and/or freeboard for each stage-raise of the dam would be very expensive.

XII.7 Condition 2

Condition 2 stated in Section 10.9 must be well understood. It is intended to ensure that tailings dams are designed according to criteria which are more stringent than the (considered acceptable) minimum criteria recommended in Tables 9 and 12, wherever this can be achieved without jeopardising the project economics.

In 1993 in western Ontario, a small earthfill dam (approximately 250 m long and up to 6 m high) was to be constructed to intercept and divert contaminated runoff from a 27 ha watershed, with the purpose of improving water quality in a lake that had been strongly affected for many years. A design criterion set for the overall site closure project called for preventing the releases of contaminated runoff under hydrologic events with return periods of up to 1 in 100 years (a short duration rainfall event represented the critical flood in this case). During the design stage, it was realised that by increasing the height *of the dam by 0.6 m only, with the dam volume increasing by 4,300 m^3, a 6-hr PMP could be intercepted, resulting in a significantly higher degree of lake protection. It followed that having a higher dam at an additional cost, which was small as compared to the total project cost, would result in a significant 'exceedance' of the minimum design criterion that had been judged acceptable. It was recommended to the owner that the dam height be increased and the owner agreed. Condition 2 thus was applied.*

[Condition 2 has explicitly been incorporated in the flood and earthquake design criteria resulting from the LLEL classification by adding notes [3] to Tables 8 and 11.]

The statement "…cannot reasonably be justified." incorporated in Condition 2 is meant to relate the increase in the cost of tailings disposal due to providing a higher protection level to the overall economics of mine operation. For instance, providing a higher level of protection (*above* that recommended in Tables 9 and 12) at an additional cost of $0.02/tonne of deposited tailings could be judged reasonable at many mining operations. Providing a higher level of protection at an additional cost of $2.00/tonne of deposited tailings could possibly be justified at very few, exceptional mine operations only.

Condition 2 is not intended to imply that a higher level of protection is equivalent to the '*what-the-owner-can-afford*' before his operation becomes a break-even enterprise. Such an approach would defy both the business practice and common sense.

Condition 2 is intended to apply to the situations where a *significant* benefit (a significantly higher level of protection) would result from the increased cost acceptable to the owner. For instance, spending additional money for constructing/re-constructing a tailings dam – spillway system capable of safely passing a flood with a return period of, say, 1,500 years rather than 1,000 years (the 1 in 1,000 years flood being acceptable according to a minimum design criterion) would not be reasonable in most cases.

Condition 2 may be somewhat disturbing since it implies that the environment could be better protected at mine sites with richer orebodies. This may be difficult to rationalise unless one looks into the common personal income tax principle. Although not necessarily voluntarily, we agree to pay higher taxes (percentage-wise!) on higher incomes, thus contributing more to the society with increased well being. Condition 2 is stated in the same spirit, with the two additional provisions: 'taxing to death' is not permissible and the taxpayer's money must not be wasted.

XII.8 Some Design Criteria Proposed by Others

- In ICOLD Bulletin 74, the recommended flood and earthquake design criteria, limited to tailings dams the failures of which would *"…result in loss of life and extensive property damage…"*, are PMF and MCE (the 'note [5]' recommendations discussed in Section XII.1 are consistent with the above recommendation, which follows ICOLD Bulletin 59).

  With respect to potential environmental impacts, no flood or earthquake design criteria are recommended in the ICOLD bulletin except that *"For* *closed circuit tailings dam, where no discharge is permitted, the tailings dam must provide sufficient freeboard to allow the storage of the PMF as a surcharge on the tailings pond."* This criterion relates to potential Type II failure only and the most stringent EDF requirement (see Sections 10.7 and XIV). Less stringent requirements for the EDF are not addressed in the ICOLD bulletin.

- Iain Bruce and Tim Eaton in '<u>Tailings Dam Seismic Design Criteria</u>' (CDSA /CANCOLD Conference, St. John's, Nfld., 1993) propose a set of earthquake design criteria for tailings dams, adapted from the '<u>Guidelines for Selecting and Applying Seismic Criteria for Dams</u>', B.C. Hydroelectric Authority, 1988, for both the ODE (Operating Design Earthquake) and ADE (Abandonment Design Earthquake), with no recommendations given on the MDE prior to abandonment.

  As pointed out in Section 10.8, the concept of ODE (equivalent to OBE) is not addressed in this Document.

  With regard to ADE, the criteria proposed by these authors are: 1/475 year, 75%MCE with AEP value of no greater than 0.001, and MCE for the Low, Significant and High incremental hazard categories, respectively. Assuming that the corresponding consequence classification categories in terms of potential environmental impacts are roughly equivalent, the criterion proposed by I. Bruce and T. Eaton would be the same as the 'closure' design event (500–1,000-year design interval) recommended in Table 13 for High category dams. For the lower range of the Significant and the Low category dams, the criteria given in Table 13 are significantly more stringent.

  It should be noted that B.C. Hydro developed their criteria for operating rather than abandoned dams.

- In '<u>Planning, Design, and Analysis of Tailings Dams</u>', BiTech Publishers Ltd, 1990, Steven G. Vick recommends that the design PEDDI *"…should be at most a few percent over the active (saturated) life of the embankment in most cases."*, when discussing earthquake design criteria. When discussing flood design criteria, he recommends that the design PEDDI *"…should not exceed a few percent, at most, depending on the consequences of failure to downstream inhabitants, downstream land users, and the mine or mill itself. Environmental consequences of failure are also very significant."*. It seems, therefore, that the recommended flood and earthquake design criteria with respect to potential environmental impacts (Tables 9 and 12) are in general agreement with S.G. Vick's views, at least for the High and the upper range of the Significant consequence categories.

The probabilistic '1 in 475 years' and '1 in 1,000 years' criteria have often been used for designing of tailings dams under a wide variety of circumstances. Tables A-2 and A-3 illustrate how these two criteria compare with the minimum flood and earthquake criteria recommended in Tables 9 and 12, respectively.

Table A-2
1 in 475 years and 1 in 1,000 years vs Recommended Design Criteria - Floods
(from design events given in Table 10)

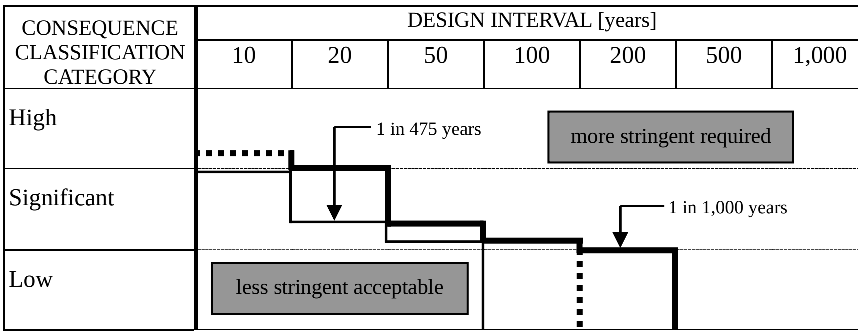
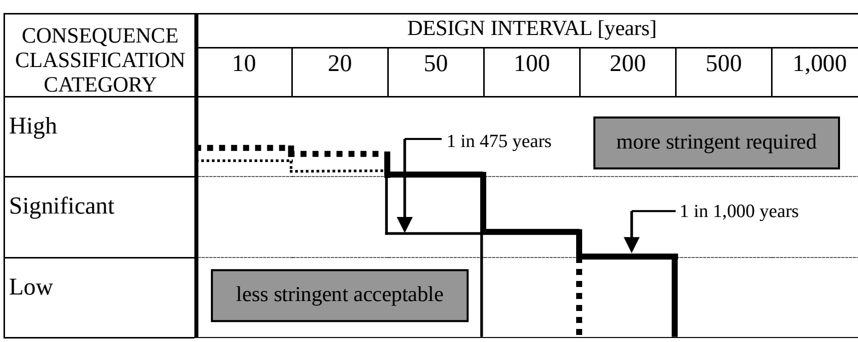


Table A-3
1 in 475 years and 1 in 1,000 years vs Recommended Design Criteria - Earthquakes
(from design events given Table 13)



It follows from Tables A-2 and A-3 that the criteria recommended herein with respect to potential environmental impacts are significantly more stringent than the '1 in 475 years' and '1 in 1,000 years' criteria for tailings dams classified in the higher consequence categories, particularly with respect to the longer design intervals. Nonetheless, it is believed that the recommended criteria (intended as being reasonable and practically achievable) can be met in the majority of cases at reasonable costs.

The recommended criteria are less stringent than the '1 in 475 years' and '1 in 1,000 years' criteria in the case of low category tailings dams and short design intervals, which would primarily apply to Phase 1. Since a tailings dam failure during Phase 1 could result in significant economic and reputation losses to the owner (neither of which is accounted for in the recommended criteria), it is believed very likely that a mine owner, given the opportunity to make a learned decision based on adequate information provided by the engineer, would insist on selecting more stringent criteria for low category tailings dams (see also Section XII.5 for relevant discussion).

XII.9 The 'Portfolio' Problem

Having a number of tailings dams (a 'portfolio' of dams) constructed based on probabilistic flood and earthquake design criteria, the owner faces a cumulative probability of dam failure, which determines the corporate risk. Similarly, a regulatory agency faces a cumulative probability of dam failure, which increases with an increase in the number of tailings (and other) dams existing within the jurisdiction. Note that a number of dams can be subject to the same flood or earthquake event, which may add to the complexity of the issue.

Accounting for the portfolio aspect in the tailings dam safety evaluation process outlined in this Document would not be possible since there seem to be no available information as to the acceptable amount of cumulative risk, whether from the owner's or the regulator's perspective. In practical terms, this issue can only be addressed by conducting a risk analysis, specific to the owner's or the regulator's portfolio.

A 'mining camp' with a number of tailings dams may raise another portfolio problem, relating to a distinct ecosystem. Again, this issue would have to be addressed on a site-specific basis. It is worth noting that it is Type II failures that would often be of primary concern in this regard (there are, for instance, major river systems heavily affected by a number of tailings disposal operations).

The portfolio problem, although obviously important from the public and corporate risk perspectives, might be of lesser significance from the technical perspective. In Section XVIII, it will be argued that only *very few* tailings dams would be expected to fail (world-wide).

Incidentally, even if a tailings dam were designed based on PMF and MCE rather than some probabilistic design criteria, still it would have to be included in the portfolio since a dam may fail for other than an extreme event reasons.

XIII HYDROLOGIC MODELLING

Hydrologic modelling often presents the most challenging component of tailings dam design. One of the primary reasons for this challenge is the response of a relatively small and heavily disturbed watershed that has to be modelled in the majority of cases.

A tailings dam 'watershed' is often quite complex. It may include tailings beach and, sometimes, dam slope, tailings pond, open pit, mine workings (underground workings may be connected to surface thus receiving also an inflow of overland runoff), waste rock dumps, mine yards, roads, cleared and uncleared terrain, *etc.* On some projects situated in mountain regions, different parts of the mine site watershed, or even the tailings dam watershed may have significantly different meteorological and/or hydrologic characteristics.

Moreover, inflow/outflow (often variable in time) streams such as the WTP influent, SCF discharge, process water and other contaminated or clean water streams must typically be accounted for when the modelling of a hydrologic event is performed. In addition, tailings impoundment management system may include an additional buffer storage, passive treatment and other ponds.

Specific to some tailings dams is the need to contain a design flood volume (Section XIV) rather than pass a peak flow. On many projects, both these requirements have to be designed for.

Specific to tailings dams where no discharges of tailings pond water under normal conditions are permitted, is the necessity to consider and compare the consequences of a short term (say, 24-hour) and long duration (say, 60-day) hydrologic events. In some cases, it is difficult to determine 'by inspection' which of these two events would govern when designing for the total or partial storage of flood volume, and both events may have to be modelled.

Since relatively small watersheds are typically involved, it is often possible to design for the containment of PMF volume (freeboard needs not be very large) or passing the peak flow generated by PMF (size of the spillway needs not be very large), or a spillway-freeboard system adequate to handle PMF.

In some cases, however, structures constructed to pass the design peak flow may be very expensive. The classic case is a tailings dam raised in stages and located across a valley having steep rock slopes, at a site where high peak flows are generated during rainfall seasons. Constructing an overflow spillway for each stage-raise could be very expensive under such conditions and other, less desirable solutions have been used (a decant structure passing through or under the dam, a tunnel under the tailings impoundment or at dam abutment, *etc.*).

To account for the complexities of a typical tailings impoundment, the preferred approach to the modelling of long duration hydrologic events involves developing a site-specific 'continuous simulation' hydrologic model based on historical meteorological database, using an appropriate computer program (*e.g.*, Qualhymo). Calibration of the model presents then the greatest challenge, particularly for new mines where no site disturbance has yet occurred (the depth of runoff increasing by up to 50% after site disturbance due to tailings impoundment construction is not uncommon). The use of gauged watershed data for model calibration will often be of limited value since such data are typically available from watersheds many times larger than the dam watershed and having significantly different land and retention (flood attenuation) characteristics.

On a project in western Ontario mentioned previously in Section XII.7, a 3-pond water management system was designed and constructed to handle acidic drainage generated in the uppermost tailings pond (277 ha tailings impoundment watershed) during Phase 3. One of the design necessities was to incorporate an existing 'reclaim' pond (13 ha watershed) situated immediately downstream of the main tailings dam for buffering the flows prior to the final 'pumphouse' pond (2.5 ha watershed) located downstream of the reclaim pond. The 'lowest' pumphouse pond (3,000 gpm capacity with an additional 125 gpm 'trickle' pump) was designed with normal operating levels below the nearby river level to prevent the release of contamination via groundwater. The need for passing the flows from the tailings pond to the pumphouse pond via the reclaim pond (preventing, at the same time: spills of contaminated water, overtopping of the various dams, unacceptable raising of hydraulic head in the pumphouse pond under a variety of hydrologic events, as well as freezing of the decant structures' inlets) required intensive hydrologic modelling. This also included developing rather 'precise' designs for the hydraulic capacities of the two decant structures, constructed of HDPE 'self-cleaning' pipes, and designed to connect the three ponds so that the entire system would be 'self-regulating' (the system was designed to pass runoff by gravity, with a manual valve designed for a 5-day response time and an automatic shut-off valve designed to prevent a spill in the case of pumphouse malfunction). As it turned out, the system is actually quite simple and relatively inexpensive, requiring minimum surveillance and maintenance only. It has been in operation since 1992 and, so far, performed according to the design assumptions, without any problems. The message here is that such systems can be designed and relied upon only if supported by adequate hydrologic modelling (a calibrated 'continuous simulation' model was used on that project).

A site-specific, continuous simulation hydrologic model is also very useful for deriving the tailings impoundment water balance (one of the most crucial aspects of tailings dam design and operation). Such a model allows for computing water balance, including tailings pond levels and available storage capacities, on a daily basis in both the short and long terms, thus providing a powerful tool for modelling the dynamics of tailings dam operation.

Diversions are often constructed upstream of tailings dams, which may or may not be designed for the same flood event as the tailings dam. Careful consideration has to be given with respect to potential failure of such diversion(s) when designing for the IDF and EDF.

XIV ENVIRONMENTAL DESIGN FLOOD

Although the concept of EDF is rather simple (Section 10.7), its determination is more complex. Since this aspect of hydrologic designs does not seem to be well publicised, a few practical remarks relevant to the determination of EDF are provided in this section.

In essence, the determination of EDF involves the estimation of return period for a critical flood, in terms of volume, that must be stored and the 'diluted' contaminant concentrations in the receiver resulting from a somewhat larger flood. The design objective is that these concentrations be elevated below certain limits only, and do not remain elevated over extended period of time, thus resulting in an acceptable environmental impact. Such an impact would be expected to occur on an intermittent basis, and is determined taking into consideration the expected frequency and the probability of occurrence of EDF. In the majority of cases, more than one contaminant has to be considered.

One way to determine the EDF is to assume a certain flood return period as a first approximation. Determination of the EDF then starts with the assumption that the volume of flood with a certain return period (say, 100 years) will be stored. The flood modelling is performed and an adequate spillway/decant structure invert elevation selected. A 'somewhat larger flood', say with a return period of 200 years, is then routed and the impoundment discharge hydrograph constructed. The impact on the receiver(s) is determined based on this hydrograph and other data such as the hydrograph of the receiver prior to, during and following the discharge, dilution available in the tailings pond, background concentrations in the receiver, dilution and attenuation available between the discharge structure and the compliance location, stream mixing characteristics, *etc.* If the impact is judged acceptable, taking into account the expected probability and frequency of its occurrences, then the spillway elevation may be assumed adequate or a flood with smaller return period may be considered to arrive at less conservative designs. If, on the other hand, the impact is determined unacceptable, then a flood with a higher return period must be considered and the spillway structure invert elevation has to be raised.

In many cases, two hydrologic models will have to be run simultaneously, one for the tailings pond watershed and one for the receiver's watershed.

Designing for IDF will have to be performed before the final spillway elevation is selected. When examining a flood 'somewhat larger' than the EDF, the common objective is to release tailings pond water slowly so that the dilution in the receiver is maximised. On the contrary, the objective of the spillway designed to pass IDF, which often corresponds to a much larger flood, is to have a large capacity so that the raise in tailings pond level is minimised. These are contradictory requirements that need be optimised by designing the most economic spillway – freeboard system.

Assumption is sometimes made that discharges resulting from all floods with return periods higher than that corresponding to the ‘somewhat larger flood’ for which environmental impact was found acceptable, would result in lesser impacts due to larger dilution available both in the tailings pond and the receiver. Although this may be intuitively correct, there seems to be no proof of it. This is because the hydrographs of the discharge structure and the receiver will typically be shifted with respect to time and this shift may be different for different floods. Hence, an ‘envelope’ of resulting contaminant concentrations may have to be constructed for several floods, from which the EDF would be selected. Even then, the outcome of the analysis needs not be straightforward as the time during which contaminant concentrations in the receiver remain elevated may have to be weighted against their magnitudes.

The experience from Canadian sites shows that the EDF must often, but not always, be selected as that corresponding to a long duration spring runoff event rather than short duration rainfall. Under other climatic conditions, this might correspond to several wettest weeks of a rainy season. A long duration runoff is usually determined from a continuous simulation of rainfalls and/or snowmelt based on historical meteorological database derived for the site.

In most cases during the floods which generate volumes smaller than the EDF volume, the net tailings pond discharge, after incorporating the tailings pond water balance with all the various input and output streams, will consist of the WTP influent, evaporation, seepage which is not returned to the tailings pond and discharge to a surge pond (if existing). Where the EDF corresponds to a long duration runoff event, it is assumed that the WTP is operating at full capacity during the flood. Where the design EDF corresponds to a short duration rainfall event, the WTP inflow is typically neglected.

The typical EDF durations have been found to be in the order of 30 to 120 days, although the spillway discharge time at a well designed and operated tailings dam would be significantly less (days or few weeks, at the most).

On a project in northern Ontario, the EDF was initially assumed as the 1 in 100 years 90-day spring runoff event (short duration hydrologic events were ruled out based on inspection). The analysed system was rather complex, with a total watershed area of about 670 acres and two sources of potential discharge of contaminated water: a tailings pond and a buffer pond. The modelling showed that in the case of 1 in 200 years event, the buffer pond spillway would overflow for a period of 13 days. In the case of 1 in 500 years event, contaminated water would be released from the tailings and buffer ponds over 21 and 15 days, respectively. The elevated concentrations in the downstream river system were conservatively estimated based on dilution only and it was judged that the resulting environmental impacts were acceptable (impacts on aquatic life and a drinking water source were examined).

It often happens that a flood generated from, say, 1 in 200 years long duration event (*e.g.*, 60-day spring runoff event) results in a higher maximum tailings pond level than a short duration PMP event (*e.g.*, 48-hour summer PMP). This has to do with limited capacities of WTPs, capable of treating only fractions of the runoff volumes generated during extreme long duration events. It follows that the concept of PMF, widely used for the design of conventional dams (PMF resulting from a short duration PMP or a combination of PMP and snowmelt), needs not be adequate for the purpose of designing for EDF.

EDF durations that need be considered may vary very significantly. On a tailings dam project in British Columbia where a very large storage volume could be made available, the EDF was selected as the sequence of wet years: 1 in 50, followed by 1 in 200, followed by 1 in 5 years event (modelling of 3-day summer PMP and spring PMP combined with snowmelt indicated lower maximum tailings pond levels), with typical runoff conditions assumed for the years following the design sequence. The selected sequence of wet years represented a very stringent design criterion considering the quality of tailings pond water. It was selected because of the sensitivity of the project and a municipal water intake located downstream of the dam.

It is essential to account for months or, sometimes, years after the end of modelled EDF event. EDF will typically result in a tailings pond level raising close to the spillway/decant structure invert. In the months to come, WTP will have to keep up ahead of the runoff reporting to tailings pond, sufficient to lower the pond level to the normal operating level within a design time period.

Concurrent discharges of contaminated water from other than the tailings dam facilities, including also treated effluent discharge, may have to be accounted for when determining the EDF, where these discharges are routed to the same receiver as the tailings pond discharge.

Since the IDF must be selected to generate high peak flows while the EDF must be selected to generate high runoff volumes, modelling of these two floods may have to be carried using different model parameters. This is an important consideration. It means, in practical terms, that the site hydrologic model may have to be calibrated independently to produce reasonably conservative peak flows and runoff volumes, or two different models may have to be used. This would not be required where a perfect (or ‘true’) hydrologic model is available.

Determination of EDF for dam sites where tailings pond discharge is routed to a lake or seashore is more complex. Modelling of the lake dynamics with reference to its assimilative capacity may be required to arrive at the EDF (providing a submerged diffuser for tailings pond discharge may allow for selecting a lower design return period for the EDF).

As emphasised in the foregoing discussion, the probability of EDF occurring during the design interval should be considered when determining the acceptable environmental impact. If the design return period for EDF is large as compared with the length of design interval (the time period during which tailings pond water under given conditions could potentially be released), the probability of EDF occurrence becomes low. Should the tailings dam construction and/or operating costs be expected excessively high as a result of the design EDF, the probability of occurrence may have to be incorporated into the determination of acceptable environmental impact, as pointed out in Section V.2.

XV DAM STABILITY ANALYSES

XV.1 Designing for Long Term

A safety factor of 1.5 in a downstream slope stability analysis (static conditions), for which the MPL is assumed, is widely used in tailings dam engineering practice and also recommended in Table 16 for Phase 1 through Phase 3 designs. However, higher safety factors are recommended with respect to tailings dams retrofitted for closure. This recommendation reflects the fact that some design uncertainties, which are more significant with respect to longer time periods, will always exist.

For example, a tailings dam located in the area of high seismicity will be subject to many earthquake loads during the long closure phase. It cannot be not be excluded that repetitive, numerous earthquake loads will result in a significant deformation of dam structure, thus resulting in excessive loss of freeboard and/or deformation of a dam zone. The widely publicised results of modelling dam deformations under earthquake loads, also supported by actual observations, do not address repetitive loads. Hence, selecting a higher safety factor could be justified in such a case, keeping in mind that the value of safety factor implicitly reflects an 'allowable' degree of dam structure deformation.

One of the most difficult predictions regarding long term conditions at tailings dam relates to the phreatic surface location. In this regard, it needs be recognised that the phreatic surface level may depend not only on the tailings pond location and hydraulic conductivities of dam materials (which may vary with time) but, also, on the slope infiltration. There are no currently available methods that would allow for predicting the maximum level of phreatic surface resulting from an infiltration event, say, the maximum phreatic surface elevation that would be expected to occur, on the average, once in 500 years. A sequence of rainfalls and/or snowmelt (where applicable) might saturate tailings dam slope to the level never experienced (recorded) in the past. One way to account for this uncertainty is to have a higher safety factor specified with respect to the static stability of dam, keeping in mind that the value of safety factor also reflects the location of phreatic surface.

Other concerns relating to phreatic surface location might include the potential for chemical precipitation, or a very slow migration of particles that could result in clogging of a filter zone. In general, it is difficult to assert that a filter zone will work as designed in the very long term (dam instrumentation might or might not allow for identifying potential problems in this regard).

Based on these and similar considerations, safety factors higher than 1.5 are recommended in Table 16 for tailings dams retrofitted for closure. Nevertheless, there are other, perhaps more effective approaches to addressing specific uncertainties relating to the parameters incorporated in dam stability analyses.

A different approach was taken on a project in Northern Ontario. The 7,000 ft long, about 100 ft high upstream tailings dam was to be retrofitted for both Phase 3 and Phase 4 (this major dam re-construction project was completed in the fall of 1998). For the static stability analyses, two sets of shear strength parameters were selected. One set included a reasonably conservative estimate of both the strength parameters and the phreatic surface location (corresponding to the maximum permissible pond level, with some consideration given to slope infiltration). For this scenario, a minimum factor of safety of 1.5 was specified. The second set included highly conservative strength parameters, with a specified minimum safety factor of 1.3. The design dam configuration was selected so that both criteria were satisfied. The intent here was to address the uncertainty relating to the long term properties of tailings comprising the dam slope. In this case, tailings were co-deposited with sludge, and are expected to generate strong acidic drainage for some years.

[With respect to 'seismic' stability, there is some evidence that the mechanical properties of tailings above water table would improve in the long term (Section XI.2). However, there seems to be no evidence that tailings properties would significantly improve in the submerged portions of tailings deposits (Section XI.2). For the portion of upstream tailings dam which is to remain permanently dry, the advantage of tailings properties improving with time becomes less critical when addressing liquefaction potential and post-earthquake stability of dam. However, an increase in the strength of tailings above phreatic surface would typically increase the margin of dam safety under post-earthquake loading conditions. In any case, as pointed out in Section XI.2, making an allowance for future increase in the strength of tailings needs be considered with caution.]

A similar, in principle, approach to addressing tailings dams stability was taken on a recent project in Eastern Canada (see the 'unique' upstream tailings dam discussed in Section XI.2). The project involved evaluating the stability of a 6 km long upstream tailings dam with respect to both the remainder of the production phase and in the long term. In this case, significant plugging of the starter dam, which is typically less than about 6 m in height, as well as the tailings slope within 1–2 m above the starter dam was observed. The plugging is a result of chemical precipitation of iron hydroxides and salts, and the associated formation of 'hardpan'. A number of high phreatic surface locations were assumed, with daylighting at up to near 2/3 of the dam slope (the dam will be about 30 m high along most of the perimeter). The computed safety factors were higher than 1.5, except for the case of the highest phreatic surface location and shallow failure surfaces, for which safety factors of 1.1–1.2 were computed (undrained strength analysis). This was judged acceptable taking into consideration the strongly conservative assumption on phreatic surface location. It was also recommended to the owner that the issue of long term chemical precipitation be addressed under the upcoming dam closure design project (the stability analyses were carried out so far without consideration given to retrofitting the dam for closure, i.e., these were carried out with reference to the 'as-is' condition).

According to note [3] under Table 16, using higher safety factors could be justified for dams classified in higher consequence categories. The rationale here is that a safety factor is primarily used to account for uncertainties that cannot be well defined at the design stage (these will always exist) and, for the same amount of uncertainties, it is reasonable that a higher category dam be exposed to a lesser 'risk', particularly in the long term. This statement refers to a prudent degree of design conservatism (Section IX) rather than a design requirement.

XV.2 Drained vs Undrained Strength Analyses

It is often said that there is a controversy or, perhaps, just a confusion regarding the use of either effective stress analysis (ESA) or undrained strength analysis (USA) for evaluating the static stability of upstream tailings dams. Typical upstream dams are constructed of loose (contractive) materials, and the increase in pore pressure due to shear deformation, referred to as the 'deformation induced' pore pressure, is the key issue underlying the controversy.

Since the factors of safety recommended in Section 10.11 for static stability analyses are given with respect to the effective stress analysis only, a commentary in this regard is provided. The following discussion does not apply to post-earthquake stability analyses.

An attempt is made in the ensuing to lay open the reasons underlying the ESA vs USA controversy. It will also be concluded that no generally applicable recommendation as to the use of 'ESA only' or 'USA only', or both, can be developed with any confidence, and the '*either* ESA *or* USA' will be advocated as a more rational approach. The following references will be quoted:

- C.C. Ladd, 'Stability Evaluation during Staged Construction', Journ. of Geotechnical Engineering, ASCE, Vol. 117, No. 4, 1991.
- W.D. Carrier, 'Stability of Tailings Dams', XV Ciclo di Conferenze di Geotectnica di Torino, 1991.
- Steven G. Vick, 'Stability Evaluation during Staged Construction', Discussion, Journ. of Geotechnical Engineering, ASCE, Vol. 118, No. 8, 1992.

There are other important publications directly relevant to the ESA vs USA controversy, which are not mentioned here. The is because the purpose of the following discussion is to provide a background to making a decision on the selection of ESA or USA for practical purposes rather than engage in a research dispute. For this purpose, references to the three above publications are sufficient.

Approaches to Slope Stability Analysis for Upstream Tailings Dams

In brief, the ESA involves the use of in-situ effective stress (acting on potential failure surface) to determine a drained shear strength parameter (s_d) or the 'resistance to failure'. The USA involves using the same stress to determine an undrained shear strength parameter (s_u). Therefore, both analyses represent an effective stress analysis. Consequently, the 'effective stress analysis' (ESA) is renamed, following a suggestion by C.C. Ladd, to the 'drained strength analysis' (DSA) in order to keep the confusion to a minimum.

From the above quoted references, the following approaches to evaluating the stability of upstream tailings dams can be identified:

Approach 1: Use DSA only (the majority of tailings dam engineers)

Approach 2: Use USA only (C.C. Ladd)

Approach 3: Use both DSA and USA (W.D. Carrier)

Approach 4: Use USA in some cases – examples given (S.G. Vick)

The Slope Stability Problem

Consistent with the methods of continuum mechanics, solving a slope stability problem requires two components: constitutive relationship for the material and a set of equations necessary for solving boundary value problems. Although we still are in the search of a reasonably comprehensive constitutive relationship for soil (or tailings) materials, we have long known that it should look something like this (neglecting the temperature and other less pronounced effects):

$$\{1\} \qquad \underline{f}\,[\,\underline{\sigma}(t), \underline{\varepsilon}(t), u(t), t\,] = 0$$

where $\underline{\sigma}$, $\underline{\varepsilon}$, u and t denote the total stress, strain, pore pressure and time, respectively. Equation {1} must incorporate parameters describing the initial properties ('internal structure') of material, including the initial density, anisotropy, preconsolidation pressure, *etc*. It must also be capable of describing such phenomena like deformation induced soil density and pore pressure changes under isotropic and/or pure shear loading, as well as induced anisotropy, coupling of elastic and plastic strains, secondary consolidation and other viscous effects, the response of highly sensitive clays, breaking up chemical bonds and particle crushing, *etc*. It follows that Equation {1}, if derived to cover all these phenomena, would have to be a rather complex constitutive relationship.

We also know a lot (but not everything) about partial solutions of Equation {1}. These primarily include the facts known from soil testing and field observations, for instance, a stress – strain – pore pressure – time relationship from oedometer testing, stress and pore pressure vs elastic and plastic strains relationship from triaxial testing, or static liquefaction occurring at an upstream tailings dam. Of interest here is that u must be included in equation {1} as an explicit variable since it can be changed independently, for instance, by raising stoplogs in a decant structure or saturation of tailings dam slope following a sequence of precipitation and snowmelt (where applicable) events.

Equation {1} must also incorporate a certain restriction necessary to define the 'failure' of material. When applied to the slope stability problem, this restriction could be expressed as a limit on $\underline{\varepsilon}(x,y,z)$, describing the state of slope deformation that would no longer be acceptable.

With respect to solving boundary value problems, powerful computers are widely available and using a numerical method to solve such problems would be relatively easy, assuming that Equation {1} is incorporated into a computer code based on some ‘equilibrium’ equations and all mathematical difficulties are removed by sufficiently accurate approximations.

In practice, the following constitutive relationship, which describes a ‘failure condition’, is commonly used in the slope stability analyses:

{2} $$f [\underline{\sigma}, u, k] = 0$$

where k is a parameter which defines a ‘strength’ property of the material assumed to exist all throughout the loading, up to the failure. [The fundamental to soil mechanics equation $s_d = c' + \sigma'_n \tan\Phi'$ is a special case of Equation {2}.] For the purpose of DSA and USA, k is selected as the s_d and s_u, respectively.

Equation {2} does not include $\underline{\varepsilon}$. This means that neither deformation induced pore pressures nor other deformation dependent properties of material can be accounted for, although these may be ‘reflected’ in the value of k. This also means that the material is and remains ‘rigid’ up to the failure, during and after which the behaviour of material can no longer be analysed or accounted for.

To solve a specific boundary value problem, Equation {2} is commonly used in conjunction with the method of slices, which is based on the limiting equilibrium method. In the method of slices, $\underline{\sigma}$ and u included in Equation {2} are the stress and pore pressure at the bottom of each slice, as predicted or measured for the conditions of the slope for which the analysis is performed.

The controversy relating to the use of DSA vs USA is a direct consequence of not using Equation {1} or, from the other perspective, the result of simplifications incorporated in Equation {2}.

The foregoing discussion has been presented to make two points. Firstly, there seem to be significant difficulties with deriving an adequate constitutive relationship for soils, including tailings, even if the phenomena such as elastic deformation, sensitivity of clays, particle crushing or, for that matter, the ‘cohesion’ can be neglected. Had we had a suitable Equation {1} and an appropriate numerical technique, the method of slices would not have been used and there would not be any controversy as to the use of DSA vs USA. Secondly, Equation {2} does not allow for the modelling of deformation dependent properties of materials, such as induced pore pressures. In this regard, we have to select an ‘appropriate’ value of k based on predictions that involve an educated guess as to the properties of material at the time of failure. In other words, we have to introduce some *ad hoc* hypotheses for which there are no rules, merely experience and judgement.

The current framework (or the ‘paradigm’) of the science of soil mechanics had been formed over a period of some 150 years with the works of Coulomb (1776), Rankine (1857), Hazen (1920), Terzaghi (1925), Fellenius (1936) and others. Following that period, more comprehensive knowledge of the behaviour of soils was quickly gained, and attempts were made to formulate Equation {1}, or its special cases. It seems that we started on the ‘right foot’ with the works of Casagrande (1936), Taylor (1948), Bishop (1954), Roscoe at al. (1958), Rowe (1962) and many others, in which the specifics of soil behav-

iour were addressed. Unfortunately, we also had an 'older brother' (who, in fact, was not really older!), being the mechanics of metals, to whom we went for help (this was somewhat similar to the conventional dam engineering being the 'older brother' of the tailings dam engineering). Starting with the works of D.C. Drucker and his associates published throughout the 1950s, the 'associated' flow rule borrowed from the mechanics of metals was heavily used in combination with Equation {2} by the 1960s for describing the behaviour of soils. In short time, some researchers discovered that this rule was highly inadequate for describing the soil behaviour and a 'non-associated' flow rule was introduced, which made equally little physical sense (quickly, various ad hoc hypotheses were added to make either of these flow rules work). With amazing disregard for soil properties, we also borrowed from the mechanics of metals some of the state variables included in Equation {1}, which are meant to relate to the real rather than mathematical properties of materials (a good example is the average principal stress, σ_{ii}*, which relates well to volume changes in mild steel and fails to relate well to the properties of sand since, for instance,* $\sigma_{ii} > 0$ *may include* $\sigma_3 < 0$*). It seems that the help sought and received from the older brother set us somewhat back from the perspective of deriving a suitable Equation {1}. As a result, we are still using the method of slices, which underlies the DSA vs USA controversy. This situation may be somewhat frustrating since we now have powerful laptops ready and waiting to run any 'finite element' slope stability program, while the 'simplified Bishop' can be handled using an advanced pocket calculator.*

Discussion

The issue of deformation induced pore pressures is illustrated on Figure A-1 (the author has found the four coin trick shown on this figure very useful when explaining to tailings dam operators the need for a liquefaction analysis or dam compaction). Only the case shown on Figure A-1b, which refers to a contractive material, is typically examined in the context of DSA vs USA analyses.

Equation {2}, as used in the method of slices, is illustrated on Figure A-2. The thick line shown on this figure indicates that no deformations or deformation dependent phenomena can directly be addressed within the method of slices framework (the four coin trick shown on Figure A-1 is a good illustration of the ideal material described by Equation {2} prior to failure). The 'forbidden zone' indicates the zone of soil behaviour that cannot be accounted for in the method of slices.

The use of USA with respect to upstream tailings dams has been strongly recommended by C.C. Ladd, and W.D. Carrier as well as S.G. Vick refer to the C.C. Ladd's work. In principle, the USA outlined by C.C. Ladd is not different from the well known Φ_{cu} analysis ('CU' denotes 'consolidated undrained'). The difference is in the method of determining the s_u.

[The laboratory methods recommended by C.C. Ladd for determining the s_u have primarily been designed for testing of *in-situ* clays, and can not practically be used for testing of tailings materials since obtaining undisturbed samples of tailings is rather difficult, and impossible at the initial design stage in any case.]

The following discussion is limited to (normally consolidated) tailings materials.

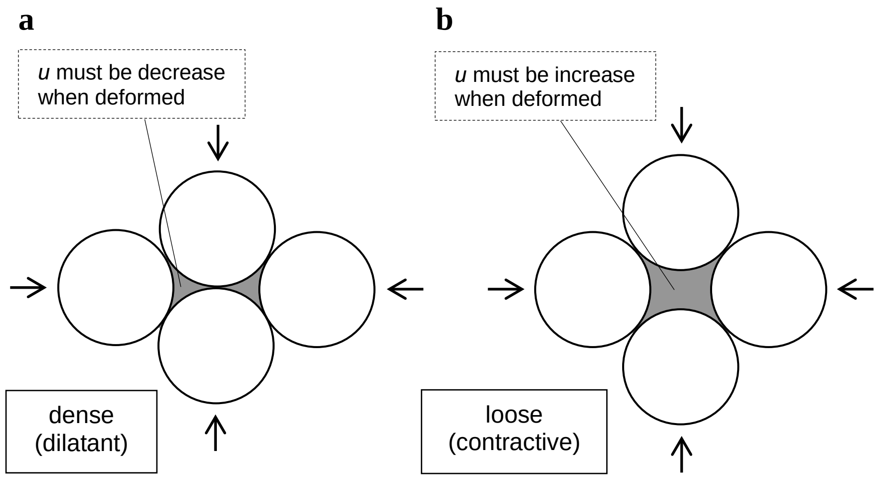


Figure A-1
Generation of Excess Pore Pressures Due to Deformation

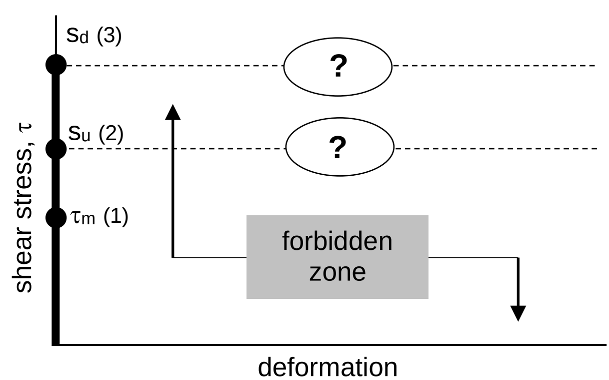


Figure A-2
Constitutive Relationship Used in Method of Slices

By recommending the use of USA for analysing the stability of upstream tailings dams, C.C. Ladd may have added to the DSA vs USA confusion. This is because his work explicitly refers to the strength of *cohesive* soils while the majority of upstream tailings dams are constructed of essentially cohesionless tailings. Nonetheless, this can be disregarded when considering upstream tailings dams, even if the dam materials comprise cohesionless tailings. According to those who advocate the use of USA for such dams, what really counts here is the generation of excess pore pressures during failure. One can comfortably assume that even if (loose) tailings comprise the sand fraction only, an increase in pore pressures will occur and persist during failure occurring in the matter of seconds or minutes.

Furthermore, C.C. Ladd developed his recommendations for *staged* construction, including the construction of upstream tailings dams. In this respect, the situation is also somewhat confusing.

In the early 1980s, the author worked as a superintendent on mine construction projects. On one of those projects in northern British Columbia, the author was responsible, among other assignments, for the construction contracts involving grading of a very large site, the construction of a small earthfill dam and the construction of a 1,000,000 m^3 tailings starter dam, both founded in part on dense silty deposits. In the first of these assignments, the relevant issue was dense to very dense sand and silt tills with groundwater table located next to the ground surface. Site grading, which primarily required excavation, caused very significant problems with the scrapers and push-cats disturbing the tills to an unacceptable degree (and, occasionally, getting 'stacked'). What happened was that by excavating a till layer, excess pore pressures were immediately generated, amplified by construction traffic (a classic earthworks construction problem). The contractor was requested to excavate a thin layer at a time and then move to another area until the excess pore pressures sufficiently dissipated. When constructing the small earthfill dam, the contractor was requested to stop fill placement for a period of time after high excess pore pressures had been generated in the foundation soils (this is another classic of earthworks construction). The construction of the tailings starter dam started in middle winter and involved the excavation of 2-3 ft thick frozen 'slabs', which resulted in an immediate generation of excess pore pressures in foundation soils. A 5 ft thick fill lift was placed during the same (day or night) shift, causing further increase in pore pressures. The fill had to be immediately placed to prevent freezing of the frost susceptible foundation soils. The lift was compacted and left until the spring break up, by which time the excess pore pressures fully dissipated (construction of a major earthfill dam under typical temperatures between -25℃ and -10℃ can hardly be claimed a classic earthwork construction problem). In all three cases, the staged construction method was used (note that the staged construction referred to in the above examples has nothing to do with the stage-raises of tailings dams referred to throughout this Document: while the former has to do with excess pore pressures, the latter has to do with dollars).

In the majority of cases, the construction of upstream tailings dam is not intended as a staged construction but, rather, as a continuous construction with the rate of dam raise defined by the mill production rate and the size of tailings impoundment. Where a tailings dam is constructed relatively quickly, the principle of staged construction concept could apply with respect to a soft clay foundation or, in some cases, the dam structure itself. Where a tailings dam is raised relatively slowly with no significant excess pore pressures generated, the staged construction concept could not be applied.

Nevertheless, it seems that the staged construction concept can be disregarded when contemplating the use of USA for designing upstream tailings dams, regardless of the rate of dam raising. In fact, the author does not see any reason why the USA approach, if valid, should not be used for an upstream tailings dam constructed of loose materials to its final height, with no predicted or measured excess pore pressures at the analysed state (this could hardly be referred to as a staged construction case). Again, according to those who advocate the use of USA for tailings dams, what really counts here is the generation of excess pore pressures during failure.

The DSA vs USA argument is illustrated on Figure A-3a following the C.C. Ladd's presentation, with reference to a tailings dam shown on Figure A-3b.

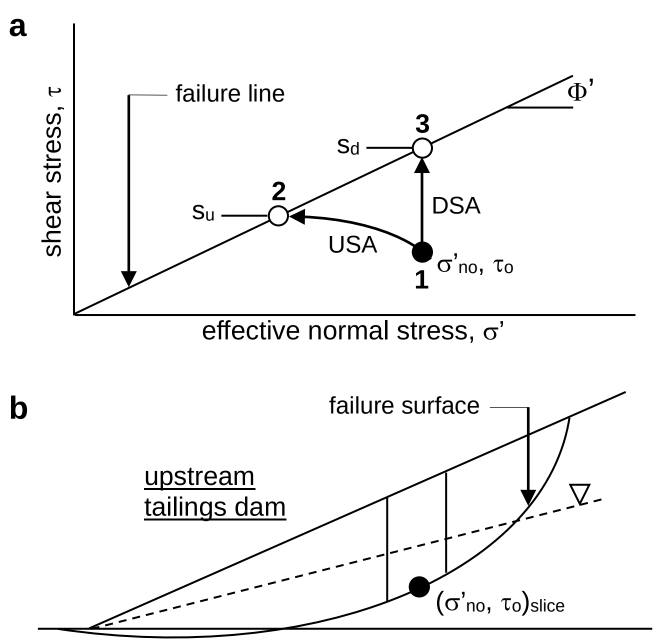


Figure A-3
DSA vs USA for Upstream Tailings Dams (Conceptual)

Figure A-3a presents a conceptual illustration only. The 'pathways' 1-2 and 1-3 cannot be accounted for in the method of slices analyses. Such analyses are carried out for the state of slope defined by point 1, for which a critical failure surface is found and the safety factor computed. A single point on Figure A-3a cannot illustrate the states of stress on the potential failure surface. For some slices, the state of stress point could be located above the failure line while for others, the section of potential failure surface would be unsaturated so that no excess pore pressures could be generated. Note also that the critical failure surface location (Figure A-3b) determined from the stability analysis would be different, depending on the type of analysis performed (DSA or USA).

The factor of safety determined using the method of slices is intended to keep point 1 on Figure A-3a reasonably far from the failure line. It is computed assuming that the dam material has a shear strength property (such as s_d or s_u) existing at point 1, which corresponds to the fully defined state of stress (σ'_{no}, τ_o), where predicted or measured excess pore pressures generated as a result of dam construction are accounted for. The difference between DSA and USA is rather simple: one uses either s_d or s_u as the strength parameter, respectively.

What really seems confusing is the argument for using the USA, which is often made as: ‘the USA type of analysis should be used because excess pore pressures must be generated during failure of loose (contractive) materials’. Within the method of slices framework, one does not analyse what happens *during* failure when a flow slide is already occurring over seconds or minutes (the term ‘failure’ refers to the situation where the stress point reaches the failure line illustrated on Figure A-3a). It is a forbidden zone, which seems rather obvious: one could hardly argue that the method of slices analysis carried out for the point 1 conditions can be related to the situation when a flow slide is at the end of forming at, say, 1.5° slope. The issue of importance here is what would have happened between point 1 on Figure A-3a, which depicts the point for which the stability analysis is carried out, and the failure line, *i.e.*, *prior to* failure.

[Assuming that a slope failure starts at point 1 would not be very satisfactory since this point can move towards the failure line with no failure occurring, which is the very essence of the slope stability analysis where the computed factor of safety is specifically designed to ‘handle’ such a situation.]

From examination of Figure A-3a one observes that both pathway 1-2 and pathway 1-3 are possible. Consider, as a concept, running a standard, σ_3=const. triaxial CD test (‘CD’ denotes ‘consolidated drained’) and being at point 1 on Figure A-3a. For discussion purposes, assume that the vertical and horizontal axes shown on this figure are changed to $\sigma_1 - \sigma_3$ and σ'_3, respectively, and the failure line is sloped at an angle of $\tan^{-1}$ [2sinΦ’/(1-sinΦ’)], consistent with the test conditions. If the valve is shut off at point 1, then pathway 1-2 would be followed, deformation induced excess pore pressures would be generated, and a failure would occur when point 2 is reached. During failure, the pore pressures might or might not further increase, depending on whether a ‘steady state’ has been reached (which is no longer of consequence since the dam would have failed). If the valve remains open, then pathway 1-3 would be followed and failure would occur when point 3 is reached, upon which the pore pressures could *start* increasing (which is no longer of consequence for the same reason). Even if the shear resistance decreases after point 3 is reached, the dam would have survived under a driving shear stress equal to s_d (being greater than s_u). Finally, if the valve remains partly open or the strain rate is increased, an *intermediate pathway* would be followed and another ‘failure’ point on the failure line would be reached, after which the shear resistance might decrease (which is no longer of consequence). In summary, what happens during failure in the matter of seconds or minutes is of no consequence to conducting a slope stability analysis.

[What would happen during and following tailings dam failure is of prime interest to establishing the CCCs. For this purpose, a flow slide analysis may be performed as discussed, *e.g.*, by Jey K. Jeyapalan, J. Michael Duncan and H. Bolton Seed in 'Analyses of Flow Failures of Mine Tailings Dams', Journ. of Geotechnical Engineering, ASCE, Vol. 102, No. 1, 1983, or Steven G. Vick, Robert Dorey, W.D. Liam Finn and Russell C. Adams in 'Seismic Stabilization of St. Joe State Park Tailings Dams', Geotechnical Practice in Dam Rehabilitation, ASCE Geotech. Spec. Pub. No. 35, 1993.]

Giving consideration to the state of stress point moving along pathways 1-2 or 1-3 is a conceptual exercise designed to show how the slope *could* behave if something unknown happens. It is the formulation of an *ad hoc* hypothesis designed to support the selection of either s_d or s_u as the design parameter (had we had Equation {1}, there would be no need for introducing such a hypothesis). Based on the conceptual model presented on Figure A-3, one cannot prove that selecting either s_d or s_u for the analysis purposes represents the right approach. One can only speculate and this, perhaps, underlies the DSA vs USA controversy.

For the state of stress point to move from point 1 towards the failure line, application of an additional load (stress, deformation, hydrostatic pore pressure) is required. Note that the application of hydrostatic pore pressure as an additional load could force a pathway located to the left of pathway 1-2. The slope still would be expected to deform and thus the horizontal pathway extending from point 1 to the failure line, which would be consistent with the behaviour of the rigid material illustrated on Figure A-2, is unlikely. For the discussion purposes, the effect of hydrostatic pore pressure increase is neglected, assuming that this should be designed for by determining appropriate pore pressure distribution for the analysed condition.

The hard part of deciding whether to use the DSA or USA relates to the fact that neither s_d nor s_u represents an intrinsic property of the material (such as specific gravity), which exists at the analysed state of material (point 1). Either of these properties would only be acquired (mobilised) when the failure line is reached. In other words, *we cannot know the most crucial property (parameter) incorporated in the method of slices analysis*. It simply does not exist at the state of stress for which the analysis is performed. To determine the value of this parameter, we are forced to make an educated guess regarding the pathway that would be followed if something unknown happens, including also an incorrect assumption that the actual failure would occur along the failure surface found critical with respect to point 1.

If a DSA vs USA confusion really exists, it may partly result from not considering the fact that neither s_u nor s_d represents an intrinsic property of material. Some 30 years ago, the author also was confused when working on the strength of cohesionless materials. It seemed that if two bodies in frictional sliding have an intrinsic property (the coefficient of friction), a cohesionless material should have this sort of a property as well. Studying the work of J.S. Courtney-Pratt and E. Eisner ('The Effect of a Tangential Force on the Contact of Metallic Bodies', Proc. Roy. Soc. A, 238, 1957) helped the author to quickly overcome the confusion. It became clear that the coefficient of friction was as *much an acquired property as the Φ' (or s_d). Some years later in an effort to define the concept of Φ', the author removed from Equation {1} all what clouded the picture (most importantly, anisotropy and deformation under isotropic loading) and showed that Φ' can be defined as an acquired property, consistent with the observed behaviour of dense, loose and 'critical density' cohesionless materials ('Elastic-Plastic Shear Deformation of Frictional Granular Materials', Int. Journ. for Numerical and Analytical Methods in Geomechanics, Vol. 7, 1983). Those and similar considerations clearly indicate that a property such as s_d or s_u does not exist at point 1 on Figure 3-1a, although we assume that it does exist within the method of slices framework. And, if it does not exist at point 1, then it cannot be said a priori that either s_d or s_u should apply.*

Concluding Remarks

As discussed above, there is an infinite number of 'point 1 – the failure line' pathways and the corresponding strength parameters, and each of them is possible. Within the method of slices framework, these parameters can have any values between, and including the s_d and s_u.

Some pathways can be declared more or less probable based on inspection. Suppose, as an example, that the state of stress and the pore pressures (as predicted or measured) are known at a tailings dam slope. For the state of stress point to move from point 1 towards the failure line, application of an additional load is required, being an unknown factor. If the load application were expected to occur over a relatively short period of time, then pathway 1-2 would be more probable since there would be less time for pore pressure dissipation. This observation is not really very helpful since the additional load represents an unknown factor and can only be speculated upon (if this factor was known, then the additional load would have to be either prevented or designed for). More useful is an inspection of the properties of dam construction materials. If the dam is constructed of, say, tailings slimes or cycloned sand, then pathway 1-2 or 1-3 would be more probable, respectively, for a certain rate of the additional load application and all other factors being equal.

[One of the reasons for cycloning to form a wide, coarse tailings beach is to make pathway 1-3 more probable in case that the unknown happens. One of the reasons for constructing a drainage blanket is to enlarge the unsaturated portion of dam slope so that the part of slope in which pathway 1-2 could potentially be followed is minimised.]

If a tailings dam is subject to an additional load, for instance, as a result of toe erosion, then a part of the slope can follow pathway 1-3, say, over weeks or months prior to failure, while another part can follow pathway 1-2, say, over minutes prior to failure. This has to do with a non-uniform strain field within the slope. Any non-homogeneity built into the dam (*e.g.,* a lens of tailings slimes) may also cause different portions of the slope to follow different pathways, regardless of the rate of the unknown load application or the 'type' of additional load. Furthermore, it cannot be excluded that a non-uniform strain field may result in a portion of dam slope deforming beyond the 'peak strength' prior to failure, if the material exhibits a 'strain-softening' behaviour. It cannot get any more complex than that. Since Equation {1} is not used, the only way to deal with such a complexity is to recognise that the method of slices is in fact a largely empirical method, which needs be supported by many case histories and a thorough inspection of each analysed case.

In the method of slices, we implicitly assume a uniform strain field within the slope with respect to failure condition (which has to with not being able to account for the $\underline{\varepsilon}$). Under this assumption, it is possible to define, at a conceptual level, the lower and upper bound solutions to the upstream tailings dam stability problem:

- lower bound: USA
- upper bound: DSA*

* The DSA also represents a lower bound, that is, a conservative solution for dense materials (Figure A-1a) since all permissible pathways would be located along, or to the right of pathway 1-3 (not precisely, since at small deformations positive pore pressures would develop in dense materials under some loading conditions).

The above discussion has not been intended to resolve any technical questions. However, if one agrees that such a conceptual (qualitative) discussion may yield some practical conclusions, one can at least eliminate Approach 1 and Approach 2 identified earlier in this subsection. Neither of these approaches can be recommended as a general rule since both pathway 1-2 and pathway 1-3 are possible, with an infinite number of 'in-between' pathways possible as well. Following Approach 1 (DSA only) regardless of dam specific conditions could be non-conservative because other pathways are possible and could be probable, *even though* hundreds of upstream tailings dams were designed based on DSA and performed well. Following Approach 2 (USA only) regardless of dam specific conditions could be overly conservative because other pathways are possible and could be probable, and *because* hundreds of upstream tailings dams were designed based on DSA and performed well.

It follows that, in fact, the 'DSA only' vs 'USA only' controversy represents nothing else but a judgement driven degree of conservatism advocated with respect to conducting a slope stability analysis.

The author is not in favour of Approach 3. Following the recommendation of W.D. Carrier, both DSA and USA would be performed for all tailings dams and "*…whichever yields the lower factor of safety controls the design...*". For the USA, W.D. Carrier recommends a safety factor (SF_{USA}) of ≈1.5. Taking into account the findings of C.C. Ladd and S.G. Vick which indicate SF_{DSA}/SF_{USA} = ±2 or more, it follows that the design SF_{DSA} would be ±3 or more. As S.G. Vick points out: "*The great majority of [upstream] tailings dams have performed successfully with [FS_{DSA}] probably in the neighbourhood of 1.5 or less.*" Hence, it seems that using both DSA and USA according to the W.D. Carrier's recommendation cannot be justified as a general rule for analysing the stability of upstream tailings dams. In practical terms, this approach is equivalent to (the most conservative) Approach 2 wherever loose materials are analysed. On the other hand, conducting both analyses could be helpful in acquiring an 'insight' into potential weaknesses of the dam, and would also be recommended by the author provided that the *a priori* 'whichever yields the lower factor of safety controls the design' is dropped, and the design decision is made based on inspection and judgement, as discussed below.

Therefore, Approach 4, although most demanding in terms of engineering effort, is also believed to be most appropriate. It may be termed 'By Inspection', *i.e.*, based on the inspection of dam specific conditions, a decision is to be made if *either* DSA *or* USA controls the designs, or perhaps something 'in-between'. Such an inspection could involve applying judgement, a case history, consideration of potential failure 'triggers' (see the following paragraph), conducting a problem-focused analysis, *etc*. S.G. Vick identifies some cases in which using the USA would be necessary, *e.g.*, where the location of slimes-sand interface is inadequate or breakdown of seepage on the embankment slope may occur.

T.A. Martin and E.C. MacRoberts ('Some Considerations in the Stability Analysis of Upstream Tailings Dams', Proceedings of the 51st Canadian Geotechnical Conference, Edmonton, 1998) identify a number of triggering mechanisms necessary for an undrained failure of upstream tailings dam to occur, thus emphasising the importance of taking potential triggers into consideration. In this respect, it needs be said that any of those potential triggers could be eliminated by adequate designs, construction and operation of upstream tailings dam (we have the ability to do these things properly). If so, using the DSA could be appropriate assuming that the dam comprises a reasonably homogeneous structure, all reasonably possible failure surfaces are located outside of the slimes deposit, slope erosion is prevented, tailings pond is properly operated, *etc.* (in many cases, construction of an under-drainage system would be necessary).

Keeping in mind that a possible value of the shear strength parameter can be anywhere between s_d and s_u, the recommended By Inspection approach does not present any definite guideline. It merely draws attention to the necessity to study each case on a site-specific basis using sound judgement, supported by experience and appropriate analyses. From another perspective, this approach warns against pre-judgements and unjustified generalisations.

For existing upstream tailings dams, applying the By Inspection approach could be difficult in some cases. This is because upstream tailings dams have been often 'manufactured' to the poorest standards, as compared with other types of tailings dams, and sufficiently comprehensive and accurate as-built information rarely exists (the various non-homogeneities built into upstream tailings dams over the years are of special concern relating to the possibility of an 'undrained' failure). This also has to do with designing of new upstream tailings dams. Can a tailings dam engineer convince himself that an upstream tailings dam will be constructed as designed?

No recommendation on the SF_{USA} is given in Section 10.11 since there seems to be no sufficient experience available based on which such a recommendation can be made, in contrast to the SF_{DSA} (Table 16). With reference to the preceding paragraph, it needs be pointed out that the first part of note [1] under Table 16 could be particularly relevant to many upstream tailings dams.

An elegant way would be to assume the design SF_{USA} = 1 (which corresponds to the lower bound solution) and SF_{DSA} = 1.5 (based on experience from many upstream tailings dams). This approach, however, would be difficult to justify, particularly in the USA case. A safety factor is designed to cover other uncertainties (e.g., approximate configuration of tailings dam or unaccounted for anisotropy of tailings material), in addition to the possible 'point 1 – failure line' pathways, and an adequate value of the design SF_{USA} cannot be deduced without having a large number of cases studied. As pointed out previously, the method of slices is a largely empirical method and recommending an adequate safety factor requires the knowledge of many case histories which, at this time, is available with respect to the DSA but not the USA.

XV.3 Liquefaction of Tailings Materials

Evaluation of liquefaction potential and post-earthquake stability of tailings dams, where the dam and/or foundation materials are susceptible to liquefaction, has become a routine part of dam design and safety reviews. Most common task involves the examination of liquefaction potential of *tailings*, particularly for conventional upstream tailings dams and other dams constructed of tailings using the hydraulic fill method. Potential liquefaction of tailings deposit adjacent to the dam, which would result in exerting an additional force on the upstream face of the dam, may also be examined in some cases. Another relatively frequent assignment involves the examination of liquefaction potential for stability assessment of 'internal' dams constructed of tailings or borrow materials and founded over saturated tailings deposits.

In most practical cases, the evaluation of liquefaction potential of tailings materials is performed using the Seed and Idriss empirical procedure, which is constantly updated and improved upon. A remarkable progress has been made in this area over the last decade. Nevertheless, significant uncertainties still exist and both expertise and sound judgement are required to avoid errors or overly conservatism.

One of the most discernible uncertainties relates to the base of the Seed and Idriss procedure, being the relationship between the cyclic stress ratio and corrected 'blowcount' values, which separates the 'liquefied' from 'non-liquefied' sites. This relationship has been derived for sands and silty sands rather than tailings materials. Tailings, although similar in general, are also significantly different from sands in some respects. As opposite to typical sands, tailings comprise very sharp-edged particles and may have specific gravity in the range of less than 2.0 to more than 4.0 while the specific gravity of typical sand is about 2.7. It is not clear how these differences should be accounted for when using an empirical procedure derived from the studies of sand deposits. Other, more general uncertainties may become apparent when using the above mentioned relationship for tailings dam stability analyses.

[It would be misleading to claim that a sophisticated finite element seismic stability analysis is free of uncertainties, nevertheless, conducting such an analysis could provide a useful ‘insight’ into the potential tailings dam stability problem.]

Therefore, it is necessary that the design study of tailings liquefaction potential and post-earthquake stability of tailings dam be as comprehensive as reasonably possible. Overly conservatism, achieved by raising somewhat each of the design parameters, is difficult to justify. Instead, a sensitivity study can be performed with respect to both liquefaction potential analysis and post-earthquake stability analysis. The sensitivity study could involve raising or lowering, as the case may be, one of the design input parameters at a time to the brink of an unrealistic or somewhat different than the estimated value. The results of the sensitivity study would then be compared with the results of the analysis carried out for all the parameters in the estimated range that yielded a satisfactory factor of safety. Following this approach may either increase the confidence in the result of the analysis, or indicate that the determined margin of safety is not sufficient. In the latter case, the designs could then be economically adjusted to address a specific uncertainty factor.

For instance, if lowering the design internal friction angle for the unsaturated portion of upstream tailings dam by, say, 1-2 degrees only results in a significant reduction of the overall safety factor (the post-earthquake stability analysis), the most economic design adjustments would be different than in the case where raising the design phreatic surface location by few feet only results in a similar effect. On the other hand, if reducing the ‘residual’ strength of a liquefied tailings zone to zero or raising the phreatic surface close to the beach-slope line still yields a safety factor of about 1.0, the confidence in the results of the liquefaction and the associated post-earthquake stability analyses would increase.

This design approach has been taken on a project in California where a chemical plant is located next to the toe of upstream tailings dam. A breach failure of the dam would likely result in a high loss of life. The dam, approximately 180 ft high, had a downstream rockfill buttress designed to provide a high strength zone and it was to be raised by 20 ft. Safety factors with respect to the stability analyses under the post-earthquake condition, which involved fully liquefiable (SF_L<1.1), partially liquefiable (1.1≤SF_L≤1.5) and non-liquefiable (SF_L>1.5) tailings zones, were computed at 1.9 or higher, with a safety factor of about 2.8 for the ‘chemical plant’ section of the dam. The next set of analyses involved applying 50% of the design peak ground acceleration of 0.30g to the post-earthquake stability analysis. This brought the safety factors to higher than 1.25, with a value of about 1.7 computed for the ‘chemical plant’ section. Further analyses involved an assumption of zero strength in the fully liquefied tailings zone (SF=1.8 was computed for the ‘chemical plant’ section), and an extreme case of the full saturation of the tailings deposit (SF=1.9 was computed for the ‘chemical plant’ section). The designs were obviously highly conservative, driven by a high potential for the loss of life. The approach in this case was selected with the purpose of identifying ‘weak points’ in the designs, recognising that the design methodology used (the Seed and Idriss procedure) is subject to significant uncertainties.

Reference to case histories (*i.e.*, actual earthquake events under which tailings dam materials did or did not liquefy) is an essential part of the design process when examining the liquefaction potential and post-earthquake stability of tailings dams. However, this design aspect has to be considered with caution. This is because there are a number of relevant factors that may differ between the tailings dam/dam site being evaluated and the tailings dams/dam sites subject to actual earthquake loads in the past.

For instance, the attenuation relationship appropriate for the site of the tailings dam being evaluated may be different, as compared with the case history(ies), even if the relevant epicentral distances and moment magnitudes are the same. On the other hand, even if the peak ground accelerations at the dam sites are the same, the appropriate accelerograms could be significantly different, resulting in different dynamic responses of the dams. Furthermore, the relevant properties of tailings materials could be different even if both the ores and the mill processes are similar. For instance, cycloning in a wet climate at a rate of, say, 20,000 tonnes/day may result in the formation of tailings deposit having different properties than the properties of a tailings deposit formed by spigotting at a rate of 5,000 tonnes/day in arid climate.

Another uncertainty with regard to the use of case histories is the fact that the available data on the response of tailings dams subject to actual earthquake loads are significantly limited from the design perspective. For instance, the fact that an upstream tailings dam did not fail resulting in a flow slide under earthquake load does not give any indication as to the actual degree of generated pore pressures, *i.e.*, the actual margin of dam safety (the safety factor) under the post-earthquake condition remains unknown.

The above discussion is not intended to negate the value of accounting for case histories in tailings dam design. On the contrary, this is an essential element of the design process, as pointed out above. Merely, caution is recommended. [See the 'unique' upstream tailings dam described in Section XI.2. The uniqueness of that dam, it seems, justifies the recommended caution. How many tailings dams similar to that 'unique' dam were exposed to strong earthquakes?]

Another, significant difficulty with evaluating the stability of tailings dams in cases where partial or full liquefaction of tailings (or foundation soils) is expected to occur, relates to the selection of the undrained shear strength parameter for use in the post-earthquake stability analysis. Although a very significant progress in this regard has been made in recent years, still it is not clear how this parameter should be determined (from standard penetration, cone penetration, cyclic or a static laboratory test?). Neither it is clear, in the first place, how the relevant 'residual' shear strength should be defined with respect to either partial or full liquefaction of material. For instance, should this strength be taken proportional to the effective vertical stress where the 'blowcount' value at a depth of, say, 20 m beneath the dam slope is 1-2 with no excess pore pressures observed?

It follows that adequate foundation preparation as well as compacting dam construction materials and keeping them unsaturated to the extent practically possible, represents by far the best method of evaluating tailings dam stability under seismic loads.

XVI DISCHARGE FACILITIES

The most common operating objectives of discharge facilities at tailings impoundments include:

- passing normal and high and/or extreme flows,
- regulating tailings pond level to control the rate of seepage, formation of tailings deposit and/or location of phreatic surface,
- regulating tailings pond level to ensure sufficient storage volume in case of extreme flood,
- regulating tailings pond volume and/or surface area to ensure sufficient retention time required for passive water treatment (suspended solids, cyanide, thiosalts, *etc.*),
- regulating tailings pond level in conjunction with controlled discharge scheme (may involve passive treatment),
- regulating tailings pond level to ensure sufficient depth of water cover,
- regulating tailings pond volume to suit water treatment schedule, and
- process water supply.

Because tailings pond level generally increases with time, discharge facilities are designed to accommodate this increase.

In some, tailings pond is maintained at a nominally constant level, with an open channel spillway or decant structure discharging the excess (clean or contaminated) water.

Often, more than one discharge facility is operated at tailings dam. Examples of the most common discharge facilities include:

- One or more decant towers designed to pass normal and high flows on a continuous or intermittent basis. These may also be designed to pass the extreme flows. A decant tower may be raised in several stages as the impoundment level increases.
- Tunnel or culvert under the tailings impoundment designed to pass normal through extreme flows. It is typically extended upstream as the size of the impoundment increases.
- Overflow (open channel) spillway designed to pass normal and high flows on a continuous or intermittent basis. It may also be designed to pass the extreme flows.
- A pumphouse arrangement designed to recycle process water and, in some cases, feed the treatment plant or augment the discharge of extreme

pond inflows. Extending the wet well or constructing a new pumphouse may be required as the impoundment level increases.

- Pump barge designed to recycle process water and, in some cases, feed the treatment plant and/or augment the discharge of extreme flows.
- Emergency (open channel) spillway or decant structure designed to pass extreme flows.

Other discharge facilities (*e.g.*, a siphon pipe or tunnel through dam abutment) are also used.

Only the pump barge scheme provides for flexibility with respect to the discharge location.

The primary disadvantage of the first two schemes listed above is that an outlet pipe, tunnel or culvert typically passes through or under the tailings dam. This forms a weak point in dam structure. At the best, such an arrangement does not significantly affect the structural stability of dam. At the worst, it may result in dam failure. Even if a permanent plug is provided upon the cessation of tailings disposal operation (or before), this weak point will exist all throughout the long closure phase. It follows that from the perspective of dam safety, these types of discharge facilities, although being practical and often most cost effective, are not really desirable. Combination of a pumping facility with an open channel overflow and/or emergency spillway excavated at a distance from the dam would, comparatively, enhance tailings dam safety.

Nevertheless, the decant tower or tunnel/culvert scheme will sometimes present significant advantages and, at some sites, may practically be unavoidable (*e.g.*, emergency decant tower in the case of upstream tailings dam forming the entire impoundment boundary would often be preferred over an open channel spillway). As pointed out in Section 10.12, detailed designs for the permanent plugging of discharge structure should be developed at the time when the structure is designed.

On a project in Newfoundland, a decant structure built into the main tailings dam was to be plugged in the early 1990s, just few years after the start up of mine operation. [The originally designed cyanide destruction system failed and a new, large pond was constructed close to the tailings impoundment, designed to enhance natural cyanide degradation. Tailings pond water was then routed to the new pond via a siphon pipe and the decant structure became redundant.] The owner decided to plug the structure without having engineering designs. The decant arrangement consisted of typical concrete tower and a CSP outlet installed over dam foundation. While pouring concrete to form the plug, some tailings pond water was still discharging through the poorly fitted stoplog wall. As a result, cement and fine aggregate were partially washed out and the concrete set leaving a gap along the top of the outlet pipe. It took about a year to finally plug the decant, including involvement of various specialists and constructing a special camera set up to examine the gap, while operating a pump station downstream of the dam.

An open channel spillway excavated in rock presents the best scheme for decanting tailings pond water from the dam safety perspective under most conditions. It should be used where physically possible and economically justifiable.

XVII USE OF CONVENTIONAL DAM GUIDELINES

In several sections of this Document, the discussions are focused on tailings dam safety with reference to conventional dam engineering practice, with the intent of emphasising that this practice would often be inadequate if applied to tailings dams. Some recommendations made herein would be either irrelevant to conventional dams, particularly where these are made with reference to the dynamics of tailings dam operation or potential environmental impacts, or inconsistent with the requirements of conventional dam engineering.

The case discussed in Section X emphasises potential problems with applying conventional dam engineering practice to tailings dams. In that case, the CDSA guidelines were used for the design of a tailings dam. Potential problems could especially arise if the conventional dam guideline used for evaluating the safety of tailings dam is focused on a specific industry (notwithstanding the merits, the CDSA guidelines primarily reflect the perspective of hydroelectric industry).

As a starting point for classifying tailings dams, the CDSA classification has been selected (Table 2), including also the flood and earthquake design criteria recommended by the CDSA (Tables 8 and 11). However, significant adjustments have been made to the CDSA recommendations. These have been introduced taking into consideration the specifics of tailings dams and mining industry, as well as some other, more general dam safety aspects.

Besides accounting for potential Type II failures and the four operating phases defined from the consideration of tailings dam operating attributes, the most discernible of those adjustments include:

- *Environmental impacts have been 'removed' from the CDSA classification, and these are considered within the impact classification framework (Section 4.2).*
- *Flood and earthquake design criteria pertaining to potential environmental impacts are considered separately from those pertaining to potential loss of life and/or economic losses, with the recommendation that the probabilistic criteria be selected based on PEDDI rather than AEP (Tables 9 and 12).*
- *The issue of potential loss of life in the case of High category dams (LLEL classification) is taken differently with respect to new tailings dams (Section XII.1).*
- *Explicit recommendation is made with respect to existing tailings dams classified in the High category (LLEL classification) to carry out an 'additional cost vs benefit' analysis where the potential for loss of life exists, and design criteria less stringent than PMF and/or MCE are contemplated (Section XII.1).*

Had another guideline developed for conventional dams rather than the CDSA guidelines been selected as a starting point for the purpose of Tables 2, 8 and 11, the end result, meaning the recommendations presented in this Document in respect to tailings dams, would have been the same.

XVIII ARE SOME TAILINGS DAMS EXPECTED TO FAIL?

The answer to this question is simply ‘yes’. Some, although *very few* tailings dams are expected to fail (world-wide). In the ensuing, this answer is examined starting with new, and followed by existing tailings dams. References are made to the layout of Figure 7 (Section 5).

Type I failure – external cause (new dams)

As summarised in Tables 14 and 15, *probabilistic* flood and earthquake design criteria are recommended herein (and otherwise commonly used) for the design of tailings dams with regard to ‘Type I failure – external cause’, based on the consequence classification method. What this means is that we are, in fact, designing tailings dams so that some of them would be expected to fail, given sufficient time and the number of dams (we have both of these, particularly with reference to Phase 4). Hence, one must conclude that:

- Some tailings dams are expected to fail as a result of external causes because they have to serve for a very long time and because there are so many of them.

  Although the ‘external causes’ are out of our control, as opposite to the ‘internal causes’, we could conceivably design all tailings dams to the highest reasonably possible standards (meaning MCE and PMF), which would allow for having the best, although not necessarily an ‘absolute’ protection. This would be very expensive at some sites and is not really necessary. This would also be inconsistent with the principle of the consequence classification method, which permits using less stringent criteria where lesser consequences of potential dam failure are predicted.

  The fact that some tailings dams would be expected to fail in the sense of ‘Type I failure – external cause’ may be seen as “it’s not the way it should be”. Nevertheless, it’s the way it is, and it is not likely that that this situation will change in the foreseeable future, simply because of the common sense economics underlying the consequence classification method. This method, one notes, seems acceptable to the majority of us since it is the way we view the things. For instance, few of us, as individuals, would be willing to spent $500 for a car security system when buying a 10-year old ‘K-car’. When buying a $100,000 luxury car, spending $500 on such a system is practically a must. In other words, we value things consistent with the amount of potential losses and secure them accordingly. Or, as a community, would we pay for replacing all highway culverts sufficient to pass PMF flows? As the experience shows, the answer is ‘no’ because the risk is not worth the expense. The consequence classification method is consistent with our way of life.

Type I failure – internal cause (new dams)

As discussed in Section 5, design and construction requirements for tailings dams with respect to potential 'Type I failure – internal cause' may include, for instance, a safety factor, filter design criterion, properties of foundation and dam construction materials, specifications for dam foundation preparation and compaction of dam materials, tailings beach formation technique, employing appropriate method of engineering analysis, conducting adequate geotechnical exploration program, *etc.* Such requirements are reasonably well understood and no tailings dam would be expected to fail in the sense of 'Type I failure – internal cause', assuming that these requirements are properly identified and implemented. Hence, the following can reasonably be stated:

- With respect to 'Type I failure – internal cause', no tailings dam, if properly designed and constructed, would be expected to fail.

  This statement can only be substantiated if we can (see Figure 1): carry out the necessary DS, DSIs and DSRs, provide adequate construction supervision and quality control, implement improvements to dam safety whenever required as well as operate, maintain and monitor tailings dams in accordance with design requirements. Since we can do all these things, tailings dams would not be expected to fail in the sense of 'Type I failure – internal cause'.

[If the consequences of potential dam failure are limited to the owner's property *and* the owner decides on having a relatively 'lenient' dam safety standard, then the chances of dam failure increase. In this regard, it is essential to remember the requirement of Section 5: "Evaluation of tailings dam safety carried out at any current or imminent operating phase must be conducted taking into consideration the anticipated dam safety requirements pertaining to all future phases". This means, in practical terms, that the design and construction requirements for tailings dams with respect to potential 'Type I failure – internal cause' (see examples given above) must not be influenced by the owner, even if the potential losses are limited to his property only. The premise here is that during the closure phase, when the 'designed and constructed' dam must remain sufficiently safe, the current owner will not be there.]

Type II failure – external cause (new dams)

In this case, we design for an acceptable environmental impact associated with design events such as flood or draught, as discussed in Section 10.7. The design objective is to ensure that under all 'external' events, the environmental impact would be acceptable. In this regard, the following can reasonably be stated:

- We have the tools to design tailings dams so that no 'Type II failure – external cause' would be expected to occur in the sense of exceeding acceptable environmental impact (again, the dam must be properly constructed, operated, *etc.*).

Type II failure – internal cause (new dams)

'Type II failure – internal cause' could result from an increase in the rate of contaminant loadings leaving the site which has not been accounted for at the design stage. This could happen for a variety of reasons, including incorrect geochemical or seepage rate predictions. Because making such predictions is inherently difficult, appropriate 'safety factors' must be incorporated in the designs. Other internal causes would primarily be associated with the failure of a confinement or release measure (*e.g.*, failure of a low permeability core, plastic liner, grout curtain or spillway/decant structure). These design aspects are well within the realm of the current 'state-of-the-art' tailings dam engineering. Therefore, one concludes that:

- We have the tools to design tailings dams so that no 'Type II failure – internal cause' would be expected to occur in the sense of exceeding acceptable environmental impact.

Inactive/Abandoned Tailings Dams

There are thousands of inactive/abandoned tailings dams which either were not designed or designed to significantly lower standards than the standards considered acceptable today. The majority of these dams are neither subject to adequate DS/DSI/DSR programs nor the necessary improvements to their safety will be made in the foreseeable future. Some of those dams would be expected to fail in the sense of 'Type I failure – external cause' even if these were designed to modern standards, as discussed under the 'Type I failure – external cause' heading. Some of these dams are causing environmental impacts in excess of the impacts that are considered acceptable by today's standards. Therefore, one concludes that:

- Some of the existing inactive/abandoned tailings dams are failing (either on a continuos or intermittent basis) in the sense of Type II failure. In the sense of Type I failure, some of these dams may fail in future.

These obviously are disturbing statements. In this regard, it needs be said that to retrofit all inactive/abandoned tailings dams to modern standards would be an enormous undertaking. Classifying these dams with respect to potential consequences of structural failure and actual environmental impacts on a preliminary basis and, based on such classifications, selecting and retrofitting the dams that represent the greatest hazards, would significantly improve the situation (such screening process has already been performed in many jurisdictions).

Existing Operated Tailings Dams

The situation is much better in the case of existing tailings dams that are still operated. The opportunity to introduce improvements to dam safety is there, although it would depend on the dam operating phase (Table 6). As a minimum, an adequate DS/DSI/DSR program can be implemented, wherever this has not been done yet, and appropriate operating, monitoring and maintenance procedures defined and adhered to. In many cases, improvements to dam structures still can be carried out at reasonable costs although, in some cases, these costs may be prohibitively high (hence note [4] has been included under Table 12). In any case, the existing operated tailings dams must not be expected to perform better than new tailings dams. Consequently:

- Some, although very few of the existing operated tailings dams may fail. However, the situation in this case does not seem to be much different than in the case of new tailings dams, assuming that an effort is put to examine the actual safety of existing dams and, where required, adequate improvements to dam safety implemented. Many owners are actually conducting such programs as of the time of this Document preparation.

General View

Regardless of any other considerations, we could not truly guarantee that no tailings dam would ever fail, even if all dams were designed, constructed and operated using the most stringent design criteria, the state-of-the-art engineering as well as all reasonable prudence and care. This is similar to the situations that other industries are facing, for instance, the aviation industry, medicine or law. Although following the highest standards is expected from these ‘industries’, it would be unreasonable to expect that no plane will ever crash, no patient will ever unnecessarily die and no innocent person will ever go to jail. Similarly, it would be unreasonable to expect that no tailings dam will ever be subject to a design, construction or operating error.

Summary

The above discussion may seem as painting a black picture, however, this is not the case. With respect to new and existing operated tailings dams, it needs be realised that it is only the external causes pertaining to Type I failure, most notably an extreme flood or earthquake load, that could lead to the failure of a well designed, constructed and operated tailings dam.

It also needs be realised that an enormous progress has been made in the area of tailings dam engineering (see the Preface), and this progress continues. The author believes that, in general, tailings dams are significantly safer today than these were two decades ago. The recent initiative of the Canadian mining industry, named the 'Mine Environment Neutral Drainage (MEND) Program', has allowed for making a leap step in few years only (the only regret the author has is that a 10% of MEND's budget had not been directed towards the other aspects of tailings dams safety). Another example of an impressive progress made in recent years is the understanding of tailings dams stability under seismic loads. The most important of all is the progress made in the way that we perceive tailings dams.

*It was emphasised at the beginning of this section that **very few** tailings dams only would be expected to fail. This statement can be substantiated based on the following arguments.*

According to the preceding discussion, it is primarily an extreme earthquake or flood event ('Type I failure – external cause') that could lead to a failure of a well designed, constructed, operated, maintained and otherwise cared for (WDCOM&OCF) tailings dam.

Regardless of the probabilistic earthquake design criteria that may be incorporated in tailings dam design, the experience shows that no WDCOM&OCF downstream or centreline tailings dam has ever failed due to earthquake event. With regard to upstream tailings dams, there is a general consensus that such dams should not be constructed in areas of moderate to high seismicity, and there seem to be no reasons to presuppose that a WDCOM&OCF upstream tailings dam could fail under a relatively low earthquake load.

As pointed out in previous discussions, the tailings dam watersheds are typically small and providing a spillway-freeboard system sufficient for passing PMF flows will often be economically feasible. In all these cases, no WDCOM&OCF tailings dam would be expected to fail due to flood (assuming that a flood larger than PMF cannot happen). A spillway-freeboard system sufficient for passing PMF flows should be provided for all new tailings dams where the potential for loss of life exists (Tables 8 and 11). Such a system should also be provided for all dams classified in the High and the upper range of Significant categories (impact classification) during the closure phase (Table 10). Although there may be some, the author has not seen a tailings site yet where a spillway capable of passing PMF could not be economically provided for the closure phase.

*It follows that only **very few** out of all WDCOM&OCF tailings dams would be expected to fail, given sufficient time and the number of dams.*

Appendix B

Sample Tailings Dam Inspection Forms

The two forms (tables) included in this appendix are intended for the inspection of tailings dam structures. The first form is designed to contain information on the general conditions of the dam. Filling this form would allow for reducing the size of DSI report.

The presented forms are rather extensive. The rationale here is that having to fill-in such detailed forms in the field, the engineer will be less exposed to potential omissions and, also, he/she may be alerted to some dam safety aspects that could otherwise be overlooked.

Nevertheless, it must be realised that a tailings dam inspection does not consist of taking pictures and filling some prescribed forms only, and an in-depth knowledge of dam design, operation and other safety aspects must be available and used so that all site-specific safety aspects can be identified and addressed.

TAILINGS DAM INSPECTION – OVERVIEW

Inspected by:	{ engineer's name } accompanied by ....., if applicable
Approved and reviewed by:	{ senior engineer's name } { principal's name }
Inspect. date & weather conditions:	{ date } { *e.g.*, sunny, raining, foggy, *etc.* }
Purpose of dam:	{ *e.g.*, retain tailings & contam. water, buffer pond, *etc.* }
Date of last DSI:	{ date | never inspected } by ...., if applicable
Date of last DSR:	{ date | never reviewed } by ...., if applicable
Initial dam construction date:	{ date } state if by contractor or mine forces
Original dam engineered:	{ yes | no } original design by ....
Type of dam:	{ *e.g.*, low permeability | upstream | highly pervious }
Relation to tailings basin:	{ *e.g.*, principal ('main') dam, saddle dam, internal dam }
Tailings basin watershed:	{ area } indicate upstream diversions, if any
Typical dam section:	{ *e.g.*, till core-rockfill shells-grouted bedrock-till foundation }
Approx. dam length & max. height:	{ length } { height }
Tailings pond adjacent to dam:	{ yes | no } indicate pond area & volume, watershed area
Typical tailings pond length:	{ length, perpendicular to dam } if adjacent to dam
Freeboard at time of DSI:	{ freeboard }
Minimum past freeboard:	{ freeboard } based on site observations or info from Owner
Discharge structure(s):	{ *e.g.*, decant tower, spillway, barge }
Emergency discharge structure(s):	{ yes | no } indicate type, *e.g.*, spillway, decant, *etc.*
Date of last raise of dam:	{ date | never raised | annual raising }
Future dam raise planned:	{ yes | no } state when, if applicable
Dam instrumentation/conditions:	{ *e.g.*, pneumatic piezometers - 5, standpipes - 6/conditions?) }
Design/as-built data available:	{ at the site: yes | no } {in engineer's office: yes | no }
Dam classification (if available):	{ High, Low, etc. } based on LLEL/impact classification
Preliminary dam classification:	{ specify } if dam classification not available
Volume and type of solids stored:	{ volume } {*e.g.*. tailings, tailings + sludge, sediment }
Tailings disposal method:	{ *e.g.*, spigott, end spill } {gravity | pumped } indicate % solids
Tailings production rate:	{ tonnage per day }
Relevant info on dam reviewed:	{ yes } indicate if not available
Special 'as-built' features:	{ yes | no } specify, *e.g.*, fault at Sta..., pipe buried at ...
U/S procedures inspect./reviewed:	{ yes | no } specify: *e.g.*, oper. pond levels, diversion ditch, *etc.*
D/S walk-over conducted:	{ yes | no }
Discharge facilities inspected:	{ yes | no } specify: decant, overflow/emergency spillway, *etc.*
Dam surveillance implemented:	{ yes | no } indicate if adequate surveillance implemented
Other dam/divers. facility inspected:	{ yes | no } specify; if yes, a separate form may be required
Operations manual reviewed:	{ yes | no } state if revisions required
Data on compliance reviewed:	{ yes | no } state if non-compliance occurred (reasons)
New developments d/s of dam:	{ yes | no } describe in text, if observed
Dam failed since last DSI:	{ yes | no } elaborate in text, if 'yes', state past performance
General conditions of dam:	{ satisfactory | require corrective works }
Next DSR recommended:	{ date } if not necessary, state why

INSPECTION OF DAM STRUCTURE

OBSERVED FEATURES		YES	NO	PHOTO NO.	COMMENT / NOTE NO.
1.0	**(visible part of) Upstream Slope**				
1.1	Erosion protection				
1.2	Evidence of erosion				
1.3	Evidence of movement				
1.4	Evidence of sloughing				
1.5	Evidence of cracking				
1.6	Mark of high pond level				
1.7	Tailings adjacent to dam				
1.8	Vegetation				
1.9	Slope visually uniform				
1.10	Other unusual conditions				
1.11	Evidence of repairs				
2.0	**Crest**				
2.1	Breach / wash-out				
2.2	Lateral movement				
2.3	Evidence of settlement				
2.4	Evidence of cracking				
2.5	Shoulder erosion				
2.6	Reduced width				
2.7	Crest visually horizontal				
2.8	Other unusual conditions				
2.9	Evidence of repairs				
3.0	**Downstream Slope**				
3.1	Erosion protection				
3.2	Evidence of erosion				
3.3	Evidence of movement				
3.4	Evidence of sloughing				
3.5	Evidence of cracking				
3.6	Signs of phreatic surface				
3.7	Evidence of seepage				
3.8	Seepage clear				
3.9	Evidence of contamination				
3.10	Vegetation				
3.11	Slope visually uniform				
3.12	Other unusual conditions				
3.13	Evidence of repairs				

INSPECTION OF DAM STRUCTURE (continued)

OBSERVED FEATURES	YES	NO	PHOTO NO.	COMMENT / NOTE NO.
4.0 Left and Right Abutments				
4.1 Evidence of seepage				
4.2 Seepage clear				
4.3 Evidence of contamination				
4.4 Evidence of erosion				
4.5 Evidence of cracks				
4.6 Evidence of movement				
4.7 Evidence of settlement				
4.8 Other unusual conditions				
4.9 Evidence of repairs				
5.0 Downstream Toe				
5.1 Toe drain exists				
5.2 Toe drain working well				
5.3 Toe ditch exists				
5.4 Flow in toe ditch				
5.5 Evidence of seepage				
5.6 Seepage clear				
5.7 Evidence of contamination				
5.8 Evidence of vegetat. kills				
5.9 Soft toe condition				
5.10 Evidence of sloughing				
5.11 Evidence of boils				
5.12 Other unusual conditions				
5.13 Evidence of repairs				
6.0 General				
6.1 Associated tailings dams				
6.2 SCF(s) at this dam				
6.3 Decant structure at this dam				
6.4 Embedded/buried structures				
6.5 Spillway at/next to this dam				
6.6 Pipelines at this dam				
6.7 Evidence of AMD				
6.8 Tailings next to dam inspected				
6.9 Crest accessible by truck				
6.10 Public access to dam				
6.11 Any unusual conditions				

About the author

Dr. Szymanski, P.Eng. worked on his first tailings dam in 1971 in Poland, as part of the Master thesis requirements. It wasn't until 10 years, including some academic endeavours later that he worked on a tailings dam again, on the other side of the globe in British Columbia, Canada.

Dr. Szymanski obtained his graduate degrees from Warsaw University, Institute of Hydrogeology and Engineering Geology, Poland (M.Sc., Ph.D.) and Carleton University, Department of Civil Engineering, Canada (Ph.D.).

At the beginning of his career as a practitioner, he worked for a number of consulting companies in Canada and USA, including EBA, Golder, Kilborn and Geotech. Presently, Dr. Szymanski is VP, Mining Projects with AGRA Earth & Environmental. Prior to joining AGRA, he was VP, Geotechnical and Geoenvironmental with Kilborn SNC-Lavalin, in charge of the Geocon department.

Dr. Szymanski's primary responsibility is the technical direction and review of geotechnical and geoenvironmental projects carried out exclusively for the mining industry. These include tailings dam design and safety evaluation projects. The most challenging assignments involve merging hydrology, geochemistry and hydrogeology with geotechnical engineering and economics, to arrive at environmentally acceptable solutions.

The author lives in Ontario with Krystyna, Gosia and Topsy, neither of whom has, or will ever read this book.

And yet, in a way, you put more effort into writing it than I did considering those countless evenings and weekends. I had fun working on this book, I admit. Now that this book has been written, I'll change. Some.

M.