



ENTRO  
**NILE BASIN INITIATIVE**  
INITIATIVE DU BASSIN DU NIL

GUIDELINE

NILE BASIN SUSTAINABILITY FRAMEWORK

# REFERENCE DAM SAFETY GUIDELINES FOR EASTERN NILE COUNTRIES

## Document Control Sheet

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Eastern Nile Technical Regional Office (ENTRO)

## **Reference Dam Safety Guidelines for Eastern Nile Countries**

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Cover Photo: Koga dam PFMA training, Ethiopia

## FOREWORD

I am pleased to launch this Eastern Nile Reference Dam Safety Guideline for planning, design, construction, operation and safety management of large and small dams.



I commend ENTRO for having completed and availed this document at this critical juncture in the water resource development history of Eastern Nile. Dam safety will become a major focus of water resource planners and managers of Eastern Nile for the foreseeable future.

I trust this document will be of practical use and thus make critical contribution to the institutionalization of dam safety in Eastern Nile.

A handwritten signature in black ink, appearing to be in Arabic script, written over a white background.

H.E. Mutaz Musa Abdalla Salim  
Minister, Water Resources and Electricity, Sudan  
ENCOM Chair

## PREFACE

As a result of countries' enhanced efforts to tap the water resources potential of the Nile, the number of large and small dams on the Eastern Nile stretch of the Nile basin has been steadily increasing over the years. These investments are expected to generate economic benefits yielding much needed energy and food demanded by steadily growing populations. While these developments are welcome, it is also necessary to ensure the safe operation of these dams.

Dam safety, therefore, will be one area where Eastern Nile countries' interests will converge, other differences notwithstanding. Dam safety will be the glue that holds Eastern Nile countries together now and in the future. Dam safety is a glaring example that demonstrates the fact that Eastern Nile Cooperation is not an option, but an existential necessity!

ENTRO has been cognizant of this fact and has striven to take the first steps in laying the foundation for the institutionalization of dam safety. Over the last two years ENTRO has identified potential technical and institutional gaps in Eastern Nile Dam safety management, large and small, and designed training modules and undertook a capacity building program targeting a range of critical stakeholders including: parliamentarians, policy makers, water resources planners and managers, dam owners and operators, academia and civil society. Thus far about 200 Eastern Nile professionals have been trained in dam operation; dam safety management in transboundary context; environmental and social considerations associated with dam safety; safety assessment of dams; planning, design and construction management of water infrastructure. To avail the lessons of experience from within Eastern Nile and worldwide to those who could not take part in these trainings and to support their adoption, ENTRO has produced three critical documents namely 1) Eastern Nile Reference Dam Safety Guideline 2) Small Dam Safety Guideline 3) Dam Safety Training Module.

Dam safety management needs to be institutionalized. The above are only the starting points. Next steps will include establishment and consolidation of national dam safety units in each Eastern Nile country and development of Eastern Nile Dam Safety Regulatory Framework, which will deal with the legal and institutional dimensions.

It is with a sense of satisfaction I launch these Dam Safety Guidelines and Training Module. I trust the relevant Eastern Nile stakeholders will find these very useful and relevant to their work.



Fekahmed Negash Nuru  
Executive Director, ENTRO

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## PREAMBLE

The Nile Basin Initiative (NBI) is a transitional cooperative mechanism of nine riparian countries.<sup>1</sup> It was established in February 1999 to realize a jointly articulated Shared Vision whose objective is “To achieve sustainable socio-economic development through the equitable utilization and benefit from the common Nile Basin water resources”. Its overriding objectives are poverty reduction, reversal of environmental degradation, promotion of economic growth, increased regional cooperation and integration, and enhanced regional peace and security. The NBI Secretariat (Nile-SEC) is based in Entebbe, Uganda

Eastern Nile Sub (EN) Basin countries have made significant strides in strengthening their cooperation since the launch of the Eastern Nile Subsidiary Action Program (ENSAP) in 1999, within the framework of the Nile Basin Initiative. The Eastern Nile basin countries comprise of Egypt, Ethiopia, South Sudan and Sudan. The Eastern Nile Regional Technical Regional office (ENTRO) is based in Addis Ababa, Ethiopia.

This guideline has been prepared as part of the Eastern Nile Technical Regional Office (ENTRO) Dam Safety Program. The dam safety program includes an updated assessment of the baseline conditions as a starting point, the development of a generic set of dam safety guidelines applicable to the region and available for adoption by each of the EN countries, a “Road Map” for the preparation of EN dam safety regulation framework and training in dam safety management. This Dam Safety Guidelines is intended for Eastern Nile dams safety management.

This guideline draws concepts and processes from various international guidelines from within the ICOLD family of Technical and National Committees and also various US Federal Agencies. Appreciation is expressed to the developers and authors of those guidelines.

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| Symbol or abbreviation | Definition   |
|------------------------|--|
| AEP                    | Annual Exceedance Probability                      |
| ALARP                  | As Low As Reasonable Practicable                   |
| ANCOLD                 | Australian National Committee on Large Dams        |
| CDA                    | Canadian Dam Association                           |
| CSR                    | Comprehensive Safety Review                        |
| EAP                    | Emergency Preparedness Plan                        |
| EG                     | Engineering Guidelines                             |
| EIA                    | Environment Impact Assessment                      |
| EN                     | Eastern Nile                                       |
| ENSAP                  | Eastern Nile Subsidiary Action Plan                |
| ENTRO                  | Eastern Nile Technical Regional Office             |
| EPC                    | Engineering, Procurement and Construction          |
| FEMA                   | Federal Emergency Management Agency                |
| FERC                   | United States Federal Energy Regulatory Commission |
| ICOLD                  | International Commission on Large Dams             |
| IDF                    | Inflow Design Flood                                |
| IWRM                   | Integrated Water Resources Management              |
| MCE                    | Maximum Credible Earthquake                        |
| NBI                    | Nile Basin Initiative                              |
| O & M                  | Operation and Maintenance                          |
| ODSP                   | Owners Dam Safety Plan                             |
| PAR                    | Population at Risk                                 |
| PCC                    | Potential Consequences Classification              |
| PFM                    | Potential Failure Mode                             |
| PFMA                   | Potential Failure Mode Analysis                    |
| PMF                    | Probable Maximum Flood                             |
| QRA                    | Quantitative Risk Analysis                         |
| RCEM                   | Reclamation Consequence Estimating Methodology     |
| RIDM                   | Risk Informed Decision Making                      |
| SMP                    | Surveillance and Monitoring Plan                   |
| SMR                    | Surveillance and Monitoring Report                 |
| SOP                    | Standing Operating Procedures                      |
| STID                   | Supporting Technical Information Documentation     |
| TADS                   | Training Aids for Dam Safety                       |
| TC                     | Telemetry to be Considered                         |
| TR                     | Telemetry Recommended                              |
| USACE                  | United States Army Corps of Engineers              |
| USBR                   | United States Bureau of Reclamation                |

# 1. INTRODUCTION

## 1.1 Objective

The objective of this report is to present a reference or regional dam safety guideline which addresses the dam safety management issues that may be applicable in the Eastern Nile countries.

Section 1 reviews the background and then presents the scope of the guidelines. Sections 2 to 14 presents recommended Reference Dam Safety Guidelines for EN countries.

Appendices A through D present supporting materials for key dam safety documentation and activities including operations and maintenance manuals, surveillance and monitoring, safety reviews and vegetation management.

These Reference Dam Safety Guidelines are intended to be a generic document for Eastern Nile countries to adapt to country level. The National Dam Safety Guidelines would consider the specific characteristics and issues of the dams in each country and be formulated based on number, size of dams and its consequences classifications, water resource development and environmental policies, regulation and water acts, institutional setup and implementation capacity.

Dam safety is among the nine key environmental and social issues identified in the Blue-Main Nile Joint Multipurpose Program identification study and was addressed in the preliminary assessment report published by ENTRO in 2013.

The major concerns regarding the large dams in the ENB is not their number, but their location, complexity and size as well as the possible consequences of a failure. It is an unfortunate fact that periodically dams do fail, sometimes causing extreme damage and loss of life downstream. This is discussed in the next two sub-sections and illustrative examples of dam incidents are presented in Appendix E. Many of the structures in the ENB are located on major trans-boundary watercourses where more than 100 million people are living downstream where dam failure can result in severe consequences for human lives, environment and property. Consequently, dam safety is an essential issue to be addressed by ENB dam owners and responsible government agencies.

Construction and operation of large water infrastructure on a trans-boundary river bring forth additional complexities and if not properly managed may result in strained riparian relations. Hence, putting in place the appropriate institutions and mechanisms to ensure integrated operation and management of these infrastructures (i.e. dams, hydroelectric power plant, etc.) is an important step towards assisting EN Basin countries to avoid adverse trans-boundary consequences.

It is recognized that integrated planning, design, construction, operation and maintenance of large water infrastructure coupled with recognition of impacts of climate change, is vital to minimize the risks of catastrophic disaster affecting downstream populations. Moreover, lesson learned from other large scale water infrastructure developments on trans-boundary rivers reveal that coordination of dam safety-related planning and management develops trust and confidence and creates strong cooperation among the riparian countries.

## 1.2 Background

Following the International Congress on Large Dams in New Delhi in 1979, ICOLD established the Committee on Dam Safety to develop guidelines. The Committee was established in 1982 as a coordinating body, to assure an integrated approach of all Technical Committees to safety issues, to guide toward action where shortcomings or gaps may be perceived, to define a common safety philosophy and to prepare general guidelines on dam safety outlined along this philosophy.

The main reasons to develop these ICOLD guidelines were:

- Several dam incidents with severe consequences had given rise to general concern about the safety of dams, and indicated the necessity for a formal safety approach;
- The height of new dams and the volume of new reservoirs were increasing, while many older dams were approaching an age at which material deterioration and decreasing operational reliability may dictate some repair and upgrading. Certainly, both the growing dimensions of new dams and the aging of older dams suggest a more rigorous approach to safety aspects; and
- An ever increasing number of dams are being built in countries with little or no tradition and experience in dam engineering. The formalization of safety considerations and the issuance of summarized safety requirements would be part of the necessary transfer of technological know-how to these countries.

In 1987 ICOLD published the Dam Safety Guideline, Bulletin 59 (ICOLD: 1987) to provide guidance for comprehensive review of all items of dam design, construction, operation, maintenance and surveillance that should be considered against the background of all scenarios that could be expected to occur during the life of a dam. It also provides recommended measures, procedures and strategies to achieve the highest, economically reasonable level of dam safety.

Recognizing these facts, most developed countries have initiated and developed their own national dam safety regulation and guidelines.

In addition, the World Commission on Dams Report, released in November 2000, highlighted the importance of the safety of dams and in particular noted that development and management of dam projects on international rivers, where two or more countries are involved, should co-ordinate efforts for the establishment of a dam safety management procedure which consist of:

- Uniformity of criteria used for hazard rating and risk classification;
- Compatibility of safety codes, basic design criteria and methods;
- River basin management compatibility with reservoir operation routines and flood and discharge control rules; and
- Co-ordination of emergency warning systems and operations, etc.

## 1.3 Dam Safety Experience

Safe functioning of dams is not only especially determined by their original design and construction. It is also determined by all actions starting from planning to routinely monitor, evaluate, identify or predict

dam safety issues during the operational lifetime of the project. In line with this, planned projects, existing dams and reservoirs should be reviewed, monitored and inspected regularly to ensure that they can still meet the safety by current standards. As knowledge of hydrology, seismicity, geological environment and material properties accumulates and technology advance, facilities once regarded as safe may need modifications. In addition, the safety of existing dams can be affected by natural phenomenon such as flooding, landslide, earthquake, and deterioration of heterogenous foundations and construction materials. Proper dam safety programs are designed and managed to provide the earliest possible detection of any flaws which may lead to failure.

According to an ICOLD study (ICOLD: 1995), the failure rate of large dams has been falling over the last four decades. 2,2% of dams built before 1950 failed, while the failure rate of dams built since 1951 is less than 0,5%. Some 70% of failures occur in the first ten years of life of the dam, and more especially in the first year after commissioning. The study revealed that the incidence of dam safety incidents has reduced progressively over the years. This is understood to be due to the improvements in dam design, construction and dam safety regulation and practice.

Among others, foundation problems are the most common cause of failure in concrete dams, with internal erosion and insufficient shear strength of the foundation, each accounting for 21% of failures. The most common cause of failure of earth and rock fill dams is overtopping (31% as primary cause and 18% as secondary cause). This is followed by internal erosion in the body of the dam (15% as primary cause and 13% as secondary cause) and in the foundation (12% as primary cause and 5% as secondary cause). With masonry dams, the most common cause is overtopping (43%) followed by internal erosion in the foundation (29%).

Where the appurtenant works were the seat of the failure, the most common cause was inadequate spillway capacity (22% as primary cause and 30% as secondary cause). The post-failure action most frequently reported was scheme abandoned (36%), construction of a newly designed dam (19%) and overall reconstruction with the same design (16%).

These guidelines outline best practice in dam safety and describe technical procedures dealing with the planning, design, construction, operation and maintenance of dams. It assists and guide regulators, Approved Dam Engineers, dam owners and operators to safely design, construct and manage their dams and protect loss of lives, property, livelihood and environmental disruption.

## 1.4 Dam Safety Regulation

Dam safety regulations are also required to address enforcement of rules and procedures, legal restrictions, roles and responsibilities of agencies and authorities, contractual obligations, licensing system for designing, constructing and operating of dams, etc.

The regulations may contain:

- A statute or law passed by the government. It should only contain the objectives and general principles governing the framework. The statute may deal only with dam safety or may deal with other issues such as management of water resources as well.
- The statute should clearly stipulate the responsibilities of all parties including the authority responsible for dam safety and the authority responsible for handling any emergencies.



- The regulations may be supplemented by non-binding guidelines. These may take the form of recommended good practice and be developed by professional societies and applied by owners on a case by case basis.

It is important to note that effective legislative implementation and management of dam safety would be very difficult without the necessary legislative environment (including regulations and an authority to implement the regulations).

### 1.5 Dam Safety Guidelines and Regulation in Eastern Nile Countries

Currently there are more than 30 existing large dams in the Eastern Nile sub-basin (ENSB). Most of these are in Egypt, Ethiopia and Sudan. No large dams currently exist in South Sudan. These, for example, include dams with large water storage reservoirs; such as High Aswan, Merowe and Tekeze Dams on Main Nile, Blue Nile and Tekeze Rivers respectively.

Another 4 large dams are currently under construction – 3 in Ethiopia and 1 in Sudan and 2 large dams are currently being designed in Sudan. The Grand Ethiopian Renaissance Dam (GERD) is one of those under construction, while there are other development plans to be implemented within the basin. Numerous smaller dams also exist in the ENB. Some of these large dams are listed below in Table 1.

Table 1: Some of the largest dams in EN

| Name                            | Basin/Location | Commissioning years      | Type                          | Height (m) | Reservoir Capacity (billion m <sup>3</sup> ) |
|---------------------------------|----------------|--------------------------|-------------------------------|------------|--|
| EGYPT                           |                |                          |                               |            |  |
| High Aswan Dam                  | Main Nile      | 1970                     | Rockfill                      | 111        | 162  |
| Old Aswan Dam                   | Main Nile      | 1902, raised 1912 & 1933 | Masonry                       | 36         | 5  |
| ETHIOPIA                        |                |                          |                               |            |  |
| Grand Ethiopian Renaissance Dam | Blue Nile      | Under construction       | RCC                           | 145        | 74   |
| Finchaa Dam                     | Blue Nile      | 1973                     | Rockfill                      | 22.2       | 0.65   |
| Neshe Dam                       | Blue Nile      | 2010                     | Earthfill                     | 38         | 0.45   |
| SUDAN                           |                |                          |                               |            |  |
| Merowe Dam                      | Main Nile      | 2009                     | CFRD + rockfill               | 67         | 12.4   |
| Dam Complex of Upper Atbara     | Tekeze-Atbara  | Under construction       | Concrete gravity + earthfill  | 54         | 3.7  |
| Khashim el Girba Dam            | Tekeze-Atbara  | 1964                     | Concrete buttress + earthfill | 50         | 0.6  |
| Sennar Dam                      | Blue Nile      | 1926                     | Masonry + earthfill           | 39         | 0.375  |

Construction and operation of such large water infrastructure brings forth additional complexities and if not properly managed result in strains in riparian relations. Hence, putting in place the appropriate policy, legal arrangement, procedures, standards and enhance the technical capacity is an important step to avoid adverse impacts.

Particularly, development and management of large scale water infrastructure on trans-boundary rivers require careful coordination of dam safety management among the countries to reduce the risks of a catastrophic disaster affecting populations residing downstream of the dams.

Despite the growing number of large water infrastructure development in the basin, there is no national or regional dam safety guideline or regulatory framework pertaining to dam safety management.

The Ministry of Water Resources and Irrigation in Egypt, the Ministry of Water, Irrigation and Energy in Ethiopia and the Ministry of Water Resources and Electricity in Sudan are responsible entities related to dam matters.

In Egypt, Ethiopia as well as Sudan there is adequate supportive policies and legal frameworks in place to properly manage environmental and social issues with regards to dams while South Sudan has a draft environmental policy available. In Egypt and Ethiopia guidelines are also available for Environmental Impact Assessments.

## 1.6 Comparative Analysis of Existing Guidelines

### 1.6.1 ENTRO 2013 Study

In 2013 ENTRO staff carried out a comparative analysis of ICOLD, Canadian, Ugandan and Malaysian dam safety guidelines, and recommended the most appropriate and suitable guideline to be adapted for Eastern Nile Countries. These four guidelines were selected based on their comprehensiveness, adaptability to EN countries and availability of the guidelines.

The conclusions of the Comparative Analysis were:

- The objective of developing a dam safety guideline is to ensure safety of dams during their whole life cycle - from the conceptual phase, through design, construction and operational stage to decommissioning;
- The dam safety guideline needs to consider existing policies, regulations, standards, directives, capability of professionals, technological advancement, institutional strength and trans-boundary nature of projects, etc. In line with this, it was attempted to review the contents and adaptability of the four dam safety guidelines; and
- Each of these guidelines has its own merits and limitations. However, considering its comprehensiveness; descriptive procedures; freely availability of supplementary reference material (ICOLD bulletins); applicability both for small and large dams; the ICOLD dam safety guideline is more suitable and appropriate for adapting to EN countries.

### 1.6.2 ICOLD Dam Safety Guidelines

ICOLD Bulletin 59, the Dam Safety Guideline was published in 1987 (ICOLD: 1987) aiming to provide guidance for comprehensive review of all items of design, construction, operation, maintenance and

surveillance of dams in assuring its safety as it was understood in terms of practices in the mid 1980's. Much of the content remains valid to-day, although certain aspects that were less developed at that time have subsequently been resolved and are dealt with in other Bulletins. The guideline is intended to apply mainly to large dams as defined by ICOLD Bulletin 59 (ICOLD: 1987), but it also provides a generic basis from which to develop guidelines to assess and improve the safety of small dams.

The ICOLD Bulletin 59 dam safety guideline mainly comprises the following five basic dam safety components in 25 Chapters and a number of Appendixes:

- A. **General aspects:** Role of regulators, operators, regulation, legal aspects, etc
- B. **Design:** Hydrologic and hydraulic design. structural design, monitoring, reservoir planning and design, instructions for safety inspection, specific aspects related to boundary rivers, enlargement, alteration, rehabilitation, repair and abandonment;
- C. **Construction:** Design-related construction, river handling and reservoir impoundment aspects, construction emergency precautions public health and environmental risks alteration or repair of existing dams and reservoirs;
- D. **Operation:** Flood discharge and flood control, structural integrity and operational safety, reservoir operation and environmental safety, monitoring and inspection. Emergency precautions and operation, hazard rating; incidents and accidents; and
- E. **Abandonment:** Remaining structures, river flow and flood discharge. Surveillance of abandoned dam sites.

**Appendixes:** Checklist for Dam Safety for each of the above-mentioned five basic dam safety components

The guideline contains the basic principles and requirements which govern the philosophy, methods and procedures of the management, surveillance and evaluation of the safety of dams and reservoirs. It is presented in the form of recommendations rather than binding requirements, and the details are purposely developed only to the extent necessary to make the principles understandable.

Subsequent ICOLD bulletins on dam safety management include:

- Bulletin 130 (2005): Risk Assessment in Dam Safety Management. A reconnaissance of Benefits, Methods and Current Applications which addresses the ever-increasing complexity of decision-making for dams, in compliance with this requirement of transparency and responsibility, and seeks new approaches for economic and safe operation, maintenance and the overall management. Risk assessment is part of these possibilities. The principles of risk assessment are logical and rational, and must be taken into account by all countries in decision-making regarding the dams. This bulletin is intended to foster discussion within the profession; to move towards a position widely accepted the role of assessing risk. It is also intended to serve as a complementary tool for engineers, owners and regulatory authorities in order to fulfill their obligations in all areas of the dam safety.
- Bulletin 154 (2012 Preprint): Dam Safety Management: Operational Phase of the Dam Life Cycle. This bulletin is devoted to the development and the implementation of a dam safety

management system for dams in the operational phase of their life cycle. It outlines the general structure of a systems approach to safety management, and strives to develop a system that can address all the interdependencies, and encompass all the arrangements necessary to ensure proper dam safety management.

The structure in Bulletin 154 is built on the principles established in Bulletins 59 and 130, as well as the general philosophy that informs them both. In that respect Bulletin 154 was not intended to update or replace the Bulletin 59 which although written in 1987 is still valid and should remain as a primary source of guidance for those professionals who are applying traditional approaches to dam safety.

In addition to this, Bulletin 154 is complemented by supplementary guidelines and special technical reports to address many dam safety issues which are available from the ICOLD website.

### 1.6.3 CDA Guidelines

The Canadian dam safety guideline was published in 2007 by the Canadian Dam Association (CDA) aiming to provide guidance for dam owners, operators, consultants and regulators in Canada (CDA: 2007). The Canadian Dam Association Guidelines is composed of six main chapters as shown below and starts with basic principles recommended for the safety assessment of dams in Canada and it is intended to apply mainly to large dams:

1. PRINCIPLES
2. DAM SAFETY MANAGEMENT
3. OPERATION, MAINTENANCE, AND SURVEILLANCE.
4. EMERGENCY PREPAREDNESS
5. DAM SAFETY REVIEW
6. ANALYSIS AND ASSESSMENT

Eleven basic dam safety management principles are also highlighted, that need to be considered during design, operation, maintenance, surveillance, emergency preparedness, and safety review and assessment process provide an overall framework for the management of existing dams.

In addition to the Dam Safety Guidelines, nine Technical Bulletins were published by CDA in 2007. The Technical Bulletins provide additional information and provide suggested methodologies and procedures for use by qualified professionals as they carry out dam analyses and safety assessments.

In 2013 CDA published a revision to the 2007 Guidelines (CDA: 2013). This revision resulted from a review and revision to Sections 6.1, 6.2 and 6.3 of the publication issued in 2007.. Other material in the 2007 Dam Safety Guidelines remains unchanged. CDA members requested additional guidance on Sections 6.2 and 6.3 which referred to both Risk-Informed and Traditional Standards-Based Approaches to dam safety assessments, without comment on their relative merits. In this 2013 revision, the CDA clarifies its endorsement of the use of a risk-informed approach, which includes traditional deterministic standards-based analysis as one of many considerations. CDA accepts that there are fundamental weaknesses in both approaches. Issues with the risk-informed approach include current challenges in the

characterization of the hazard, the dam system performance, and the consequences. The traditional standards-based approach not only shares these difficulties but has a number of additional significant limitations. Of particular concern are:

- Focus on extreme natural hazards in isolation, which can lead to preferentially implementing expensive solutions that may not necessarily improve the safety of the dam over that which could be achieved by other more economical means; and
- The inability to define standards for a number of dam failure modes, which may lead to inappropriate or misleading assessment of safety.

There are also other recognized difficulties in the application of the 2007 version of Sections 6.2 and 6.3. For example, selection of the level for seismic annual exceedance probability “must be justified to demonstrate conformity to societal norms of acceptable risk.” Resolution of this and other difficulties will require extensive discussions at a societal and governmental level, to answer the question of how safe new or existing dams should be. The CDA, as a non-governmental organization, does not in any way consider this question to be their responsibility; however, it recognizes that guidance is required in the interim until such larger issues are resolved.

CDA note that there are many instances where the prevailing capability and resources of dam owners will preclude the use of a comprehensive risk-informed approach. Continued use of a standards-based approach is inevitable in these cases, with appropriate additional conservatisms. A standards-based approach may be appropriate for certain elements of dam design and assessment. The CDA has identified the need for continued development and acceptance of the risk-informed approach. The revised Sections 6.1, 6.2 and 6.3 should be considered interim guidance, to be used until the above difficulties are addressed over time.

#### 1.6.4 ANCOLD Guidelines

The Guidelines for Dam Safety Management developed by the Australian National Committee on Large Dams (ANCOLD) address dam safety management in a very comprehensive, but conceptual level framework (ANCOLD: 2003a). These Guidelines focus on overall management and do not include specific design criteria for floods, earthquakes etc. or investigation requirements for hydrology, geology, seismicity, etc. These more specific issues are dealt with in supplementary guidelines.

These ANCOLD dam safety guidelines are intended to apply to what might be termed conventional dams (e.g. for water supply, irrigation, power and flood mitigation). Guidelines for dam safety management of tailings dams are published separately. These guidelines have been developed by ANCOLD with the aim of promoting appropriate dam safety management practices in Australia. It is recognized that circumstances vary enormously from dam to dam and different administrative frameworks apply in each state and in other countries. Some states have specific dam legislation while others rely on more general provisions. For these reasons, ANCOLD put this guideline forward as an advisory document that must be interpreted by appropriately qualified and experienced professionals in each case. In no sense is it intended that they should be regarded as a standard.

The ANCOLD dam safety guidelines don't specifically address the dam safety issues related to trans-boundary rivers which need to be considered in the EN situations.

ANCOLD advises that their 2003 guidelines will again be reviewed when knowledge and practice have developed to the point where an upgrade is required. Current practice in Australia has moved towards more general use of risk informed decision making particularly with frequent consideration of potential failure modes.

### 1.7 Trend towards Risk Informed Decision Making (RIDM)

In most countries of the world there is a very diverse portfolio of dams, some regarded as being designed and constructed before there was a good understanding of the loading conditions that could apply. Sometimes there is limited knowledge of the actual details of construction and always there is a desire to ensure that the community's resources are properly applied. The difficulty facing those who allocate funds for the benefit of the community measure the cost against the benefit achieved and to compare that with opportunities available.

Risk informed decision making uses tools to estimate the likelihood of a circumstance occurring and of its consequences. It also uses the tools to estimate what these will be after any improvement. These tools are diverse and can be imprecise. ANCOLD has developed Guidelines on Risk Management to help address this diversity of dams and the circumstances associated with them and offered this document as an indicator of an approach that may be taken.

Managing the risks associated with a dam or a portfolio of dams involves three distinct stages. These stages, each having their own purpose and function, are:

1. Risk Analysis (including a Potential Failure Mode Analysis - PFMA)
2. Risk Assessment
3. Risk-Informed Decision Making

In the United States, Risk-Informed Decision Making Engineering Guidelines (RIDM EGs) are being introduced to analyze and assess the risk associated with the United States Federal Energy Regulatory Commission (FERC) regulated dams. For the foreseeable future the FERC will maintain both the existing, deterministic, Engineering Guidelines and these RIDM Guidelines. In the near term the RIDM Guidelines will be used on an exception basis where either a licensee may request to utilize a RIDM approach or the FERC may suggest that a RIDM approach be considered. Over time the RIDM approach may become the standard of practice with the deterministic Guidelines then being used either on an exception basis or for dams with very low consequences. In general, the RIDM EGs do not address methods for conducting stability analyses or reproduce other parts of the deterministic guidelines. The RIDM EGs focus on how to use the information from deterministic analyses along with probability-based analysis tools.

ICOLD Bulletin 130 (2005): Risk Assessment in Dam Safety Management recommends that the principles of risk assessment are logical and rational, and must be taken into account by all countries in decision-making regarding the dams

Accordingly, in these "Reference Guidelines" RIDM methods and tools are introduced as an overall framework which uses the traditional "standards based" approaches and supplemented by risk analysis tools when significant uncertainty affects the decision making. RIDM can be used in specific instances and may become more universal as experience with the methodology is gained.

## 1.8 Recommended Dam Safety Management Processes for the EN Basin

Dam safety management for both new dams during planning, design and/or construction and for existing dams includes the following activities:

- Safety evaluations of feasibility studies, and design and construction plans for new dams;
- Establishing an Owner's Dam Safety Plan (ODSP);
- Safe operation and maintenance of existing dams according to established Standing Operating Procedures (SOPs) and Operation and Maintenance Manuals (O&M Manuals);
- Surveillance and monitoring according to established Surveillance and Monitoring Plans (SMP);
- Periodic Dam Safety Reviews;
- Maintaining effective Emergency Action Plans (EAPs).

Risk of dam failure can be reduced using traditional standards for planning, design, construction, operation, maintenance, surveillance of dams and emergency plans.

The dam safety evaluation process, to be employed in evaluations of new dams and comprehensive safety reviews for existing dams, starts with a Potential Consequences Classification (PCC) followed by a Potential Failure Mode Analysis (PFMA) and a Risk Matrix evaluation:

- For those potential failure modes that are amenable to standards-based analysis and which show relatively high risks (yellow or red cells) or large uncertainty in the PFMA Risk Matrix, a traditional standards-based approach can be used to assess their acceptability, and when required, modify the design of new dams or design remedial measures for existing dams.
- Otherwise, risk analysis techniques extending the results of the PFMA into event trees with qualitative likelihood estimates may be considered to more clearly define actual risks and the needs and benefits of design modifications or remediation requirements.

Remedial action to achieve risk reduction by either design modifications or remedial measures is required at a dam when the evaluation indicates it no longer meets an acceptable level of safety. The remedial action evaluation process should select a timely and cost effective course of action, which could include detailed analyses and investigations, interim or long-term design changes, remedial works, maintenance, changes to operating procedures, or decommissioning.

The Owners Dam Safety Program (ODSP) is the most important factor in maintaining safe dams and preventing dam failures. Dams with owners who do not have an effective ODSP represent a higher risk.

A dam safety program that is well documented, reviewed annually, and up-to-date sends a message, to all affected parties up to the highest level of authority both within and outside an owner's organization, that dam safety is important. Recognizing that each organization is unique, an ODSP should be specifically tailored to the particular situation considering the portfolio of dams, dam types, and the associated life safety and financial risks.

Proper operation and maintenance of a dam system is critical to safety and performance and thus to managing potential impacts on the public, the environment, and other stakeholders. This should be documented fully in an Operation and Maintenance (O&M) Manual.

The surveillance and monitoring program should provide for regular monitoring and evaluation of dam performance starting during construction. The program should be documented in a formal Surveillance and Monitoring Plan (SMP) with regular surveillance and monitoring reports (SMR) evaluating and presenting the results.

Dam Safety Reviews should be performed at critical stages of the dam life cycle. These may involve:

- Independent Review Panels during design and construction and/or in the event of a serious dam incident
- Comprehensive Safety Reviews (CSR) during design and construction and periodically once the dam is in operation. The Comprehensive Safety Reviews will normally involve the dam safety evaluation process steps outlined above.

An Emergency Action Plan (EAP) should be in place if lives are at risk or if implementation of emergency procedures could reduce the potential consequences of failure. The emergency management process should be updated over the full life cycle of the dam, including the construction phase and whenever significant cofferdams are required. For a new dam, the plans should be established prior to first filling of the reservoir.

### 1.9 Trans-Boundary Considerations

As discussed in the initial ICOLD Dam Safety Guidelines Bulletin 59, ICOLD 1987, dams on trans-boundary rivers require particular safety considerations. To avoid the possibility of accidents caused by the dissimilar application or interpretation of safety criteria, the development of dams on trans-boundary rivers requires careful coordination of safety-related aspects.

Such coordination should be assured, if necessary, by a bilateral or multilateral agreement or treaty between the governments of those countries, states or provinces whose territory extends into the drainage area of the river.

At the operational level, coordination of the safety-related aspects should preferably be handled by the responsible government agencies that represent their jurisdiction.

The coordinating efforts should include, but not be limited to, the establishment of uniform criteria for safety, liability, operating regulations and emergency provisions, and, in the case of dams and reservoirs on a reach where the river constitutes a border, the definition of local responsibility and administration as well as the jurisdiction over the dam and reservoir regarding safety requirements.

The government agencies represented in the coordinating group should maintain continuing liaison with each other.

### 1.10 Reference Guideline Basic Components

The guideline is a practical tool to provide procedures and promote a common approach to dam safety management dams taking into account its design, construction, and operation and maintenance phases.



The main components of any dam safety guideline should include, but are not limited to, the following aspects during planning, design, construction, operation and maintenance and abandonment phases. In the case of EN Guidelines, the inclusion of trans-boundary considerations, as discussed in the initial ICOLD Dam Safety Guidelines Bulletin 59 (ICOLD 1987) is especially important. Such considerations are inserted throughout this Guideline.

In addition, also as discussed in the initial ICOLD Dam Safety Guidelines Bulletin 59 (ICOLD 1987) environmental and social factors that may affect dam safety need to be addressed. These issues are addressed throughout the Guideline and discussed generally in Section 12.

Rather than developing very prescriptive standards, basic principles and minimum standards of design, construction, operation and maintenance general guidelines are recommended. In line with this, the dam safety guideline starts by establishing key dam safety objectives and then elaborates on each topic.

The recommended Reference Dam Safety Guidelines for EN Countries presented in Sections 2 to 14 is therefore composed of the following main elements.

1. Key Objectives;
2. Dam Safety Management;
3. Analysis and Assessment;
4. Planning and Design;
5. Construction and Commissioning;
6. Operations and Maintenance;
7. Surveillance;
8. Safety Reviews;
9. Dam Safety Emergency Planning;
10. Remedial Actions; and
11. Environmental and Social Factors.

The guidelines outline the role and responsibility of dam owner, regulatory authorities, the Approved Dam Engineer, operators and the need to develop a national dam safety program.

An overview of investigation, design, construction and commissioning in the context of dam safety is also broadly described in the guideline. It recommends using additional references for detailed analysis and assessment.

The following risk reduction options are discussed in the document.

- Interim Remedial Actions;
- Long-Term Remedial Works;
- Decommissioning;
- Disuse;
- Abandonment;
- Site Rehabilitation;

The guideline provides an outline of a remedial action evaluation for a dam which could be adopted or adapted as necessary for particular situations.

The guidelines recommends development of operating and maintenance procedures and manuals (O & M Manuals) by the dam owner for the safe operation of a dam under adverse (even worst case) scenarios as well as normal conditions, including coordination of releases with other dams, communication security, liaison with counter disaster and other agencies and discharge or flood warning to downstream areas.

The guidelines discuss the need for formal Surveillance and Monitoring Plans (SMP) establishing comprehensive programs for dams with regular evaluation and reporting in formal Surveillance and Monitoring Reports (SMR). These programs should commence as early as possible in the life of the dam (preferably during the construction phase) and continue throughout the project life to detect the development of any problem or unsafe trends and to provide full background information on the dam's performance. The scope of the surveillance program should be based on the results of the PFMA including recognition of the consequences of dam failure, the level of risk at the dam, the type and size of the dam, and the value of the dam to the dam owner and target the key "Performance Parameters" that are early indicators or the initiation of a potential failure mode.

Frequency and regular inspection requirement for abnormalities in conditions and for deterioration of dams are highlighted and four general levels of dam safety inspection program, discussed in the guideline. The frequency of inspections, taking into account the consequences of dam failure, the level of risk at the dam, the type and size of the dam and the value of the dam to the dam owner and the community is elaborated.

Safety Review requirements and procedures for assessing the safety of a dam are presented. These, normally include, a detailed study of structural, hydraulic, hydrologic and geotechnical design aspects and of the records and reports from surveillance activities.

In addition, the Guideline recommends the following two types of emergency plans.

- A Dam Safety Emergency Action Plan developed by the dam owner; and
- A separate Disaster Plan developed by appropriate State or local emergency management agencies to provide protection for downstream communities in the event of a dam safety emergency.

This Guideline was compiled based on consideration of several different existing guidelines, in particular the ICOLD Bulletin 59 of 1987, the CDA Guideline of 2007 and its revision of 2013, the ANCOLD Guideline of 2003 (2003a), FERC Dam Safety Guidelines (2014) and USBR (2011).

### 1.11 Applicability

In general a “dam” can be defined as follows:

“An artificial barrier, together with appurtenant works, constructed for storage, or control of water, other liquids, or other liquid-borne material (excluding concrete/steel ring tanks reliant on hoop stress for structural stability). This classification normally excludes canals and levees, but these guidelines may also be used as a basis for developing safety management plans for these structures.”

These guidelines apply to any “dam with a safety risk”. A “dam with a safety risk” is defined as any dam which can contain, store or dam more than 50 000 m<sup>3</sup> of water, whether that water contains any substance or not, and which has a wall of a vertical height of more than 5 m, measured from deepest foundation level to highest structure crest level.

Such dams will include large dams as defined by ICOLD as any dam with:

- Maximum height (H), measured from deepest foundation level to highest structure crest level, more than 15m, and
- $10\text{m} < H < 15\text{m}$ , and any of the following conditions:
  - Dam wall length more than 500 m;
  - Reservoir storage capacity more than 3 million m<sup>3</sup>;
  - Flood discharge more than 2 000 m<sup>3</sup>/s; and
  - Unusual characteristics in dam type or foundation.

The safety objectives and principles in this guideline are applicable to both large and small dams with safety risks.

## 2. KEY OBJECTIVES

### 2.1 Justification for dams

#### OBJECTIVE 1

Dams should be constructed and operated only if they yield an overall benefit to society.

The construction of a dam imposes risks on society, with the risks often distributed unevenly, so that those who benefit from the dam are not necessarily those on whom the risk is imposed (benefits include all social and environmental benefits and are not restricted to quantifiable economic benefits). For dam and reservoir activities to be considered justified, the benefits that they provide to society as a whole should outweigh the risks that they create. For the purposes of assessing benefit and risk, all significant consequences of the operation of dams and reservoirs have to be taken into account, including any potential trans-boundary impacts.

### 2.2 Dam Safety Management System

#### OBJECTIVE 2a

The public, infrastructure and the environment shall be protected from the effects of dam failure, as well as release of any or all of the retained fluids behind a dam, such that the risks are kept as low as reasonably practicable.

The owner is responsible for the safe management of a dam. Dam safety management takes place within the context of public policy and the business objectives of the owner. The standard of care applied to the management of safety should reflect society's values and priorities in allocating and distributing resources to protect lives, the environment and property. The absence of specific regulation does not negate the owner's responsibility for safe management.

Dam safety management is the management of risks associated with dams, including release of fluids as a result of structural failure, mis-operation, planned operation, or any other cause. For dams that retain contaminants of any sort, protection of the public and the environment should extend to seepage and pathways not necessarily associated with catastrophic failure of the retaining structures.

Established conservative practices may be assumed to provide protection that is as low as reasonably practicable (ALARP). The current, most widely applied approach to decision-making is based on deterministic principles, rules, and requirements aimed at ensuring a relatively high but unspecified level of safety. The rules and requirements are adjusted to provide proportionately higher safety levels when hazards or consequences of failure are greater. The decision process typically relies on classification of dams on the basis of the consequences of failure, as well as on engineering analysis and assessment and the application of engineering judgment.

These days it is recognized that the inherent variability and persistent uncertainty involved in safety analyses of dams must be addressed. As a result, risk informed decision making (RIDM), is emerging as a framework for improving the way safety decisions are made, particularly as those decisions become more complex and society demands more transparency and accountability. If resources and knowledge are available, risk assessment tools can be considered to incorporate the particular circumstances of the dam under consideration within a broader context.

By definition, risk incorporates both the consequences of an adverse event and the probability of such an event occurring. It is recognized that determining the probability of failure is a complex task that is not readily accomplished, given the current state of knowledge. However, qualitative methods such as potential failure modes analysis (PFMA) and the use of event trees are available to allow some consideration of the likelihood of failure modes and deal with the associated uncertainties.

The safety management framework should make transparent all factors considered, thus reassuring the public and the stakeholders that risks to people, property, and the environment are being properly addressed. At the same time, the framework should ensure that the dam owners, in responding to economic pressures, will not be imposing intolerable risks. The framework should address all ethical, social, and economic considerations of how to achieve the necessary trade-offs between benefits to society and adequate protection for individuals.

## OBJECTIVE 2b

The standard of care to be exercised in the management of dam safety shall be proportionate to the potential consequences of dam failure.

The potential consequences of dam failure may include loss of life, injury, and general disruption of the lives of the population in the inundated area; environmental and cultural impacts; and damage to infrastructure and economic assets. To assess the potential consequences, the potential failure modes for the dam and the existing conditions downstream from the dam should be determined, the resulting discharge characteristics estimated, the impacted areas mapped, and the consequences quantified.

The estimate of consequences should cover both downstream and upstream impacts, including:

- Cascade effects where a given drainage basin has a series of dams;
- Trans-boundary impacts; and
- Environmental and social impacts including release of contaminants.

The dam consequences category should be determined by the highest potential consequences, whether population at risk, infrastructure, economic and social factors, or environmental and cultural factors.

The category should be based on the failure scenario that would result in the worse consequences: either sunny day failure or flood failure. This classification should be used for all the stages of a dam's life cycle including general management oversight, design of the overall project, inspection, maintenance, and surveillance and emergency action programs. For determining design criteria for specific components at a site, the consequences of failure of the components may be evaluated separately and their design basis established accordingly.

## OBJECTIVE 2c

Due diligence shall be exercised at all stages of a dam's life cycle. This includes an Approved Dam Engineer or an Approved Dam Engineer supported by a team of specialists for high consequence dams being responsible for all tasks carried out during a dam's life cycle.

The principles of dam safety apply at all stages of the life cycle (planning, design, construction, operation, decommissioning and long-term closure).

All analysis and assessment tasks during the life cycle of a dam should be carried out by an Approved Dam Engineer or an Approved Dam Engineer supported by a team of specialists (for high consequence dams) with appropriate experience for the particular tasks whether it be design, construction, operation or the performance analysis of dams.

During initial construction and (or) rehabilitation, the project specifications must be strictly followed; any deviation should be subject to an appropriate review and approval process. Quality control and documentation must be maintained throughout the construction period. Temporary construction facilities should be designed and constructed such that the risks to the safety of the dam, cofferdam, and appurtenant structures are appropriately managed.

During the operational stage, public safety should be an important element of the dam owner's due diligence.

Prior to decommissioning and closure, the dam owner should prepare a detailed plan for withdrawing the dam from service, indicating measures necessary for site safety. The possibility that any remaining structures might be exposed to loads or combinations of loads not foreseen in the original design or exposed to otherwise unacceptable conditions should be carefully addressed.

## OBJECTIVE 2d

A dam safety management system, incorporating policies, responsibilities, plans and procedures, documentation, training, and review and correction of deficiencies and non-conformances, shall be implemented.

The dam safety management system provides a framework for safety activities, decisions, and supporting processes within the context of public policies and regulations and the owner's business objectives.

The owner's policy should clearly demonstrate commitment to safety management throughout the complete life cycle of the dam. The policy should cover the following:

- Level of safety that is to be provided - Applicable regulations must be met, and industry practice and due diligence must be taken into account;
- Ultimate accountability and authority in the organization for ensuring that the policy is implemented. Responsibilities and authorities need to be delegated within the organization for all dam safety activities; and

- Decision-making process within the organization for decisions related to dam safety. Critical safety decisions with significant societal or financial implications must be made or approved at the highest level.

The safety management system should take the following into account:

- Dam safety should be considered in the planning, design and construction of all new dams;
- An inventory of dams and appurtenances in the system, including any that may have trans-boundary impacts;
- Safe operation, maintenance, surveillance, emergency preparedness, public safety, and security;
- Periodic Dam Safety Reviews during planning, design and construction of new dams;
- Follow-up, prioritization, and correction of deficiencies in dam performance, supporting infrastructure, operation, maintenance, surveillance, security procedures, and the management system;
- A permanent record of the design, construction, operation, and performance of the dam and the management of its safety (record should include design documents, instrumentation readings, inspection and testing reports, Potential Failure Modes Analysis (PFMA) reports, Dam Safety Review reports, operational records, investigation results, Supporting Technical Information (STI) documentation and current closure plans if applicable);
- Qualification and training of all individuals with responsibilities for dam safety activities (training records should be maintained); and
- Regular review of the safety management system.

## OBJECTIVE 2e

The dam safety management system shall be documented and implemented according to an “Owner’s Dam Safety Program”.

The Owners Dam Safety Program (ODSP) should address:

- Acknowledgment of Dam Safety Responsibilities;
- Communication;
- Clear Designation of Responsibility;
- Allocation of Resources to Dam Safety;
- Maintaining design, construction and operation records; and
- Learning Organization.

## 2.3 Analysis and Assessment

The purpose of all dam safety analysis/assessments for the whole life cycle of a dam (planning, design, operation, etc.) is to determine the capability of the dam system to retain the stored volume under all conditions and to pass flows around and through the dam in a safe, controlled manner. An interdisciplinary approach is needed that encompasses aspects of hydrotechnical, seismic, geotechnical, structural, mechanical, electrical and environmental engineering.

Dam safety analysis should consider the full range of applicable conditions in order to determine how the structures are expected to perform and what amount of deviation from the normal condition is tolerable. Design, construction, and operation should be integrated in the analysis to ensure that the design intent has been incorporated into the dam.

### OBJECTIVE 3a

The dam system and components under analysis shall be defined.

At the start of a dam safety analysis, bounds for the system and processes must be established. The system to be analysed could range from a specific concern pertaining to one component of the dam to the entire safety management system that applies throughout the life cycle of the dam. Components of dams include all fluid retaining and conveyance structures, the reservoir and downstream areas, the flow control equipment, and other subsystems supporting safety (access roads and notification systems, for example).

Data and information about the dam system must be adequate (sufficient quantity and quality) for reliable assessment of the safety status of the dam.

### OBJECTIVE 3b

Hazards external and internal to the dam shall be defined.

Hazards may change in nature and significance at different stages of a dam's life.

External hazards originate outside the boundary of the dam and reservoir system and are beyond the control of the dam owner and may be trans-boundary in nature. External hazards may include the following:

- Meteorological events, such as floods, intense rainstorms (causing local erosion or landslides), temperature extremes, lightning strikes, and windstorms;
- Seismic events, either natural, caused by economic activity such as mining, or even reservoir induced;
- The reservoir environment, including rim features, such as upstream dams and slopes around the reservoir that pose a threat; and
- Vandalism and security threats.



Internal hazards may arise from the ageing process or from errors and omissions in the design, construction, operation, and maintenance of the dam and water conveyance structures. Internal hazards can be subdivided by source:

- Components that retain or interface with the body of water;
- Water conveyance structures required to direct water around or through the dam in a controlled way;
- Mechanical, electrical, and control subsystems; and
- Infrastructure and plans, including instruments, operating orders, maintenance strategies and procedures, surveillance procedures, and emergency plans, as well as inflow forecasts.

### OBJECTIVE 3c

Potential Failure Modes, sequences, and combinations shall be identified for the dam.

A potential failure mode (PFM) describes how a component failure occurs to cause loss of the system function. Failure modes may be interdependent and change in nature and significance at different stages of a dam's life. In any analysis, the failure characteristics, including extent and rate of development, should be determined to an appropriate level of detail. A thoroughly developed PFM describes the progression from initiation through to failure, the probability of failure, so that the risk can be adequately understood.

Dam safety risk management is directed to:

1. Prevention of the initiation of a failure sequence;
2. Control of a deteriorating situation; and
3. Mitigation of situations where the failure sequence cannot be stopped.

Dam safety risk management is the umbrella under which risk is used to inform decisions by designers, constructors, owners and regulators of new and existing dams. This may involve three stages in the process; the PFMA, Risk Analysis and, Risk Assessment, with risk-informed decisions being included under the Risk Assessment stage. Communication is a critical part of each component of risk management and is facilitated by the explicit nature of the treatment of the issues.

### OBJECTIVE 3d

The dam shall safely retain the reservoir and any stored solids, and it shall pass flows as required for all applicable loading conditions.

The purpose of dam safety analysis is to determine the capability of the dam system to retain the stored volume under all conditions, to pass flows around and through the dam in a safe, controlled manner and to prevent the development of any identified Potential Failure Modes.

### OBJECTIVE 3e

An Approved Dam Engineer or an Approved Dam Engineer supported by a team of specialists for high consequence dams should be responsible for all analysis and assessments tasks carried out during a dam's life cycle.

All analysis and assessment tasks during the life cycle of a dam should be carried out by an Approved Dam Engineer or an Approved Dam Engineer supported by a team of specialists (for high consequence dams) with appropriate experience for the particular tasks whether it be design, construction, operation or the performance analysis of dams.

## 2.4 Planning, Design, Construction and Commissioning

### OBJECTIVE 4a

Dam safety should be considered in the planning, design, construction and commissioning phase of all dam projects.

The owner is responsible to ensure that safety management is fully considered in all stages of planning, design, construction and commissioning of a project. The standard of care applied to the management of safety should reflect society's values and priorities in allocating and distributing resources to protect lives, the environment, and property.

Comprehensive design and construction records should be kept to provide a readily available and reliable basis for safety management. These records should be secure and maintained for use throughout the entire life cycle of all dams.

### OBJECTIVE 4b

An Approved Dam Engineer or an Approved Dam Engineer supported by a team of specialists for high consequence dams should be responsible for the planning, design, construction and commissioning of a dam.

The planning, design, construction and commissioning tasks of a dam should involve an Approved Dam Engineer or an Approved Dam Engineer supported by a team of specialists (for high consequence dams) with appropriate experience for the particular tasks whether it be design, construction, operation or the performance analysis of dams.

An Approved Dam Engineer appointed to carry out a task on a dam must:

- ensure that the task is carried out according to acceptable dam engineering practices;
- keep the prescribed records;
- compile the prescribed reports; and
- where the task includes constructing, altering or repairing a dam, issue a completion certificate to the owner of the dam to the effect that the task on that dam has been carried out according to the applicable design, drawings and specifications.

## 2.5 Operation, Maintenance and Surveillance

### OBJECTIVE 5a

Requirements for the safe operation, maintenance, and surveillance of the dam shall be developed and documented with sufficient information in accordance with the impacts of operation and the consequences of dam failure.

A critical part of the dam safety management system is the development, implementation, and control of procedures for the operation, maintenance, and surveillance of the facility, taking into account public safety and security.

The presence of a dam, its special features, and its operation, coupled with the river morphology, can present safety hazards to the public while participating in activities at or around the dam site.

Operation, maintenance, and surveillance procedures should be initially developed for the particular site during the construction phase and then updated when there are major changes to the structures, flow control equipment, or operating conditions. These procedures should be documented in an Operation and Maintenance Manual (O&M Manual) and a Surveillance and Monitoring Plan (SMP). The procedures and practices should be reviewed regularly (as a minimum, during the periodic Dam Safety Reviews) to ensure that the information is up to date. This review is required for complete life-cycle management, from construction through major rehabilitation or replacement to closure or decommissioning of the dam. These procedures and documents should be compiled by an Approved Dam Engineer.

Ongoing log books, records, or reports should be maintained to show that the specified activities and observations have been carried out and that the dam safety requirements are being met. The appropriate level of detail in the O&M Manual and the SMP and corresponding records depends on the complexity of the site and the severity of the potential consequences of failure. A simple dam with minimal consequences of failure might have a brief combined O&M Manual and SMP that also includes the Emergency Action Plan (EAP) and public safety documentation.

### OBJECTIVE 5b

Documented operating procedures for the dam and flow control equipment under normal, unusual, and emergency conditions shall be followed.

Proper operation of a dam system is critical to safety and performance and thus to managing potential impacts on the public, the environment, and other stakeholders.

Development of operating procedures should take into account the complexity of the site and the consequences of mis-operation. The operating procedures should not violate dam safety design parameters. The availability of staff to respond to changing conditions, the type and size of flow control equipment, and other site-specific considerations should be taken into account.

Operating procedures should consider the availability of reliable data, including the following:

- Headwater and tail water elevations;

- Remote indicators of the operation of flow control equipment;
- Flood-forecasting information; and
- Operations of other dam owners that affect inflows to the reservoir and the need for operations to discharge excess inflows.

Operating procedures should address the following:

- Flood management, including clear operating procedures for local staff;
- Public safety issues, including the use of recreational areas and restricted zones;
- Notification plan for changing flows or conditions;
- Prevention of unauthorized entry to the site or operation of equipment;
- Ability of the flow control equipment, including backup power supplies, to operate under all expected conditions;
- Management of debris and sediment to ensure operability of discharge facilities; and
- Trans-boundary impacts of operations.

Dam operators need to be aware of situations in which operations may go from normal to abnormal or become an emergency. The authority of operating staff to initiate emergency procedures should be clearly defined and linked to the emergency plan.

#### OBJECTIVE 5c

Flow control equipment shall be tested and be capable of operating as required.

Testing of flow control equipment should be carried out to demonstrate that it will reliably handle the expected operating loads and site conditions, retaining or releasing water upon demand.

The operational capability of equipment should be assessed with consideration of both normal and unusual conditions and the consequences of equipment failure. Test procedures should take into consideration upstream and downstream effects, including impacts on public safety and environmental concerns. Normal and standby power sources, as well as local and remote controls, should be tested. Test results should be documented.

#### OBJECTIVE 5d

Documented maintenance procedures shall be followed to ensure that the dam remains in a safe and operational condition.

Maintenance of equipment and systems is important to ensure operational availability, safe operations, and integrity of the dam. This is particularly true of mechanical and electrical systems used for flow control, where failure can be sudden. Maintenance needs also vary seasonally through different stages in the life cycle.

The particular maintenance needs of critical components or subsystems, such as flow control systems, power supply, backup power, civil structures, public safety and security measures, and communications and other infrastructure, should be identified.

Maintenance activities should be prioritized, carried out, and documented with due consideration of safety implications. Maintenance procedures for closed or decommissioned dams should take into account the availability of appropriate personnel to perform the maintenance activities.

### OBJECTIVE 5e

Documented surveillance and monitoring procedures shall be followed to provide early identification and to allow for timely mitigation of conditions that might affect dam safety.

Surveillance, including visual inspections and instrument monitoring, is a method for checking whether the dam is performing satisfactorily. Effective dam surveillance is based on an understanding of how the dam might fail (failure modes), what early signs of failure to look for, and what inspection or monitoring measures could be used to detect a developing failure.

The surveillance and monitoring program should provide regular monitoring of dam performance, as follows:

- Compare actual and design performance to identify deviations;
- Detect changes in performance or the development of hazardous conditions;
- Confirm that reservoir operations are in compliance with dam safety requirements; and
- Confirm that adequate maintenance is being carried out.

The program should be documented in a formal Surveillance and Monitoring Plan (SMP) with regular surveillance and monitoring reports (SMR) evaluating and presenting the results.

The frequency of inspection and monitoring activities should reflect the consequences of failure, dam condition and past performance, rapidity of development of potential failure modes, access constraints due to weather or the season, regulatory requirements, security needs, and other factors. In addition to scheduled and documented inspections, surveillance can take place each time staff visits a site for other routine activities. Special inspections should be undertaken following unusual events, such as earthquakes, floods, or rapid drawdown. Training should be provided so that inspectors understand the importance of their role, the value of good documentation, and the means to carry out their responsibilities effectively.

Instrumentation may be useful or necessary, depending on the consequences of dam failure and on the need to understand performance parameters that should be measured quantitatively. The installation of an automated instrumentation data system should not preclude routine visual inspections.

The SMP should document how often instruments are read and by whom; where instrument readings will be stored, how they will be processed, and how they will be analysed; what threshold and action values or limits are acceptable for triggering follow-up actions; what the follow-up actions should be; and what instrument maintenance and calibration are necessary.

Follow-up actions might range from continued or enhanced inspection and monitoring, to remedial repairs, to upgrading of the dam system. The dam owner should establish procedures for appropriate follow-up of surveillance findings. In some situations, immediate action, such as reservoir lowering or emergency repairs, may be necessary to manage the risks.

## 2.6 Emergency Action and Response

### OBJECTIVE 6a

An effective emergency management process shall be in place for the dam.

All dams should have emergency action plans (EAPs) (including emergency response procedures) in place if lives are at risk or if implementation of emergency procedures could reduce the potential consequences of failure. The emergency management process should be updated over the full life cycle of the dam, including the construction phase and whenever significant cofferdams are required. For a new dam, the plans should be established prior to any significant storage behind cofferdams or first filling of the reservoir (whichever happens first). The EAP should be compiled by an Approved Dam Engineer with experience in emergency management.

The level of detail in the procedures and plans should be proportionate to the consequences of failure. Evaluation of the consequences should generally be done by carrying out dam-breach analysis and preparing inundation maps, followed by consequence assessment. If the consequences are low, the plans can usually be very simple; with the approval of the regulator. Plans may not be required in some cases.

The absence of government regulations does not negate the owner's responsibility for emergency action planning.

### OBJECTIVE 6b

The emergency management process shall include emergency response procedures to guide the dam operator and site staff through the process of responding to an emergency at a dam.

Emergency response procedures in the EAP should outline the steps that the operations staff is to follow in the event of an emergency at the dam. Documentation should clearly state, in order of priority, the key roles and responsibilities, as well as the required notifications and contact information.

Natural floods can create urgent situations that must be managed. These situations may include the passage of floodwater through or over a dam. In most cases the floodwater is well below the level that would threaten the structural integrity of the dam. However, downstream stakeholders are interested in the effects of inundation, whether caused by a major flood, the passing of discharges through a spillway, or a dam breach. For this reason, the dam owner's procedures should cover the full range of flood management planning, and normal operating and surveillance procedures should be linked with the emergency response procedures.

The emergency response procedures should include the following:

- Procedures for identification and evaluation of the emergency- Potential dam safety hazards (whether natural, structural, or caused by human actions) should be addressed in a manner consistent with identified potential failure modes and consequences of failure;

- Contact information and communication procedures - Procedures should be documented for informing the authorities responsible for emergency response and evacuation, the dam owner's staff and people in the inundation zone who are in immediate danger, the upstream and downstream water-retention facilities, and regulators about the emergency; and
- Remedial and management actions - Procedures should be documented for providing the emergency responders with communication systems, equipment, materials, site access, inundation maps, other resources, and data.

### OBJECTIVE 6c

The emergency management process shall ensure that effective emergency action procedures are in place for use by external response agencies with responsibilities for public safety within the floodplain.

The emergency management process should be documented, distributed, and clearly communicated, in advance, to all response agencies with responsibility for public safety within the floodplain including the relevant agencies of all the countries of a trans-boundary river.

Developing partnerships with key downstream stakeholders and other response agencies is a critical element in the owner's emergency planning. Local responders should ensure that their emergency plans include a section addressing potential dam safety hazards (whether natural, structural, or caused by human actions).

Roles and responsibilities of the dam owner and response agencies should be defined and accepted. Where no formal response agency exists downstream of a dam, the dam owner should have in place reasonable and practical measures to protect those at risk.

Inundation maps and critical flood information should be available to downstream response agencies to assist them in identification of critical infrastructure that may be affected by large releases or the failure of a dam.

### OBJECTIVE 6d

The emergency management process shall ensure that adequate staff training, plan testing, and plan updating are carried out.

Exercises should be carried out regularly to test the emergency procedures. There are significant benefits to testing the procedures in cooperative exercises involving both the dam owner's staff and the external agencies with response roles.

Emergency action plans (EAPs) should be updated regularly, and distribution should be controlled so that all copies are kept up to date.

## 2.7 Dam Safety Reviews

### OBJECTIVE 7a

A safety review of the dam ("Dam Safety Review") shall be carried out periodically.

The Dam Safety Review is a systematic review and evaluation of all aspects of design, construction, operation, maintenance, processes, and other systems affecting a dam's safety, including the dam safety management system. The review defines and encompasses all components of the "dam system" under evaluation (dams, spillways, foundations, abutments, reservoir, tailraces, etc.).

The review should be based on current knowledge and methods, which may be different from the acceptable practices at the time of original construction or a prior Dam Safety Review.

A Potential Failure Modes Analysis should be performed for any dam with a safety risk prior to the dam safety review. The review should then focus on the results of the Potential Failure Modes Assessment to assist in identifying key safety issues and provide a consistent basis for surveillance and monitoring and emergency action plans.

The level of detail in the Dam Safety Review should be sufficient either to demonstrate that the dam meets dam safety requirements or to identify areas where conformance cannot be demonstrated and future investigation or action is needed. The level of detail may be modified on the basis of previous assessments, complexity of the dam, continuity of surveillance and records, external and internal hazards, operating history, dam performance and age, and the need for public protection during operation.

The Dam Safety Review should include a visual inspection of the dam and a review of:

- Results of a Potential Failure Modes Analysis (PFMA),
- Inflow design flood, seismic loads, other loads and load combinations, stability and performance, reliability and functionality of discharge facilities, and overall effectiveness of safety management at the dam;
- Consequences of dam failure;
- Operation, maintenance, and surveillance documentation and practices;
- Emergency action plans and procedures; and
- Previous Dam Safety Reviews.

The frequency required for the Dam Safety Review should be based on the consequences of failure, external hazards, potential failure modes, the ongoing surveillance and monitoring program, and demonstrated dam performance.

The Dam Safety Review should be documented in a formal report, with conclusions and recommendations, to enable the dam owner to conform to accepted practices in dam safety and to comply with regulations.



## OBJECTIVE 5b

An Approved Dam Engineer or an Approved Dam Engineer supported by a team of specialists for high consequence dams shall be responsible for the compilation (including the technical content, findings, and recommendations) of the Dam Safety Review and report.

The Dam Safety Review should be carried out by an Approved Dam Engineer (or an Approved Dam Engineer supported by a team of specialists for high consequence dams) with appropriate experience in the Safety Review of that particular type of dam.

The findings and recommendations of the Dam Safety Review should be independent of conflict of interest.

## 2.8 Trans-boundary River Considerations

### OBJECTIVE 8a

The planning, design, construction and operation of dams shall include the management of trans-boundary river considerations at all stages of a dam's life cycle.

An effective international institutional structure is required to address trans-boundary dam safety issues. Ideally it should be at a technical level where professional personnel from the respective countries discuss dam safety issues of mutual interest and provide feedback reports to the decision-makers. Information exchange is a vital matter which builds trust and understanding amongst the respective countries.

Safety related aspects of the design of all dams and reservoirs to be built on a boundary river should be compatible with each other. Therefore the Approved Dam Engineer, when fixing the design concept and criteria, must be well aware of special requirements, standards, restrictions and regulations established by agreement for the development of the river. If no such agreement exists, the Approved Dam Engineer should seek advice from the regulator which should take the necessary steps to determine criteria that would be acceptable to all parties involved.

The agreement for the development of a boundary river should as far as design is concerned include, but not be limited to, the following items:

- Hydrographic observation systems, procedures and equipment as well as transmission, processing and availability of hydrologic data;
- Determination of design floods and spillway capacity;
- Utilization of flood plains;
- Basic design philosophy and safety criteria;
- Water use and river-bound activities;
- Basic criteria for the operation of, and the release of water from, the reservoirs;
- Environmental protection; and

- Emergency precautions.

If no specific advice or instructions can be obtained, the Approved Dam Engineer should on his own initiative take the necessary precautions to avoid the transfer of unreasonable risk or hazard to other riparian entities.

## 2.9 Management of Environmental and Socio-Economic Factors

### OBJECTIVE 9a

The dam safety management system shall include the management of environmental and socio-economic issues that may affect dam safety.

Environment and socioeconomic considerations should be integrated in the planning, design, construction and operation of dams in order to achieve a sustainable and safe use of dams for hydropower, flood management, water supply, ground water recharge and other uses.

## 3. DAM SAFETY MANAGEMENT

### 3.1 Program

The objective of dam safety management in the Eastern Nile Basin is to protect life, property (e.g. community infrastructure, dam) and the environment from the failure of any dam. This objective can be achieved by implementing and maintaining an appropriate dam safety program. It is a system that incorporates dam safety values as part of the culture of the dam owners and the day-to-day operation of a dam.

A dam safety management program comprises regulations, guidelines, policies and procedures which minimizes the risk of dam failure.

Its benefits are that the:

- Regulators, the owner and downstream communities are aware that the dam complies with current engineering standards for safety;
- Regulators, the owner and downstream communities are assured that the dam is operated in a safe manner;
- Regulators, the owner and downstream communities have recognized that the condition of the dam assessed on a regular basis;
- The owner is prepared for an emergency situation at the dam; and
- The risk of dam failure is minimized.

#### 3.1.1 Documentation

Dam owners must incorporate dam safety into its plans for design, construction, operation, maintenance and decommissioning of their dams and establish an "Owners Dam Safety Program" (ODSP) detailing how this will be accomplished at each dam.

A dam safety management program should ultimately result in the following documentation being available for each dam. These are:

1. Planning (Reconnaissance, Pre-feasibility, Feasibility study reports), Investigation, Design, and Construction Documentation including Data Book, Design Report and As-Constructed Details (or Construction Report);
2. Standing Operating Procedures (SOPs);
3. Operation and Maintenance Manuals (O&M Manuals);
4. Potential Failure Modes Assessment Reports (PFMA);
5. Inspection and Evaluation Reports;
6. Surveillance and Monitoring Plans (SMPs); and

## 7. Emergency Action Plans (EAPs).

The regulating body and dam owners should securely store these documents. Dam owners should ensure that each of the levels of documentation is identified for inspection and auditing purposes. The documentation could either be combined into a single document or left as groups of documents.

### 3.1.2 Training of Operating Personnel

Supporting processes need to be in place for the effective implementation of a dam safety management system. These processes include adequate training and qualification of all individuals with responsibilities for dam safety activities. The training programs should be geared toward developing and maintaining the competency of these individuals and should take into account the complexity of operating systems, and any significant changes in the facilities or operating criteria. Training records should be maintained.

Individuals performing dam safety activities must be qualified and have a comprehensive understanding of the facility and its safe operation. This should include a basic understanding of the civil structures, flow control facilities, control systems, operating procedures, interaction of facility operations with other stakeholders, potential hazards and failure modes, and other relevant information. Typically, training should address site-specific issues and ensure that all failure modes, site intricacies, and interactions of site components are covered. Some type of competency check is also valuable to ensure that participants have understood the topics being delivered.

Staff training in emergency action should be given to all staff that may have a response role during an emergency. Testing of the emergency action plans is an integral component of this training.

Staff should also be encouraged to become aware of new and updated technologies and maintain competency by becoming involved in industry and learned organizations. Owners should participate, and encourage their staff to participate, in the efforts of the dam industry to improve knowledge and update practices and technologies.

It is the owner's responsibility to determine that any Approved Dam Engineer retained is appropriately qualified and experienced in dam design, construction, safety assessments, or any other activities to be carried out.

### 3.1.3 Quality Management

All factors affecting the safety of a dam during planning, design, construction, and operation and decommissioning should be reviewed on a systematic basis at appropriate levels of authority.

Responsibility for dam safety management activities should be formalized by the documentation of its management structure and the procedures to be followed. Audit points need to be identified within the structure to allow measurement of the effectiveness of each dam safety program and its components.

Developing and maintaining comprehensive documentation for a dam safety management program as described in these guidelines and quality management audits provide elements of a quality management system.

The Regulator, dam owner, or a third party should conduct quality management audits on a systematic basis. When an internal auditor is used, it may be necessary to establish a management structure in which the dam safety functions are independent of the dam operator.

A quality management audit of documentation should establish:

- Adequacy of the policies and the dam safety management program as a whole (systems audit);
- Adequacy of the process and the necessary studies used to establish the documentation (process audit);
- Adequacy of specific procedures, documentation or a specific investigation (validation audit);
- Some of the specific issues, which should be examined in a quality management audit, include:
  - The authority for performing activities;
  - Allocation of responsibilities for particular activities; and
  - Actions to be undertaken and circumstances for such action.

### 3.1.4 Environmental Management Systems

It is a requirement that all hydropower and dams schemes implement an independently audited environmental management system. An environmental management system should allow for effective management of the range of environmental issues associated with the on-going operation of the scheme that could affect dam safety.

The associated monitoring programs and environmental plans should ensure a program of continuous improvement in environmental management over the life of the project.

### 3.1.5 Public Consultation

The public should be consulted in the development of works involving dams and their operation.

The dam owner should develop and organize procedures for early assimilation of those public views, which affect possible design, construction, operating parameters or decommissioning and, in turn, influence dam safety.

## 3.2 Managing a Dam Safety Program

### 3.2.1 Introduction

The management of a dam safety program should ensure that the program addresses the needs and concerns of the owner and the community. This would be achieved by:

- Identifying the responsibilities of owners', governments' and dams' personnel;
- Ensuring adequate funding and resources are available for dam safety management;
- Making the public aware of dams and dam safety issues;
- Maintaining information about the dam for public and stakeholder reference, and for use in future investigation, surveillance and reviews;
- Responsible management of risks posed by dams;

- Implementing appropriate planning, design and construction procedures;
- Implementing appropriate dam operation / maintenance procedures and practices;
- Educating and training dams' personnel in emergency procedures and responses;
- Having a quality management program;
- Revising procedures and outputs as required;
- Consulting the public about their concerns; and
- Applying appropriate expertise.

The life of a dam is often in excess of one hundred years. For this reason, the effects of ageing, deterioration and technological obsolescence have to be considered periodically.

The principal activities are planning, investigation, design, construction, surveillance, operation and maintenance, safety review, remedial action, education and training and emergency preparedness.

### 3.2.2 The Role of Government

The role of government is to enact legislation to protect the community. Legislation should establish regulatory authorities that ensure dam engineers, owners, and potential dam owners, are taking appropriate actions in regard to dam safety and also enact regulations as part of the legislation.

The precise form of the legal instruments will vary depending on the legal traditions in the country. The legal instruments should at least contain:

- A statute or law passed by the government dealing with dam safety. It should only contain the objectives and general principles governing the framework;
- The statute should clearly stipulate the responsibilities of all parties including the regulatory authority responsible for dam safety and the authority responsible for handling any emergencies; and
- Regulations that contains at least the following:
  - Clear criteria determining which dams are covered by the regulatory scheme. This should be according to size and "Potential Consequences Classification" (PCC);
  - Definition of the scope of the regulatory scheme. This should address all stages of the life cycle of a dam including planning, design, construction, first filling, operation, alteration, decommissioning and removal;
  - Clarification that the owner is responsible for dam safety and can be held liable for any damage that results from dam failure;
  - Stipulation of the dam safety standards that an owner is expected to comply with;

- Establishment of the required qualifications of the person/team that does safety evaluations of the dams for the owner;
  - Stipulation that the owner/operators make periodic reports to the regulators on the results of their reviews, inspections and monitoring of the safety of the dam and also the content of these reports;
  - Stipulation that the owner/operators report any incident or failure of any component at a dam;
  - Stipulation of the frequency that the owner/operator should conduct safety inspections and reviews;
  - Stipulation that the owner/operator maintain complete set of the dam supporting technical information including records of design construction and operation, with copies of O&M Manuals, PFMA's and Safety Reviews, SMPs, SMRs, EAPs at the project and supply a complete copy of this information to the regulator;
  - Stipulation that all new projects are subjected to PFMA and a "dam safety review panel" which will be responsible for reviewing and ensuring that all necessary safety measures are provided at different stages of a dam project;
  - Stipulation that the dam owners must incorporate dam safety into its plans for design, construction, operation, maintenance and decommissioning of their dams and establish an "Owners Dam Safety Program" (ODSP) detailing how this will be accomplished at each dam;
  - Requirement that all dams have an Operation and Maintenance Manual (O&M Manual) and an adequate budget for operations, maintenance and supervision;
  - Requirement that all dams have a Surveillance and Monitoring Plan (SMP) and an adequate budget for installation, operation and maintenance of the monitoring system and data management;
  - Requirement that dams with any potential for loss of life or other significant consequences have an Emergency Action Plan (EAP) that is provided to the regulatory authority and to all relevant authorities and downstream communities that could be affected by a dam failure; and
  - Clear indications of what actions the regulator is empowered to take should a dam owner not comply with the regulatory scheme.
- The regulations may be supplemented by non-binding guidelines and/or manuals. These may take the form of recommended good practice.

### 3.2.3 Responsibility and Accountability

#### 3.2.3.1 Regulatory Authorities

The regulatory authority should be provided with adequate human and financial resources to perform its duties. The regulatory authority should facilitate and monitor the implementation and ongoing development of a comprehensive Dam Safety Management Program which should include:

- Classifying each dam in the country using the Potential Consequences Classification system;
- Maintaining and periodically updating the Potential Consequences Classification system (PCC) for all dams in the country;
- Maintaining an inventory or register of all the dams in the country that are covered by the regulations as well as maintaining an inventory or register of all incidents or failures at dams covered by the regulations using the ICOLD dam incidents and failure database as a basis;
- Maintain an archive of all the documentation submitted for each dam by the owner of each dam;
- Adopting the Reference Dam Safety Guidelines with modifications as required to suit the local conditions and which will be available to be adopted by each EN Country. This could be based on selections from the existing dam safety guidelines developed elsewhere in the world such as those reviewed in Section 4 herein;
- The progressive use of “Risk Informed Decision Making” (RIDM) to assist in the understanding risk issues and prioritization of risk reduction measures;
- Review, approval and oversight of implementation of design reports and construction plans for new projects and significant modifications to existing projects.
- Conducting periodic dam safety inspections of the projects including detailed review and evaluation of the owner’s surveillance and monitoring reports;
- Specifying the frequency and scope for PFMA’s and periodic comprehensive safety inspections and reviews by the owner;
- Establishment of the required qualifications and case by case approval of Approved Dam Engineers and their supporting teams who perform tasks during the life span of a dam;
- Observing tests of key safety equipment such as spillway gates and emergency power systems;
- Review, approval and oversight of project operations in the event of dam safety incidents and implementation of any required risk reduction measures;
- Facilitating the establishment of national ICOLD dam committees and provide leadership in future for these organisations; and



- Establish relationships with other river basin organisations as well as international (for example ICOLD) and regional institutions (Africa Club and other National dam committees) with regards to dam safety aspects.

The powers of the regulating entity should include:

- The power to identify and develop norms, standards and guidelines for dam safety;
- A voice in decisions to grant permits or grant licences for the construction and operation of dams;
- The power to monitor inspections and accept or reject the finding;
- The power to carry out its own inspections when necessary;
- The power to approve the party selected to do the dam safety inspections;
- The responsibility to maintain an inventory or register of all the dams in the country that are covered by the regulations including an inventory or register of all incidents or failures at dams covered by the regulations;
- The responsibility to advise owners and other interested parties such as affected communities about dam safety issues;
- The responsibility to make periodic and publicly available reports on dam safety issues to higher authorities in the executive government and the legislature; and
- The power to enforce the dam safety regulatory framework.

### 3.2.3.2 Dam Owner

The owner of each dam is responsible for its safety. This responsibility requires the provision of sufficient resources to meet its safety program requirements. It is important to note that the “owner” includes the person in control of the dam. The dam owners should:

- Ensure that all their dams are operated and maintained in a safe manner;
- Ensure that Potential Consequence Classifications are known and regularly reviewed and updated when necessary;
- Ensure that suitable corporate governance structures and internal reporting processes are in place;
- Establish an “Owners Dam Safety Program” (ODSP) which clearly recognizes the owner’s responsibility and presents the management organization and resources for dam safety management at each dam for review and approval by the regulator;
- Approved Dam Engineers and supporting teams are engaged during all the tasks at the dam;

- Implement a “Dam Safety Review Panel” for all new projects which will be responsible for reviewing and ensuring that all necessary safety measures are provided at key stages of design, construction, first filling and operation of dam projects;
- Incorporate dam safety into its plans for design, construction, operation, maintenance and decommissioning of their dams;
- Carry out PFMA’s for new dams during design, before first filling considering the particular hazards associated with first filling, then as built considering the planned operation of the dam and then prior to any significant modifications to existing dams considering the proposed changes and carry out subsequent periodic dam safety reviews on all dams;
- Implement the recommendations of the PFMA’s and Dam Safety Review Panels;
- Establish an Operation and Maintenance Manual (O&M Manual) at all dams for review and approval by the regulator and an adequate budget for operations, maintenance and supervision;
- Establish a Surveillance and Monitoring Plan (SMP) for review and approval by the regulator and an adequate budget for installation, operation and maintenance of the monitoring system and data management. The appropriate surveillance programs should be based on PFMA’s;
- The SMP should include “Threshold” and “Action” values for all key performance parameters (eg. Piezometers, flow-meters, deformations etc.) which may be early indicators of the development of a potential failure mode;
- Prepare periodic Surveillance and Monitoring Reports (SMR) which include comprehensive evaluations and reviews of surveillance and monitoring records and instrumentation data for review and approval by the regulator;
- At dams with any potential for loss of life or other significant consequences establish an Emergency Action Plan (EAP) based on its PFMA’s for review and approval by the regulator and which is provided to the regulatory authority and to all relevant authorities and downstream communities that could be affected by a dam failure;
- Carry out EAP exercises involving the dam operators and downstream entities;
- Report any dam safety failures or incidents and/or abnormal conditions which may have safety implications to the regulator and submit plans for management of such situations for review and approval. These abnormal conditions include:
  - Significant damage of the dam wall or spillway caused by natural phenomena such as floods and earthquakes;
  - Failure or unusual movements or subsidence of any part of the dam or foundation thereof;
  - Unusual seepage or leaks which occur or which increase abnormally in the course of time or which remove material;

- Defects in the dam wall or its components, which could in the course of time lead to a failure of the dam;
  - Deterioration of the dam wall or the forming of cracks, including the starting of new cracks or the lengthening or widening of existing cracks;
  - The occurrence of sinkholes in the dam wall or reservoir;
  - The movement of material masses near the perimeter of the reservoir;
  - Abnormal instrument readings;
  - Significant damage to slope protection;
  - unserviceability of spillways and floodgates;
  - unserviceability of outlet works required for lowering of the water-level in an emergency; and
  - Incidents of sabotage or vandalism.
- Assemble and develop a complete set of the supporting technical information documentation (STID) for each dam including records of design construction and operation, O&M Manuals, PFMA's and Safety Reviews, SMPs, SMRs, EAPs to be available at the project and supply a complete copy of this information to the regulator.

### 3.2.3.3 Approved Dam Engineer and Supporting Team of Specialists

The planning, design, construction and commissioning tasks of a dam should involve an Approved Dam Engineer or an Approved Dam Engineer supported by a team of specialists (for high consequence dams) with appropriate experience for the particular tasks whether it be design, construction, operation or the performance analysis of dams. The Approved Dam Engineer should be professionally registered.

An Approved Dam Engineer appointed to carry out a task on a dam must:

- ensure that the task is carried out according to acceptable dam engineering practices;
- keep the prescribed records;
- compile the prescribed reports; and
- where the task includes constructing, altering or repairing a dam, issue a completion certificate to the owner of the dam to the effect that the task on that dam has been carried out according to the applicable design, drawings and specifications.

An approved professional person appointed to carry out a dam safety review must:

- consider whether the safety norms pertaining to the design, construction, monitoring, operation, performance and maintenance of the dam satisfy acceptable dam engineering practices; and

- compile a report according to the prescribed requirements and submit the signed and dated report to the owner of the dam within the prescribed period.

#### 3.2.3.4 Dam Operators

Dam operators should be aware of the damage potential of the dam and be able to recognize and report deficiencies, or adverse trends that could lead to failure, to the owner and/or the Approved Dam Engineer as well as the regulator.

### 3.3 Classification of All Dams

The Potential Consequences Classification (PCC) is a classification system for all dams with a safety risk according to their potential incremental impacts or consequences as a result of failure.

In a traditional “Standards Based” approach a PCC is applied to dams in order to ensure that designs provide appropriate levels of investigation, design criteria and procedures, construction control, maintenance and operation. A dam's PCC also determines the frequency and magnitude of ongoing internal and external performance reviews.

In a Risk Informed Decision Making (RIDM) approach the PCC is used when categorizing the risk in a “Risk Matrix” as discussed in Section 2.4.4.1 below.

Table 2 presents this classification scheme that should be used for the standard of care expected of dam owners and Approved Dam Engineers and used in selecting design criteria. Estimates of potential incremental consequences of dam failure are categorized to distinguish dams where the risk is higher than others. The classification should consider both national and international or trans-boundary factors. The Potential Consequences Classification (PCC) of the dam should be the highest classification obtained from the various risk categories shown.

Table 2: Potential Consequences Classification for Eastern Nile Dams

| Dam Class            | Loss of life  | Infrastructure, Economic and Social Factors  | Environmental & Cultural Factors   |
|----------------------|---|--|--|
| VERY HIGH<br>Level 4 | Large potential for multiple loss of life involving residents and working, traveling and/or recreating public. Development within the potential inundation area (the area that would be flooded if the dam fails), considering both national and international or trans-boundary areas, typically includes communities, extensive agricultural, commercial and work areas, main highways, railways, ports and locations of concentrated recreational activity. Estimated loss of life could exceed 1 000. | Very high economic losses affecting infrastructure, public and commercial facilities in and beyond the inundation area considering both national and international or trans-boundary areas. Typically includes destruction of or extensive damage to large residential areas, concentrated agricultural and/or commercial land uses, hydroelectric generation facilities, highways, railways, ports and shipping facilities, power lines, pipelines, water supply and other utilities. Estimated direct and indirect (interruption of service) costs could exceed \$100 million. | Loss or significant deterioration of nationally or locally important fisheries habitat (including water quality), wildlife habitat, rare and/or endangered species, unique landscapes or sites of cultural significance. Feasibility and/or practicality of restoration and/or compensation are low. |
| HIGH<br>Level 3      | Potential for multiple loss of life involving residents, and working, traveling, and/or recreating public. Development within inundation area typically includes highways and railways, ports, agricultural, commercial and work areas, locations of concentrated recreational activity and scattered residences. Estimated loss of life between 100 and 1 000.   | Substantial economic losses affecting infrastructure, public, agricultural and commercial facilities in and beyond inundation area. Typically includes destruction of or extensive damage to concentrated agricultural and/or commercial land uses, hydroelectric generation facilities, highways, railways, ports and shipping facilities, power lines, pipelines, water supply and other utilities. Scattered residences may be destroyed or severely damaged. Estimated direct and indirect (interruption of service) costs could exceed \$1 million.                         | Loss or significant deterioration of nationally or locally important fisheries habitat (including water quality), wildlife habitat, rare and/or endangered species, unique landscapes or sites of cultural significance. Feasibility and practicality of restoration and/or compensation is high.    |
| MODERATE<br>Level 2  | Low potential for multiple loss of life. Inundation area is typically underdeveloped except for minor roads, temporarily inhabited or non-residential farms and rural activities. There must be a reliable element of natural warning if larger development exists. Estimated loss of life between 10 and 100.  | Low economic losses to limited infrastructure, public and commercial activities. Estimated direct and indirect (interruption of service) costs could exceed \$100,000.   | Loss or significant deterioration of regionally important fisheries habitat (including water quality), wildlife habitat, rare and/or endangered species, unique landscapes or sites of cultural significance. Likelihood of recovery or feasibility of restoration or and/or compensation is high.   |
| LOW<br>Level 1       | Minimal potential for any loss of life. The inundation area is typically undeveloped. Estimated loss of life between 1 and 10.  | Minimal economic losses typically limited to owners' property. Virtually no potential for future development of other land uses within the foreseeable future.   | No significant loss or deterioration of fisheries habitat, wildlife habitat, rare and/or endangered species, unique landscapes or sites of cultural significance.  |
| REMOTE<br>Level 0    | No potential for any loss of life. The inundation area is typically undeveloped.  | Minimal economic losses typically limited to owners' property. Virtually no potential for future development of other land uses within the foreseeable future.   | No significant loss or deterioration of fisheries habitat, wildlife habitat, rare and/or endangered species, unique landscapes or sites of cultural significance.  |

When estimating the potential loss of life the effectiveness of the Emergency Action Plan (EAP) should be considered. For example, if considering a natural flood, then the specific characteristics of the flood and evacuation scenarios should be considered to ensure that the appropriate level of safety is provided. As a starting point, a Population at Risk (PAR) assessment may be used to conservatively estimate the potential loss of life and classify the dam and determine required safety levels and procedures.

Environmental, cultural, and third-party economic losses, considering both national and international or trans-boundary factors should be estimated separately and taken into account in assigning a dam to a class.

The dam class should be determined by the highest potential consequences, whether loss of life, infrastructure, economic and social or environmental and cultural losses.

For the purposes of general management oversight, as well as design, construction, inspection, maintenance, and surveillance programs, an overall classification for the dam system should be used, based on the failure scenario that would result in worse consequences: either sunny- day failure or flood failure.

The PCC should be used for determining appropriate design criteria for new projects. For specific components at a site, the consequences of failure of the components may be considered separately for the relevant design to prevent individual failure modes and their combinations.

All dams classification should be review during their obligatory safety reviews to ensure that the consequence classification has not been changed by movements in population or industry or by greater understanding of the social or environmental consequences.

It is the responsibility of the owner of a dam to reclassify the dam every time there is a significant change to the structure or the immediate downstream development.

Higher consequences dams need a higher level of investigation, design input and optimization, construction testing monitoring, and ongoing performance monitoring. Small or lower consequence dams may employ a lower level of investigation and design. The application of an appropriate category helps to ensure an appropriate effort is put into these components of dam building and operation.

### 3.3.1 Physical Factors Affecting the Consequences of Dam Failure

There are many factors which can affect the potential consequences of dam failure. These can include:

- The dam height (the higher the dam, the higher the potential energy of the water and the faster the water may escape);
- The volume stored behind the dam (the bigger the storage the bigger the damage potential);
- The nature of the stored materials (e.g. water versus mine tailings or toxic wastes)
- The shape and hydraulic characteristics of the downstream valley which affects the nature and extent of potential flooding;

- The downstream conditions, particularly habitation or public areas and the valley environment which would be exposed to the effects of dam failure;
- The effects to a community of depriving them of the stored water which may be critical for water supply.
- Other factors may affect the likelihood of a dam failure if they are not correctly dealt within the investigation, design, construction or operational phases of the dam's life. These may include:
  - Difficult or unusual foundation conditions;
  - Construction materials;
  - Proximity to active faults;
  - Catchment use (e.g. forestry operations with associated risk of debris)
  - Proximity to volcanic hazards; and
  - Landslides in the reservoir area.

### 3.3.2 Inundation Area

The inundation area shall be estimated by using available computer programs. The inundated area shall extend downstream for the least of a distance equal to the distance that the flood wave is estimated to travel in 12 hours or until the flood wave height is estimated to have reduced to 600 mm above the river flow without dam break. Care must be taken in routing flows through lakes to ensure that the effect of natural levees and the like is taken into account.

For dams less than 10 meters high the inundated area may be taken as the crest level of the dam reducing at the rate of 1 meter per kilometer as the wave moves downstream. The downstream area shall be taken as the minimum of the distance the flood wave is estimated to travel in 6 hours or until the flood wave height is reduced to 600 mm above the river flow without dam break.

The Approved Dam Engineer shall examine the inundation area, the population at risk and potential loss of life, the environmental and social risks and the assets likely to be destroyed by a dam break event.

### 3.3.3 Population at Risk and Loss of Life

The Population at Risk is the estimate of the total number of people likely to be within the inundated area at any time. It is not an estimate of the likely number of casualties due to a dam failure as no reduction is made for those likely to escape or survive the flood.

The number of people at risk from dam failure shall be estimated by:

- Counting the number of residences (including hotels, hostels, camps etc) within the estimated inundated area and multiplying by the average occupancy rate determined for the area in question or by 3.5.

- Estimating the average number of people (in vehicles, walking, fishing etc) on any bridge within the inundated area (including the dam where this functions as a bridge) during daylight hours and multiplying by 0.7.
- Estimating the number of people recreating, or employed, on the river within the inundated area during the busiest eight hours of a day and multiplying by 0.4.
- Obtaining the total number of students and staff at schools within the inundated area and multiplying by 0.3.
- Obtaining the total number of workers at industries within the area and multiplying by 0.4.
- Estimating the maximum number of patients, staff and visitors and hospitals, clinics and similar institutions and multiplying by 0.8.
- All other places where people could congregate (e.g. churches, temples, mosques, sporting grounds, community halls etc.) the average number of people should be calculated using a similar method which would produce the average over time of the number of people at risk.

The Population at Risk (PAR) is obtained by adding all these estimates. The estimated potential “Loss of Life” to be used in Table 2 should consider the PAR and the availability and effectiveness of warning and evacuation systems.

In critical areas with a large permanent PAR, a more detailed classification may be appropriate on the basis of estimates of potential loss of life using various tools such as DSO-99-06, A Procedure for Estimating Loss of Life Caused by Dam Failure, USBR 1999, or the recent Interim Guidelines for Estimating Life Loss for Dam Safety Risk Analysis, RCEM – Reclamation Consequence Estimating Methodology, USBR, February 2014.

### 3.3.4 Infrastructure, Economic and Social Factors

The infrastructure, economic and social factors are determined by examining the inundated area, the population at risk, the environmental consequences, the impact on transport and industry and estimate the consequences on the communities involved. This study shall take into account the capacity of the communities to recover and the ability to make temporary arrangements. Any health risks should be considered under this heading.

The estimation of economic risk will take into account:

- The value of the dam and associated assets and the cost of clean-up and replacement.
- The value of buildings, bridges, power lines, pipelines, communicating assets and the contents of buildings and the estimate the cost of clean-up and replacement.
- The cost of temporary accommodation required prior to replacement of the assets.
- The loss of production arising from the loss of assets.



- The loss of production arising from the loss of water for irrigation or water supply. This will take into account any temporary works which could be constructed.
- The loss of production arising from the loss of power generated. This should not exceed the cost of alternative power being obtained.
- The economic impact on the disruption to communication and transport infrastructure.

The total economic consequences should estimate the total cost to the nation on the loss of the assets and the Economic Risk Classification.

### 3.3.5 Environmental and Cultural Factors

The environmental and cultural factors are determined by examining the inundated area, taking into account the dam break flow velocity obtained from the computer models or estimated by other means. It will normally be assumed that the flood wave contains large amounts of debris and will result in complete removal of debris and destruction of any building subject to more than 600 mm inundation.

The recovery rate of the damage will have to be based on the type of vegetation and habitat destroyed and similar examples available worldwide.

The significance of environmental losses should be assessed in terms of whether restoration of the environment is feasible and how long it would take. Since the nature of environmental and cultural loss is multifaceted it would be impractical; if not impossible, to arrive at a single numerical value characterizing the extent of the damage. For these reasons, a qualitative assessment may be more appropriate.

### 3.3.6 Incremental and Total Consequences

These guidelines are based on the traditional assumption that due diligence and the standard of care expected of a dam owner relate to the potential damage above and beyond that caused by a natural event when the dam does not fail. The incremental consequences of failure are defined as the total damage from an event with dam failure minus the damage that would have resulted from the same event had the dam not failed.

## 4. ANALYSIS AND ASSESSMENT

### 4.1 Introduction

Dam safety calls for safe planning, design, construction, operation, maintenance and in some cases even decommissioning that adheres to regulations and recognized practices. However, the level of safety cannot always easily be measured using traditional methods. In a lot of cases specific methods, standards, and procedures have been adopted with the expectation that, in following the prescribed approach, the desired safety objective will be achieved although the level of protection is still not actually known.

Safety management is ultimately concerned with management of risk and should provide answers to the following questions:

1. What can go wrong?
2. What is the likelihood (probability) of it happening?
3. If it occurs, what are the possible consequences?

To understand how the structures are expected to perform and what level of deviation from the normal condition is tolerable, dam safety analyses should consider the full range of applicable conditions. Planning, design, construction, operation and decommissioning should all be considered in the analysis to ensure that the intent of the design has been achieved. These dam safety analyses can be formed either through a formal risk assessment, the traditional deterministic approaches or a combination of the two.

A formal risk assessment is a structured and systematic method for understanding possible outcomes, impacts of interactions, and areas of importance and uncertainty. In the traditional approach to dam safety management, regulations and standards are largely based on deterministic concepts of reliability. The likelihood of hazard occurrence is explicitly addressed only for floods and earthquakes, whereas other adverse events or elements of outside influence are introduced through selection of initiating events and consequence scenarios.

The traditional approach and the risk-informed approach complement each other to a degree, in that the overall objective in both cases is to ensure that the “dam is safe” to the extent reasonably and practicably achievable, given the limitations of each approach. In general, all dam safety assessments are carried out in the context of risk, with proven deterministic practices being used to varying degrees to reduce the analytical burden associated with probabilistic methods and to support decisions when quantifiable risk values are unattainable. The same information required for a deterministic assessment is also used in a probabilistic assessment. In the latter, additional information requirements and more complex analyses are introduced to simultaneously account for uncertainties in the models and in the physical processes affecting the dam. The probabilistic approach can be used to validate deterministic results and calculate more precise results where the data are available. Thus, within the constraints of practicality, a probabilistic assessment can provide an improved basis for decision-making that balances social, environmental and other benefits and the residual risks of a project .

The two approaches to dam safety decision-making are outlined below. It should be noted that the setting of minimum safety levels should be a matter of public policy and regulation. Engineering analyses and assessments are used to confirm and demonstrate compliance or to develop alternative measures to meet the identified requirements.

### 4.2 Risk-Informed Approach

Risk, understood as a measure characterizing both the likelihood of an undesired event and the consequences of such an event, can be used as a performance goal to demonstrate that required levels of safety are met. In the context of dam safety, the undesired events might include, for example internal erosion; failure of the flow control equipment, problems with remote controls and monitoring; structural instability of concrete structures or human error.

In view of the large uncertainties involved with dam engineering, a risk-informed approach to dam safety assessments is encouraged. Such an approach includes traditional deterministic standards-based analysis as one of many considerations, as shown in Figure 1.

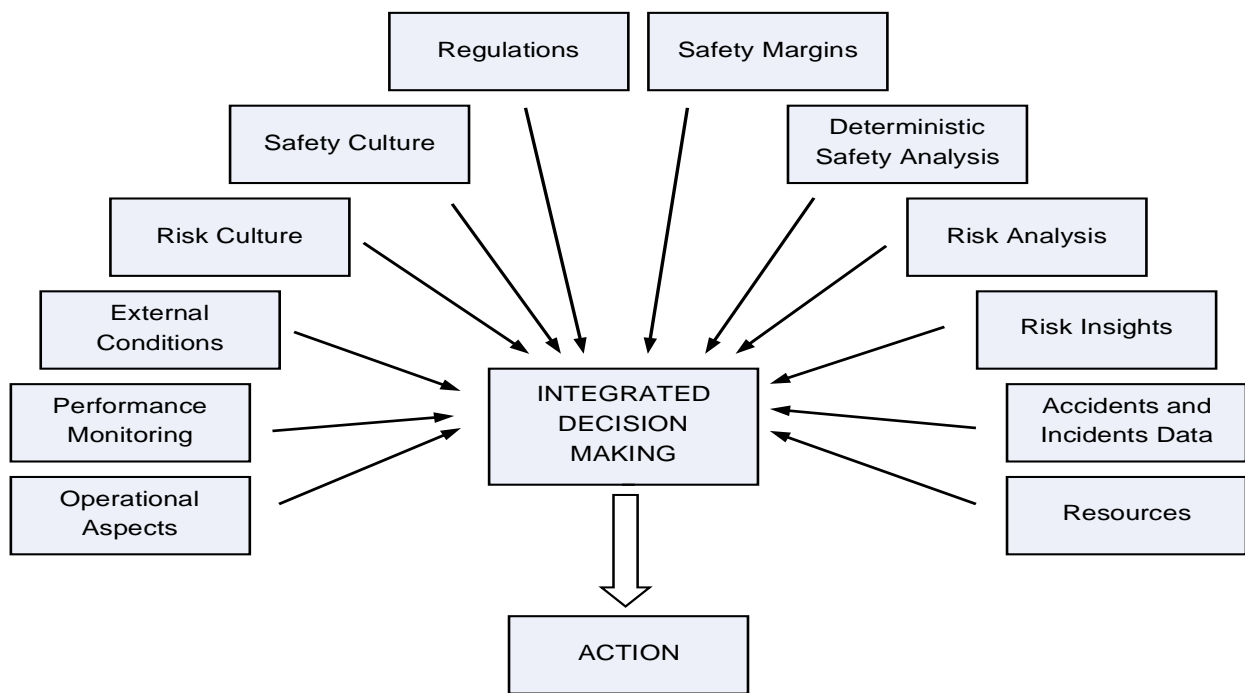


Figure 1: Integrated Risk Informed Decision Making (ICOLD: 2012)

Quantitative risk assessment seeks to provide a complete mathematical description of the uncertainty in the calculated estimates of risk. The use of quantified risk methodologies is preferable for appropriate situations where the scientific techniques are available. However, determination of the probability of failure is a complex task that is not readily accomplished with the current state of knowledge.

Qualitative risk assessment characterizes uncertainty in non-mathematical form and uses schemes for indexing, scoring, and ranking risk factors (see Section 4.2.3 for more detail).

The concept of tolerability of risk is fundamentally a matter of political choices, preferences and policies even when dealing with trans-boundary dams as well. The emerging view is that risk and uncertainty, as essential factors that have to be considered in the dam safety decision-making process, should be

explicitly included and expressed. The decision-making processes should be logical, consistent, and capable of clearly identifying the trade-offs between economic efficiency and social and environmental equity especially in trans-boundary rivers.

The overall dam safety framework should ensure that no individuals or communities are unduly affected in the interest of the broader societal interests. On the other hand, society does not have infinite resources to spend on managing risks and often the resource spent inefficiently in one area is the same resource that is missing in another area where investment could be more beneficial. For trans-boundary dams, downstream countries should also not have unreasonable demands in the managing of risks by the upstream trans-boundary country. Effective application of the balanced equity-efficiency approach requires acknowledgment that both economic efficiency and social and environmental equity are legitimate goals that society wants to pursue.

One effective way to address individual and societal concerns about the hazards posed by dams is by characterization in terms of risk and derivation of tolerability criteria:

- Individual risk relates to concerns of how individuals see the risk from a particular hazard affecting them and their property. It is usually defined as the risk to a hypothetical member of the public living in the zone that can be affected in the event that a hazard occurs. The criteria for individual risk depend on such factors as whether or not the exposure is voluntary, whether the individual derives benefit from accepting the risk, whether the individual has some control over the risk, and whether the risk engenders particular dread;
- Societal risk generally refers to hazards that, if realized, could impact society and thus cause socio-political response. Societal risk may be seen as a relationship between the frequency of a particular hazard and the number of casualties if the hazard is realized. In applications dealing with hazards from engineered installations where the predominant issue is life safety, societal risk is characterized by graphs showing frequency of events that could cause multiple fatalities.

Risk assessment for dam safety should consider the approach as shown in Figure 2, which presents life safety risk guidelines that are consistent with values used in general in society and with the principle that risks should be made as low as reasonably practicable (ALARP – for more detail see Section 4.2.1.3).

An action to reduce the risk is clearly necessary if the risk is not acceptable. The ALARP principle is based on the duty to reduce risks to life to the point where further risk reduction is impracticable or requires action that is grossly disproportionate in time, trouble, and effort to the reduction of risk achieved.

In engineering applications, risk usually means a combination of the probability and the adverse consequences of an event. If this combination is expressed as the product of probability and consequences, it simply represents the probabilistic expectation (expected value) of the consequences.

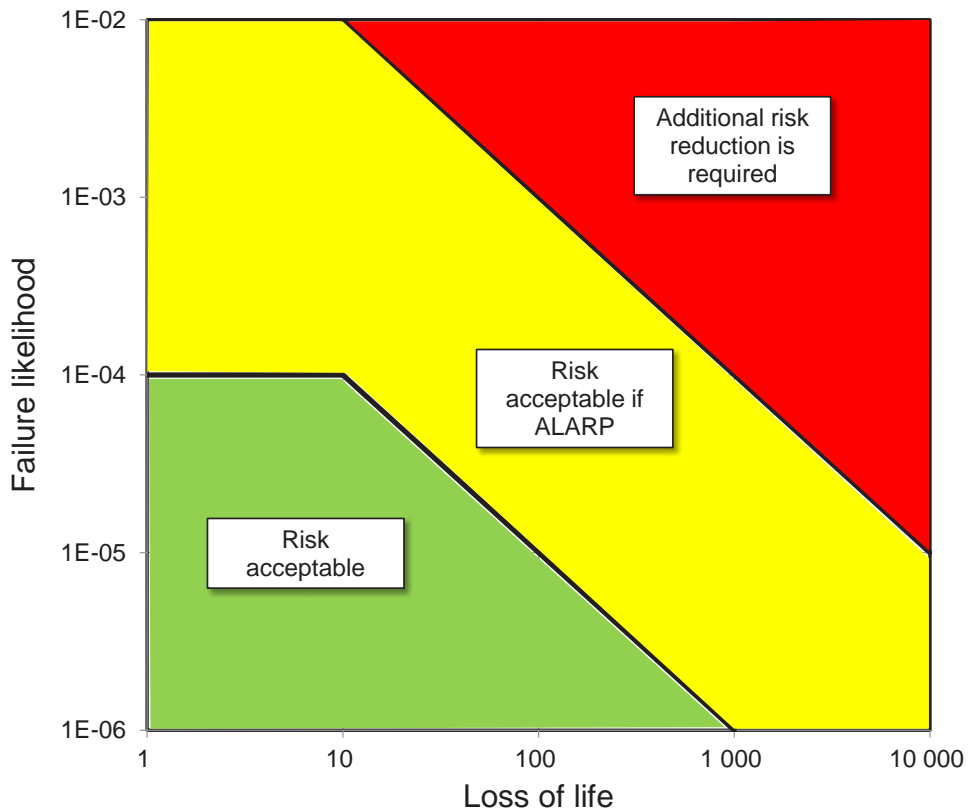


Figure 2: Risk levels for Dam Safety using loss of life societal consequences

Quantitative estimates of the risk (probabilities and consequences of possible adverse events) can be used as indicators of safety levels achieved and may be compared with specific safety goals also expressed in probabilistic terms. A probabilistic safety goal is usually expressed in terms of the annual probability of an adverse event and the associated consequences. A flood characterized by a peak daily inflow with a certain return period (frequency of occurrence, or probability of exceedance) is an example. Such defined safety goals can be subsequently used as a design or operational objective and interpreted as a desirable target for establishing reliable performance of safety. The selection of safety goals can either be based on arbitrary criteria or be established within the broader context of societal and individual tolerance/acceptance of risk.

In addition to accounting for societal risk in dam safety decisions, the individual risk should be considered in terms of the “maximally exposed individual” that is permanently resident downstream of the dam. Typically the maximally exposed individual is exposed to the hazard significantly more than 50% of the time. The maximum level of individual risk is generally given as less than  $10^{-4}$ /year.

The conditional probabilities that dams will fail, given an event, vary widely depending on the failure modes and the nature of the loadings. The actual value for a particular dam and event is often difficult to determine precisely. Hence, in some cases where no additional information is available, valid dam safety decisions can often be made on the basis of relatively simple analyses by making the very conservative assumptions that conditional probability that the dam will actually fail = 1 and conditional probability of loss of life, given dam failure = 1. For example, these conservative and necessary assumptions are applicable to flood events resulting in major overtopping of unprotected earth embankments.

The general risk analysis and assessment approach is an appropriate framework for dam safety management. Although the current ability to reliably quantify risk is limited, the approach has considerable benefits in providing well-defined and justifiable safety targets (performance goals). In terms of the risk informed approach described in the following sections, the dam owner is expected to demonstrate that the resulting level of risk is justifiable and that the safety management of the dam conforms to the Principles of these Guidelines.

Table 3 presents minimum initial target frequency levels for the flood and earthquake hazards, for use in load-resistance performance analyses based on historic frequencies. The frequency levels given in the table are based on the expected loss of life and assume that the hazard would actually induce failure. The onus is on the owner to demonstrate that the assumption, that the fragility is 1, is overly conservative and suitable levels of societal risk will be achieved at a lesser hazard if the fragility is properly considered. A comprehensive risk analysis will address the uncertainties in the risk analyses. The maximum performance capacities to withstand flood and earthquake hazards, derived from a risk analysis, might be loosely compared to those achieved through the standards-based approach.

This table addresses two major natural hazards only, and does not consider the many other types of hazards that must be considered in dam safety assessments. Similar target levels for the other types of hazards should also be used.

Table 3: Target levels for initial consideration of hydrologic and seismic hazards for the risk-informed approach

| Dam Category | Minimum Annual Exceedance Probability (AEP) of the Natural Hazard * | Societal Risk Target     |
|--------------|---|--------------------------|
| Remote       | $1 \times 10^{-2}$  |                          |
| Low          | $1 \times 10^{-3}$  | $1 \times 10^{-4}$       |
| Moderate     | $1 \times 10^{-4}$  | $(1/N) \times 10^{-3**}$ |
| High         | $1 \times 10^{-5}$  | $(1/N) \times 10^{-3}$   |
| Very High    | $1 \times 10^{-6}$  | $(1/N) \times 10^{-3}$   |

Acronyms: AEP - annual exceedance probability; N - number of fatalities

\* AEP levels for floods and earthquakes are the mean estimates of the hazard.

\*\* Simple extrapolation of flood statistics beyond  $10^{-3}$  AEP is normally perceived not to be acceptable. The given AEP values should be based on detailed probabilistic assessments and definition of uncertainty bounds. Results should be compared against Probable Maximum Flood and Maximum Credible Earthquake values and their associated uncertainty (where available).

## 4.2.1 Risk Analysis Tools

### 4.2.1.1 Qualitative Risk Analysis

Qualitative risk analysis may be a practical alternative in some situations. This may allow simple but useful estimates of the likelihood of some PFMs. This can be accomplished by developing event trees of

various PFM scenarios and in doing so develop a deeper understanding of the factors affecting the PFM. Then a judgement is made regarding the likelihood of the PFM. A framework for the Risk profiling part of this is described below in Section 4.2.3 Risk Profiling of dams.

#### 4.2.1.2 Quantitative Risk Analysis

Quantitative Risk Analysis (QRA) is a method that has many benefits in identifying and resolving dam safety issues including:

- Better understanding of the Potential Failure Modes (PFMs);
- Identification of previously unidentified PFMs;
- Consideration of a full spectrum of potential consequences (not just Very High, High, Moderate, Low or Remote);
- Explicit accounting of life loss and all other consequences (including economic, social and environmental);
- Explicit accounting of the probability of failure across the full range of PFMs;
- Explicit accounting for uncertainty in the analyses; and
- Identifying critical systems and components.

However, QRA requires a high level of expertise and needs to recognize that quantification of many common risks in dam safety evaluations, such as internal erosion or operator error, is difficult.

The need and benefits of the use of QRA will therefore depend on the particular circumstances and should be considered on a case by case basis.

#### 4.2.1.3 ALARP

The “As-Low-As-Reasonably-Practicable” (ALARP) concept provides a way to address efficiency in reducing risks. The concept for the use of ALARP considerations is that risk reduction beyond a certain level may not be justified if further risk reduction is impracticable or if the cost is grossly disproportional to the risk reduction. ALARP only has meaning in evaluating the justification for, or comparison of, risk reduction measures: it cannot be applied to an existing risk without considering the options to reduce that risk.

Determining that ALARP is satisfied is ultimately a matter of judgment. In making a judgment on whether risks are ALARP, the following factors should be taken into account:

- The level of risk in relation to the risk guidelines;
- The disproportion between the sacrifice (money, time, trouble and effort) in implementing the risk reduction measures and the subsequent risk reduction achieved;
- The cost-effectiveness of the risk reduction measures;

- Any relevant recognized good practice; and
- Societal concerns as revealed by consultation with the community and other stakeholders.

ALARP considerations may be helpful when societal risks are estimated in the range where the Annualized Failure Probability is remote and the estimated loss of life is high. They can also apply to other situations. For example, it may be possible to reduce risk to just below the guidelines for a given cost, but to get it comfortably below the guidelines (e.g. an order of magnitude) could require a substantial increase in cost. ALARP considerations could be used to decide whether that extra cost is justified.

#### 4.2.1.4 Risk Analysis References

Quantitative and Qualitative Risk Analyses are not considered further in the Guidelines. These and the ALARP principle are addressed in various international Guidelines such as ANCOLD's Guidelines on Risk Assessment (2003b) and USBR's Dam Safety Public Protection Guidelines (2011).

#### 4.2.2 Potential Failure Modes Assessment

A key component of risk-informed decision-making is a well done Potential Failure Mode Analysis (PFMA) with fully developed and described potential failure modes (PFMs). A thoroughly developed PFM describes the progression from initiation through to failure, the probability of failure, so that the risk can be adequately understood. In addition, as lessons from dam safety incidents are shared, the dam safety community increases its understanding of the potential failure modes that may be associated with a particular dam.

PFMAs should be employed in the design of new projects and existing projects with a PCC of LOW or higher. PFMA's will usually be beneficial in all cases but for lower PCC dams the decision to carry out a PFMA may be made on a case by case basis.

PFM descriptions should provide the information necessary to adequately assess the risk at a dam and implement a dam safety surveillance and monitoring program (SMP), risk reduction measures and provide a rational basis for the Emergency Action Plan.

It is important to include, but also think beyond, traditional analyses when identifying potential failure modes. Dams are engineered systems, and significant thought must be put into the details surrounding the interactions between the various features of a particular facility. Some of the greatest risks for uncontrolled reservoir release may be due to operational problems or potential failure modes that do not lend themselves to standard engineering calculations.

An adequate job of identifying potential failure modes can be performed only after all relevant background information for a dam is diligently collected and thoroughly reviewed. This includes information related to geology, design, analysis, construction, flood and seismic loading, operations, and performance monitoring. Photographs, particularly those taken during construction or unusual events, are often vital to identifying vulnerabilities. It is essential that the records be reviewed by more than one person, as something might have been overlooked in previous reviews, and one person may pick up on critical information that another person might miss. A site visit, looking for clues to dam safety vulnerabilities and with a view toward potential failure modes, is also important.



Identifying potential failure modes is best done in a team setting, with a small diverse group of qualified people. Input from operating personnel is essential to the process. A facilitator guides team members in developing the potential failure modes, based on the team’s understanding of the project vulnerabilities resulting from the data review and current field conditions.

All PFMs should be fully developed and describe the complete potential failure sequence. This starts with the initial condition(s) (i.e. loadings, reservoir level, structural condition of the component(s) involved in the failure mode, etc.) at the initiation of the failure mode; the steps necessary for the failure to continue and progress (including location, path, other events during the progression that impact, the progress of the failure mode being studied, etc.); and finally, the failure mode’s impact on the particular structure (fast failure, slow failure, full breach, partial breach, etc.) and how would the reservoir be released. This process is shown visually in Figure 3.

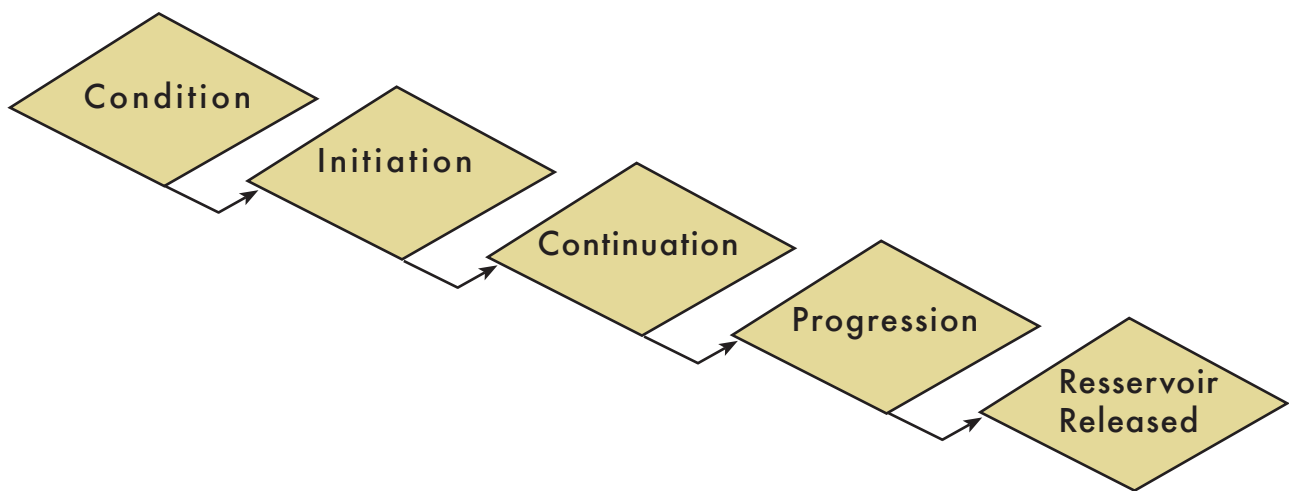


Figure 3: Steps in the description of a Potential Failure Mode

In simplistic terms, qualitative or quantitative risk analysis generates numbers associated with the risk of dam failure or uncontrolled release of the reservoir. Risk assessment is the process of determining what the numbers mean. Risk-informed decision making is the process of determining what, if anything, should be done to reduce the risk and how the risk should be managed in the long-term.

### 4.2.3 Risk Profiling of Dams

#### 4.2.3.1 The Risk Matrix

Risk Profiling of dams provides a basis for determining the acceptability of a proposed new dam design or the condition and operation of an existing dam. This can be accomplished using the results from the PFMA in a “Risk matrix”. . An example summary graphic presentation of the risk for significant PFMs is shown in Figure 2.

The risk matrix allows positioning of failure modes judged to be risk-drivers for the dam. The matrix cells represent approximate order of magnitude estimates of the “Consequences” on the horizontal axis and “Failure Likelihood” on the vertical axis. In general those potential failure modes that plot toward the

upper right corner of the matrix represent the highest risks, while those plotting toward the lower left corner represent the lowest risk. For each potential failure mode, the confidence in the Likelihood Category and Consequences Category assignments are noted, ranging from Good to Poor. The descriptors for the consequences classification are defined in Section 3.3 above. The basis for the “Likelihood” and “Confidence” categories, and associated confidence levels, are described below.

An evaluation of the potential risk (a combination of failure likelihood and consequences) may be made using the following qualitative or semi-quantitative (depending on the amount of available information) descriptors:

- The Failure Likelihood (see Section 4.2.3 for more detail). A level of confidence is assigned to the failure likelihood category using the definitions described in Section 4.2.3.4. Both the categorization as well as the assigned confidence level should be justified with sufficient detail for future use;
- This is followed by assigning a “Consequences Classification” using the descriptors summarized in Section 3.3 with confidence levels as described below.

The result for each PFM are then represented on a “Risk Matrix” with “Failure Likelihood” on the vertical axis ranging from “Remote” to “Very high” and the “Consequences” on the horizontal axis ranging from “Remote (Level 0)” to “Very High (Level 4)”.

#### 4.2.3.2 Risk Classification

For the purposes of prioritizing any possible follow-up actions, and to allow a general comparison with historical failure experience for dams, the risk may be viewed in the following three categories (the PCC will be given as levels to avoid possible confusion):

- Classification 1 (Red): Failure likelihood category “Moderate” and Consequence category “Level 4”, Failure likelihood category “High” and Consequence categories “Level 3 and 4” and Failure likelihood category “Very high” and Consequence category “Level 2, 3 and 4”;
- Classification 2 (Yellow): Failure likelihood category “Low” and Consequence category “Level 4”, Failure likelihood category “Moderate” and Consequence categories “Level 3”, Failure likelihood category “High” and Consequence category “Level 1 and 2” and Failure likelihood category “Very high” and Consequence categories “Level 1”. It is important to note that this region would be where the ALARP principle is applicable; and
- Classification 3 (Green): Failure likelihood category “Low” and Consequence category “Level 1 to 3”, Failure likelihood category “Moderate” and Consequence categories “Level 1 and 2”. Finally, considerations for additional monitoring, risk-reduction, data collection or analysis were identified for each PFM.

The results for each PFM may then be presented on the same risk matrix to provide a preliminary overall view of the risk for this particular dam. A prioritization scheme for PFMs to reduce the overall project (or portfolio) risk levels is indicated in Table 4.

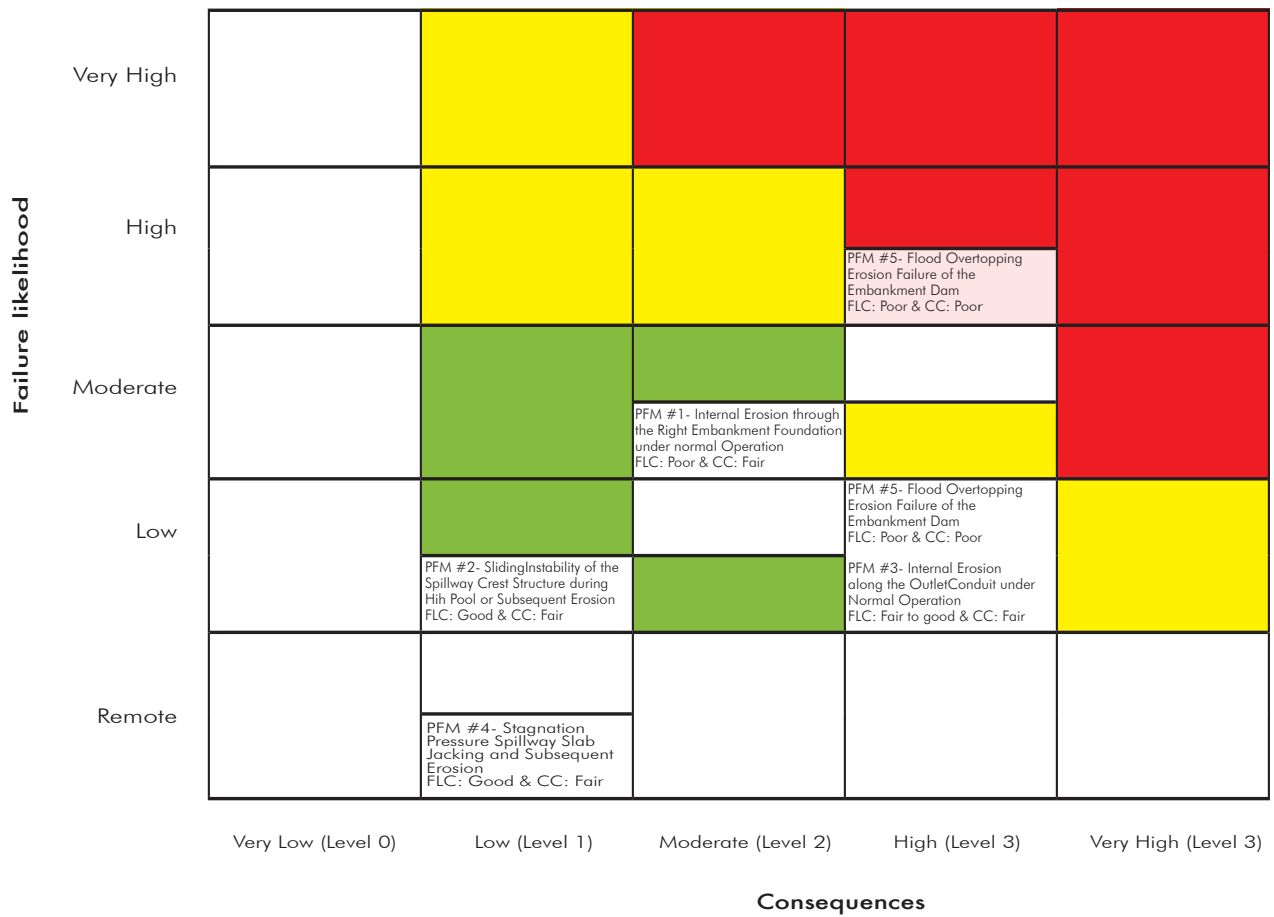


Figure 4: Risk Matrix

Table 4: Prioritization of PFMs

| Classification | Confidence | Ease of risk reduction | Priority |
|----------------|------------|------------------------|----------|
| 1 (Red)        | Good       | Easy                   | 1        |
| 1 (Red)        | Poor*      | Easy                   | 2        |
| 1 (Red)        | Good       | Difficult              | 3        |
| 1 (Red)        | Poor*      | Difficult              | 4        |
| 2 (Yellow)     | Good       | Easy**                 | 5        |
| 2 (Yellow)     | Poor*      | Easy**                 | 6        |
| 2 (Yellow)     | Good       | Difficult              | 7        |
| 2 (Yellow)     | Poor*      | Difficult              | 8        |

\* - Consider first collecting more information unless it costs less to fix.

\*\* - Consider a higher priority if this does not impact on the “Classification 1” risk priorities (in other words these could be re-prioritise to be done before Priority 3).

Note: Action is not usually required for Classification 3 (Green) PFMs. However, if the confidence in the classification is “Poor”, and additional information might raise the Classification, then prioritize in the same manner after Classification 2 (Yellow) PFMs.

#### 4.2.3.3 Failure Likelihood Categories

The following failure likelihood categories were considered for each PFM:

- Very High – There is direct evidence or substantial indirect evidence to suggest it has occurred and/or is likely to occur. Or, a flood or an earthquake or any other hazard with an annual exceedance probability more frequent (greater) than 0.001 would likely trigger the potential failure mode;
- High – The fundamental condition or defect is known to exist, indirect evidence suggests it is plausible, and key evidence is weighted more heavily toward likely than unlikely. Or, a flood or an earthquake or any other hazard with an annual exceedance probability between 0.001 and 0.0001 would likely trigger the potential failure mode;
- Moderate – The fundamental condition or defect is known to exist, indirect evidence suggests it is plausible, and key evidence is weighted more heavily toward unlikely than likely. Or, a flood or an earthquake or any other hazard with an annual exceedance probability between 0.0001 and 0.00001 would likely trigger the potential failure mode;
- Low – The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred or that a condition or flaw exists that could lead to its development. Or, a flood or an earthquake or any other hazard with an annual exceedance probability more remote than 0.00001 would likely trigger the potential failure mode; and
- Remote – Several events must occur concurrently or in series to trigger failure. Most, if not all of the events are very unlikely; failure potential is negligible or non-credible.

#### 4.2.3.4 Confidence Levels

The following classification may be used to describe the confidence of the category for both the “Failure Likelihood” as well as the “Consequences” of each PFM:

- Good: It is unlikely that additional information would change the assigned category;
- Poor: Key additional information could very well change the assigned category; and
- Fair: Confidence in estimated category is in between High and Low. It is uncertain whether additional information would change the assigned category.

#### 4.2.4 Risk Informed Decision Making (RIDM) Process

The decision-making process in RIDM, which is a blend of traditional deterministic methods with the use of selected risk assessment tools, can be applied to design and construction reviews for new dams and comprehensive safety reviews for existing dams. The process includes:

- Potential Consequences Classification (PCC) which is a classification of dam according to their potential incremental impacts as a result of failure;
- Clearly defining the purpose and scope of the safety evaluation in view of the PCC;
- Collection of all relevant supporting technical information (STI) including, when available, design basis memoranda, design and analysis reports including hydrology, geology etc., construction specifications, as built drawings, construction records and photographs, operation records, inspection reports, safety evaluations;
- Clearly defining the dam system, i.e., all parts that contribute to risk, in order to develop a risk model;
- Conducting/refining the Potential Failure Mode Analysis (PFMA) to a level needed for the quantification of the risk;
- Evaluate the risk profile of the dam in terms of the PFMs in a Risk Matrix;
- For those potential failure modes that are amenable to standards-based analysis and which show relatively high risks (yellow or red cells) or large uncertainty in the PFMA Risk Matrix , a traditional standards-based approach can be used to assess their acceptability, and when required, modify the design of new dams or design remedial measures for existing dams;
- Otherwise, risk analysis techniques extending the results of the PFMA into event trees with qualitative likelihood and associated confidence estimates may be considered to more clearly define actual risks and the needs and benefits of design modifications or remediation requirements;
- Combining these estimates into an estimate of the risk for each dam;
- Assessing the risk at a dam to determine whether the risk is tolerable or if there is a need for risk reduction measures, including dam safety modifications;
- If needed, analyse risk reduction alternatives and justify potential dam safety modifications by making the case for these actions in terms of the “As-Low-As-Reasonably-Practicable” (ALARP) concept;
- Identifying the urgency and priority of dam safety risk reduction actions; and
- Incorporating a periodic review of the analyses and assessment for each dam as part of the overall Dam Safety Review Program.

The above process can apply to proposed new dams or existing dams. In the case of proposed new dams the PFMA and risk analysis works with the investigations, the proposed design and specifications. The decision making would then address potential risk reduction options for the design and specifications. The same process can then be updated as construction proceeds and consider any significant modifications to the design. For existing dams the process addresses the “as built” condition. In this case the assessments rely on available information which can be limited for older dams or cases

where ownership has changed over time but will still yield valuable insights and provide the best possible basis for risk management.

Many of the benefits of RIDM can be achieved through a well done PFMA. This will identify the critical components although assessing the relative importance of various PFMs may be difficult. In these situations simple semi-quantitative estimates of likelihoods can be helpful. In addition to assessing likelihoods it is important to also recognize the degree of uncertainty associated with the PFMs. RIDM decisions should address both the likelihood and uncertainty of the risks.

### 4.3 Traditional Standards-Based Approach

Established practice in safety assessment of dams relies mainly on a standards-based approach, a deterministic concept, largely because it is computationally straightforward; provides the reassurance of a well-known method; and uses numerical measures, such as safety factors. The deterministic approach requires the determination of stability or stress state for a critical region in the dam or its foundation. These states are typically analysed for a set of usual, unusual, and extreme load combinations. The deterministic loads and resulting stresses are then related to the deterministic ultimate stability and failure criteria. The quantitative definitions of the factors of safety are determined primarily by empirical evidence, experience, and engineering judgment.

A deterministic design or assessment of unique structures is typically based on either (i) worst- case values for the input variables or (ii) nominal values with a safety factor applied to the result. Thus, the approach accounts for uncertainty by

- Assuming conservative (extreme) values for the loads;
- Assuming conservative (safe) values for resistance variables; and
- Applying conservative safety factors.

The usual (normal), unusual, and extreme cases can be considered from the perspective of exceedance probability. The most critical loads—seismic and hydrologic—are to some extent characterized on the basis of statistics, reliability theory, and probability. In this way, the deterministic approach has been gradually transformed to a semi-probabilistic concept. The calibration and numerous simplifications introduced in the final format of a standards-based procedure are often hidden in the background, and thus the deterministic method may be called prescriptive.

It should be noted that a particular factor of safety is physically meaningful only with respect to given design assumptions and equations. Engineering guidelines or regulations may provide precise instructions for calculation of the factor of safety. This ensures a certain uniformity of approach on the part of different Approved Dam Engineers. However, practising engineers must have a full understanding of the actual reliability assessment methods and meanings of factors used to express the safety, durability, and serviceability of structural components.

The actual probability of failure and the reserves in structural capacity cannot be explicitly evaluated by using a deterministic approach. The risks are managed implicitly, often by application of a classification scheme that reflects potential consequences of dam failure.

Table 5 suggests values for the inflow design flood (IDF) and the design earthquake based on the traditional deterministic approach to dam safety assessment.

Table 5 defines frequency-based target levels for consequence categories. This table is based on the concept of assuring safety up to the physical limits of inflow or earthquake events (which the PMF and MCE attempt to approximate). As these events are considered to be at the maximum physical limits of nature, they approach a zero probability of occurrence and have undefined uncertainty with respect to their magnitude, resulting in their being of limited value in the assessment of dam safety risks. Further, their use may create a false sense that safety has been achieved under the ultimate natural loadings.

In essence, a deterministic approach does not account for the fact that there is considerable uncertainty regarding both the load intensities and the ability of the dam to resist given loads. The approach does take into account the probability of failure of a structural component exposed to variable load combinations in which one might consider the contributions of variable yield stress, variable geometrical properties, and random imperfections. However, this is carried out implicitly without any formal analysis or quantifiable information on probabilities involved. For these reasons, the annual exceedance probability (AEP) values for earthquakes in Table 6-1B applicable to the high, very high, and extreme classes have to be justified, to demonstrate that they conform to societal norms of acceptable risk. This justification can be provided with the help of failure modes analysis for the dam focused on the particular modes that can contribute to failure initiated by a seismic event.

Despite the shortcomings discussed above, the traditional deterministic methods have generally been very successful. They remain essential methods of dam design and dam safety management, even as emerging risk-informed approaches are introduced to provide insight into uncertainties and to improve interaction between engineers and decision-makers.

As with the risk-informed approach, when the standards-based approach is used, the dam owner is expected to demonstrate that the resulting level of risk is justifiable and that the safety management of the dam conforms to the principles of these guidelines.

Table 5: Extreme flood and earthquake hazards for the standards based assessments

| Potential Consequences Category | Annual Exceedance Probability (AEP)      |                    |
|---------------------------------|--|--------------------|
|                                 | Hydrologic:<br>Inflow Design Flood (IDF) | Seismic            |
| Remote                          | $1 \times 10^{-2}$                       | $1 \times 10^{-2}$ |
| Low                             | $1 \times 10^{-3}$                       | $1 \times 10^{-3}$ |
| Moderate                        | PMF                                      | MCE                |
| High                            | PMF                                      | MCE                |
| Very High                       | PMF                                      | MCE                |

Acronyms: AEP - Annual Exceedance Probability; PMF – Probable Maximum Flood; MCE – Maximum Credible Earthquake

## 4.4 Hydrotechnical

Hydrological safety hazards include extreme rainfall events that can lead to natural floods of variable magnitude. The maximum flood for which the dam is to be designed or evaluated is termed the inflow design flood (IDF); the IDF should be selected on the basis of the potential consequences of failure using the Potential Consequences Classification. Tables 3 and 5 suggests IDFs that could be used in dam design and assessment to provide appropriate levels of protection against dam-breach inundation downstream depending on the type of approach followed.

Accuracy and reliability of hydrological data derived from historical records should be evaluated for reasonableness by means of theoretical computation. To this end, procedures based on precipitation records, comparison with runoff data from neighbouring drainage areas, etc., may be applied. Conversely, values resulting from purely theoretical computations should be checked by similar comparative techniques against available data records. If little or no historical record is available, data on which design can be based may be obtained from correlation with hydrologic and meteorologic records from neighbouring drainage areas. However, care must be exercised in determining relationships and conversion factors. The resulting values should be checked in the field by runoff measurements, comparison with marks left from floods, etc.

All available hydrometric and pluviometric data should be taken into account when determining the design flood. Statistical and/or deterministic methods, such as the Probable Maximum Flood (PMF) may be used.

### 4.4.1 Statistical Flood Analysis

Statistical analysis is required for estimating the flood peaks and volumes associated with a range of annual exceedance probabilities (AEPs). In addition to the peaks, the volumes and the associated hydrographs for the floods of interest are usually required for reservoir routing or dam- breach and downstream channel routing.

Flood statistics are subject to a wide margin of uncertainty, which should be taken into account in decision-making. In particular, the following should be noted:

- Results obtained may vary significantly from one statistical distribution to another, and no reliable method exists for the selection of the most appropriate distribution. This task relies entirely on the hydrologist's judgment.
- The evaluation of the highest floods on record often depends on the extrapolation of the rating curve at the station, which may be subject to a large degree of uncertainty.
- Beyond an AEP in the order of 1/500 year, statistics give only an "order of magnitude" estimate. For the purpose of flood evaluation in the dam safety process, extrapolation beyond the 1/1000 year flood is discouraged.
- Evaluation of the confidence limits on the statistical estimate is recommended.



#### 4.4.2 Probable Maximum Flood

Extreme floods, including the Probable Maximum Flood (PMF), are normally evaluated by deterministic methods that maximize the various factors contributing to the generation of a flood. The PMF is defined as the most severe flood that may reasonably be expected to occur at a particular location. The PMF is generated by the probable maximum precipitation (PMP).

#### 4.4.3 Freeboard

The freeboard at all structures should be evaluated for normal and extreme conditions. It should exceed the minimum required freeboard established to minimize the probability of dam overtopping by waves. Additional freeboard or provision for overtopping may be required for dams with reservoirs subject to landslide-induced waves.

The minimum specified freeboard depends on the type of structure. Criteria are more stringent for embankment structures, which are more likely to fail from overtopping, than for concrete or other rigid structures that can withstand some overtopping without serious damage.

In addition, the maximum still-water level of the reservoir should be maintained at all times below the top of the impervious core, unless analysis can demonstrate that temporary exceedance of the top of the core does not endanger the dam.

For concrete dams or other rigid structures with abutments that are resistant to erosion, the freeboard can be based on an economic analysis of damage, provided that safe access to the water control structures is maintained at all times.

#### 4.5 Seismic

Consideration of earthquake motion in the design of a dam to be built in a region of natural seismic activity is mandatory. Earthquake engineering is a field of specialization subject to rapid evolution. Therefore, the analysis of the response of a dam to seismic activity should be based on the latest standards and methods.

For major dams and reservoirs, even in regions with little or no historical seismicity, a site specific seismic hazard analysis shall be made considering local and regional lithology, stratigraphy, geologic and tectonic structure and subsurface permeability. To evaluate seismic potential, historical earthquake records as well as the influence of faulting or other tectonic features on the estimated occurrence, magnitude and location of possible seismic activity should be carefully examined. If it is determined that no seismic forces should be considered in the structural analysis, such determination should be justified and documented.

Seismic analysis should be based on the Maximum Credible Earthquake (MCE), which is defined as the hypothetical earthquake that could be expected from the regional and local potential sources for seismic events and that would produce the severest vibratory ground motion at the site. The analysis should not be limited to structures but be extended to all equipment essential for safe operation as well as those slopes of the reservoir rim and river valley the failure of which would endanger life and/or result in major property damage, and shall be carried out in accordance with current technology.

In recent decades there has been increasing concern regarding the potential for reservoir-induced seismicity in regions previously considered to have extremely low natural seismic activity, or to be completely free of it. Though little is known about the direct causes and the mechanism of the phenomenon, the probability of its occurrence is indicated to increase with the depth and volume of the reservoir and with the degree of local and regional faulting. In dams exceeding 100 meters high or storing more than  $1 \times 10^9 \text{ m}^3$  of water, due consideration should be given to the possibility of reservoir induced seismicity when establishing seismic loading even in regions without any historical seismicity. In this case, the characteristics of the design earthquake shall be determined by the Approved Dam Engineer and approved by the regulator.

An attempt should be made to determine the characteristics of the flood wave that may be produced by the design earthquake, and the stability of the dam should be checked under the assumption of exposure to such a flood wave.

#### 4.6 Geotechnical

For geotechnical consideration, the overall dam system includes the dam embankment and appurtenant structures, their foundations, abutments, and the reservoir rim.

The geotechnical assessment of any potential or existing system should begin with a geological interpretation of the area. This interpretation generally consists of a review of available geo maps, site reconnaissance, and possibly aerial photo interpretation. A well-founded geological program provides a basic understanding of the foundation conditions and the basis for establishing an effective geotechnical site investigation program.

It is emphasized that, because of the almost infinite variety of geologic conditions from site to site, it would be unreasonable and impractical to attempt to set forth in these guidelines specific investigation programs. Detailed guidance is available in ICOLD Bulletin 129 (2005) and others. Typically a geotechnical site investigation program should at least determine the following:

- The general geologic setting of the area at and near the project.
- The geologic conditions related to selection of the site.
- The characteristics of the foundation soils and rocks.
- Any other geologic conditions that may influence design, construction, and long term operation.
- Seismicity of the area.
- The sources of construction material.

From the above it is evident that a geotechnical site investigation program helps to determine the nature and variability of the foundation conditions and the potential borrow zones. The design of a new embankment are greatly influenced by the amount and quality of the borrow materials available at the project. These investigations commonly consist of borehole drilling and sampling, in situ testing, and groundwater monitoring to identify the geological and hydrogeological sequences. When the near-surface materials are of primary importance, as in situations where the topsoil thickness needs to be

established or impervious and granular borrow materials need to be identified, test pitting is often substituted for drilling. In situ testing methods most commonly used are the standard penetration test, cone penetration test, field vane test, pressure meter test, flat dilatometer test and permeability test. Surface or down hole seismic or resistivity measurements obtained by geophysical logging can also be used to supplement stratigraphic information obtained by the borehole drilling. The samples from these investigations are then tested in the laboratory to define the engineering properties of the material and to establish appropriate design parameters.

Foundation investigations and material testing should focus on establishing the engineering properties most relevant to the type of analyses to be undertaken. Typically, these properties include shear strength, gradation, compressibility, compatibility and permeability. Of particular importance to most applications is the identification of discontinuities and anomalies such as jointing, fissures, and weak seams that if present, will generally control foundation behaviour.

When interpreting the results of laboratory and/or field tests, it should be kept in mind that results relate to samples. To transform such results into numerical data upon which design can be based, the relationship of the samples to the geological structure as a whole has to be considered. In situ grouting trials and test excavations can yield information on a larger scale of dimension and may be helpful to determine design parameters.

By taking advantage of appropriate field observations during excavation, design decisions may be based on the most probable foundation conditions that can reasonably be expected, rather than on the most unfavourable conditions which would be deduced from the analysis of a necessarily limited amount of data from foundation exploration. As construction proceeds, reliable information on the subsurface conditions will be obtained and possible shortcomings in the design can be remedied. Thus, unnecessarily conservative solutions determined a priori and the corresponding higher cost can possibly be mitigated. If observation during construction indicates the necessity of stronger or more sophisticated foundation, an additional investment may be appropriate. Using this approach, it would be absolutely necessary to devise in advance appropriate means for the reliable solution of problems which may develop should observations disclose less favourable conditions than those upon which the design has been based. In any case, details of foundation treatment, especially of minor geologic features, must be adjusted to actual conditions encountered.

Engineering analyses need to be performed to demonstrate that the dam, foundation, and abutments will remain stable under all hazards and loading conditions. Geotechnical hazards include the following:

- Hydraulic fracturing
- Piping
- Internal erosion
- Surface erosion
- Slope instability

- Static and dynamic liquefaction
- Seepage
- Deformation

Loading conditions include the following:

- End of construction
- Rapid drawdown
- Reservoir surcharge
- Wind and wave action
- Steady-state seepage
- Earthquakes

For stability analysis, the structure and its foundation should be considered as a unit. The possible influence of the deformation of foundation and abutments on the deformation of the structure should also be investigated.

Overtopping as a result of exceeding the reservoir capacity is the most common mode of failure for embankment dams. Although this is generally considered a storage or discharge capacity issue, settlement of the dam crest can be a contributing factor. Once overtopping occurs, the uncontrolled flow may cause the dam to breach, depending on the erodibility of the materials exposed along the flow path. The rate of breaching is also dependent on this erodibility.

Loss of material due to internal erosion and piping is the second most common cause of embankment dam failure. Internal erosion and piping occur as a result of concentrated, excessive particle migration caused by seepage flow. Particle migration can occur when seepage passes from a fine-grained material into an exceedingly coarser grained material; or perhaps more critically, material is carried into or through cracks or discontinuities in the dam, foundation, or abutments. Differential settlement and hydraulic fracturing are the most common causes of cracking in embankment dams. Hydraulic fracturing occurs when internal hydraulic pressures exceed the minor principal stresses inherent in the embankment material. Well-designed granular filters strategically placed within the embankment and between the embankment and the foundation have proven to be the best defence against internal erosion and piping failure.

The dam embankment and abutment slopes must be adequately stable to withstand all foreseeable loading conditions. In general, a limit equilibrium analysis should be sufficient to verify the stability of the slopes under normal operating conditions. Acceptance criteria are usually described in terms of factors of safety. A factor of safety in this case is defined as the ratio of available shear resistance along a potential plane of failure to the activating shear forces along the same plane. Accepted factors of safety should take into account the reliability of inputs to the stability analysis, the probability of the loading condition, and the consequences of potential failure.

The appropriateness of these calculated factors of safety depends on the conservatism of the assumptions made regarding stratigraphy, strength of materials, pore-water pressure, and loading. Lower calculated factors of safety for static assessment may be acceptable for existing structures with demonstrated performance supported by appropriate monitoring or more sophisticated analysis.

For large dams, dams with complex cross sections or foundation conditions, or dams subjected to seismic loading, it is usually appropriate to apply more sophisticated methods of analysis, such as numerical finite-element models. In these cases, other acceptance criteria, based on stress, strain, and displacements, should be set for elastic response under usual loads, quasi-inelastic response under unusual loads, and inelastic response under extreme loads. The stress-strain field, state of deformation, and distribution of pore-water pressures in the entire continuum of the dam system should be evaluated for different loading cases and stages, such as the following:

- During construction and immediately after construction
- During impoundment and transient seepage
- After full reservoir level has been reached and steady-state seepage has developed
- During long-term consolidation and creep
- Under transient loading, such as rapid or sudden reservoir drawdown, floods, and earthquakes

In general, for advanced numerical modelling, acceptance criteria for allowable maximum levels of stress, strain, and displacement are dependent on material strength and should be established for each project on a case-by-case basis. However, it is possible to set criteria based on a local factor of safety, for example ratio of shear strength to maximum shear stress at each point in the continuum of the dam and foundation.

The geotechnical assessment should also take the following into account:

- Seepage exit gradients should be within acceptable limits for the embankment and foundation materials. The usual techniques used to reduce seepage through the pervious units are impermeable upstream blankets, cutoff trenches, grout curtains, sheet pile walls, slurry trench cutoff walls, and other thin cutoffs. Strategically placed granular filter materials can also be used to provide an acceptable exit condition.
- The dam should be designed to retain the reservoir safely despite any cracking that may be induced by arching, settlement, or hydraulic fracturing.
- Final freeboard, including camber, should be sufficient to accommodate expected settlement of the crest.
- For embankment dams, the maximum reservoir level, including the effects of wind, should be at or below the top of the impervious core, unless it can be demonstrated that for the duration of reservoir surcharge, no damage would be incurred.
- The following failure mechanisms should be assessed for seismic loading:

- Slope instability leading to overtopping
- Permanent deformation leading to overtopping
- Fissuration or cracking leading to internal erosion failure
- Liquefaction (both triggering and post-liquefaction stability conditions)
- The upstream slopes of the dam and its abutments should have adequate protection against erosion and possible breaching due to wave and ice action. The downstream slopes should be protected where necessary against the erosive action of runoff, seepage flows, traffic, frost, and burrowing animals.
- The stability of reservoir slopes should be evaluated under seismic loads, heavy rainfall, rapid drawdown, and any other loading conditions if slope failure could induce waves that would pose an unacceptable risk to public safety, the dam, or its appurtenant structures.

Monitoring instrumentation should be in place to provide the following:

- Data to validate design assumptions about settlement, pore pressures, stresses, displacements, deformation, and seepage.
- Information on the ongoing performance of the dam, its abutments, and its foundations.
- Observation of performance of critical areas.

For concrete dams founded on bedrock, the geotechnical aspect of safety assessment should focus on the concrete-foundation interface, joints or discontinuities within the foundation that can result in differential movement of the dam, cracking, and potential failure.

For concrete dams and appurtenant structures founded on soil consideration should be given to bearing capacity, settlement; differential settlement; swelling, uplift pressure, drainage, lateral earth and hydraulic pressure, and lateral displacements. Of particular importance in the design of concrete structures are possible long-term differential movements that could occur between components and excessive hydraulic uplift pressures that could lead to failure. Measures that may mitigate these conditions include the following:

- Minimizing excavation to reduce rebound
- Allowing rebound and swelling to occur between excavation and construction
- Sub-cutting and replacing soft or compressible foundation materials with granular materials
- Providing a sufficiently thick granular base beneath the structure to facilitate drainage and minimize frost heave

Even though these measures may be sufficient to reduce differential movements and uplift pressures, general practice is to introduce joints within the structure that can accommodate some differential movement, along with a well-designed under-slab drainage system to relieve hydraulic uplift pressures.

## 4.7 Structural

This section focuses on structural analysis of concrete dams but the principles can be applied to other water-retaining structures that rely on their own weight for stability. Discussion of geotechnical considerations for foundations and structure-foundation interfaces is provided in the previous section. The design of new structures and the assessment of existing structures should be carried out using a full range of normal to extreme loads consistent with the site conditions, consequences of failure, applicable regulations, and current good practice in the industry.

The adequacy of structures and foundations to resist all specified loading conditions, including interactions with geotechnical interfaces, should be assessed on the basis of appropriate performance indicators. These include the position of the resultant force, normal and shear stresses, and calculated sliding factors.

Acceptance criteria for assessment of stability should reflect the degree of uncertainty associated with the analysis and an understanding of the imposed loads and material properties, as well as the consequence classification of the structure.

Identification of possible failure modes should be undertaken as part of any safety evaluation in order to identify the potential failure scenarios that may apply to the project. The emphasis in analysis should be on ensuring the safety of the structures against the identified failure scenarios.

Determination of the loads should take into account the actual field conditions. The consequence classification of the dam will determine the flood and earthquake loading. The following loads should be considered in the design and assessment of concrete structures:

- Maximum normal headwater level, combined with the most critical concurrent tail water level;
- Maximum flood headwater level based on the IDF, with corresponding tail water levels;
- Internal water pressure and foundation uplift;
- Vertical and horizontal loading due to rock or soil backfill, including potential effects of liquefaction, as well as loads from silt deposited against the structure;
- Temperature-induced loads for stability and stress analysis of concrete structures with grouted contraction joints, especially buttress and arch dams;
- Other loads, such as tensioned structural anchors, forces generated by the expansion of concrete caused by chemical reactions, and debris; and
- Seismic loads.

Loads should be combined in accordance with the nature of their likelihood of occurrence into load combinations corresponding to the usual, unusual, and extreme load cases.

Concrete dams should be designed to resist and prevent the following:

- Sliding at the dam-foundation interface, within the dam, and at any plane in the foundation
- Overturning
- Overstressing of the concrete dam or foundation
- Excessive seepage through the foundation or through joints in the concrete

If the concrete appears to be damaged or weakened either (i) tests should be carried out to determine its strength parameters or (ii) suitably conservative assumptions should be made in the analysis. Shear should be assumed to be zero, unless tests prove the existence of cohesion.

The effects of static and dynamic (seismic) loadings on support structures for mechanical and electrical equipment used for dam safety should be examined to ensure that structural integrity and functionality are preserved.

The selection of the appropriate analytical method to evaluate the safety of a dam should take into account the type of structure, the characteristics of the loads and materials, the geological conditions, and the behaviour and condition of the structure. The analytical method should be selected for its ability to evaluate the safety of a dam against its principal failure modes. Extreme- consequence and very high consequence dams should generally be analysed in more detail and by more sophisticated methods than lower consequence dams.

#### 4.8 Mechanical and Electrical

Mechanical and electrical equipment at dams consists of the flow control equipment (including gates, valves, stop logs, flashboards), auxiliary equipment, power supplies, and control systems.

Spillway reliability relies on sound design, including appropriate redundancy and segregation as well as a program of inspection, testing, and maintenance to ensure that the gate system remains reliable. The flow control equipment should be adequate for all anticipated conditions and meet present-day dam safety requirements. Over time, there may have been changes to the physical arrangement, corrosion damage, operating conditions, and applied loads.

The scope of analysis and assessment depends on a number of factors, including the following (some of which might only be applicable to existing equipment):

- Age of the equipment;
- Condition of the equipment;
- Operating history;
- Anticipated operating requirements;



- Potential failure modes and their consequences; and
- Criticality of the equipment to the safety of the dam.

When performing an assessment of an existing dam, as a minimum the assessment should include an examination of available information on the equipment, especially the original design calculations, identification of appropriate loading conditions, and an analysis to determine the safety factors under these loading conditions.

The design review for a typical sluice would cover the superstructure, the gate hoist, and the gate itself. For the superstructure, the design loads include dead loads of the gates and the superstructure and wind loads, maximum loads exerted by the gate hoist, and seismic loads.

The design loads that apply to the hoist include the gate weight, wheel or trunnion bearing loads, gate seal friction loads, gate cracking loads, hydraulic down pull and static friction loads and loads due to the gate jamming as it is raised. These loads can be exerted in various combinations.

The design loads on the gate itself include hydrostatic pressure loads on the skinplate and structural members, wheel and trunnion loads, and hoist attachment point loads.

All mechanical and electrical equipment that is required to operate for the dam to pass the inflow design flood should be tested periodically. The testing program should demonstrate that the equipment is in good working order and confirm that the equipment can pass the required flows. It can also demonstrate that the operating loads are still within the expected and acceptable values. Two types of test are recommended:

- Annual functional test to verify that the gate, log sluice, or valve will operate under normal flows. This test can be carried out at less than the full flow, for instance to 10% of gate opening. For regularly used equipment this test could be a part of normal operation.
- Full flow test carried out periodically, for example as part of the Dam Safety Reviews. The test is intended to verify the design capability of equipment. It is recommended that the equipment be fully opened so that the device and its auxiliary equipment operate close to their design loads.

## 5. PLANNING AND DESIGN

Dam engineering frequently involves handling uncertainties and risks beyond prevailing knowledge and, as such, is a mixture of science and art. Although it draws heavily on mathematical principles and physical laws, great reliance is placed on experienced judgment and known safe practices.

Dam safety management requires that critical uncertainties are recognized, investigated and resolved to acceptable risk levels. Consequently, the planning, design and construction phases of dam engineering play an important role in dam safety. This section deals with the planning and design phases. It is important to note that the various analysis and assessments used in the planning and design phases are discussed in more detail in Section 4.

It is essential and necessary to bring social and environment considerations early into the planning and design processes. This will allow planners and designers to consider project locations and design elements that will better address environment and social requirements and enhance dam safety. These considerations are discussed in more detail in Section 12.

### 5.1 Planning

This section addresses important items and issues to be considered during the planning phase. It involves the following levels of study, the sequence of which typically is as follows:

- Reconnaissance;
- Pre-feasibility; and
- Feasibility.

Each stage may involve some review and reconsideration of the results of the preceding stage because of new and more accurate information. Site locations and sizes of dams are usually identified during the Reconnaissance/Pre-feasibility level and fixed at the feasibility stage which supports and justifies an authorization for project construction, but some adjustments in sites and sizes are possible in the detail design investigation up to the point of making final designs for construction. It is important to note that the Approved Dam Engineer needs to be involved during the different planning phases to ensure that all dam safety risks are identified from the beginning.

#### 5.1.1 Reconnaissance Phase

This type of study is generally based on reconnaissance which will identify needed data that may be expensive and may require considerable time to obtain.

The reconnaissance serves to identify the probable scope of a project plan, both as to geographic locations, numbers and types of project functions to be considered, and to show some indication of the magnitudes, and approximate sizes of structures. It should also disclose any major problem areas likely to be encountered.

The Approved Dam Engineer needs to be involved at the start of the Reconnaissance Phase in order to ensure that dam safety risks are identified and appropriate measures are recommended to be further investigated during the following stages of planning.

During this phase a preliminary dam safety management plan should be prepared.

### 5.1.2 Pre-feasibility Study

A Pre-feasibility study is the preliminary versions of a feasibility study ; taking into account all the physical, engineering, economic, social, and environmental factors, though with less accuracy. It is made with available data supplemented where most important with limited collection of new data, and by preliminary types of surveys.

If the pre-feasibility is completed in this brief form and indicates prospective project feasibility, it is then necessary to perform most of the plan formulation work in the beginning phases of the feasibility investigation.

### 5.1.3 Feasibility Study

The purpose of the feasibility study is to determine and demonstrate the soundness and justification of the project for implementation from the standpoint of objectives, accomplishments, benefits, costs, economic, and social and environmental considerations. At this stage all dam safety requirements shall be identified and discussed with the dam owner.

Consequence and Failure Mode Analysis (potential life loss, economic damages, and environmental damages) and Preventative Measures need to be prepared at this stage. The geologic site conditions that could lead to failure are to identified, the associated failure mode described, and present the design steps taken to prevent the failure from occurring

### 5.1.4 Other Procurement Arrangements

Engineering, Procurement and Construction (EPC) contract arrangements are increasingly being used for dam construction. Such an arrangement does not follow the conventional planning and design procedures mentioned above. It is therefore very important to give due considerations for dam safety issues.

As in the conventional project cycle dam safety issues need to be incorporated during the preliminary concept design stage and all through the level one and level two design document preparations, construction, operation and decommissioning stages. Dam safety should be made one of the cardinal contractual obligations of the EPC contractor and employer's representative. The concept of the involvement of an Approved Dam Engineer at all the different project stages should however assure the proper consideration for dam safety issues.

## 5.2 Design

This section addresses important items and issues to be considered during the design planning phase. It involves the following levels of study, the sequence of which typically is as follows:

- Concept design; and
- Detail design.

The Approved Dam Engineer needs to be involved during the design phase. For HIGH and VERY HIGH PCC dams a Dam Safety Review Panel should also be established and carry out thorough review of all aspects of the project at each stage.

### 5.2.1 Concept Design

A concept design report should be subjected to a PFMA and then the results submitted by the Approved Dam Engineer to the regulator for approval before proceeding with the detail design. It is advised that the concept design be audited by the regulator and/or an independent panel on behalf of the regulator. The concept design report should prove the validity of the concept and present sufficient documentation to allow proposals to be developed for a final design.

The main aspects of the investigation that should be considered, but are not limited to, are:

- Determination of the Potential Consequences Classification (PCC);
- Foundation investigations;
- Hydrology and flood capacity;
- Stability (static & seismic);
- Erosion resistance (internal and external);
- Availability and properties of construction materials;
- Environmental issues;
- Adequacy of proposed reservoir operations;
- Designer's Operating Criteria;
- Stakeholder issues;
- Project options and risks;
- Cost estimates; and
- Construction methodology / contract strategy.

Particular care needs to be taken during project investigation and design to ensure that the hydrological yield has been carefully estimated and the uncertainty associated with this figure is made clear. Investigations need to include catchment characteristics such as erosion and runoff and the inflow and management of silt is properly considered. The skill and experience of environmental and social professionals retained to advice on these issues must be suitable for the task.

Investigations are generally also on going through the construction period, which is when the foundations become fully exposed, or the extent of grouting work becomes known. As such, reports will need to be amended (and updated) as construction proceeds, so that, by the time construction is complete; a full and comprehensive report is available as a reference for on-going surveillance of the dam.

Sufficient time, depending on size and complexity of the dam and foundation, shall be allowed for investigation prior to commencement of design works.

Specific areas of dam safety concerns during the concept design phase include the following items.

- Design Criteria;
- Public Safety Awareness;
- Downstream Lands;
- Low-level Discharge Facilities; and
- Instrumentation and Monitoring.

## 5.2.2 Hydrologic and hydraulic design

### 5.2.2.1 Design methods and criteria

Design methods and criteria should be in conformity with the current state of technological evolution and be compatible with the codes and standards to be used. To guard against indiscriminate or even erroneous employment, any computer software used in the design must be reasonably understood by the persons responsible for its application and those who use it.

Before starting the actual design work, the criteria upon which hydrologic and hydraulic design are to be based should be defined and documented. In the selection and definition of design criteria, account should be taken of such items as: the amount and accuracy of available hydrologic and correlated data; availability of processing methods and equipment; degree of precision of computational methods including computer software to be employed; and the possibility of substantial modification in the drainage area that may influence runoff conditions and flood pattern in the near or medium future.

The effect of wind and waves should be analysed when determining the freeboard of the dam above the maximum reservoir level and in designing the slope protection of fill dams.

It is strongly recommended that, in every particular case, an evaluation be made of the need for and suitability of hydraulic model testing, as a check on hydraulic layout and design derived from theoretical analyses.

The hydraulic layout and design should take into account the possibility of a future enlargement of the dam and/or its appurtenant structures, if deemed necessary and possible because of a foreseeable increase in demand and the availability of developable resources.

Before the dam is turned over to the operator, the Approved Dam Engineer should establish a program for prototype testing to check the hydraulic performance and operational behaviour under actual site conditions.

### 5.2.2.2 Spillway and Other Flow Control Structures

The ability to safely route floods through a reservoir system is of paramount importance for dam safety. Flow control structures include the service and auxiliary spillways, low-level outlets, and other outflow structures. The following points should be considered:

- The design capacity of the structures, including resistance to uplift, cavitation, and erosion, should be correctly evaluated. Model testing may be appropriate.
- The channels leading to the flow control facilities should not be obstructed by floating debris or landslides during passage of the flood.
- Water conveyance structures downstream from the flow control sections, including energy dissipation structures, are integral parts of the flow control system. They should be designed to perform their function without being damaged, at least up to the IDF capacity.
- The flow control equipment must be operational at the most critical moment during a flood (or after an earthquake, if applicable).
- The discharge facilities should be capable of passing the IDF, taking into account the routing effect of the reservoir, without infringing on the minimum freeboard requirements.
- Proper operating rules should be available for all floods up to the IDF and should be well understood by the operating staff.
- Unless it can be clearly demonstrated that outlet works or hydropower stations can be operated reliably during flood events, the discharge capacity of these structures should not be included in calculations of the discharge capacity during floods.
- Safe access and a secure power supply to control structures should be maintained at all times.

### 5.2.2.3 Tail water conditions

Tail water flow conditions should be analysed over a sufficiently long stretch of the river to avoid risks from backwater effects. For instance, difficulty may develop when a sudden flood requires the quick opening of a large number of spillway gates when the tail water level is influenced by a downstream reservoir filled to its maximum level. Similarly, any possibility of an artificially low tail water level causing deficient energy dissipation or other shortcomings should be analysed.

The flow pattern in the tail water should be examined for floods up to the design flood, with special attention to the possible development of return currents which may cause erosion or scouring and thus endanger the stability of the dam. Such a situation can occur as a consequence of an unfavourable combination of flow volume and certain operations of spillway and outlet works. The best method of investigation is model testing.

### 5.2.2.4 Reservoir Operating Rules

Reservoir operating rules consist of a set of specified maximum and minimum levels to be maintained at specified dates in the year. If a large inflow (that is, flood) occurs, outflow structures need to be operated to maintain the reservoir level within the levels specified for that date by the operating rules. These rules should be defined in such a way that the operator increases and decreases the project outflows in response to observed monitoring data such as reservoir rise, climate data that correlates to near term reservoir inflow, or other relevant real-time observed data. The rule curves should not be prescribed in a manner that requires the operator to guess the magnitude of the incoming flood, because, unless sophisticated flood forecasting is available, there is no way to know in advance the exact magnitude of

an incoming flood. The best that can be known about the incoming flood is that it will be a large one if observed rainfall and snow accumulation are greater than usual. When developing rule curves, the following flood operating rules should be observed:

- The minimum freeboard at the dam should be reached only if the incoming flood is the IDF.
- Whatever the magnitude of the flood that actually occurs, and regardless of what was forecasted or anticipated, the resulting reservoir level after the passage of the flood should be in the range of levels normally observed for that time of the year.

Reservoir management during emergencies should be documented in operations procedures and emergency plans, as appropriate.

Under some circumstances, it may be good practice to spill before the arrival of an anticipated large flood. However, such an operation should be based on inflow forecasting information and an understanding of the potential consequences.

The Approved Dam Engineer should compile an operation and maintenance manual as part of the design that should include these operating rules.

#### 5.2.2.5 Downstream flooding

The effects and consequences of the discharge of floods from the dam should be investigated along the whole downstream reach of the river that would be substantially affected by a catastrophic flood with special attention to possible danger and damage to life and property. For this investigation, the most severe discharge conditions should be taken into account, i.e., the combination of spillway discharge at full capacity with the maximum total from all other outlets such as low level, power plant, etc., in addition to natural downstream runoff.

A probabilistic flood schedule based on foreseeable operating conditions of the reservoir and the production facilities it serves (power plant, locks, etc.) should be prepared as a basis for the occupational utilization of the downstream flood plains. Appropriate safety measures should be related to each probability value for which a hydrograph is prepared. As a general rule, a dam should not cause more severe downstream floods than occurred before it was built.

A spillway operating scheme compatible with the established downstream safety measures should be prepared for each flood hydrograph. Such operating schemes will often reduce peak flood heights but prolong the duration of high flow when compared with flooding conditions that existed before the dam was built.

### 5.2.3 Structural design

#### 5.2.3.1 Design Methods and Criteria

Design methods and criteria should be in conformity with the current state of technological evolution and be compatible with the codes and standards to be used. To guard against indiscriminate or even erroneous employment, any computer software used in the design must be reasonably understood by the persons responsible for its application and those who use it.

Before beginning the actual design work, the criteria upon which the structural design is to be based should be defined and documented. Methods of structural analysis to be used, their degree of precision and the intended employment of computer programs should be taken into consideration when selecting and defining the design criteria.

All water retaining appurtenant works and structures or any structural component, the damage or failure of which could endanger the dam's stability, should be designed with the same criteria for safety as the main dam.

The design strategy should take into consideration the following specific safety related requirements:

- Performance of all design work by an organization specializing in the design and construction supervision of dams under the auspices of an Approved Dam Engineer that should coordinate the work of a team of specialists in such a way that possible gaps between the various fields of specialization are avoided.
- Avoidance of unnecessarily complicated structural concepts and details. Compatibility of design and available construction know-how, technology and equipment.
- Careful theoretical and experimental investigation of new design concepts and/or unconventional construction methods and materials, if either one should be employed.
- Provision for adequate access to all critical areas and structural components of the dam in order to facilitate safety surveillance and possible future repair or rehabilitation work.
- Provision of structural arrangements that will facilitate future repair and/or replacement of defective or outworn electrical and mechanical equipment.
- Provision of adequate ventilation of galleries, shafts, tunnels, water carrying ducts or other enclosed spaces that can be entered for work or inspection or in which inflammable gases can accrue.
- Provision for as simple operation and maintenance conditions as possible.

The Approved Dam Engineer should be well experienced in the construction of the type of project being designed to be able to recognize the inherent difficulties of certain operations and procedures, and to avoid unrealistic requirements in the specifications.

During planning and design of the dam, the Approved Dam Engineer should give thought to the possibility of future enlargements of the dam and appurtenant structures and incorporate the necessary provisions in the design.

Design computations, considerations, investigations, testing, conclusions and decisions should be thoroughly documented and include thorough checks of all calculations and independent reviews.

The Approved Dam Engineer should supply the constructor with complete details of all civil engineering structures. No detailing should be left for the owner, the operator or the constructor. All materials and construction methods, the employment of which is essential to attain the quality anticipated by the design as well as the procedures to be followed for quality control, should be specified. The Approved Dam



Engineer should also specify the mechanical and electrical items and check the corresponding design documents prepared by the manufacturers.

The effect of wind and waves should be analysed when determining the freeboard of the dam above the maximum reservoir level and in designing the slope protection of fill dams.

The hydraulic layout and design should take into account the possibility of a future enlargement of the dam and/or its appurtenant structures, if deemed necessary and possible because of a foreseeable increase in demand and the availability of developable resources.

### 5.2.3.2 Deterioration of materials

The design documents should include instructions for the protection from deterioration of materials and structural components of the dam. An adequate allowance for corrosion should be provided when designing structural steel components of the dam. The potential for alkali-aggregate reactions should be considered well in advance of construction for all massive concrete structures and appropriate precautions taken.

If and where the overall safety of a dam depends on particular structural components or elements such as water stops or drains, a second line of defence should be considered. Materials investigations should be compatible with the size and type of structure and include tests to determine the presence of properties or ingredients that could give rise to deleterious deterioration with age.

### 5.2.3.3 Equipment and safety devices

The design of equipment essential for the dam's safety such as flood gates, drainage pumps and valves, uplift relief systems, fire protection systems, control and alarm schemes, and others, should include precautionary measures to ensure functioning under possible emergency conditions. For example, suitable precautionary measures may be the duplication of devices and installations, local control in addition to remote control, automatic triggering of safety devices, and manual emergency operation.

When designing structures that will house or support mechanical or electrical equipment which affect the dam and/or reservoir safety, due attention should be paid to the necessity of access under emergency and other exceptional circumstances, such as severe summer conditions, storm, flood, failure of electricity supply and others.

Equipment essential for safe operation should be connected to at least two power sources independent of each other. Power supply lines and sources should be designed with due consideration for possible natural and operational emergency situations.

The design documents should include a plan of preventive maintenance aiming at regular replacement of wearing parts before they start to cause malfunctioning of the equipment.

The Approved Dam Engineer should provide an operation and maintenance manual for all mechanical and electrical equipment, based on the specific documentation prepared by the equipment manufacturers.

If the rupture of a water carrying conduit would result in a threat to life and/or considerable damage of property, an automatic shut-off device should be installed.

## 5.2.4 Reservoir planning and design

### 5.2.4.1 Flood handling

The discharge from or through a power plant, lock or any other production facility should not be taken into account when determining or checking the spillway capacity. If no allowance for partial blockage or operational failure of gates is made when determining the spillway capacity, the outlet capacity of such production facilities may be considered for emergency discharge. Such emergency or alternate outlet capacity should be provided to an extent to be determined jointly by the Approved Dam Engineer and the operator, and approved by the regulator, in accordance with the risks involved.

The design documents should include detailed operating instructions for the spillway and other outlet devices. Such items as gate opening, closure time and sequence should be subject to full scale field testing.

Besides the primary power supply system for the operation of all flood control and shut-off devices, a completely independent auxiliary power supply source should be permanently available.

### 5.2.4.2 Reservoir bank stability

Critical reservoir rim areas should be surveyed for banks which may become unstable during or after reservoir filling or drawdown the collapse of which may affect the safety of the dam or any other facility in the vicinity of the reservoir.

An adequate means of protection of unstable banks should be determined by the Approved Dam Engineer in case sliding would endanger the dam or public safety. If the danger of large slides into the reservoir should exist, a means of protection such as anchoring, drainage, etc., should be complemented by a suitable monitoring system.

If and where necessary, the Approved Dam Engineer should determine adequate measures to prevent bank erosion.

### 5.2.4.3 Reservoir sedimentation

Planning of the reservoir should include the investigation of the transport action of solids by the river and of potential sources of sediments within the drainage area upstream of the dam site. If necessary and feasible, adequate means should be established to forestall excessive sedimentation of the reservoir.

The accuracy and reliability of suspended silt and solid bed flow data derived from historical records should be checked by comparison with data from neighbouring drainage areas with similar geomorphologic characteristics and situated within the same geological formation. Origin and reliability of all data should be checked to avoid reliance on basic errors which may have been introduced into observation and data processing systems and procedures.

A forecast of the rate of sedimentation of the reservoir should be used to consider the design of flushing facilities and take into account the thrust of the layer of sediments on the design load of the dam. In the case of rivers with high sediment loads, particularly in semi-arid regions, the deposition of sediment may completely change the characteristics of the reservoir in a relatively short time. This could have the result of substantially raising backwater levels and increasing the upstream area which will be subject to

flooding as the result of the dam. If such consequences are to be expected, the Approved Dam Engineer should inform the owner accordingly for possible provisions to forestall future damage.

In regions where seismic activity may be expected, protective measures such as intake walls should be considered to prevent material from sediment deposits lying in the upstream vicinity of the dam from choking low level outlets upon its liquefaction during earthquakes.

Sluices and low level outlets should be designed and their operation scheduled in such manner as to reduce the rate or to control the pattern of silt and bed load deposition in the vicinity of intakes. Design should include an analysis of the likely future problems of concrete and steel abrasion when erosive sediments pass through the outlet in large concentrations and should indicate possible remedial measures.

#### 5.2.4.4 Floating debris

The design should include an analysis of the type, dimensions and amount of floating or submerged debris which may appear, especially during major floods.

If reliable data required for such an analysis is unavailable or insufficient, it may be obtained from neighbouring drainage areas situated in a similar natural environment. Log booms should be installed to keep the floating debris from reaching discharge facilities, or proper design should ensure that debris can be safely passed through the structures. Ideally, any significant amount of debris on a reservoir should be removed periodically.

#### 5.2.4.5 Environmental safety

The design should include an environmental safety assessment for the entire reservoir area and its immediate surroundings and for the river basin downstream of the dam. The assessment should include, but not be limited to, such items as: reservoir clearing, preservation of water quality, health hazards, fishing and safety for navigation.

If adverse environmental conditions are to be expected in the reservoir, the occurrence should be forestalled by appropriate measures determined by the Approved Dam Engineer.

#### 5.2.4.6 Flood warning

A flood warning scheme should be established cooperatively by the owner, operator and the Approved Dam Engineer, subject to approval by the regulator, unless a reliable warning scheme established by other organizations can be used.

Specific flood warning provisions should be included in the design documents taking into account the particular characteristics of the drainage area and the river valley.

### 5.2.5 Trans-boundary Considerations

Safety related aspects of the design of all dams and reservoirs to be built on a trans-boundary river should be compatible with each other. Therefore, the Approved Dam Engineer, when fixing the design concept and criteria, must be well aware of special requirements, standards, restrictions and regulations established by agreement for the development of the river. If no such agreement exists, the Approved

Dam Engineer should seek advice from the cognizant government agencies which should take the necessary steps to determine criteria that would be acceptable to all parties involved.

The agreement for the development of a boundary river should as far as design is concerned include but not be limited to, the following items:

- Hydro graphic observation systems, procedures and equipment as well as transmission, processing and availability of hydrologic data;
- Determination of design floods and spillway capacity;
- Utilization of flood plains;
- Basic design philosophy and safety criteria;
- Water use and river-bound activities;
- Basic criteria for the operation of, and the release of water from, the reservoirs;
- Environmental protection; and
- Emergency precautions.

If no specific advice or instructions can be obtained, the Approved Dam Engineer should on his own initiative take the necessary precautions to avoid the transfer of unreasonable risk or hazard to other riparian entities.

### 5.3 Design Records

The Approved Dam Engineer should provide appropriate documentation as part of their design function for the dam owner. The level of documentation should be commensurate with the hazard and risks posed by the dam. This should cover all relevant details on the investigation and design of the dam and include relevant commissioning requirements (ie Designers Operating Criteria) to validate design considerations and provide a basis for ongoing dam safety management practices.

The Approved Design Engineer should produce a Design Report incorporating a comprehensive description of the design process, including assumptions made, analytical methods used and results obtained. The Design Report should set out how load cases were selected, how the loads were computed and how strengths were determined. Information on the verification of computer programs should be included or referenced. Any statistical results and reliability studies undertaken should be described. Normally a Draft Design Report is produced prior to construction and appropriately reviewed by the regulator / Client / Owner. After construction is complete the Design Report should be finalized to include information gained and changes made during construction. The regulator should review this final document.

It has been the practice of some owners to require comprehensive, indexed calculations to be provided and retained. Computerization of the design process often results in detailed calculations being embedded within programs. The documentation of a large volume of calculations can be an expensive process and they are rarely, if ever, used. A detailed Design Report is of much greater value to the

operator and any future dam safety reviewer. The use of design calculations to assist in the analysis of any future dam safety problem or to assist in the development of any major future modifications to the dam is considered unsatisfactory.

## 6. CONSTRUCTION AND COMMISSIONING

It is seldom possible to fully identify all the characteristics of the foundations, and materials to be used, in investigation and design stages of a dam. Once the foundations have been fully exposed and prepared there may be a need to amend the design because the conditions interpreted by the investigating team and the parameters adopted by the Approved Dam Engineer are at variance with the actual conditions. In such cases it is the responsibility of the construction engineer / project manager to ensure that the design implications of such proposed changes are evaluated by the Approved Dam Engineer, whose responsibility it is to conduct a site inspection to facilitate the assessment of such changes. Any changes so approved by the Approved Dam Engineer should be immediately documented and signed by all parties concerned. It would be advisable to take and keep photographic records of the conditions before and after the changes.

The construction engineer / project manager (owners and constructors) should ideally be a dam engineer, or at least an engineer with some experience in dams construction, able to detect when variations to specified procedures are necessary, or special attention to foundation treatment or aspects which can influence the safety of the dam, is required.

Regular site visits, and inspections, by the Approved Dam Engineer, independent review engineers (e.g. geotechnical engineers and specialists, where appropriate), and the regulator, with joint discussions with the construction engineer, should be arranged by the owner's project manager, as required. Construction Reports should preferably be prepared for all dams to compile invaluable background information for use in future dam safety assessments.

A PFMA shall be performed for all HIGH and VERY HIGH PCC dams before first filling and it shall consider the particular conditions and issues associated with first filling. This PFMA may lead to special requirements for monitoring and surveillance during this critical phase.

Regular reviews by the Dam Safety Review Panel shall be carried out for all HIGH and VERY HIGH PCC dams during construction. The reviews shall be made at least once in a year and at important stages of construction and, in particular, before first filling.

### 6.1 Design-Related Construction Aspects

#### 6.1.1 Field changes to design

Any alteration of the original design due to changed conditions found in the field, or changes desirable to facilitate construction, should be made exclusively by the Approved Dam Engineer.

Field changes of minor details made by the field representative of the Approved Dam Engineer should be subject to approval by the design staff. Such changes must be in strict accordance with the criteria, concept and principles of the original design. Changes and alterations that affect basic design decisions should not be made or approved without a formal, documented analysis by the design staff.

Geotechnical exploration should continue with the advance of excavation to either confirm the design assumptions or to provide the data and information needed for the required design changes.

### 6.1.2 Construction methods and equipment

Construction methods and equipment must be suitable to obtain the specified quality of work. If this cannot be achieved for any reason, possible changes may be proposed to the Approved Dam Engineer. They should not, however, become effective before being formally approved by the Approved Dam Engineer.

Preferably, the Approved Dam Engineer should maintain continuous contact with the contractor's construction staff to avoid unnecessary risks from a possible gap between the design intent and the capacity and practice of construction.

Even if the Approved Dam Engineer is not directly involved in construction supervision, he should at least have an assignment for providing technical guidance to the organization in charge of construction supervision. This should include involvement as a continuous advisor, making frequent periodic visits to the site, and, preferably, being a permanent representative at the construction site for direct liaison with the design staff.

### 6.1.3 Construction supervision and inspection

Construction supervision and inspection should be carried out under the management of a dam engineering « generalist » with enough experience in both construction and design to understand the interdependence of construction practice and the principles and goals of design.

During construction close liaison should be maintained between the design and construction staffs. The construction site should be frequently visited by the design staff for general inspection- of site conditions, construction progress and quality. The construction staff should be continuously informed by the Approved Dam Engineer of design philosophy, criteria and decisions in order to improve the understanding of the design concept and details and the significance of special requirements. The field personnel should inform the Approved Dam Engineer of any critical situation, of deficiencies or alterations of the quality or properties of construction materials, or of any suspected changed conditions that might be incompatible with design.

Irrespective of which organization is entrusted with the supervision of construction - Approved Dam Engineer, owner or a third party - the supervising staff should carefully watch the compliance of construction quality with the specifications and design documents as well as the compatibility of field conditions with the assumptions of design. The supervising staff must be able to recognize when the latter are not compatible with the conditions being encountered. The supervising staff should also watch for compliance with construction safety regulations to avoid accidents.

Mapping of geologic structure and features should be continued during excavation and submitted for the Approved Dam Engineer's appraisal and analysis. Foundations and foundation treatment should be formally approved before placing of fill material.

Deformation of structures, foundations and abutments under the increasing dead load of the dam, as well as stress and strain, should be continuously checked and compared with the values predetermined by design computations, in all cases in which such checking is required because of foundation conditions or the magnitude of the dam.

During construction, seepage volumes and pressure should be measured and compared with the results of permeability and uplift pressure computations. Sources and clarity of seepage water should be investigated by the Approved Dam Engineer. A chemical analysis to determine the content of dissolved substances may become necessary if the danger of washout, for instance of a grout curtain, exists. Seepage flow should be watched to evaluate the efficiency of foundation grouting.

A working scheme for, as well as functions, responsibility and procedures of, quality control should be formally established as part of the construction supervision organization. Routines, test methods and criteria for approval of work should be fixed jointly by the Approved Dam Engineer and owner. If construction inspection is not regulated by law, the Approved Dam Engineer and owner should agree upon the required qualifications of the field inspection staff.

Quality control and construction inspection should be exclusively governed by the construction specifications, design documents and/or standards specified by the Approved Dam Engineer and should be exercised parallel with, but independent of, contractor or vendor management. Results of quality control and construction inspection should be documented and filed as construction records. Such records should include, but not be limited to, information on materials and construction methods, results of exploration and testing, geological mapping of excavations, and reports on foundation treatment and inspection.

Reading of monitoring instruments should be started as early as possible to check the functioning and the reliability of the observation system and to provide maximum comparative data. The instrument readings should be reported to the Approved Dam Engineer to enable the latter to review the design if warranted.

Any deviation from original design should be immediately recorded on construction record drawings for future reference. Information which might be useful for possible repair work, for the detection of possible leakage paths, or for any other future safety considerations, such as : type, quality and brand of material; irregular interruption of concrete pouring or placing of fill material; detected cracks, etc., should be noted on the construction record drawings. The complete and carefully identified set of construction photographs and record drawings should be filed with the construction records.

Grouting operations should be supervised and documented. Specific features, such as drill logs, results of initial water pressure test, duration of operations, ambient temperature, grout mix, grout pressures, grout take, stages of grouting, grout return through vents, deformation or cracking, if any, of grouted structures or foundation, and the results of subsequent pressure testing should be recorded and filed for possible future reference.

Supervision and inspection should extend to the erection and testing of operating equipment.

A special inspection should be carried out following unusual events that may occur during the construction phase such as large floods, earthquakes, fire or sudden changes of instrument readings.

## 6.2 River Diversion

Criteria and the basic concepts upon which the design of the river diversion scheme will be based, such as: probability of flood recurrence, diversion design flood hydrograph, acceptable risks, etc., should be determined by the Approved Dam Engineer and owner in cooperation with the contractor, if necessary, and approved by the regulator.



The river diversion should be based on the available records of flood characteristics and runoff and precipitation records.

Since the various phases of the river diversion scheme are closely linked to predetermined stages of construction and seasonal runoff conditions, the conformity of each of these factors with the established diversion plan must be checked every time diversion is to be shifted from one phase to the next. Any deviation from the pre-established plan such as delay in construction, change in timing of diversion operations, or diminution of the discharge capacity of the diversion channel or conduit will change the risk. If any such deviation should occur, possible consequences have to be analysed to decide if the deviation can be accepted without modification of the diversion scheme.

### 6.3 Construction Records

The construction engineer / project manager should document, as part of the supervision function for the dam owner, all information on construction of the dam.

All phases of the construction should be documented, including reporting of routine and special activities. Changes in construction plans and departures from expected site conditions should be documented, with any consequent design changes. The record should include information on material and construction processes, field exploration and test results, geologic mapping of foundation and excavations, inspection records, as constructed drawings, and decisions to adapt the design to actual field conditions.

Detailed records, including comprehensive photographs, and videos, foundation survey and surface mapping of rock defects, material test results and instrumentation data should be maintained and logically compiled throughout the construction period so that on completion, these, together with a detailed report prepared by the construction engineer, will provide a complete record of the construction and assist in determining a solution to any subsequent safety problems which may arise during the life of the dam.

Photographic documentation of stripped foundations, significant events (including floods), and dam safety problems should be provided. The inspection program and record during construction should give special attention to factors that may have a future influence on dam safety. For all dams, As-Constructed Drawings should be prepared as facilities are completed, and certainly before completion of the project. These should be made available to operation and maintenance personnel, to the dam inspection staff and to the Approved Dam Engineers. These drawings should be included in the Data Book / Base for the dam.

At the end of the construction phase, the construction record as outlined above should be summarized into a Construction Report and Data Book / Base, as appropriate.

It is the responsibility of the prospective dam owner to ensure that funds are available for the preparation of such a Construction Report. The report should be prepared by the construction engineer / project manager during the project on an ongoing basis and especially immediately after any major changes to the design have been made, as described in section 2.9.1 above.

The final signed Construction Report should be submitted to the owner, on completion of construction, so that the knowledge of any personnel involved in design / construction matters is not lost after completion of the project.

A copy of all construction reports shall be submitted to the relevant Regulator as well as the Owner.

## 6.4 Commissioning

A commissioning schedule for the facilities of each dam outlining to the dam owner the procedures and practices (both operational and surveillance) should be developed and reviewed and approved by the Approved dam Engineer and then put in place to establish the basis for bringing the dam into full operation. In addition, it is desirable that an addendum to the dam's Emergency Action Plan (EAP) is developed to include matters particular to the first filling of a dam and also reviewed and approved by the Approved Dam Engineer. For substantial dam projects, it is common for the Approved Dam Engineer to prepare a commissioning report (or as part of the initial comprehensive report) that documents the response and, where necessary, revises the geotechnical and engineering models used in design. This is of particular significance if problems arise in the subsequent operation of the dam.

An Operations and Maintenance Manual should be established for the dam prior to completion of the dam and reviewed and approved by the Approved Dam Engineer and submitted to the Regulator. The construction engineer / project manager should ensure all facilities at the dam are commissioned prior to handover of the dam to the owner for operation. The commissioning should include operating all facilities in accordance with the Operations and Maintenance Manual. The Manual should be updated where deficiencies are noted during commissioning.

Commissioning shall be made together with independent dam experts to make sure that all precautions are made prior to hand over.

### 6.4.1 First Reservoir Filling

First filling of a reservoir is a benchmark activity, but it is also a period in a dam's life with increased failure likelihood as loads are brought to bear on new structures. The impoundment is the first test of the dam to perform the function designed for. Therefore, it is necessary that a carefully prepared surveillance strategy or filling plan be developed and followed during this critical period by a team of personnel including the Approved Dam Engineer, construction management and on site representatives.

The following key issues must be addressed:

1. Controlling the rate of reservoir filling rise, analysis of preferred rate, the option available to control the rate of filling and the consequences operating under those options;
2. The presentation of emergency identification scenarios describing the most likely types of problems that might develop during the initial filling, and surveillance necessary to detect those problems;
3. A plan for the reading of instrumentations devices, and evaluation of their data with regard to the filling plan;
4. A plan for "on – the – ground" inspection of the dam and downstream areas prior to and during filling, including specification of the frequency of the inspection with the rate of pool rise;

5. Instructions for observations on conditions that may require immediate attention, and alternative actions that might be taken to mitigate them;
6. The clear identification of those personnel, and their alternatives with responsibilities for emergency decision making; and
7. A plan of emergency notification listing names, responsibilities, and current communication procedures.

Monitoring of the dam and environs before, during, and after, reservoir filling provides the evidence that validates the Approved Dam Engineer's conceptual, geotechnical and engineering models used in the design.

The Approved Dam Engineer should prepare a schedule of items requiring surveillance during initial filling and subsequent operation of each dam (ie Designers Operating Criteria). Each dam owner should ensure that such surveillance is carried out and is securely documented and reviewed by the Approved Dam Engineer or another dam engineer as a key risk management practice. These records should be stored by the owner with other records for the dam.

First reservoir filling operations should not be started before authorization by the regulator. Before applying for authorization of impoundment, all work in the reservoir area must be completed in accordance with design specifications and safety requirements. Special attention should be paid to elimination or effective sealing of garbage, sanitary and/or hazardous waste dumps. Especially in the case of the fining of large reservoirs, rescue schemes for man and wildlife should be set up.

Immediately prior to starting the filling operation, the reservoir should be inspected by the Approved Dam Engineer and/or representatives of the organization responsible for the supervision of work in the area to be covered by the future reservoir.

During impoundment the structural behaviour of the dam and its foundation should be continuously monitored and all structures inspected for movement, seepage, leakage, uplift pressure or any possible irregular performance in accordance with detailed instructions issued by the Approved Dam Engineer. The whole filling operation should follow a predetermined detailed plan (see above). If possible, impoundment should be carried out in stages with interpolated delays for careful inspection. The whole operation should be well documented. Records should include, but not be limited to, a detailed description of the filling conditions and procedure, justification of deviations from the original plan, results and findings of inspection, monitoring data and their interpretation, and photographic documentation.

If reservoir-induced seismicity is expected, the seismographic monitoring system should be continuously observed. Experience has shown that a major reservoir-induced earthquake may announce itself over weeks or months by increasing seismic activity.

## 6.5 Emergency Precautions

### 6.5.1 Emergency Prevention

Before initiating major activities at the construction site, preventive measures to be taken in case of the development of a possible emergency should be planned jointly by the contractor, the Approved Dam

Engineer and the owner, included in an Emergency Action Plan (EAP) for construction and submitted to the regulator for approval.

Emergency prevention planning contained in the Emergency Action Plan for construction should deal with:

- Emergency situations and occupational safety at the construction site;
- Hazard and emergency situations which may evolve from the construction activities as a threat to the safety of third parties;
- Catastrophic situations caused by natural disasters (force majeure);
- Exceptional situations caused by riots, sabotage or other criminal action.

Besides instructions for emergency operations and actions, rescue schemes, availability and use of emergency equipment, emergency medical care, maintenance of public safety in exceptional situations etc., the plan should contain a clear definition of authority and decision-making procedures to be followed in emergency situations.

Detailed emergency instructions written in easily understandable language should be issued to every working unit and distributed in such a way that they will be readily available. Personnel assigned to emergency operations should receive proper training.

### 6.5.2 Emergency Surveillance and Notice

With the help of the regulator, the contractor and owner should jointly set up a reliable surveillance scheme by which the construction staff will be informed immediately of floods developing upstream of the project site, to enable taking the necessary precautionary steps as early as possible.

The owner should also submit the Emergency Action Plan for construction into existing public emergency frameworks (e.g., civil defence system) and related emergency warning schemes. If the construction site is located on a trans-boundary river, such coordination should be done within the principles outlined in Section 14 of these guidelines.

## 6.6 Alteration or Repair of Existing Dams and Reservoirs

### 6.6.1 Major Contracts

Major construction activities for the enlargement, alteration or repair of existing dams and reservoirs requiring substantial equipment and manpower and resulting in extensive site operations should be governed by the principles outlined in the foregoing sections for the construction of new dams and reservoirs. These should include PFMA's and Dam Safety Review Panels for significant changes to HIGH and VERY HIGH PCC dams.

Special care and precautions should be taken to protect existing structures and facilities from hazards and damage which may result from construction activities such as blasting, excavation, etc.

If the work carried out under the contract required the emptying or partial drawdown of the reservoir, the latter should not be drained or refilled before authorized by the government agency.

### 6.6.2 Minor Repair Work

Minor repair work carried out either by a contractor or by the operator's maintenance force should be governed, with respect to safety requirements, by relevant technical standards, occupational health regulations and the principles outlined in the foregoing sections, as far as applicable. However, safety requirements should be kept within reasonable limits.

If the repair work has been necessary to restore operational safety, the completed work should be approved by the government agency.

## 7. OPERATIONS AND MAINTENANCE

### 7.1 Responsibilities

Dam owners are responsible for the safe operation and maintenance of their facilities (including occupational, health and safety requirements). Proper operation and good maintenance is essential in ensuring the continued viability and safety of a dam and its appurtenant structures. Improper operation and poor maintenance will invariably result in abnormal deterioration, a reduced life expectancy or failure.

Approved Dam Engineers must provide for a large number of natural hazards and phenomena such as floods, earthquakes, landslides and the vagaries of foundations. Approved Dam Engineers should expect that owners will operate and maintain the dam to standards established in the O&M Manual.

The proper operation and good maintenance of a dam not only provides protection for the owner but the general public as well. Furthermore, the cost of proper operations and maintenance is small compared with the costs of the consequences of a dam failure. Such could include major repairs, possible loss-of-life, property damage and litigation.

### 7.2 Operating Procedures

All dam owners should ensure that their dams and reservoirs are operated in a safe and proper manner, in accordance with accepted safe practice and relevant legislation.

Operating procedures should be developed and documented by the dam owner for the safe operation of a dam under adverse (even worst case) scenarios as well as normal conditions. Operating procedures should take a wider view than the physical operation of the dam. They might also include coordination of releases with other dams, communication security, and liaison with counter disaster and other agencies and discharge or flood warning to downstream areas.

Operating procedures should be regularly reviewed (at least every five years or when circumstances change) and tested, by the owner, operations staff and dam engineers to ensure they continue to meet the needs of the owner, the expectations of downstream residents and users, as well as safety criteria.

### 7.3 Maintenance Procedures

Maintenance work can be described as preventive, corrective or emergency. Preventive maintenance can be either routine (e.g. time based operations such as operating and lubricating gates, cleaning pressure relief drains) or condition based (e.g. repairing concrete, painting). Routine maintenance should be scheduled in the Operations and Maintenance Manual and in the owners maintenance management system if applicable. It should also be properly controlled and recorded in a data book / base. Condition based maintenance should be identified, scheduled and budgeted for annually. Where the owner's resources are limited, condition based maintenance may be prioritized according to a risk assessment across the owner's dam portfolio and other assets.

Financial provision should be made for corrective and emergency maintenance to cover the unforeseeable repair of assets that have suddenly deteriorated or failed (e.g. blockage of a piezometer, flood damage).

## 7.4 Operations and Maintenance Manual

### 7.4.1 General

All dams should have Operations and Maintenance Manuals. The level of documentation should be commensurate with the hazards posed by the dam. This document should be compiled by an Approved Dam Engineer with sufficient knowledge.

The Operations and Maintenance Manual for a dam should be prepared in order to collect in one document, with possible associated supporting documents or other information, the complete, accurate and up-to-date operating, maintenance and overhaul instructions for the dam and its appurtenant structures. Its purpose is to ensure adherence to approved operating procedures regardless of the passing of time and changes in operating personnel. The instructions also enable responsible persons unfamiliar with conditions at the particular dam to operate the dam during an emergency situation or at such other times as may be necessary.

The Manual is prepared primarily for the dam operations staff and their supervisors who are assigned the responsibility for the physical operations and maintenance of the dam. It should contain, as a minimum, all information and instructions necessary for them to perform their allotted tasks. In addition to instructions for dam operations staff, the Manual should include all necessary instructions for other staff with a direct or indirect interest in operating and maintaining the dam. Care must be taken to ensure that the language and form of the Manual is suitable for the use of those responsible for each part of the operations and maintenance.

This might require a different form for some parts of the Manual.

It is essential that the Manual or at least a draft of the Manual be available prior to the initial filling of the reservoir. It should include all available information at the time. Where existing and new dams are without Manuals, the fact should be noted as a deficiency in the first convenient report on the dam such as a Comprehensive (Surveillance) or Safety Review Report.

### 7.4.2 Structure of Manual

The Manual should be structured into:

- General Information (such as background, administration, responsibilities and supporting documentation);
- Operating Procedures and Maintenance Procedures;
- Reservoir and Spillway Operations;
- Dam Safety and Surveillance; and
- Responsibility, Accounting and Reporting.

An outline of a typical Manual is provided in Appendix A.

Those components of a dam, and operating or maintenance procedures which are critical to the safety of the dam, users of the dam and other people, businesses or infrastructure that may be directly impacted by the operation of the dam should be specially identified in the Manual.

For example:

- Where public have access to the dam structure or water surface there needs to be properly maintained personal safety features (e.g. barriers, warning signs, life buoy, etc); and
- Where a road, house or business interest may be flooded by the opening of a gate or scour, there needs to be an appropriate warning communication.

The Operating Procedures should contain the detailed information required by a dam operator to ensure proper and safe operation of the dam and its associated structures and equipment.

Procedures for performing preventive maintenance should be given in detail, so that new personnel can understand the task and experienced personnel can verify that they have completed the work properly.

### 7.5 Maintenance

A maintenance program based primarily on systematic and frequent inspections should be developed for all dams. A proper and regular or timely maintenance program is essential in ensuring the prolonged life and safety of a dam. Poor maintenance could result in major repairs and ultimately failure.

An Operations and Maintenance Log should be provided (as part of the database / book) at all dams and entries should be periodically verified by the dam owner or his suitably qualified representative to ensure compliance with authorized procedures and instructions set out in the Manual.

Operations and Maintenance Manuals should be "controlled" documents and dam owners should ensure that all relevant personnel have copies which are current and that no unauthorized (uncontrolled) copies are used in the operations of the dam. Records should be kept of the location and status of each "controlled" copy of the Manual. Manuals should be reviewed (and, if necessary, updated) at 5 yearly intervals or when circumstances change.

### 7.6 Emergency operation requirements

In case of imminent danger or of a major accident, corrective action must be taken immediately and independently of normal administrative procedures. Enough authority should be vested in the operator's top level technical personnel to order emergency preventive or repair measures without asking for special authorization from management.

Clear and easily understandable emergency instructions should be issued to all operating units and stations. These emergency instructions, which must include a definition of the supervising units authorized or obliged to issue orders under emergency conditions should be easily accessible. The need for updating should be checked periodically and always after institutional, operational and administrative changes. Copies of emergency instructions should be available in the office and home of each person involved in an emergency operation assignment. These should also be included in the formal emergency action plan for the dam.



The proper functioning of emergency equipment should be checked at intervals to be established in relation with the importance, complexity and reliability of every item.

Operating staff should be trained and periodically retrained in emergency operations. Training programs and procedures should be updated in accordance with advancing technology and alterations introduced in the emergency action plan.

### 7.7 Incidents and accidents

Incidents and accidents, their causes, and their consequences should be investigated. The results and findings of such an investigation should be recorded in a formal report and made available to all parties involved in the safety surveillance scheme. If the findings are of general importance, the owner should consider publishing the report as a contribution to dam safety, to assist in avoiding repetition of mistakes or errors or eliminating conditions that could lead to the same kind of incident or accident at other dams or reservoirs.

If any part of a dam has been damaged by an incident or accident, it must be restored to a safe operating condition as quickly as possible.

## 8. SURVEILLANCE & MONITORING

### 8.1 Principles

Continuous surveillance and monitoring of the performance of dams to minimise the risk of dam failures and to provide adequate warning of potential or impending failures is an essential part of a dam safety program.

A Dam Safety Surveillance and Monitoring Plan (SMP) based on the principles presented in this section shall be developed and implemented for all dams with a safety risk and a Potential Consequences Classification (PCC) of LOW or higher. The SMP shall be based on the results of PFMA and identify key performance parameters and developed to apply to the particular phases of the dam life cycle, such as construction, initial filling, normal operation, etc. and updated periodically as the operation and conditions evolve.

This section presents:

- Performance monitoring principles and methods used to aid in routine surveillance and evaluation of a structure at all stages of its lifetime; and
- Performance monitoring procedures and principles for a number of common adverse responses or conditions that typically are indicators or contributors to potential failure modes.

The next section, Section 10, presents principles and procedures for periodic and special safety reviews.

These basic principles and procedures provide general guidance which shall be made specific for an individual dam for the potential failure modes identified as part of the PFMA process.

In addition, any requirements for “General Health Monitoring” independent of an identified potential failure mode should be identified for monitoring the general health of a dam. Recommendations made by the Approved Dam Engineer with respect to the SMP are actionable items should be included in the final recommendations section of the Safety Review Report. The adverse responses and conditions and the companion monitoring procedures and principles described in this guideline should not be considered as complete, as each dam will have its own characteristics. All combinations of failure, and particularly operating conditions that may present more complex potential failure modes and failure scenarios, must be developed and the appropriate means for monitoring these unique or complex potential failure modes established.

The causes and processes of dam failure are varied. The knowledge gained from previous dam failures has contributed to the advance of specialized knowledge essential to the prevention of future failures. Case histories of dam incidents reveal many remarkable similarities in antecedent conditions and processes of deterioration. Often deficiencies have developed over extended periods of time, yet these conditions have either gone undiscovered or were incorrectly appraised. Surveillance programs should be capable of detecting such conditions and processes early enough for corrective measures to be taken.

Surveillance and monitoring programs should commence as early as possible in the life of the dam (preferably during the construction phase), to detect the development of any problem or unsafe trends and to provide full background information on the dam’s performance.

All dams should have an appropriate surveillance program. The scope of the surveillance program should be based on the consequences of dam failure, the level of risk at the dam, the type and size of the dam, and the value of the dam to the dam owner.

Generally, low consequence dams, that do not threaten life or property, need less surveillance. However an appropriate surveillance program for these dams can generally be implemented at small cost and potentially lowers the dam owner's business risk (e.g. loss of water, dam failure).

Approved Dam Engineers, in conjunction with the Regulator, should be consulted on the nature and extent of appropriate surveillance programs for each dam which shall be documented in a Surveillance and Monitoring Plan (SMP) which should include:

- Inspections;
- Monitoring;
- Collection of other information relating to dam performance (eg. investigation, design and construction reports);
- Evaluation and interpretation of observed data and other information;
- Data file management and security;
- Surveillance and Monitoring Reports (SMR); and
- Independent review of the surveillance and monitoring program.

## 8.2 Purposes of Inspections

Dam safety inspections are a key part of the surveillance programs and should be conducted to determine the status of the dam and its features in terms of its structural and operational safety. Different levels of inspection are required for different purposes. Four general levels of dam safety inspections are recommended (see Table 7).

"Comprehensive Inspections" will normally be undertaken in conjunction with Comprehensive Safety Reviews.

"Intermediate Inspections" are undertaken between Comprehensive Safety Reviews. These concentrate on recording any activities, changes to programs, and evaluations of surveillance data since the last Safety Review including the Routine Visual Inspections.

"Routine Visual Inspections" usually comprise daily to weekly visual observations of the dam by the operator.

"Special or Emergency Inspections" will be an essential first step of any Special Safety Reviews.

Some details of inspection procedures and practices are provided in Appendix B.

Inspections should be carried out by experienced people, trained to recognize deficiencies in dams. Inspections, requiring technical evaluations, should generally be carried out by a dam engineer, and other specialists. However, the detection of many deficiencies is not beyond the capability of trained operations personnel. Dam owners should ensure that all operational personnel are suitably trained and are aware of the consequences of failure of the dam and of the deficiencies that have been found in similar dams. Table 6 summarizes the main types and purposes of inspections.

Table 6: Dam Safety Inspections

| Type of Inspection  | Personnel   | Purpose   |
|---------------------|---|---|
| Comprehensive       | Approved Dam Engineer and Specialists <sup>1</sup> (where relevant) | The identification of deficiencies by a thorough onsite inspection by evaluating surveillance data and detailed visual inspection normally as part of a Comprehensive Safety Review.<br><br>Equipment should be test operated to identify deficiencies.   |
| Intermediate        | Dam engineer  | The identification of deficiencies by visual examination of the dam and review of recent surveillance data, with recommendations for corrective actions.<br><br>Equipment is inspected and, preferably, test operated.                                    |
| Routine Visual      | Operations Personnel  | The identification and reporting of deficiencies by visual observation of the dam by operating personnel as part of their duties at the dam.  |
| Special / Emergency | Approved Dam Engineer and Specialists <sup>1</sup>                  | The examination of a particular feature of a dam for some special reason (e.g. after earthquakes, heavy floods, rapid drawdown or any other emergency situation) as part of a Special Review to determine the need for pre-emptive or corrective actions. |

Note: Examples of specialists include mechanical and electrical engineers, to inspect outlet works, spillway gates and automated systems.)

### 8.3 Frequency of Inspection

The frequency of inspections should be established by taking into account the consequences of dam failure, the level of risk at the dam, the type and size of the dam and the value of the dam to the dam owner and the community. As a guide, the frequency of inspections for a dam considered to be in sound condition with no deficiencies should be according to the Potential Consequences Classification (PCC) as shown in Table 7. More frequent inspections may be necessary where a dam is known to have some form of deficiency. Less frequent routine visual inspections may be appropriate for particular types of dams, such as retarding basins that are normally empty. However, this would be balanced by the need to inspect these basins after/during significant storm events.

Operating personnel familiar with the dam should be made available to contribute to all Approved Dam Engineer inspections and to foster the potential educational and training aspects of the inspection program. Taking into consideration the technical capacity of dam owners and lessons learned from existing dam safety assessments the following frequency of inspection is recommended.

Table 7: Frequency of Inspection

| PCC              | Inspection Type                 |                    |                        |                   |
|------------------|---------------------------------|--------------------|------------------------|-------------------|
|                  | Comprehensive                   | Intermediate       | Routine Visual         | Special/Emergency |
| HIGH & VERY HIGH | On first filling then 5 Yearly  | Annual             | Daily                  | As required       |
| MODERATE         | On first filling then 5 Yearly  | Annual to 2-Yearly | Twice Weekly to Weekly | As required       |
| LOW              | On first filling then 10 Yearly | 2-Yearly           | Monthly                | As required       |

Note: Dam owners may undertake a review to determine if a reduced or increased frequency of inspection is acceptable. The review should be carried out by an Approved Dam Engineer and take into account such matters as Regulator requirements, dam hazard and risk, type and size of dam, dam failure modes and monitoring arrangements.

### 8.4 Conduct of Inspections

All inspections should be systematically organized so that the status of all critical aspects of the dam can be evaluated and accurately recorded. Field inspection checklists should be drafted as part of the design or safety review process. Inspectors must be aware of the relationship between features being observed and possible deficiencies associated with them.

Reference to previous inspection reports should be made before carrying out an inspection. Appendix B provides further detail on matters to be considered in formulating inspection programs. Excellent training aids on preparation for dam safety inspections are available (FEMA, 1987) and (FEMA, 1990). In addition, several accredited Water Operators' training packages are available through the Training Aids for Dam Safety system of FEMA (1990), or are in preparation, to provide competency-based training in dam safety surveillance.

### 8.5 Inspection Reports

All dam safety inspections should be fully documented by the inspecting personnel to provide an ongoing record of the condition and any observable trends of the dam and its appurtenances to provide the basis for recommended action by the dam owner. Inspection reports should be signed off, as appropriate, and kept securely and should be readily available for review as required.

Routine inspection reports should be written up on specifically drafted report sheets that cover the relevant details of the dam (see Appendix B).

A summary at the start of each intermediate and comprehensive report should identify items needing urgent attention, along with recommendations on actions required. While these reports will contain subjective interpretations of visual observations, they should be kept as factual as possible and must be prepared by the inspecting personnel. All reports should be prepared using a similar format and structure. Guidance on report preparation can be found for example in the training module "Documenting and Reporting Findings from a Dam Safety Inspection" (FEMA, 1990)

### 8.6 Monitoring

Dam monitoring is one means of determining trends in structural performance. This process consists of the collection, recording, analysis and presentation of data from measuring devices installed at or near dams. The items that need to be monitored, and the relevant associated instrumentation in the dam, should be identified by the PFMA and approved by the Approved Dam Engineer undertaking the safety review of the dam and based on the results of the Potential Failure Modes Analysis. The instruments

should monitor the key performance parameters that provide early warning of the development of the identified potential failure modes.

Threshold and Action limits should be developed for all key performance parameters and the criteria used to develop them should be documented. A Threshold value is the value used in the analysis or design, or is established from the historic record. An Action Level is the instrument reading that triggers increased surveillance or an emergency action. Threshold and Action limits should be established based on the specific circumstances. In some cases, they can be based on theoretical or analytical studies (e.g. uplift pressure readings above which stability guidelines are no longer met). In other cases, they may need to be developed based on measured behaviour (e.g. seepage from an embankment dam). Sometimes they may be used to identify unusual readings, readings outside the limits of the instrument's historic range, or readings which, in the judgment of the responsible engineer, demand evaluation. Both magnitude and rate of change limits may need to be established. If trends or inter-relationships between data are not clear, it may be appropriate to take more frequent measurements or collect additional complementary data. All data should be compared with design assumptions. For example, measured phreatic levels and uplift pressures should be compared against those used in stability analyses. If data are available for unusual load cases, such as rapid drawdown and floods, they should be compared with assumed pressures.

The dam engineer conducting the surveillance program should ensure that the maintenance and appropriate modification of the monitoring system is carried out. The dam owner is responsible for resourcing the activities.

Modern technology can greatly enhance traditional monitoring methods. It provides the opportunity to collect and analyze dam performance information in real time or historically through electronic data logging. Technology supplements, but does not replace, site surveillance. The value of employing technology should be considered when developing or reviewing a surveillance program. Electronic data should be compared regularly, where possible, with manual readings to check data quality.

Some of the items to be monitored include:

- Reservoir water levels, which provide a record of the loadings on the dam;
- Seepage, which may be measured at any point on the dam, abutments, or reservoir rim or even well downstream of the dam, and is probably the best indicator of a dam's performance;
- Rainfall (at dam and in catchment), which may relate to the amount of seepage;
- Pore-water pressures and water table levels, which may be related to seepage, reservoir level and rainfall;
- Surface and internal movements;
- Stresses, which may be measured in embankments or structural concrete;
- Stresses in post-tensioning anchor cables; and

- Seismic events, which may be measured on a regional or local basis by owners who elect to instrument their dams for seismic response. Interpretation and maintenance of this monitoring should preferably be conducted by a seismologist.

## 8.7 Frequency of Observation

The frequency of monitoring should be determined by taking into account the consequences of dam failure, the level of risk at the dam, the type and size of the dam, and the value of the dam to the dam owner and the community. The higher the hazard and risk, the more frequent the monitoring.

During the construction and initial filling stages, monitoring should be more intense than during the operational phase to provide early warning of adverse developing situations as the dam experiences initial loadings. In addition, during prolonged draw downs and subsequent refilling, close monitoring should be undertaken to determine any deleterious effects of drying out of dam embankments, cores, foundations and abutments.

After special events, such as large floods, rapid draw downs and earthquakes, more intense monitoring should be undertaken. Also more frequent monitoring should be undertaken if any adverse trend develops.

As a guide, the frequency of observations should be determined initially by the Approved Dam Engineer (preferably in conjunction with the dams engineer responsible for long term surveillance). However, the dam engineer responsible for surveillance should regularly review the monitoring program. Typically this should be done in conjunction with the comprehensive inspections.

The frequencies shown in Table 8 are a guide for dams that are “in service” and have no known deficiencies.

Table 8: Guide for “In Service” Dam Monitoring Frequencies

| Monitoring                                | Potential Consequence Classification (Pcc) |  |                            |
|---|--|--|----------------------------|
|   | Low  | Moderate                                 | High & Very High           |
| Meteorological data                       | Monthly                                    | Twice Weekly to Weekly (TC) <sup>2</sup> | Daily (TR) <sup>2</sup>    |
| Storage Level                             | Monthly                                    | Twice Weekly to Weekly (TC) <sup>2</sup> | Daily (TR) <sup>2</sup>    |
| Seepage                                   | Monthly                                    | Twice Weekly to Weekly (TC) <sup>2</sup> | Daily (TR) <sup>2</sup>    |
| Chemical analysis of seepage <sup>5</sup> |  | Consider                                 | Consider                   |
| Pore pressure <sup>3</sup>                | Consider                                   | 3-Monthly to 6-Monthly                   | Monthly to 3 Monthly       |
| Surface movement, control <sup>4</sup>    |  | Consider                                 | 5-Yearly                   |
| Surface Movement, Normal                  | Consider                                   | Consider                                 | Yearly                     |
| Internal movement/stresses <sup>3</sup>   |  | Consider                                 | Yearly                     |
| Seismological <sup>3</sup>                |  | Consider                                 | Consider (TR) <sup>2</sup> |
| Post tensioning <sup>6</sup>              |  | 10-Yearly                                | 5-Yearly                   |

**Note 1:** These frequencies may need to be varied according to the conditions at, and the type and size of dam, and applies to instrumentation already installed at the dam.

**Note 2:** The frequencies quoted assume manual reading of the instrumentation. Where automated readings are available more frequent reading would be appropriate (TR-telemetry recommended) (TC-telemetry to be considered).

- Note 3:** The frequency of reading and location of the monitoring instruments need to be at the discretion of the dam's engineer. Seismological instruments, where installed, are recommended to be incorporated into state-wide seismic networks.
- Note 4:** A control survey uses monuments that are remote from the dam site to check the location of the survey monuments at the dam site.
- Note 5:** Recommended annually for concrete dams, tailings dams and embankments constructed from, or on, potentially dispersive materials where specified by the Approved Dam Engineer or safety reviewer.
- Note 6:** Preferably all cables, but at least a significant representative sample, to be monitored.

## 8.8 Principles of Monitoring

The purpose of instrumentation and monitoring is to maintain and improve dam safety by providing information to 1) evaluate whether a dam is performing as expected and 2) warn of changes that could endanger the safety of a dam.

Instrumentation and monitoring, combined with vigilant visual observation, can provide early warning of many conditions that could contribute to dam failures and incidents. For example, settlement of an embankment crest may increase the likelihood of overtopping; increased seepage or turbidity could indicate piping; settlement of an embankment crest or bulging of embankment slopes could indicate sliding or deformation; inelastic movement of concrete structures could indicate sliding or alkali-aggregate reaction.

Detailed guidelines on monitoring and surveillance are provided in various references ICOLD publications (1989, 1992, 2000, 2009 & 2012b). In addition, a number of principles are provided in Appendix B.

## 8.9 Data File

The "data file" encompasses the documentation of investigation, design, construction, operation, maintenance, surveillance, remedial action, as well as all monitoring measurements. The safe long term maintenance and availability of the data file is of high importance and great care should be taken to preserve the data intact and readily available for future normal or emergency uses.

Much of the information will never be changed and is suitable for reduction and permanent storage electronically with backups. Sufficient information should be kept on hand in a data book / base in easily accessible form to meet any situations which could arise. Some data items, which change with time, are derived from dam safety surveillance, monitoring, operations and maintenance activities. Such data should be accumulated in the inspection and comprehensive (surveillance) reports.

## 8.10 Surveillance Evaluation and Reporting

Surveillance and Monitoring Reports (SMR) should be prepared periodically based on the Surveillance and Monitoring Plan (SMP). The SMR shall include a thorough evaluation of the up to date monitoring results and previous inspection reports. One of the main purposes of the SMR is as source document for the comprehensive and intermediate inspections as it is important to have a detail understanding of the monitoring results and the previous inspection results to focus these inspections. There are the following



three types of Surveillance and Monitoring Reports:

- **Comprehensive SMRs:** Those to be compiled for use during the comprehensive safety inspections of the comprehensive safety reviews. These reports should include the comprehensive reviewing and evaluating the performance of a dam with a view to stating whether or not the dam is considered to be safe. The report should summarize and extend previous reports to provide a clear picture of long-term trends. The reports should be prepared by An Approved Dam Engineer or appropriate specialist with the relevant experience;
- **Intermediate SMRs:** Those to be compiled for use during the intermediate safety inspections. For VERY HIGH and HIGH PCC dams these reports should be prepared by An Approved Dam Engineer or appropriate specialist with the relevant experience. For other PCC dams these reports should be compiled by an appropriately trained engineer involved with the inspections who is familiar with the detailed history of the dam including criteria and limitations used in design and sound knowledge of performance of the dam up to the present;
- **Special SMRs:** Those to be compiled for use during special the comprehensive safety inspections of the specials safety reviews. The detail contained in these reports is similar to the Comprehensive SMRs. The reports should be prepared by An Approved Dam Engineer or appropriate specialist with the relevant experience;
- Evaluation is an important step where decisions affecting the safety and operation of the dam are made. Many dam deficiencies are detected by visual inspections. There are cases where instrumentation has not detected problems that are known to exist. There are also situations where an instrument may indicate an anomaly but no visual distress can be seen. It is however important to have an idea from the results of the monitoring as well as observations made during previous inspections where possible problems exist.

The frequency of the different Surveillance and Monitoring Reports (SMR) shall be as shown in Table 9.

Table 9: Frequency of Surveillance and Monitoring Reports (SMR)

| PCC              | Inspection Type                 |                    |             |
|------------------|---------------------------------|--------------------|-------------|
|                  | Comprehensive                   | Intermediate       | Special     |
| HIGH & VERY HIGH | On first filling then 5 Yearly  | Annual             | As required |
| MODERATE         | On first filling then 5 Yearly  | Annual to 2-Yearly | As required |
| LOW              | On first filling then 10 Yearly | 2-Yearly           | As required |

**Note:** Dam owners may undertake a review to determine if a reduced or increased frequency of inspection is acceptable. The review should be carried out by an Approved Dam Engineer and take into account such matters as Regulator requirements, dam hazard and risk, type and size of dam, dam failure modes and monitoring arrangements.

### 8.11 Independent Audit or Peer Review

The dam owner should obtain an independent audit, sometimes referred to as a “Peer Review” of the dam’s surveillance and monitoring program at regular intervals (e.g. 10-yearly).

The purpose of such an audit is to assess the continuing appropriateness of the dam monitoring and inspection programs and the adequacy of surveillance evaluation and reporting. It should determine the extent to which the current dam safety procedures and practices meet the dam owner’s obligations and/or specified requirements and should provide the dam owner with independent assurance that appropriate resources are committed to the program and that sound technical practices are in place. The audit should be undertaken by an Approved Dam Engineer who is independent of the on-going surveillance program.

## 9. SAFETY REVIEWS

### 9.1 Purpose

No dam can be considered one hundred percent safe as there will never be a complete understanding of the uncertainties associated with natural and manmade destructive forces, material behaviour and construction processes. The dam owner must therefore ensure uncertainties are balanced with competent technical judgment.

A Safety Review is a procedure for assessing the safety of a dam, and comprises, where relevant, a detailed study of structural, hydraulic, hydrologic and geotechnical design aspects and of the records and reports from surveillance activities. The purposes of various types of review are summarized in Table 10.

Table 10: Dam Safety Reviews

| Type of Safety Review | Personnel   | Purpose  |
|-----------------------|---|--|
| Comprehensive         | Approved Dam Engineer and Specialists <sup>1</sup> (where relevant) | <p>The Comprehensive Report should be done in conjunction with a Comprehensive Inspection. The identification of deficiencies by a thorough onsite inspection by evaluating surveillance data; and by applying:</p> <ul style="list-style-type: none"> <li>• Current criteria and prevailing knowledge.</li> <li>• The results of a PFMA</li> </ul> <p>Equipment should be test operated to identify deficiencies.</p> <p>For a Safety Review consider:</p> <ul style="list-style-type: none"> <li>• Draining of outlet works for internal inspection.</li> <li>• Diver inspection of submerged structures.</li> </ul> |
| Special / Emergency   | Approved Dam Engineer and Specialists <sup>1</sup>                  | <p>The examination of a particular feature of a dam for some special reason (eg. after earthquakes, heavy floods, rapid drawdown, emergency situation) to determine the need for pre-emptive or corrective actions.</p>  |

**Note:** Examples of specialists include mechanical and electrical engineers, to inspect outlet works, spillway gates and automated systems.)

As part of the safety reviews, the Dam Safety Engineer shall assess the Potential failure Modes Analysis (PFMA), the Surveillance and Monitoring Plan (SMP) and the Emergency Action Plan (EAP) for the dam and project as a whole or develop them if they don't exist.

A Safety Review should assess the integrity of a dam against potential failure modes (PFMs) and mechanisms for the various types of dams in terms of safe acceptance criteria (engineering standards, dam safety guidelines) or risk management criteria. A report is produced to document the Safety Review and to recommend remedial or maintenance work. Dam owners may use risk informed decision making (RIDM) techniques with Safety Reviews to determine the urgency and extent of works and to prioritize remedial works within their portfolio of dams. A safety review should be performed by an Approved Dam Engineer.

## 9.2 When to Undertake a Safety Review

Safety Reviews are required by a dam owner as an independent and external examination to satisfy the dam owner or regulator as to the dam's safety. Periodic Safety Reviews shall normally be performed at intervals ranging from 5 to 10-years (depending on risk level, PCC and technology changes) are considered appropriate. Typically dams with a PCC of MODERATE to VERY HIGH require safety reviews every 5 years while the dams with lower PCCs only require safety reviews every 10 years.

The requirement for a Special Safety Review may be based on a deficiency or weakness identified during the surveillance program or by other means. It may also be initiated due to the age of the dam, or by a change in accepted standards of adequacy, PCC or technology, or changes in arrangements at the dam.

A Special Safety Review may be required at short notice if any inspections, monitored results or unusual events such as flooding, earthquake or landslide indicate that an adverse trend or condition exists. A Special Safety Review may also be undertaken as part of progressive / continuous improvement of a risk assessment process or to update the risk profile of a dam.

The frequency of Safety Reviews shall be as shown in Table 11.

Table 11: Frequency of Safety Reviews

| PCC              | Comprehensive                   | Special     |
|------------------|---------------------------------|-------------|
| HIGH & VERY HIGH | On first filling then 5 Yearly  | As required |
| MODERATE         | On first filling then 5 Yearly  | As required |
| LOW              | On first filling then 10 Yearly | As required |
| REMOTE           | On first filling then 10 Yearly | As required |

**Note:** Dam owners may undertake a review to determine if a reduced or increased frequency of inspection is acceptable. The review should be carried out by an Approved Dam Engineer and take into account such matters as Regulator requirements, dam hazard and risk, type and size of dam, dam failure modes and monitoring arrangements.

## 9.3 Personnel

The personnel engaged in such Reviews should be Approved Dam Engineers suitably experienced in dam safety reviews. Where necessary, the services of a specialist supporting including for example suitably experienced geologists, hydrologists, risk assessment analysts and other specialists should be utilized.

## 9.4 Safety Review Report

Background information should first be collected. This includes all relevant historical investigation, design, construction, commissioning, remedial, operation and maintenance, monitoring and inspection data.

The performance of the dam is then addressed in terms of the results of the PFMA and compared with the standards and criteria set by the Approved Dam Engineer and the relevant standards and guidelines existing at the time of review. The design standards and criteria should be evaluated for correctness and

relevance. If a design standard is not available or known for the dam, the Review should include a prediction or assessment of the theoretical performance of the dam.

Updating of the PFMA and any other risk assessment studies should also be undertaken as part of the Review. When assessing a dam's safety, care should be taken to view the dam in its entirety. It should be realized that results of various features being monitored can often have little significance when considered alone, but when viewed in conjunction with other monitored results or observations, can have significant meaning.

Before conclusions relating to a dam's safety can be satisfactorily drawn, further investigation may be required. Where insufficient plans or data exist, the dam may have to be surveyed and new plans drawn, or sampling and testing of materials in the dam and its foundations, geotechnical drilling and mapping and calculation of new design flood, or revised earthquake loadings may be required. Particular attention should be given to changes in land use that may have occurred since construction of the dam. This includes such activities as mining, urbanization or clearing of the catchment area. Attention should also be given to changes in developments downstream of the dam which may be affected by, or influence unusual releases from the dam. It is of utmost importance that an appropriate survey be conducted during each review to confirm the current free board available at the dam.

For older dams the Review may require more extensive investigations because of lack of data, change in design criteria (e.g. uplift under a concrete dam, additional flood or earthquake data) and deteriorating conditions due to inadequate maintenance or for other reasons, such as siltation.

Conclusions should be drawn, where relevant, regarding the adequacy of the main features of the dam (i.e. foundations, main wall, spillway, outlet works, associated equipment and monitoring system). Comments should also be made regarding the frequency of inspections, surveillance program, and operation and maintenance procedures. Such comments and conclusions should take into account modern developments in hydrology, hydraulics, geotechnical engineering, engineering geology, structural analysis and design criteria relating to dams.

Details of the Review should be outlined in a report. The amount of detail in a Safety Review Report will depend on the consequences of failure of the dam. The report should include a summarized statement on the safety of the dam indicating whether or not the dam is in a acceptable condition for continued operation, its risk status, and what remedial or emergency action should be carried out and when to rectify any deficiencies in the dam. The report should also indicate remedial options and preliminary estimates of cost. The report should conclude with a bibliography and appendices detailing all relevant reference material, photographs, drawings, data plots, inspection reports, test results and any other information which relates to the dam's safety.

Appendix C shows a suggested procedure for the Dam Safety Review, together with a sample checklist of matters to be considered in the review.

Typically the following issues should be addressed in the report:

- Physical details of the dam;
- A review of the dam's PCC;
- Observations during the inspection;
- What has occurred since the previous inspection (eg. incidents, actions arising from recommendations made previously and other actions);
- A review of the PFMA Report;
- Comment on the acceptability of operations and maintenance procedures and manuals (O&M MANUAL);
- Comment on the acceptability of the surveillance and monitoring plans (SMP);
- A review of performance as indicated by operational and surveillance data and the Surveillance and Monitoring Reports (SMR) since the previous inspection with respect to identified potential failure modes and key performance parameters as well as general health indicators;
- A review of monitored data and other information. (What are the issues being addressed? Is the SMP effective? Does the surveillance program need to be altered?);
- An evaluation of discharge equipment, gates and outlets and flood handling capability;
- An evaluation and interpretation of the structural performance and stability of the structures;
- Comment on the acceptability and potential effectiveness of the emergency action plan (EAP);
- A statement on the assessed safety risk of the asset against current standards;
- The need for any additional investigations, remedial actions or risk reduction measures;
- A statement on whether the dam is in an acceptable condition for continued operation; and
- A statement on the adequacy of the dam safety programme.

A summary should be included to provide a comprehensive statement of the report findings and recommendations.

## 10. DAM SAFETY EMERGENCY PLANNING

### 10.1 Dam Safety Emergency Action Plans

The design, construction, operation, maintenance and surveillance of dams will minimize the risk of dam failures. However, conditions or incidents that could result in dam failure or damaging releases of their storages do occur. Therefore, it is prudent for dam owners to identify conditions which could lead to these situations, and for dam safety emergency planning to be put into effect to mitigate the consequences of such events.

Two types of emergency plans are required:

- A Dam Safety Emergency Action Plan should be developed by an Approved Dam Engineer for the dam owner; and
- A separate Disaster Plan, developed by appropriate State or local emergency management agencies to provide protection for downstream communities in the event of a dam safety emergency.

It is important that these two plans be linked in a compatible way.

Dam Safety Emergency Action Plans should exist for all dams where there is the potential for loss of life in the event of dam failure. A Dam Safety Emergency Action Plan (EAP) is a formal plan that:

- Identifies emergency conditions which could endanger the integrity of the dam and which require immediate action;
- Prescribes procedures which should be followed by the dam owner and operating personnel to respond to, and mitigate, these emergency conditions at the dam; and
- Provides timely warning to appropriate emergency management agencies for their implementation of protection measures for downstream communities.

The plan should list actions that the owner and operating personnel should take if an incident or emergency develops. Each plan must be tailored to site-specific conditions and the requirements of the dam owner and consider all credible potential failure modes. Careful research, a thorough potential failure modes assessment (PFMA) and coordinated planning with all involved parties will lay the foundation for a responsible and thorough EAP.

The process of developing an EAP generally involves some or all of the following actions:

- Carrying out a Potential Failure Mode Analysis (PFMA) to identify Potential Failure Modes (PFM) that could result in dam failures and assess the likelihood of their occurrence;
- Determine and identify those conditions that could forewarn of the development of a PFM leading to an emergency and specify the actions to be taken, and by whom;
- Inundation mapping to identify the extent, depths and potential impacts of flooding that may occur in the event of a dam break;
- A threat and vulnerability assessment of a dam can assist in preparing an EAP. This is likely to be a Government requirement for owners of assets critical to the community;

- Identify all jurisdictions, agencies, and individuals who could be involved in the EAP.
- Co-ordinate the development of the EAP with these parties;
- Identify primary and back-up communication systems, both internal (between persons at the dam) and external (between dam personnel and outside entities);
- Identify all necessary dam safety resources, tools, equipment, and keys, and where they can be located, if required in an emergency;
- List and prioritize all persons and entities involved in the notification process, and draft a Notification Flowchart;
- Develop a draft of the EAP;
- Hold meetings with all parties (including emergency management agencies) included in the notification list for review and comment on the draft EAP;
- Make any revisions, obtain the necessary plan approval, and disseminate the EAP to those who have responsibilities under the plan; and
- Test and revise the EAP at regular intervals.

## 10.2 Disaster Plans

Plans should be developed for the timely flood evacuation of communities below all dams where there is the potential for loss of life in the event of dam failure, as part of the overall disaster planning for communities.

In this context, the generic terms "Disaster Plan" or "Flood Plan" refers to the plan or hierarchy of plans developed by relevant Regional Disaster preparedness agencies or authorities to provide for the protection of communities downstream of a dam.

## 10.3 Responsibilities

The dam owner should:

- Develop and maintain a dam safety emergency action plan for all dams where there is the potential for loss of life in the event of dam failure;
- Determine the area, height, rate and timing of potential inundation from relevant dam break floods downstream of the dam;
- Establish and resource a warning / communication system for the timely notification, to operating personnel and emergency authorities, of impending / actual emergencies;
- Provide relevant State, or local, emergency management agencies with details of dam safety emergency response actions (e.g. water releases) and their downstream effects;
- Liaise regularly with emergency agencies to coordinate and maintain appropriate emergency planning arrangements. Ensure personnel with responsibilities under the plan have access to controlled copies of the plan; and
- Regularly update and periodically test the plan.



Regional Disaster preparedness authorities may have separate guidelines for the preparation of Disaster Plans.

#### 10.4 Preparation and Maintenance of Dam Safety Emergency Action Plans

Guidelines and training literature for the preparation of EAP's are contained in the References FEMA (1987) and FEMA (1990).

Upon completion of a first draft of the EAP, it should be reviewed to evaluate its workability and comprehensiveness, and to make sure that nothing has been overlooked. It should then be signed off by all involved agencies and controlled copies distributed.

Even after the EAP has been developed, approved and distributed, the job is not done. Without periodic maintenance and consultation with emergency authorities, the EAP will become outdated, lose its effectiveness, and no longer be workable. If the plan is not tested, those involved in its implementation may become unfamiliar with their roles.

If the plan is not updated, the information contained in it may become outdated and useless.

##### 10.4.1 Testing the Plan

It is essential that an EAP be tested periodically by conducting a drill simulating emergency conditions. Testing is necessary to train participants, as well as to identify weaknesses in the plan. For HIGH and VERY HIGH PCC dams (and dams with recognized deficiencies), an annual in-house review is recommended for dam owner personnel and, at least once every five years, a drill (e.g. field or desk top) should be conducted that is co-ordinated with all State and local counter disaster officials having downstream planning responsibilities in association with the EAP.

Lesser testing frequencies could be implemented for other dams, depending on the risks involved, but a drill at least every ten years is recommended.

For a dam owner with a number of dams, particularly dams that are grouped in one area or are of one particular type, the requirement to exercise the EAP of every dam at the frequency suggested above may be onerous. For such owners it may be possible to trial the EAP of one dam that is typical of the group of dams, with its operations staff, and use the opportunity to train the other operations staff in the area as well.

Immediately following a test or actual emergency, a critique should be conducted with all involved parties. The critique should discuss and evaluate the events prior to, during, and following the test or actual emergency, actions taken by each participant, the time required to become aware of an emergency and implement the EAP, deficiencies in the plan, and what improvements would be practicable for future emergencies. After the critique has been completed, the plan should be revised, if necessary, and the revisions disseminated to all involved parties.

##### 10.4.2 Updating EAP Plans

It is recommended that emergency contact numbers in all EAP s be updated at least annually. In addition to regular testing, a periodic review of the overall plan should be conducted to assess its workability and efficiency (i.e., timeliness), and to plan for the improvement of weak areas. This includes such aspects as a periodic review of the downstream area to identify changes or new developments that might affect the

priority of notification and evacuation and the information shown on inundation maps. Again, once the plan has been revised, the updated version (or simply the affected pages) should be distributed to all involved parties. It is recommended that, for HIGH and VERY HIGH PCC dams, the entire EAP be reprinted and distributed to all parties at least every five years and ten yearly for other dams.

#### 10.4.3 Trans-boundary Coordination of Emergency Warning Systems

An emergency warning system for the river valley downstream of the uppermost dam should be set up through direct cooperation of the government agencies of all countries, states or provinces involved. The regulator may delegate all or part of this task to a working group or special commission but should remain responsible for guidance and overview and for formal representation.

If a dam and reservoir under design should require the adaptation or modification of existing emergency warning systems in other countries, states or provinces, the owner and the Approved Dam Engineer of the project should, on request of the regulator, supply all relevant data and information. Contacts should preferably be through the regulator.

The emergency warning system should be established or revised as early as possible in order to have time enough for mutual adaptation. It should be operational when construction of the dam is started.

#### 10.5 Sabotage

Sabotage is a possibility in the Eastern Nile region. Unplanned and executed resettlements without proper compensations may result in disgruntled communities that may threaten the safety of the dam with sabotage. Political instability and threats of extremists may require enhanced security assessment for dams in the Eastern Nile region.

It is recommended that as a minimum, a security assessment should be conducted every five years, using established risk assessment methodology and dams should have physical security plans

## 11. REMEDIAL ACTION

### 11.1 Introduction

Remedial action (i.e. risk reduction) is required at a dam when it no longer meets an acceptable level of safety. The remedial action evaluation process should select a timely and cost effective course of action, which could include interim or long-term remedial works, maintenance, changes to operating procedures, or decommissioning. This process should be conducted by an Approved Dam Engineer.

The following guidelines represent an outline, which could be used in the remedial action evaluation for a dam and should be adopted or adapted as necessary for particular situations.

### 11.2 Identification of Dam Deficiencies

Dam remedial actions are initiated by the recognition of the existence of a dam safety problem. These problems are usually discovered during surveillance programs, evaluations, or safety reviews. Deficiencies can result from a variety of causes such as:

- Inappropriate or deficient design or construction;
- Changes to safety criteria (e.g. design, regulation);
- Changes to PCC;
- Time based deterioration or breakdown of materials;
- Maintenance related problems;
- Inappropriate operating techniques;
- Interpretation of updated knowledge (e.g. analytical techniques, material properties) and data;
- Inadequate surveillance procedures; or
- Damages from natural incidents (e.g. earthquakes).

Deficiencies can vary in severity from mild uncertainty about documentation to those with imminent potential for dam failure. The type of remedial action required, and its urgency, is determined by the nature of the deficiency, the associated risks to the dam and the dam's PCC.

### 11.3 Deficiency Assessment Process

On detection of a dam safety deficiency it should be promptly investigated and information gathered for analysis. This may involve geotechnical investigations, site monitoring and document reviews relevant to the particular deficiency. An assessment should be made of the consequences of a worsening situation and its likelihood. The outcomes of the investigations could be a resolution that there is indeed no deficiency or that further investigations are required. In acute cases where time is critical, and the risks are high, or where high hazard situations are associated with considerable uncertainty, Dam Safety Emergency Plans should be activated and interim risk reduction measures expedited (e.g. lower the storage).

In most cases it is usual to undertake a safety assessment (i.e. evaluation against prescriptive and/or risk based criteria) to determine the severity of the deficiency and whether maintenance, or a more appropriate solution, is required. An extensive decision analysis and Safety Review may not be necessary in all dam deficiency studies and a degree of judgment is required. Interim remedial measures could be justified as precautions while uncertainties are investigated. However any analyses should lead to a report on the possible deficiencies, directed to owners. Risk reduction concepts may also be included as part of any report.

For remedial action to be considered in response to a dam deficiency a determination must be made on technically sound engineering principles. Risk Informed Decision Making techniques should be used in the process of studying dam deficiency problems to enhance the quality, consistency and equity of solutions or remedial actions. These techniques may involve both quantitative and qualitative methods to provide structured and systematic ways to make decisions.

The following paragraphs contain steps that need to be undertaken in the deficiency review process.

### 11.3.1 Determination of Likelihood of Dam Failure

Dam safety deficiencies are situations, or conditions, which suggest that dam failure scenarios are possible under certain conditions. The likelihood of each scenario should be determined in the review and compared with acceptance criteria or case histories. Typically the critical risk for most scenarios is controlled by a predominant contributing factor (see Table 12).

Table 12: Common Causes of Dam Problems

| Typical Dam Failure Scenarios          | Contributing Factors  |
|--|---|
| Overtopping.                           | Inadequate spillway capacity or freeboard for Peak Flood, discharge gate failure, spillway blockage |
| Stability                              | Material deterioration, yield, high internal pressures.   |
| Piping                                 | Filter consistency, material properties   |
| Deformation                            | Earthquake, material deterioration  |
| Containment Loss (hazardous materials) | Inflow volume, operation.   |

### 11.3.2 Consequence Assessment

Justifying remedial actions require examining the consequences due to a dam failure. If it has not previously been undertaken, the review should include an assessment to demonstrate whether dam failure substantially increases the loss of life and damage to property, and the environment, beyond that caused by the failure-initiating event (i.e. flooding or earthquake) if failure did not occur.

### 11.3.3 Risk Evaluation

While the risk to life should be the predominant consideration, the risk evaluation should include a risk evaluation (e.g. an Economic Risk Analysis) based on:

- Costs of remedial action solutions;

- Costs associated with property damage averted;
- Determination of various social or environmental losses; and
- Costs associated with installing permanent or temporary community support services.

This is accomplished using reasonable (judgmental) estimates of loading frequencies, failure response probabilities and damage values. Dam owners may also wish to consider other relevant matters such as the ALARP principle, regulatory requirements and business interests in their evaluation.

#### 11.3.4 Reporting

A summary of the deficiency review should be documented in a report to management or the dam owner. The report should:

- Indicate the dam deficiencies causing the problems and their severity against acceptable criteria (risk or standards based);
- Clearly demonstrate whether there is an unacceptable likelihood that the dam would fail under potential loading conditions;
- Recommend remedial actions. These should primarily be to reduce the risk to life from a dam failure to tolerable levels; or otherwise demonstrate, on the basis of an economic risk assessment that the economic benefits exceed the cost of the remedial works;
- Indicate the degree of urgency or priority for remedial action. For dam portfolios, or dams with multiple identified deficiencies, those posing the greatest public hazard together with those having the highest risk of failure, or greatest deviation from acceptable risk criteria, are usually given priority for further study or remedial action.

#### 11.4 Remedial Action Study

A Remedial Action Study may be required to develop alternative risk reduction options for a dam deficiency (structural, non-structural or combinations of both). These options may also include traditional standards based engineering options. It is also required to evaluate the effectiveness (i.e. level of risk reduction) and costs of these alternatives and to present information on them to the dam owner in a manner such that a preferred option may be identified and implemented.

The study should be undertaken by a dam engineer, and other appropriate specialists, with all available information reviewed. Where information deficiencies are determined, action should be instigated at an early stage to obtain the additional information required. Both interim and long-term remedial measures should be postulated and examined. Interim measures can be modified as the understanding of the deficiency and its implications becomes clearer. Staged and prioritized implementation of remedial measures may be necessary for practical reasons.

The alternatives should be compared primarily on the basis of reduction in risk to life, followed by other damage costs and risk costs. All impacts should be identified and described including those, which are difficult to give a monetary value to (i.e. social, environmental, legal). Costs should also include future expenditure to make the measures effective. Indirect costs may also be involved.

An optimum remedial option should be recommended and suitable detailed investigations should have been undertaken to determine that the solution proposed is practical and will not create other problems. It may not necessarily be the least cost solution.

Any report on proposed remedial action should demonstrate that the proposed action is aimed at reducing risks to the public, from dam failure, to tolerable levels. Ideally, it should also demonstrate that any proposed risk reduction action is cost effective and consistent with technical, environmental and publicly accepted standards.

## 11.5 Implementation of Risk Reduction Options

### 11.5.1 Interim Remedial Actions

Interim remedial actions are those required when a deficiency has been identified at a dam, to provide an early reduction in the risk or consequence of a dam failure. These actions may include but are not limited to implementation of:

- Dam Safety Emergency Plans, and Disaster Plans, which could involve evacuation of persons at risk in the event of a dam emergency;
- Warning systems based on actual dam failure or, preferably, on conditions which could result in a dam failure;
- Modifications to the dam operations including controlled release of the storage to lower storage levels; and Increased surveillance.

Interim remedial actions are undertaken as temporary measures prior to the determination of the final long-term solution to the problem. In some cases the interim remedial action may be then adopted as the long-term solution, or as an adjunct to it.

### 11.5.2 Long-Term Remedial Works

Long-term remedial works are those works required at a dam to reduce the risk of a dam failure to an acceptable level for the continuing life of the dam. They may also be included in overall augmentation of the dam undertaken for other reasons such as increased storage.

Dam remedial works vary considerably and no listing of possible remedial works could be exhaustive. However, there are many references, some listed, which could be of assistance to the dam engineer in assessing and deciding on what remedial works are required. Some of the remedial works, which could be considered for specific problems, are:

- Enlarging or raising a dam to increase flood handling capacity;
- Augmenting a spillway (or providing a second spillway) to increase its flood discharge;
- Improving operating controls and procedures;
- Strengthening a dam (e.g. post-tensioning, buttressing) to improve stability during extreme floods or earthquakes and to bring it up to currently recognized standards;

- Grouting or slurry trenches to reduce seepage under a dam;
- Clay blanketing to reduce leakage through storage foundations in tailings dams;
- Provision or retrofitting of properly designed drainage / filter protection to reduce uplift, control leakage, or control piping;
- Stressing, anchoring, internal grouting or surface treatment of concrete dams to improve stability or arrest deterioration; or
- Upstream river regulation to reduce or control inflow.

All modifications should be documented and included in the records for the dam.

### 11.5.3 Decommissioning

A dam is decommissioned when it is taken out of service and appropriate actions are taken such that only a negligible residual hazard remains in the long term. A detailed examination of the site conditions and downstream situation should be undertaken to determine any appropriate decommissioning works. These could include one or more of the following:

- Re-routing of inflow away from the dam's storage or past the dam;
- Effective removal of all or part of the dam wall;
- Permanent enlargement or opening of the outlet works;
- Lowering of the spillway crest or removal of the spillway control gates or stop-boards;
- Treatment of retained liquid or sediments prior to discharge in a safe condition; or
- Removal or encapsulation of impounded deleterious material.

Planned decommissioning may require assessment of environmental impacts and the addressing of unearthed issues (e.g. acid soils, control of sediment erosion). Under acute emergency conditions, decommissioning may have to be carried out with reduced consideration of possible environmental impacts.

### 11.5.4 Disuse

A dam may be considered "disused" if there is no current use for it or its storage contents and it is not practical to remove the dam. Even though no longer required, a disused dam, which impounds water or other contents at normal or flood periods, still poses a downstream hazard and must be maintained in a safe condition at all times. It is therefore the dam owner's responsibility to continue normal dam safety management practices at the dam.

### 11.5.5 Abandonment

A dam should not be abandoned until sufficient of the dam structure has been removed or otherwise modified to make it incapable of impounding a storage, either temporarily or permanently, to a degree

which constitutes a risk to life or property. Therefore, it should no longer require continued operation, maintenance and dam safety and surveillance activities.

The most effective abandonment of a dam is its complete removal and the reinstatement of the site but this may not be practical for all but the smallest of dam structures. The actual extent of structural or hydraulic modification required at a dam for safe abandonment should be assessed by an experienced dam engineer.

#### 11.5.6 Site Rehabilitation

Site rehabilitation (including dam and storage areas) is generally required as part of the decommissioning of dams retaining or containing solid or liquid materials which are acceptable for discharge to the environment now, or in the future, and it is the dam owner's responsibility to comply with relevant legal requirements in this regard. For effective rehabilitation, no structure, landforms, or contaminated materials, should be left on site which:

- Can endanger life or property (including the environment);
- Are dimensionally unstable particularly with respect to erosion; and
- Will contaminate surface runoff, seepage, or groundwater to an injurious degree.



## 12. ENVIRONMENTAL AND SOCIAL FACTORS

As discussed in the initial ICOLD Dam Safety Guidelines Bulletin 59, ICOLD 1987, the consideration of environment and social issues in dam projects needs to consider both the impacts of the dams on the environment and society and the impacts of environment and social factors on the safety of the dams. This Guideline focuses on the latter, the factors affecting the safety of dams during all phases of the dam's lifetime including construction and operation. Environmental and social factors management is to be treated separately.

The interactions between dams and the environment are complex. ICOLD B159, Committee on the Environment: Supplement to the position paper on dams and the environment, supplementary paper 2012, in its introduction states the following: "Global problems such as climate change have impacts on dam safety. Dams can therefore be both affected by global problems and help provide solutions to them."

### 12.1 Climate change

A climate change may give rise to more extreme floods and may require additional considerations in the design and construction of dams beyond the conventional design and construction process. Currently, there is no full understanding nor established methodology for predicting the impact of climate change on water structures. This is a global challenge as well as for the Eastern Nile region. However, to the extent possible, consideration should be given to such potential changes in the planning and design of dam projects. This may be in the form of changes to the original design or as "Precautionary Measures" such as where provision is made for possible future increases in spillway capacity or other economic means to facilitate future adaptations should they become necessary.

### 12.2 Environmental and Social Factors

The following relevant environmental and social factors are addressed in the USACE dam safety guidelines and are also covered in the ICOLD recommended practices regarding environment and social issues of dam safety.

#### 12.2.1 Water quality

Changes in water quality are likely to occur within and downstream of the development as a result of impoundment. Major issues include reduced oxygenation, temperature, stratification potential, pollutant inflow, and propensity for disease proliferation, nutrient capture, algal bloom potential and the release of toxicants from inundated sediments.

Adequate data collection and an EIA process that identifies potential problems prior to dam design are critical. Design and operational systems that minimize as much as possible the negative impacts within the storage and downstream; examples include multilevel off-takes, air injection facilities, aerating turbines, and de-stratification capability. While removal of vegetation from proposed impoundments is expensive, the potential benefits for water quality means that at least some removal should be considered. Working with local communities and regulatory authorities in improving catchment management practices can have significant water quality benefits for hydro reservoirs.

Severe water quality degradation in reservoirs may also affect the integrity of gates and upstream dam facing material.

### 12.2.2 Sediment transport and erosion

The creation of a reservoir changes the hydraulic and sediment transport characteristics of the river, causing increased potential sedimentation within the storage and depriving the river downstream of material. Sedimentation is an important sustainability issue for some reservoirs and may reduce the long-term viability of developments. Reduction in the sediment load to the river downstream can change geomorphic processes (eg. erosion and river form modification).

Development proposals need to be considered within the context of existing catchment activities, especially those contributing to sediment inflow to the storage. Reducing reservoir sedimentation through cooperation with local communities and regulatory authorities in improving catchment management practices is an option. Specific actions, such as terracing or reforestation, may need to be considered. In some cases sediment by-passes, flushing systems or dredging should be investigated. Operational or physical mitigation measures to reduce erosion of downstream should be considered for both proposed and existing developments and appropriate objectives set.

### 12.2.3 Downstream hydrology and environmental flows

Changes to downstream hydrology impact on river hydraulics, in-stream and streamside habitat, and can affect local biodiversity. Operating rules should not only consider the requirements for power supply, but also be formulated, where necessary and practicable, to reduce downstream impacts on aquatic species and human activities.

Operating schedules should, where necessary and practicable, incorporate environmental water release patterns (including environmental flows) within the operational framework for the supply of power. Downstream regulating ponds and other engineering solutions may provide cost-effective alternatives to environmental flow releases directly from power stations. It is important that the environmental objectives of any flow release are identified in a clear and transparent manner. These releases need to be developed within the context of environmental sustainability and also take into account local and regional socio-economic factors. It is desirable that the environmental flow objectives be agreed with local communities.

### 12.2.4 Rare and endangered species

The loss of rare and threatened species may be a significant issue arising from dam construction. This can be caused by the loss or changes to habitat during construction disturbance, or from reservoir creation, altered downstream flow patterns, or the mixing of aquatic faunas in inter-basin water transfers. Hydropower developments modify existing terrestrial and aquatic habitats, and when significant changes cannot be avoided, mechanisms to protect remaining habitats at the local and regional scale should be considered in a compensatory manner.

Plans to manage this issue need to be developed prior to construction and options for mitigation identified and assessed. Habitats of critical importance should be identified (within a wider regional context) and impacts to these avoided or minimised as much as possible during the design phase. Targeted management plans need to be developed for species of conservation significance. Translocations or habitat rehabilitation may be options, along with identification of suitable habitat for 'reserve' management.

### 12.2.5 Passage of fish species

Many fish species require passage along the length of rivers during at least short periods of their life-cycle. In many places the migration of fish is an annual event and dams and other instream structures constitute major barriers to their movement. In some cases the long-term sustainability of fish populations depend on this migration and in developing countries local economies can be heavily reliant on this as a source of income.

The passage of fish is an issue that must be considered during the design and planning stage of proposed developments (dam site selection) and adequate consideration should be given to appropriate mechanisms for their transfer (e.g. Fish ladders, mechanical elevators, guidance devices and translocation programs). Large-scale downstream migration of some species may require mitigation measures to reduce mortality by passage through turbines. Appropriate and feasible options for facilitating passage are also an issue for existing developments.

### 12.2.6 Pest species within the reservoir (flora & fauna)

In some regions a significant long-term issue with reservoirs, irrespective of their use, is the introduction of exotic or native pest species. The change in environment caused by storage creation often results in advantageous colonization by species that are suited to the new conditions, and these are likely to result in additional biological impacts. In some instances, proliferation may interfere with power generation (e.g. clogging of intake structures) or downstream water use through changes in the quality of discharge water (eg algal bloom toxins, deoxygenated water).

Identifying the risk of infestation prior to development should also help identify potential options for future management or mitigation. Shorter residence time of water is one viable mechanism for reducing risk. Downstream water uses must also be considered when examining potential options for control.

### 12.2.7 Health issues

The changes brought about by hydropower developments have the capacity to affect human health. Issues relating to the transmission of disease, human health risks associated with flow regulation downstream and the consumption of contaminated food sources (eg, raised mercury levels in fish) need to be considered. The potential health benefits of the development should also be identified.

Public health and emergency response plans should be developed in conjunction with local authorities. These plans, and their associated monitoring programs, should be relevant to the levels of risk and uncertainty. The health benefits due to improved water supply, economic improvements and flood control should be recognized. Proper reservoir management can be highly effective in eliminating mosquito-borne illnesses such as malaria.

In regions where water-borne, water-related or other diseases occur endemically, responsibility for strict medical control should be determined prior to starting any activities at the site.

All construction forces and their families residing in the construction area should be subject to obligatory control to avoid the transmission and dissemination of endemic diseases. If necessary and possible, medical control should be extended to the local native population.

If disease transmitting vectors are already present at, or in the surroundings of, the construction site and camp, the contractor and, if existent, a public health organization should provide for the necessary means and steps for their elimination.

Adequate health care service should be provided for the population displaced from the reservoir area during relocation operations and as part of resettlement projects.

### 12.2.8 Construction activities

Construction needs to be carried out so as to minimize impacts on the terrestrial and aquatic environment. Where a new development is planned, there are a range of activities that can result in environmental impacts, both terrestrial and aquatic. Noise and dust may also be issues where the development is close to human habitation.

These issues should be adequately addressed during the EIA stage and plans developed to manage these issues. Plans to manage specific issues may be required; e.g., rehabilitation of borrow pits, management of construction site drainage, storage and handling of chemicals. Similar plans to manage disturbance to terrestrial and aquatic fauna may also be required.

The construction camp as well as the construction site should be equipped with all necessary facilities, equipment and services, such as: water treatment, sewage collection and treatment, garbage and waste collection and controlled disposal, etc. If existing local communities may become subject to a substantial increase in population, even though temporary, as a direct consequence of the project, their sanitary and public health facilities, equipment and services should be enlarged to cope with the expected population growth on the basis of an agreement with the contractor and the owner. A health and hygiene education program should be initiated, if so required by local conditions.

Treatment facilities for sewage and other project waste should be scheduled for installation at the earliest stage of preconstruction. These shall be of a type and capacity to insure against the discharge of hazardous and/or contaminated effluents and, thus, against adverse effects upon the water supply of down-stream communities.

Work sites should be supplied with treated drinking water and equipped with sanitary toilet facilities.

### 12.3 Managing Social Impacts

There are various issues that require management to ensure that change affecting communities and individuals is effectively managed during the planning, construction and operation of hydropower facilities.

Possible social impacts that require consideration are identified below.

1. Changes to resource use and biodiversity in the area of the proposed project and the impacts this may have on the local community.
2. Distribution of benefits among affected parties.
3. Effectiveness and on-going performance of compensatory and benefits programmes.

4. Public health issues that can result from the modification of hydrological systems, especially in tropical and sub-tropical areas, where water-borne diseases can be a significant issue. In some reservoirs, a further concern is the management of the temporary rise of mercury levels in fish.
5. The impacts of displacement on individuals and communities. These impacts include:
  - The physical loss of homes and lands;
  - The transition to alternative means of earning a livelihood, particularly for populations that rely heavily on local land and resources for their way of life or that have a traditional existence;
  - Disruption of established community networks and loss of cultural identity.

### 13. SUPPORTING TECHNICAL INFORMATION DOCUMENTATION

Supporting Technical Information (STI) should be assembled in a single comprehensive document for all dam projects with a safety risk, (and also for others if resources permit).

The purpose of the STI is to summarize those project elements and details that may be required to perform safety evaluations and provide essential information to assist all parties respond to emergencies. The dam owner is responsible for compiling the “Supporting Technical Information” (STI) document and shall create and maintain this document for use by themselves, their engineers and the regulator.

The STI should include sufficient information to understand the design and current engineering analyses for the project such as:

- A complete copy of the Potential Failure Mode Analysis report
- A detailed description of the project and project works
- A summary of the construction history of the project
- Summaries of Standard Operating Procedures
- Operations and Maintenance Manuals
- A description of geologic conditions affecting the project works
- A summary of hydrologic and hydraulic information
- Summaries of instrumentation and surveillance for the project and collected data
- Summaries of stability and stress analyses for the project works
- Pertinent correspondence from the regulator and other dam safety organizations related to dam safety.

The STI should use tables, figures, and drawings in preference to text and need not include complete copies of the original documents except for the “Potential Failure Mode Analysis” study report. Only key paragraphs of the original reports should be included in this document for clarity.

The STI is a “living” document, in that as new data or analyses become available they are appended to the initial STI and outdated material is removed. The document should be bound in a three ring binder to facilitate updating the STI as necessary.

The Owner should coordinate this document with the inspection and safety review reports to be sure the Approved Dam Safety Engineer will have all the information necessary for review of the project. Hard copies and digital copies of the initial STI should be kept at the dam site and owners head office with copies submitted to the regulator.

Updates to this document shall be provided to the current Approved Dam Safety Engineer for review, to the regulator and to other document holders. Document holders should be requested to insert the updated pages in the STI, and add the revision to the revision notice log in the front of the STI.

Owners should include complete copies of the reference documents referred to in the STI, or, in some instances, all documents reviewed in the PFMA session, in CD or DVD format with the STI document.

The complete STI should be reviewed and reprinted at least every 15 years and hard copies submitted with the safety review report.

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## GLOSSARY OF TERMS

ALARP (As Low As Reasonably Practicable) Principle:

That principle which states that risks, lower than the limit of tolerability, are tolerable only if further risk reduction is impracticable, or if its cost is grossly disproportionate (depending on risk level) to the improvement gained.

Annual Exceedance Probability (AEP):

The probability of a specified magnitude of a natural event being exceeded in any year.

Abutment:

That part of the valley side against which the dam is constructed.

Approved Dam Engineer:

A professionally registered engineer with appropriate experience approved by the regulator to perform a task at a specific dam. An Approved Dam Engineer should be involved in all stage of the life span of a dam.

Appurtenant Works:

All ancillary structures of a dam including, but not limited to, spillways, inlet and outlet works, tunnels, pipelines, penstocks, power stations and diversions.

Base of Dam:

The general foundation area of the lowest portion of the main body of the dam.

Catchment:

The land surface area which drains to a specific point, such as a reservoir.

Collapse:

The physical deformation of a structure to the point where it no longer fulfils its intended purpose.

Consequence:

Effects of an action or event.

Controlled Document:

A document subject to managerial control over its content, distribution and storage. It may have legal or contractual implications.

**Dam:**

An artificial barrier, together with appurtenant works, constructed for storage, or control of water, other liquids, or other liquid-borne material (excluding concrete/steel ring tanks reliant on hoop stress for structural stability). This classification normally excludes canals and levees, but these guidelines may be used as a basis for developing safety management plans for these structures.

**Dam Construction Engineer**

A professional engineer who is suitably qualified and recognized by the engineering profession as experienced in dams construction.

**Dam Crest Flood:**

The flood event which, when routed through the reservoir, results in a still water reservoir level at the lowest crest level of the dam.

**Dam Owner:**

Any person, organisation or entity legally deemed to be the owner of a dam. A dam owner includes the person in control of a dam.

**Dam Safety Emergency Action Plan (EAP):**

A continually updated set of instructions and maps that deal with possible emergency situations or unusual occurrences at or related to a dam or reservoir.

**Dam with a safety risk**

Any dam which can contain, store or dam more than 50 000 m<sup>3</sup> of water, whether that water contains any substance or not, and which has a wall of a vertical height of more than 5 m, measured from deepest foundation level to highest structure crest level.

**Data Book/ Base:**

An abbreviated convenient source of information summarising all pertinent history and records related to the safety of a dam that is required to assess the performance and safety of a dam.

**Decommissioned Dam:**

A dam which has been taken out of service and which has been rendered safe in the long term.

**Designer Operating Criteria (DOC):**

Comprehensive operating criteria which state the Approved Dam Engineer's intentions in the use and operation of equipment and structures in the interest of safe, proper and efficient use of the facilities.

**Disaster Plan (Flood Plan):**

A plan developed by emergency management agencies to provide community protection in the event of emergencies (e.g. floods).

**Disused Dam:**

A dam where the storage is no longer used.

**Emergency:**

An emergency in terms of dam operation is any condition which develops unexpectedly, endangers the integrity of the dam or downstream property and life and requires immediate action.

**Failure:**

The uncontrolled release of the contents of a dam through collapse of the dam or some part of it, or the inability of a dam to perform its design functions, such as water supply, or hazardous substance containment.

**Flood Control Dam:**

A dam which temporarily stores or controls flood runoff and includes dams used to form flood retarding basins.

**Foundation:**

The undisturbed material on which the dam structure is placed.

**Freeboard:**

The vertical distance between a stated water level and the lowest level of the non-overflow section of a dam.

**Full Supply Level (FSL):**

The maximum normal operating water surface level of a reservoir when not affected by floods.

**Hazard:**

A hazard is any source of potential damage, harm or adverse health effects on something or someone under certain conditions at work.

**Height of Dam:**

Normally the maximum height from the lowest point of the general foundation area to the top of the dam. (Some legislation takes the lowest point along the downstream toe.)

**Incident:**

An event which could deteriorate to a very serious situation or endanger the dam.

#### Inflow Design Flood:

The extreme flood event for which all components of a dam should be design for.

#### Inspection (Dam):

A careful and critical viewing and examination of all visible aspects of a dam.

#### Inspector (Dam Safety):

A technical person suitably trained to undertake dam safety inspections.

#### Large dam

ICOLD defines a "Large Dam" as a dam with:

- maximum height (H), measured from deepest foundation level to highest structure crest level, of equal to or more than 15m; or
- with a  $10\text{m} < H < 15\text{m}$ , and any of the following conditions:
  - dam wall length more than 500 m;
  - reservoir storage capacity more than 3 million  $\text{m}^3$ ;
  - flood discharge more than 2 000  $\text{m}^3/\text{s}$ ; and
  - unusual characteristics in dam type or foundation.

#### Maintenance:

The routine work required to maintain existing works and systems (civil, hydraulic, mechanical and electrical) in a safe and functional condition.

#### Maximum Credible Earthquake:

The hypothetical earthquake that could be expected from the regional and local potential sources for seismic events and that would produce the severest vibratory ground motion at the site.

#### Monitoring:

The observing of measuring devices that provide data from which can provide quantitative data regarding the performance and behavioural trends of a dam and appurtenant structures, and the recording and review of such data.

#### Operator (Dam):

The person, organisation, or legal entity which is responsible for the control, operation and maintenance of the dam and/or reservoir and the appurtenant works.

**Outlet Works:**

The combination of intake structure, conduits, tunnels, flow controls and dissipation devices to allow the release of water from a dam.

**Population at Risk (PAR):**

All persons directly exposed to floodwaters within the dambreak affected zone if they took no action to evacuate.

**Potential Consequences Classification (PCC):**

A Potential Consequences Classification (PCC) is a classification of dam according to their potential consequences as a result of a dam failure.

**Potential Failure Mode (PFM)**

A sequence of events that can lead to the failure of a dam.

**Potential Failure Modes Assessment (PFMA)**

A workshop process that identifies and assesses potential failure modes for a dam. It can be used alone or as the first step in a risk assessment.

**Probability:**

The likelihood of a specific event or outcome.

**Probable Maximum Flood (PMF):**

The flood resulting from PMP and, where applicable, snow melt, coupled with the worst flood-producing catchment conditions that can be realistically expected in the prevailing meteorological conditions.

**Probable Maximum Precipitation (PMP):**

The theoretical greatest depth of precipitation for a given duration that is physically possible over a particular catchment area, based on generalised methods.

**Project Manager:**

The person accountable for management of a project.

**Recommended Inflow Design Flood (RIDF):**

The flood event which has the recommended annual exceedance probability or proportion of PMF inflow and which produces the highest flood to be considered for the safety of the dam.

**Regulator:**

The person or organisation that administers the relevant Act that controls aspects of dam safety.

#### Remedial Action:

Any action required to rectify a deficiency to an adequate safety standard.

#### Reservoir:

An artificial lake, pond or basin for storage, regulation and control of water, silt, debris or other liquid or liquid borne material.

#### Reservoir Capacity:

The total or gross storage capacity of the reservoir at FSL.

#### Retarding Basin:

A type of flood mitigation dam used to temporarily store some, or all, of the stormwater runoff from an urban catchment.

#### Risk

Risk is defined as the potential for realization of unwanted, adverse consequences affecting human life, health, property and the environment. Risk is usually estimated by multiplying the probability of an event by the consequences of the event.

#### Risk Analysis

The use of available information to estimate the risk to individuals or populations, property or the environment. The procedure includes identifying and quantifying risk by establishing potential failure modes, providing estimates of the likelihood of an event in a specific time period and estimating the magnitude of the consequences. A quantitative risk analysis yields a numerical estimate of the risk of adverse consequence.

#### Risk Assessment

The process of making a decision recommendation on whether existing risk is tolerable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation stages.

#### Risk Evaluation

The process of examining and judging the significance of risk. The risk evaluation stage is the point at which values and value judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, economic and other consequences, in order to identify and evaluate a range of alternatives for managing the risks.

#### Risk Informed Decision Making (RIDM)

RIDM is the process of making safety decisions considering the quantitative or qualitative estimates of risk (the risk analysis), along with all significant related social, environmental, cost, temporal, and other

factors to determine a recommended course of action to mitigate the risks or conclude that the risk is tolerable.. The decision-making process in RIDM is different than that used with deterministic or standards based methods in which set criteria and/or factors of safety for certain loadings are used to make decisions rather than considering the end result of a potential failure mode.

#### Risk management

The systematic application of management policies, procedures and practices to the tasks of identifying, analysing, assessing, mitigating and monitoring risk.

#### Safety Review:

The assessment of dam safety by methodical examination of all design, construction and surveillance records and reports, and by the investigation and analysis of potential failure modes including any matters not addressed previously or items subject to new design criteria or possible deterioration.

#### Seepage (Leakage):

The unregulated escape of water through, under or around the dam.

#### Spillway:

A weir, channel, conduit, tunnel, gate or other structure designed to permit discharges from the reservoir normally under flood conditions or in anticipation of floods.

#### Spillway Crest:

The lowest portion of the spillway overflow section.

#### Surveillance:

The continuing examination of the condition of a dam and its appurtenant structures and the review of operation, maintenance and monitoring procedures and results in order to determine whether a deficiency trend is developing or appears likely to develop.

#### Tailings Dam:

A dam constructed to retain tailings or other waste materials from mining or industrial operations.

#### Tailwater Level:

The level of water in the channel immediately downstream of a dam.

#### Toe of Dam:

The junction of the downstream (or upstream) face of dam with the ground surface (foundation). Sometimes "Heel" is used to define the upstream toe of a concrete gravity dam.



Top (Crest) of Dam:

The elevation of the uppermost surface of a dam proper, not taking into account any camber allowed for settlement, kerbs, parapets, crest walls, guardrails or other structures that are not a part of the main water retaining structure. This elevation may be a roadway, walkway or the non-overflow section of a dam.

## APPENDIX A - OPERATIONS AND MAINTENANCE MANUAL

### Introduction

The efficient and effective management of a dam is enhanced by the provision of an Operations and Maintenance Manual.

### Suggested Contents

Information and instructions in an Operation and Maintenance Manual should follow a reasonably standardised format. The following major section headings are suggested as a basic Manual outline for the majority of dams and should be varied as required; particularly for reservoirs and dams with unusual features:

- Preliminary Pages
- Dam Safety Emergency Action Plan and Communications Directory (referenced for VERY HIGH PCC dams, included for other dams as appropriate).
- Chapter 1 - General Information
- Chapter 2 - Structural Operation and Maintenance Procedures
- Chapter 3 - Reservoir and Spillway Operations (normal and extreme conditions)
- Chapter 4 - Dam Safety and Surveillance
- Chapter 5 - Responsibility, Accountability and Reporting
- Appendices

Preliminary pages should include the cover sheet, title page, table of contents, revision sheet, as well as any necessary certification and/or verification required by the dam owner. It is also desirable to include an aerial photograph of the dam and reservoir in these pages. Details on the Dam Safety Emergency Action Plan, and associated Communications Directory, are covered elsewhere in these Guidelines. For VERY HIGH PCC dams, these can be lengthy documents, which are usually prepared separately and referenced in the Operation and Maintenance Manual.

The first chapter, "General Information" should contain detailed information and instructions concerning the administration of the dam and reservoir as well as information on the Manual.

The second chapter, "Operations and Maintenance Procedures" should contain the detailed information and instructions necessary for the operation and maintenance of the dam, its appurtenant structures and equipment.

The third chapter, "Reservoir and Spillway Operations" should contain the detailed information and instructions necessary on all aspects of reservoir operations. It should also include a Storage Management Plan detailing water quality and environmental management issues/practices. This is particularly important when there are public use management issues round the storage.

Details on the fourth and fifth chapters are covered elsewhere in these Guidelines.. Appendices should contain all necessary drawings, maps, photographs, charts, lists of supporting and reference material.

### Editorial Suggestions

Manuals should give detailed understandable instructions able to be followed by a responsible person knowledgeable in dam and reservoir operations but not necessarily familiar with the particular dam in question. The use of drawings, marked photographs, colour coding and numbering valves, switches, concrete blocks, drains etc. physically and in the manual are recommended to supplement step-by-step operation or maintenance instructions. These aids simplify instructions considerably and reduce the chance of error in their use.

The following editorial comments are suggested to improve the readability of the manual and to assist in the preparation and revision of the manual:

1. Start each chapter on a new page (to facilitate revision) and use coloured card dividers between chapters.
2. Each chapter should stand alone without reference to other chapters.
3. Page numbering should be in the form 1-1, 2-1, etc. for the different chapters to allow for future revision without affecting overall page numbering.
4. Use lists rather than narration to outline instructions and information whenever possible.
5. Include drawings, sketches, graphs, manufacturer's instructions, photographs, references etc in Appendix or text.
6. Avoid vague words (ie periodically).
7. Bind manual in loose-leaf folder for ease of revision, additions and updating.
8. Give each manual an identification number and keep a record of the location and status of each copy.

## GENERAL INFORMATION

### Purpose, Location and Description

The authorised purpose/s of the dam, its reservoir and appurtenant structures should be clearly indicated in this part of the Manual. A brief history of the dam from inception to the present time, indicating significant dates and events, should be included. Where appropriate, other significant data, landmarks or unique features and pertinent information on the dam and dam site should also be detailed including comments on identified problems from design, construction and subsequent behaviour.

The river or watercourse on which the dam is situated and location of the dam relative to readily identifiable points such as towns or cities is required in the manual.

Information should also be given on the access routes to the dam site including condition and alternatives. Where applicable, airports, either commercial or private, railway stations and seaports

should also be identified. The most expeditious route should be indicated. The availability of special equipment for accessing the dam (helicopter, four wheel drive vehicles, etc) should be noted.

Suitable location and/or topographic maps, kept up-to-date, should be included. These maps should be clear and precise.

A detailed description of the dam and its appurtenant structures should be included.

### Administration, Operations and Responsibilities

All areas of responsibility in the administration, operations and maintenance of the dam, dam site and reservoir should be clearly indicated in the Manual. Some of the responsibilities that should be identified are as follows:

- Ownership;
- Administration;
- Operations of equipment at the dam;
- Reservoir inflow and flood forecasting;
- Authorising spillway flood releases;
- Authorising irrigation releases;
- Recording reservoir data;
- Routine inspection;
- Maintenance;
- Modifications (i.e. dam and equipment); and
- Dam safety and surveillance.

Administrative and operational relationships between the various operating and end user organisations should be detailed. Formal agreements as well as more informal arrangements should be referenced.

Agreements with other agencies or organisations, which have an essentially indirect interest in the dam or its operations and maintenance should be detailed. These agencies or organisations could have an interest in the following:

- Land management;
- Civil defense, counter disaster or emergency service activities;
- Environmental protection;
- Fish and/or wildlife;

- Forests;
- Geological surveys;
- National parks;
- Outdoor recreation;
- Soil conservation;
- Dam safety; or
- Water resources.

Organisation arrangements in the form of flow charts would be advantageous. The operating personnel responsibilities should be specifically identified in the Manual. This should include regularly scheduled duties which they are required to perform. A typical schedule for the duties is given in Section A.5

### Data Reporting and Operations Log

Brief instructions and standardised forms for the collection and reporting of all types of dam and reservoir data should be included. Lengthy or more detailed instructions, if required, should be included in another more appropriate subsection of the manual, in the appendices or in the supporting documents. Instructions should cover type, frequency, form and disposition of the data reports.

For example, routine data may be required at a dam on the following:

- Reservoir water surface elevation;
- Reservoir inflow;
- Spillway outflow;
- River releases;
- Irrigation, water supply and hydropower draw off;
- Weather;
- Surveillance and monitoring; and
- Water quality.

Each dam should have an Operations Log whether or not it has full or part time attendants or is normally unattended. This log should be maintained by operations personnel preferably in a bound book and should contain a chronological record of all important events at the dam for future reference. This log could be helpful in providing clues to the cause of equipment failure and the development of unusual conditions.

Records in the log would vary according to the type and needs of the individual dam but typical entries could include details of the following:

- Attendance at dam;
- Normal or emergency operations of the outlet works or spillway gates;
- Start-up and stopping of mechanical equipment;
- Tests on standby equipment;
- Tests and exercising of outlet and other valves, gates, penstocks or stoplogs;
- Tests and exercising of spillway gates and associated controls;
- Minor and major maintenance activities including both scheduled and emergency;
- Reservoir and dam inspections;
- Unusual conditions or occurrences, including acts of vandalism;
- Emergency attendance at the dam;
- Changes to normal operating procedures;
- Communications network checks;
- Safety and special instructions;
- Names and addresses of official visitors (eg. staff carrying out comprehensive inspection); and
- Other relevant items pertaining to the operation and maintenance of the dam in both normal and emergency situations.

### Public Safety and Health

Instructions for public and personnel safety and protection at the dam or on the reservoir should be included in the Manual. Instructions required by the relevant legislation existing in the state in which the dam is located should be included. Unsafe conditions and hazardous areas should be listed. The type and location of warning signs and other safety features or equipment should be noted.

Areas of the dam and reservoir restricted to the public should be detailed. Purpose of restriction should be explained.

Restricted areas which are potentially hazardous could include the following:

- Confined spaces, especially those with no ventilation;
- Spillway approach areas, chutes and stilling basins;

- Control buildings and valve areas;
- Intake or outlet channels adjacent to hydraulic structures subject to surging or rapid changes in water level during releases;
- Active landslide areas.

Suitable warning and restriction signs should be positioned at appropriate places around the dam and referenced in this Manual.

Reference should be made to the Communications Directory for local law enforcement, medical and fire services.

### Attendance, Communication and Warning Systems

The individual or operating unit responsible for and extent of attendance at the dam should be noted in the Manual. Attendance could be either:

1. full-time (working hours)
2. part-time (specify period) or
3. unattended or remote operated

If unattended the frequency of inspection and other details relating to the operation of gates and valves and collection of data should be noted.

The means of communicating with the dam both in normal and emergency situations should be identified. All available communication means including phones, facsimile, relevant cell phones, radio and relevant pager links whether to public or private facilities or individual should be noted. If no facilities are available at the dam the location and owner of the nearest phone or radio should be noted.

It is preferable that actual phone numbers and other communication numbers should be listed in the Communications Directory for the dam. However, a suitable reference to the Communications Directory should be included in this section of the Manual.

In addition to communication facilities a brief description of the emergency warning systems including alarms at the dam should be included. Reference should be made to the Dam Safety Emergency Plan.

### Control of Operations and Maintenance Manuals

Distribution of Manuals should be determined on the basis of need for operations, maintenance, supervisory purposes and records only. To ensure that they are kept continuously revised a record should be kept of the distribution and location of all Manuals.

The person or organisation responsible for revising and recording the location and distribution of all Manuals should be clearly nominated. Formal procedures should be clearly established for revising the Manual with periodic reviews being conducted to ensure that the instructions are still relevant and/or are

being observed by all personnel. All revisions or other changes to a manual should have approval of the responsible person or organisation.

In revising a Manual it is recommended that each revised sheet should clearly show the revision number and date. A summary listing of revised sheets should also be filed in the preliminary pages of the Manual to provide a convenient method of checking for current completeness.

### Training

Suitable schedules, outlining frequency, subject matter and personnel involvement, should be established for routine training of operations, maintenance and other staff associated with the dam, reservoir and appurtenant structures. Standby or alternate staff should receive the same training. Training should encompass all activities relating to the operation and maintenance as well as safety precautions and procedures to be adopted in accident or emergency situations.

### Supporting Documents and Reference Material

Supporting documents comprise the necessary instructions for all phases and levels of responsibility in the operation and maintenance of the dam and reservoir. All supporting documents that are part of the total instructions should be listed. The distribution of these documents and responsibility for preparing, updating and revising should also be listed.

These documents will vary according to the size, type and usage of the dam but may include the following:

- Designers operating criteria;
- Dam Safety Emergency Plan;
- Relevant state or federal government legislative acts;
- Flood forecasting and operating criteria;
- Basin or river operating plan;
- Power station operating instructions;
- Irrigation operating instructions;
- Administrative procedures;
- Damsite security plan;
- Reservoir or river pollution contingency plans;
- Regional emergency handbook;
- Major maintenance procedures;
- Maintenance schedules;



- Manufacturer's instructions and drawings;
- Reservoir management plan (land, recreation, fish and wildlife);
- Regional communications directory for dams; and
- Instrumentation reports and/or results.

Reference material should consist of a listing of relevant manuals, contract documents, drawings, and memorandums of understanding, reports and other reference books which contain information useful in the operating and maintenance of the dam.

## Operations Instructions

### Details

Basic data required to accompany the instructions should include, but not be limited to, the

Following:

- Dam structure details including type, height and other dimensional data, location, year completed and hazard classification;
- Full Supply Level and Minimum Operating Level of the reservoir;
- Spillway type, capacity and associated details including spillway design flood;
- Outlet works type, capacity, reservoir draw-down rates and associated details; and
- Capacity and surface area curves.

Following the basic data, the detailed procedures and practices to be followed for particular situations should be detailed. Some of the situations that should be covered are as follows:

- Normal operation, including riparian release procedure;
- Flood emergency release procedure;
- Flood warning practices; and
- Limitations on reservoir draw-down rate to prevent dam reservoir slopes and embankment instability, downstream surges.

Each procedure or practice should provide complete, clear, step-by-step instructions for operating all necessary equipment associated with a dam including the outlet control valve and spillway gates. The frequency and nature (eg flow test, static test, dry test) of operational check testing of this equipment should be specified. Correct sequences should be emphasized and sketches, drawings and photographs to aid in identifying specific handles, buttons, levers, etc., should be included. Provision and usage of backup equipment should be outlined.

The correct method and sequence of opening and closing guard gates, gate usage during low and high flow, openings at which excessive vibrations are experienced and operating problems peculiar to a specific gate should also be listed. For hydraulic and electric gates, a schematic diagram should be provided showing each component (including back-up equipment) and its place in the operating sequence.

Instructions should also be issued for the general operation of the reservoir, including monitoring and regulation of inflow and outflow. These might include maximum water levels to be allowed at different times of the year and maximum and/or minimum permissible carry over storage and outlet releases. Instructions should also describe operation of the outlet to limit or prevent excessive spillway flow, and the method for periodic drainage of the reservoir to permit inspection of normal submerged areas, eg outlet or foreshore slope.

Reservoir operating curves should be available for each normal mode of operation and for emergency conditions.

### Other Considerations

An auxiliary power system, such as a petrol or diesel-operated generator or other appropriate energy source, is essential if the outlet and spillway gates and other dam facilities are electrically operated. This system should be clear of extreme flood levels and access and lighting for extreme events is essential.

All spillway and outlet gates should be tested on a regular schedule including alarms and indicators. The test should include use of both the primary and the auxiliary power systems.

Site security is a matter of concern at all major dams. This includes terrorism implications and preventing structural damage by vandals and unauthorized operations of outlet or spillway gates. In most cases restricting public access is essential, and in some instances electronic security devices and/or watchmen should be considered.

Public safety is also of paramount importance at all dams and reservoirs. Specifically, public safety on the reservoir near the dam, in areas adjacent to the reservoir, and below the dam should be considered. Safety measures could include identification of high watermarks to indicate past or probable reservoir levels and stream flows, posting of safety instructions at highly visible and key locations, and providing audible safety warnings upstream of and below outlets as appropriate. Communications should be maintained among affected government bodies and with the public to enhance the safety aspects of the operation of the dam. Communication alternatives include written communications, radio, telephone, television and newspapers

### Maintenance Instructions

#### Maintenance Priorities

Maintenance is a task that should never be neglected. If it is, the consequences and costs could multiply. Maintenance could be prioritized as follows:

- a) Corrective Maintenance, which may require immediate remedial action and even prior emergency action, such as evacuation, if warranted. These relate to the most critical of conditions

at a dam, which call for immediate attention. These conditions may include, but are not limited to:

- o A dam being over-topped or about to be over-topped;
  - o A dam about to be breached by erosion, slope failure or other circumstances;
  - o A dam showing signs of piping and/or internal erosion;
  - o A blocked or otherwise inoperable spillway at a dam; or
  - o A dam showing signs of excessive seepage.
- b) Preventive Maintenance - This can be further broken down into routine or condition based maintenance.
- i. Condition-Based Maintenance - This may be relatively urgent. It should be scheduled bearing in mind the dam owner's resource constraints, the risks involved with not doing the maintenance and the owners priorities on the dam and within his dam portfolio. These may include, but are not limited to:
    - o Clearing undergrowth and trees from embankments, sealing any consequent piping / erosion areas, and establishing a good grass cover;
    - o Regrading and reseeding eroded areas and gullies;
    - o Repairing defective but still operational spillways, gates, valves and other appurtenant features;
    - o Repairing deteriorated concrete, metal or jointing compounds; and
    - o Maintenance and repair of cracks and joints in concrete structures.
  - ii. (ii) Routine Maintenance - Routine scheduled maintenance tasks at a dam. These could include:
    - o Mowing and general minor repairs;
    - o Maintenance of electrical and mechanical equipment and systems (eg. servicing stand by generator, gantry crane, spillway gates);
    - o Operation of electrical and mechanical equipment and systems (eg. Exercising valves, exercising gates);
    - o Operation of scours and outlets to keep them clear of silt;
    - o Maintenance of monitoring equipment;
    - o Testing monitoring equipment and alarms;
    - o Testing security equipment;

- Testing communication equipment;
- Inspections (discussed elsewhere in these guidelines); and
- Monitoring upstream and downstream developments, which could have an impact on the dam or its PCC.

## Details

Specialists should prepare maintenance checklists and schedules indicating the maintenance procedures, frequencies and protective measures for each structure and for each piece of operating, communications, and power equipment, including monitoring systems. Special attention should be given to known problem areas.

Special instructions should be provided for checking operating facilities following floods, earthquakes, and other natural phenomena.

Maintenance procedures include preventative measures such as painting and lubrication as well as repairs to keep equipment in intended operating condition, and minor structural repairs such as maintaining drainage systems and correcting minor deterioration of concrete and embankment surfaces. The design staff should be advised of any significant maintenance work.

Maintenance of retarding basins is essential to ensure their ongoing performance. Outlets should be maintained clear and tree growth in overflow sections removed to maximize performance during floods. Grass cover should be maintained to prevent scour and erosion during flood events.

A list of tasks included in the maintenance instructions may comprise but is not restricted to the following:

- Removing brush and trees;
- Removing debris, including silt upstream of outlets;
- Regarding the crest and/or access roads;
- Removing harmful fauna;
- Operating and lubricating gates;
- Adding rip-rap when needed;
- Sealing joints in concrete facings;
- Clearing seepage measuring weirs, surface drainage channels and pits;
- Maintaining monitoring points;
- Maintaining security of operating equipment;
- Repairing damaged or deteriorating concrete;

- Cleaning uplift pressure and other drains;
- Maintaining all associated electrical and mechanical equipment;
- Reporting any abnormalities observed during the course of maintenance (eg higher than normal seepage or new seepage locations);
- Removing floating debris from the reservoir;
- Maintaining spillway protection floating booms;
- Painting of metal and timber surfaces;
- Maintaining road bridge bearings and expansion joints across spillways;
- Maintenance of coating and protection from impact for steel conduits outlet works;
- Maintaining outlet works tunnels;
- Maintaining valves; and
- Maintaining safety signs and barriers.

### Sample Duty Schedule for Operating Personnel

The following checklist should be used as a guide in preparing a duty schedule for operating personnel. The frequencies of these duties should be varied according to circumstances (e.g. the condition of the equipment). In particular, safety monitoring should accord with 11-2 of these Guidelines. All activities, or lack of activities with reasons, should be recorded in the dam logbook.

#### Daily

- Visual inspection of dam;
- Crest of dam;
- Upstream and downstream faces;
- Visible portions of foundation and abutment contacts;
- Galleries;
- Record water surface elevation;
- Record reservoir inflow and spillway discharges;
- Record releases;
- Record seepage; and
- Complete logbook which should include the above information.

## Monthly

Check condition of:

### Dam and Reservoir

- Spillway stilling basin;
- Outlet works stilling basin;
- Critical landslide areas;
- Reservoir area;
- Drainage systems, toe drains;
- Measuring devices and alarm levels;
- Fauna problems;
- Security and safety devices;
- Communication devices; and
- Vegetation growth (there may be too much or too little).

### Electrical System

- Standby generator
- Run for minimum of 1 hour
- Keep battery charged
- Check fuel supply
- Replace light globes

## Three monthly

### Outlet Works

- Operating instructions - up to date and legible;
- Check gate air vents on downstream face;
- Clean gate control switchboxes;
- Check security and safety devices;
- Read weather gauges and record data;

- Make required changes in gates and valves;
- Check log or safety boom;
- Check spillway outflow channel for debris;
- Check instrumentation schedule;
- Record pertinent information in Operating Log;
- Check seepage weir condition;
- Grease hydraulic gate hanger;
- Check
  - Signs that warn public of hazards;
  - Trash rack of intake structure;
  - Outlet works stilling basin; and
  - Valve house.

### Spillway

- Check for debris in inlet channels;
- Check operation of gates;
- Check fence condition and caution signs;
- Check and clear bridge drains; and
- Clean inside of motor control cabinet.

### Six monthly

#### Outlet Works

- Check hydraulic oil lines;
- Check oil reservoir level in hydraulic system;
- Lubricate gate rollers;
- Check rubber seals and seal clamp bar; and
- Check hoist cables – lubricate.

## Electrical System and Equipment

- Change oil in standby generator;
- Check exposed electrical wiring;
  - Outlet works, valve house;
  - Spillway bridge; and
  - Gate hoists.

## Annualy

### Outlet Works

- Paint:
  - Metalwork;
  - Colour-coded valves; and
  - Woodwork and trim.
- Exercise gates and valves.

## Spillway

### Exercise equipment.

## Five yearly

Examine intake structure, trash racks and stilling basin, which normally are underwater; less frequent if experience indicates. This should coincide with the Comprehensive Inspection and may need to be done by divers.

## Dam and Reservoir

### Review the Operation and Maintenance Procedures.

## Mechanical

- Check and re-paint metal work on gates, bridges, pipes, fences, etc.;
- Check hoists cables – lubricate;
- Check mechanical hoist bearings and flexible coupling bearings;
- Check gear cases:
  - Hoist gear case, replace grease; and



- o Spur gear units and gear motors.

### Electrical

- Check electrical conduits, pull-boxes and switches;
- Outlet works valve house;
- Gate hoists;
- Spillway;
- Galleries;

### Outlet

Check condition of interior and exterior of outlet conduit.

## APPENDIX B - DAM SURVEILLANCE & MONITORING

### Dam Safety Inspections

#### Personal Safety

For safety reasons it is advisable to have two or more personnel on each inspection. This applies particularly to travel to, and operations in, isolated areas.

#### Equipment

The following items are often useful:

- checklist, field book and pencils;
- recording device;
- cameras (still and video);
- hand held levels;
- probe;
- safety gear; (eg waders, harnesses, hard hats, safety boots, breathing apparatus, gas detector and anything else to comply with safety regulations);
- tape measures;
- torch ("mine safe" for unventilated conduits, tunnels or adits);
- shovel;
- geologist's hammer;
- binoculars;
- first aid kit;
- stakes and flagging tape;
- crack gauge; and
- Lock-off labels.

#### Recording Inspection Observations

Check and record status of all items on a checklist (see Section B.1.13). Provide accurate location of questionable areas and take photographs. Note extent of such areas (i.e. length, volume, width and depth or height). Give a brief description of any anomalous condition, such as:

- Quantity/quality of drain outflows, seepage and its source(s);

- Location, type and extent of deteriorated concrete;
- Location, length, displacement and depth of cracks;
- Extent of moist, wet or saturated areas; or
- Changes in conditions from previous inspection(s).

### Records

A signed dated report should be completed for each inspection, and filed with any photographs taken (These must be dated and labelled). Related monitoring readings and weather conditions (especially air temperature and recent rain) should also be included in the inspection report along with the dam's water level.

Observations should be promptly compared with previous records to look for unexpected differences.

### Routine Inspections

The most important activity in a dam surveillance program is the frequent and regular inspection of the dam for abnormalities in conditions and for deterioration. The earliest detection of obvious problems will come from the daily to weekly visual observations by the dam operator. However, the dam engineer (surveillance) or the dam owner may require a more thorough and wide-ranging observation of the dam and its surrounds by a trained inspector other than the daily operator, specifically for dam safety purposes, and considered recommendations for corrective action. These latter reports would form the basic "formal" records of the dam's condition for archiving and future surveillance reference.

### Routine Visual Inspection and Surveillance

Routine visual inspections are carried out generally by the dam operator and a brief written report is made. A typical Routine Visual Inspection report form is included below and should be adapted to suit the particular dam with reference to the checklist given in Section B.1.13. The report should be used to record new developments and changes to existing developments, as well as to record action items.

The reports are to be reviewed by the dam engineer, responsible for surveillance, action items noted and the report filed for future reference. If appropriate the reports are referred to the dam owner for noting any actions required.

The Routine Visual Inspection report form must include clear instructions for the inspector on immediate actions, and who to contact, in an emergency situation.

### Crucial Inspection Times

Inspection is recommended, regardless of the regular schedule, in the following cases:

- During and immediately after the first reservoir filling of a new dam or after augmentation;
- During and after a significant rapid drawdown;
- Before a predicted major rainfall, snow melt or filling;

- During (if possible) and after heavy flooding (or severe windstorm); and
- Immediately following an earthquake, sabotage or overtopping, and then regularly for several months to detect any delayed effects.

### Embankment Dams

The following items should be noted, and inspecting staff should be trained to appreciate the implications of their occurrence.

#### Upstream Slope

Cracks, slides, cave-ins or sink holes, erosion and deterioration of rip-rap. When a reservoir is emptied, the exposed area should be thoroughly inspected and photographed to record its condition.

#### Downstream Slope

Cracks, slides, sink holes, excessive erosion, inappropriate vegetation, or turbid, excessive or new seepage should be noted. Slope failures require immediate evaluation. Early warning signs include a bulge near the toe of an embankment or vertical displacement in the upper portion of an embankment. If any of the above conditions are seen or suspected, they should be recorded and the opinion of an experienced dam engineer should be obtained.

#### Top of Dam (or Crest)

Questionable conditions on the crest should not be disturbed or obscured before the opinion of an experienced dam engineer has been sought.

Some potentially threatening conditions are longitudinal cracking, transverse cracking, misalignment and excessive settlement.

#### Seepage Areas

No dam is completely leak proof. However, changes in the nature of the seepage, (eg flow or turbidity) should be observed as an indicator of potential problems occurring inside the dam or foundations. An inspection for seepage should be made when a reservoir is full and the seepage can be expected to be at its maximum.

### Concrete Dams

Concrete dams may fail due to the development of structural cracking, foundation and abutment weakness or severe concrete deterioration. In addition, concrete dams can react particularly to seasonal effects with temperature induced movements and cracks opening more in winter than in summer. These effects can be greater than hydrostatic load induced movements and should be considered when setting surveillance requirements and reviewing surveillance data.

Access to the downstream face, toe area, and abutments of concrete dams may be difficult and require special safety equipment and procedures. However, regular inspection with powerful binoculars initially can identify areas where change is occurring.

Monitoring helps detect structural problems in the dam, abutments, or foundation. Cracks may develop slowly at first. If a suspected structural crack is discovered, the opinion of an experienced dam engineer should be sought. The installation of monitoring instruments, such as crack pins, may be required to be read on a regular basis.

### Spillways

A spillway should provide a safe exit for excess water from a reservoir. A conscientious annual maintenance program should be pursued and inspections should note whether this is in effect.

Water must be conveyed safely from the reservoir to a point downstream of the dam without endangering the spillway or the embankment. A range of spillway flows should be observed to confirm that the design is adequate.

Spillway inspection should also look for obstructions, cavitation erosion, deterioration of floor and walls, deterioration of joint sealants, misalignment at joints, or cracking.

Walls of spillways usually have weep (or drain) holes and occasionally spillway floor slabs also have these. When it is safe to enter the spillway, plugged weep holes should be probed and where necessary cleaned out (to restore drainage). Care should be taken not to damage or remove any drainage filter material placed behind the wall or below the spillway floor. Misalignment of spillway walls or floor slabs should be noted and compared with that of previous inspections, to check for progressive or unexpected deformation.

### Outlets

An outlet should always be operable. Before a valve or gate is operated, it should be inspected and all appropriate parts lubricated and repaired if necessary. It is also prudent to advise downstream residents of unscheduled large or prolonged discharges. Such discharges should be increased gradually, so as to minimize the risk of damage downstream. All aspects of the outlet should be checked for deterioration (e.g. rusting, dissimilar metal corrosion, protection systems, weld cracks etc).

For routine testing of a valve or gate for operability, appropriate operating procedures for isolating the valve or gate from the reservoir pressure should be applied.

For testing valves or gates under 'in-service' conditions, or simulated emergency conditions, appropriate fail-safe test procedures should be applied.

Outlet pipes, 750mm or greater in diameter, can be inspected internally, provided the system can be emptied and entry made safe. Tapping the conduit interior with a hammer can help locate voids outside the pipe, and between the lining and the pipe. Smaller diameter pipes can be inspected by remote TV camera.

Great care should be taken to observe appropriate procedures when refilling the outlet pipes so as to safely discharge all air trapped during refilling.

Appurtenances underwater should be inspected whenever the reservoir is drawn down or at least at five-year intervals. If a significant problem is suspected, or the reservoir remains full over extended periods, divers should be used for an underwater inspection.

The full range of valve or gate settings should be checked. The operation of all mechanical and electrical systems, backup electric motors, power generators, and power and lighting wiring associated with the outlet should also be checked.

### Operational Preparedness Checks

All mechanical equipment should have operating instructions and prescribed operation and maintenance plans. Equipment, including spillway gates, sluice gates, valves, stop logs, pumps, flash-boards, relief wells, emergency power sources, siphons, and electrical equipment should be operated as prescribed in the operations plan. Testing, as appropriate, should cover the full operating range under actual operating conditions. Each operating device should be permanently marked for easy identification, and all operating equipment should be kept accessible. All controls should be checked for proper security to prevent vandalism. All operating instructions should be checked for clarity and maintained in a secure, but readily accessible location.

### Other Areas for Inspection

The foundations, abutments, and reservoir rim should all be inspected regularly (e.g. weekly to monthly).

Inspections should be made far enough downstream to ensure that there are no problems developing that could affect the safety of the dam, such as excessive foundation seepage, valley slope failure or blockage downstream of the spillway.

The reservoir surface and shoreline should also be inspected regularly (e.g. weekly to monthly) to identify possible problems for the dam's safety. Whirlpools indicate that water is escaping rapidly. If this is not attributable to the outlet system, a very dangerous situation exists. A build up of rafts of weed, timber and debris can be blown along the reservoir and cause blockage at outlets and spillways. Wave and rainfall erosion of exposed banks can cause continuing turbidity problems. In steep country, large landslides coming into the reservoir could cause waves that will overtop the dam or could cause water quality problems; and suspect areas should be appropriately monitored.

Development upstream, and other catchment characteristics that might influence the quantity or quality of reservoir water or silt inflows, should be noted in major inspection reports to anticipate possible problems or the need for modifications to the dam.

Development downstream in flood plains should also be regularly assessed, as the extent of development and the population at risk downstream dictates the level of inspection, monitoring and surveillance required at the dam and the extent of flood preparedness planning, which relate directly to the damages and legal liability should the dam fail.

## Sample Inspection Checklist

(Select appropriate items for particular dam inspection)

### GENERAL

Record:

- Names and roles of persons making the inspection;
- Date of inspection;
- Weather conditions (cloud cover, rain, wind, temperature) on day of inspection;
- Dates and amount of most recent rainfalls;
- Storage level; and
- Date and magnitude of most recent flood (earthquake).

### EARTH/ROCKFILL EMBANKMENT INSPECTION

Check for:

- Bulges, displacements, depressions (particularly in crest);
- Alignment;
- Crest condition;
- Cracks-longitudinal / transverse (give width and location);
- Seepages, damp spots;
- Sinkholes;
- Gullying;
- Tree or shrub growth / Condition of grass cover;
- Burrows;
- Rip-rap condition;
- Wave beaching;
- Debris accumulations;
- Evidence of soil dispersivity;
- Operator or public safety issues; and

- Other anomalous conditions.

## CONCRETE DAMS

Check for:

- Offsets at joints;
- Cracking (describe type, width, location and orientation);
- Spalling;
- Matrix condition;
- Lift joint condition (efflorescence, seeps);
- Leakages;
- Erosion;
- Joint filler condition;
- Metalwork condition;
- Pressure relief drains, holes (note flows, blockages, etc.);
- Condition of any lighting, ventilation provisions;
- Operator or public safety issues; and
- Other anomalous conditions.

## INSTRUMENTATION

Check:

- Seepage weir flow depths;
- Clarity of seepage;
- Fines accumulation?
- Iron precipitates;
- Drowning of weirs?
- Condition of weirs including obstruction and sedimentation;
- Condition of piezometers / groundwater holes / monitoring enclosures etc;
- Piezometer readings;



- Surface settlement points condition;
- Relief well flows / pressures;
- Condition of tilt meters, pendulums;
- Condition of any other instrumentation; and
- Operator or public safety issues.

## SPILLWAYS

### Approach Channel

Check:

- Alignment;
- Depth;
- Obstructions (trees, flood debris, rockslides, etc.); and
- Log boom.

### Control Structure

Check:

- Condition of mechanical / electrical equipment (eg gates);
- Offsets at joints;
- Cracking (describe type, width, location and orientation);
- Spalling;
- Matrix condition;
- Lift joint condition (efflorescence, seeps);
- Leakages;
- Erosion;
- Joint filler condition; and
- Pressure relief drains, holes (note flows, blockages, etc.).

## Chute

## Check:

- As for control structure where concrete;
- Erosion (note present extent and say whether stable or progressive);
- Instability due to erosive undercutting?
- Tree growth and its effect on spillway operation; and
- Debris.

## Energy Dissipator and Stilling Basin

## Check:

- As for control structure where concrete;
- Evidence of gravel abrasion of concrete;
- Sediment accumulations;
- Erosion (record present extent and say whether stable or progressive);
- Debris;
- Instability due to erosive undercutting; and
- Tree growth and its effect on spillway operation.

## ABUTMENTS / IMMEDIATELY DOWNSTREAM / RESERVOIR RIM

## Check for:

- Stability (e.g. slips, slumps, movements);
- Seepages;
- Sinkholes;
- Erosion;
- Evidence of artesian pressures; and
- Vegetative cover.

## OUTLET WORKS

Check:

- Condition of concrete;
- Condition of metalwork;
- Condition of valves;
- Condition of mechanical / electrical equipment;
- Condition of protection systems; and
- Maintenance requirements.

## SPECIAL INSPECTION / REVIEW AREAS

(To be considered by dam engineers during comprehensive inspections / Safety Reviews etc)

Check:

- Access conditions (normal, flood post earthquake, changes);
- Communications (normal, flood, post earthquake, changes);
- Documentation (drawings, reports, O&M manual, DSEP, log books);
- Key dimensions against documentation;
- Procedures adequacy (normal, emergency);
- Operator knowledge, experience, training;
- Inspection / monitoring frequency and adequacy;
- Site security (access, manning, alarms, locks);
- PCC update (changes to affected population, infrastructure, environment);
- Incidents, concerns;
- Site geology; and
- Design adequacy (flood, seismic, operations).

## Monitoring

### Installation of Measurement Devices

Devices must be robust enough for long-term use and simple enough for operations personnel to make observations and their installation should be controlled by specialists. Check readings should be taken before, during and after installation, so that, where possible, replacements can be made for damaged items, or adjustments can be made. Simple instruments such as seepage weirs, stand pipe piezometers, rain gauges, river discharge measurement devices shall be encouraged.

Similarly, independent check readings and calibration checks should be made at regular intervals throughout the life of the instrument.

### "Up-Front" Review of Data

Data should be under continual scrutiny from the earliest possible time to ensure that the processed results make sense. This is particularly important for instrumentation linked to alarm telemetry. The following points generally apply:

- Raw data should be simple and unambiguous;
- Since data forms the basis of any mathematical model used for judgment on safety, at least two mutually corroborative sources should, where possible, be used in such a model (e.g., surface movement targets and internal movement devices); and
- Each data reading system should have facilities to detect the occurrence of "obviously different" data, which can be caused by either:
  - Transcription errors;
  - Instrumentation malfunction; or
  - Abnormal behaviour of the dam.

Such situations should be investigated immediately. If it is found that change is attributable to abnormal behaviour, the owner should initiate further investigations to explain the abnormality and ensure that it is not indicative of a worsening situation with respect to dam safety. Given that time may be a critical factor in responding appropriately, the dam owner should preferably consult an experienced dam engineer, familiar with the dam, to fast-track any response.

### Long Term Storage of Data

Data "screened" of obvious errors and thus available for the evaluation of dam safety should be stored in perpetuity as hard copy, micro-fiche or on computer. The data provides a record of the behaviour of the dam from its inception and will be invaluable as a past record. If the computer is to be the sole means of storage, then backup files, on separate systems, are absolutely essential.

Stored information should be secured within the framework of a data file system, with appropriate back-ups. Dam owners should note that where the format of data storage becomes outdated, it will need to be carefully transferred to updated systems to ensure future users have ready access to the data. Where ownership of a dam changes, the new owner should ensure that stored data is transferred from the previous dam owner. A copy of all such available data shall be sent to the MWIE and kept in the library.

### Data Presentation

Instrumentation readings and inspection reports can result in a rapidly expanding mass of data which should be reduced to a form suitable for clear presentation. Once the data are presented, graphically or numerically, the interpretation and evaluation phase can follow.

### Personnel

Since monitoring can be expected to extend over the life of a dam (100 years or more) new or "change-over" staff require adequate documentation of, and training in, dam instrumentation.

It is essential to have, and keep, as-constructed records of the instrumentation. Ideally there should always be at least two members of the "extended" surveillance staff capable of maintaining and repairing any of the instrumentation. Education and training of staff involved in instrumentation must be on-going.

### Automation

Special points to note are:

- Any telemetry system should be regularly tested and maintained, be compatible with its instrumentation, and transmit data to a continuously manned or alarmed station at the dam or elsewhere;
- The danger that automation may interrupt the vital direct link between primary event and human judgment should be avoided;
- Since a well designed and maintained dam is generally more reliable than any single alarm device, the facility to quickly corroborate alarm information should be available and used; and
- Periodical testing and, verification of equipment/alarms is essential.

Further details are provided in ICOLD Bulletin 41(1982).

### Computerised Systems

A computerised system of receiving and reviewing numerical data and some related text is generally as outlined in Figure 3. However, the following points should be considered (Stirling, 1989):

- The database selected should be of the relational type or, possibly, the object oriented type appropriate to the database being managed;
- The system should have a good user interface which makes entry to and extraction from the database relatively simple;

- The data base package chosen should have a good query language, so that the interrogation of the data base is relatively simple;
- Ideally the system should include automatic reading and recording of dam instrumentation (i.e. data logging);
- The system should enable correlation of seepage, storage level and rainfall;
- Data entry routines should have some form of error checking (data validation);
- The results from surface movement surveys should be incorporated into, and analysed in, the same database as embedded dam instrumentation data. Instruments used for surface movement surveys should, where possible, be capable of automatically recording observations;
- The data stored in the database should include raw instrument readings as well as corrected or calibrated data; and
- Ideally, and where a very sophisticated understanding of the dam's behavior is required, the system should be capable of displaying three-dimensional computer graphics, as well as being able to produce conventional two-dimensional plots for the presentation of surveillance data and trends which have been extracted from the database.

The sophistication of the data base should be tailored to the amount of data received from a dam. Many dams would not need a computer data base. However, all dams require some form of systematic and readily retrievable "data file" to store relevant reports and historical information; and this should be preserved for the life of the dam.

To preserve such records in perpetuity is not often an easy task and could involve lodging records in a relevant public or commercial archive.

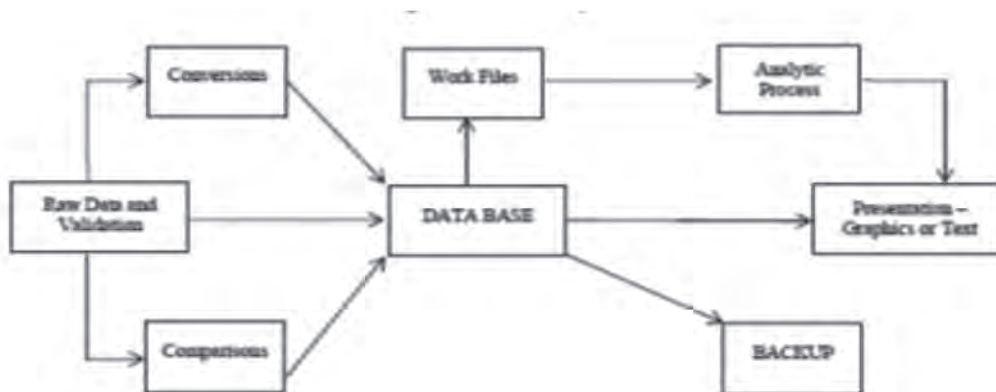


Figure 5: Typical Data Systems

## Surveillance Evaluations

### General Interpretation

All new data should be thoroughly examined in context with existing data. The sophistication of the evaluations should be tailored to the amount and variety of data received from the dam, which should in turn relate to the importance of the dam. It is recommended that for evaluations for all HIGH and VERY HIGH PCC dams, the dam owner should consult an Approved Dam Engineer.

#### (a) Situation "Normal"

Normally the latest set of observations can be quickly scanned as numbers in a table or points on a plot and be seen to be as expected. In simple cases such as settlement or horizontal deflection of fill or gravity dams the reading should be within a millimetre or two of expectation, for a well planned observation schedule.

For high thin-arch dams, reservoir water level and seasonal temperature variations can justify statistical regression checks and here again the observation should be within a few millimetres of a well organized prediction from regression.

Leakage and piezometric data, when notionally cleared of local runoff effects, should generally follow any significant reservoir head changes. Seasonal opening and closing of joints or cracks in concrete dams can be reflected in gallery or toe drain flows, but after allowing for such influences, there should be negligible long term change.

#### (b) Anomalies - Real or Not?

It sometimes happens that an isolated instrument reading, or a survey observation, will indicate some severe distress or a strain, deformation or pore pressure, which, if valid, would represent a real threat to the dam.

Every effort should be made to urgently assess such a situation, with repeat readings, repair of blown fuses, or possibly even extra instruments, targets or reference pillar checks.

If, on inspection, the dam is not in distress, and the adjacent parts are not indicated as behaving abnormally, that instrument reading or survey observation must be taken as anomalous, however carefully it purports to have been checked as "correct".

#### (c) Typical Assessment (Of "Overall Picture")

In foundations with piezometers in-line upstream and downstream of grout and drainage curtains, and flow measurement of drains or drainage adits, it is possible to develop a good picture of the water table.

Ideally the piezometers will continue to indicate a roughly linear head drop along the seepage path. Rises and falls can be expected to follow reservoir level changes.

If tightening of foundation joints by creep causes a slow reduction in the long term mean leakage flow, the head pattern described above should still apply.

If pressures build up downstream of the drainage curtain that cannot be attributed to seasonal influences, consideration of some extra drainage drilling is indicated.

#### (d) Emergency Action "Triggering"

The dam engineer (surveillance) should be familiar with the designs, recent performance and possible failure mechanisms of all dams for which he has surveillance responsibility.

If the perceived need arises, and there is a recommendation for emergency action, immediate personal access should be available to the dam owner's personnel to put the action into effect.

Senior management persons must not usurp the authority of the appointed dam engineer unless they are appropriately qualified and experienced and ready to accept possible criminal charges related to the consequences of dam failure.

Staff at the dam should be sufficiently trained to recognize an emergency and have the authority to trigger emergency action in the event of a disruption in communication. Close, regular liaison with those responsible for emergency services should be maintained by owners of HIGH and VERY HIGH PCC dams, particularly with regard to inaugurating, testing or upgrading Dam Safety Emergency Plans.

### Factors for Consideration

The evaluation of a dam's performance usually requires a close inspection of the dam and its appurtenances, examination of water pressures and seepage records and the various measured movements relative to the abutments or of differential movement within the dam. These data are then compared with design assumptions, predictions and historical behaviour patterns to fully evaluate the existing situation.

### Seepage

Seepage through, around or under a dam is expected. The quantity and nature of seepage, the seepage paths, and the velocity of the seepage waters are of concern in analysing the dam's structural behaviour.

The quantity and nature of seepage is important for several reasons:

- a) Leaching - Seepage may dissolve or leach some of the chemical constituents of the concrete, rock or soil. Leaching may provide an enlarged seepage path resulting in progressively increasing seepage. Dams founded on limestone are subject to this problem. Evaluation of the composition of the seepage water (e.g. turbidity, dissolved salt content, etc) can give a further insight into dam behaviour.
- b) Weakening - Seepage water may completely saturate soils and rock, and cause excessive uplift (pore pressures) as well as softening and weakening of soil and rock.
- c) Loss of Storage - Excessive leakage may, in extreme cases, compromise the storage capability of the reservoir, especially in the case of dams storing hazardous materials.



- d) Indication of Behavior- Increases in seepage quantity with time may indicate the onset of internal erosion, and decreases may indicate infilling of seepage paths, with possible build up of internal pressures in dams and their foundations.

The location of a seepage path is of concern because:

- a) Piping - If seepage is confined to a few discrete paths and the velocity becomes sufficiently high to move soil particles, progressive erosion may occur resulting in a "piping" failure.
- b) Leaching - Seepage waters may result in concentrated dissolution.
- c) Drainage - If discrete seepage paths are present and are not intercepted by drains, then drains should be installed.

Seepage (or pore) pressures within a dam and its foundations, if above design values, may compromise the stability of a dam.

### Movements

Some movement of all or part of a dam can be expected (e.g., seasonal movements due to temperature change or rainfall absorption, or changes in water level). Movements may be in the vertical plane, the axial plane (along the dam's axis), the upstream-downstream plane, or rotational. It is common for more than one direction and mode of movement to be present in a dam.

Vertical movements occur as a result of consolidation of the foundations or the material in the embankment. Such settlement is typically greater along the crest of the dam than along the heel or toe and is also usually greater near the centre of the dam than near the abutments.

Such settlement can result in cracking. Minor upward vertical movement (heave) can also occur at the toe of an embankment dam due to fill creep or excess uplift pressures.

Vertical movement of the centre of a fill dam with respect to the abutments is generally associated with horizontal movement toward the centre of the dam. This axial movement results in tension, which can involve cracking of the core or face membrane.

Upstream-downstream movements are usually in the downstream direction and are typically due to hydrostatic forces acting on the upstream face of the dam. These movements can be horizontal or rotational. Upstream movements in a concrete dam are usually associated with "bowing" of the dam due to expansion and are usually temperature driven. Upstream movements of an embankment dam are usually of a rotational-type and may occur during "rapid drawdown". These rotational movements may be a deep-seated or a relatively shallow configuration in the upstream face and indicate formation of a slope failure. The slides may extend into the foundation, intersect at the dam's heel or toe, or may be entirely contained within the dam. The general cause of such movements is deficient shearing resistance along the often saturated failure surface associated with high uplift pressures and reduced effective stresses.

## Critical Times for Evaluation

During the life of a dam, from initial planning, through construction, reservoir filling, and operation, an evaluation may be necessary as follows:

### Preconstruction

Evaluation of pre-construction conditions using various instruments can be valuable. During the initial planning and design stages several important considerations affecting dam safety should be investigated. They include:

- a) Normal groundwater levels - The existing ground-water level in the abutments, dam area, reservoir rim, and downstream of the dam and its seasonal variation should be determined.
- b) Quality of the ground-water - Ground-water mineral composition can be compared with later seepage water mineral composition and the reservoir water to aid in determining if dissolution is occurring.
- c) Seepage at abutments - Seepage due to natural ground-water at abutments prior to construction will affect the design of the dam and later evaluation of the dam's performance.
- d) Landslide scars/faults - Old landslide scars and faults in the vicinity of the dam indicate the potential for additional sliding during reservoir construction and operation.
- e) Permeability of existing materials - For the foundation, abutments, and reservoir floor, treatments such as grouting cut-off walls and upstream blankets may be required to reduce the effect of excessively permeable materials.
- f) Foundation consolidation - Knowing the characteristics of foundation materials allows anticipated settlement of the dam to be estimated.
- g) Fill and foundation shear strength – The shear strengths of the relevant materials are needed to determine the stability of the dam.
- h) Seismic - The seismic risk at the dam site is used to design the dam to resist loading up to the Maximum Credible Earthquake. Preparations should also be made to assess the potential for reservoir induced seismicity.
- i) Hydrologic - Catchment conditions, flood potential and the likelihood of changing conditions affecting future flood magnitude are important in determining spillway capacity.

### During Construction

Installation and observation of instrumentation begins during construction to provide essential background data for the behaviour of a dam and to ensure that the dam is performing in accordance with the Approved Dam Engineer's intent. Visual observation is also vital during this period. Important considerations affecting dam safety during the construction phase of a dam include:

- a) Instrument Installation - Many types of instrument may be installed during dam construction. These include piezometers, pressure cells, strain gauges, settlement and movement measuring devices and thermometers. It is absolutely essential that proper care be taken during their installation, and to protect them from construction operations, otherwise no information of value will be obtained from them. Incorrect installation techniques produce information detrimental to interpretation. Instruments must be tested as they are installed. Continuous supervision by specialists with authority to require repair or replacement is vital in the rough construction environment.
- b) Settlement - Consolidation of foundation and embankment materials result in settlement of the surface of the dam as it is constructed. Settlement measuring instrumentation (such as hydrostatic manometers and cross arms), installed during construction, record such settlement.
- c) Observation of Excavations – During construction, excavations for foundation and core trenches should remove undesirable materials. Visual observations by experienced personnel during this phase are extremely valuable and should be carefully recorded. Based on these observations, there may be need for instruments to be relocated, or added, or for design changes. This information can be important in diagnosing subsequent anomalous behaviour.
- d) Increasing Pore Pressures - Rapid construction of embankments, at high moisture contents, may cause excessive pore pressures, which would result in instability if not allowed to dissipate. Records of such construction pore pressures can be of long-term significance.
- e) Slide Movements - Slide movements due to high pore pressure building up during construction may be noted either visually or by instrumentation.
- f) Temperature - Excessive temperatures, built up from cement hydration in concrete dams, may cause subsequent thermal cracking if not controlled.
- g) Permeability - Filter permeability should be checked as placement can compact a filter more than specified.

### During First Reservoir Filling

The first filling of a reservoir is normally the critical condition for dams. At that time, the first true analysis of the behaviour of a dam with reservoir loading can be made.

Instrumentation readings and visual observations should be conducted very frequently during this period with particular attention paid to the following matters:

- a) Seepage - As the water level in the reservoir rises, it is especially important to watch both the dam and abutments for increases in seepage quantities, changes in seepage clarity, new seepage locations and the functioning of drains.
- b) Pore Pressure - At this time frequent reading should be taken to monitor pore pressure changes and patterns.

- c) Dam Movements - The increasing load from the reservoir water will cause movements of the dam, particularly in the downstream direction. These require close monitoring, ideally including correlation with movement controlling factors.

### During Normal Operations

The normal trouble free operation of a dam over many years is the goal for which the dam was built. The water level in many reservoirs fluctuates each year resulting in seepage quantity and pore pressure fluctuations on a regular, somewhat predictable basis. It is therefore important to establish a regular instrumentation monitoring schedule and a regular visual inspection of the facility and to summarise the findings in regular surveillance reports on the dam. Any significant unusual changes noted should be an immediate cause for further investigation.

### During Record Reservoir Fillings or Following Earthquake

Record fillings of reservoirs and earthquakes can subject a dam to loading conditions that it has never been subjected to before. These can be critical. Instrumentation readings and visual observations should be conducted very frequently during and following these times with particular attention paid to the first filling matters.

### During Rapid or Prolonged Drawdown

Occasionally, the reservoir level is lowered rather quickly for some reason. The term "rapid" depends on the type of material in the dam and abutments. In some relatively permeable materials, "rapid" may mean hours or days, while in low permeability materials, a "rapid drawdown" might cover a period of weeks, months or longer. During drawdown the external reservoir water pressure is removed but the internal pore pressures in the dam and abutments remain, to dissipate much more slowly in impermeable materials. This creates a condition wherein slides and movements may occur in the upstream face or core of an embankment, the abutments, or anywhere along the reservoir rim. In addition, collapse compression has been experienced in upstream "dirty" rock fill shells after drawdown leading to stressing of the adjacent core. Surface movements and pore pressures in the upstream shoulders and core of embankment dams require special monitoring at this time and subsequent refilling.

### Interpretation of Data

#### Data Presentation

The use of graphical presentation of instrumentation data is normally considered necessary for the evaluation of dams. Graphical presentation by computers is simple and rapid and reduces the chance of plotting errors and enables ancillary computations and data variation checks to be performed.

Data presentation, when properly done, is of very significant value, but incorrect data plotting may cause errors in interpretation. The characteristics of incorrect plotting include:

- a) Improper Scale - Proper and consistent scales must be used. Movements should not normally be shown larger than full-scale (1:1).
- b) Excessive data - In general, each plot should contain only two variables; (e.g. water level and time.) There may, however, be a large amount of data points on a single instrument or even a

number of instruments. The number of instruments shown on a single sheet of plotting is a matter of common sense. Each line should be clearly specified in the plot legend.

### Detection of Errors

Data errors can usually be detected either in the field at the time of reading or in the office during processing or reviewing. Often, it has been found that if the instrument reader knows what the previous reading on an instrument was, he can re-check the current reading if it differs significantly. In addition, the risk that the reader will report a reading close to the previous one without actually making an observation, or even where a different reading is actually obtained, has to be considered.

### Normal and Abnormal Conditions

Application of the terms "normal" and "abnormal" depends on the particular characteristics of a dam in question. The behaviour of pressures, strains, movements, and seepage, should be compared to the behaviour anticipated during the design of the dam and any pre-construction data gathered from the dam site. It is important for Approved Dam Engineers to state acceptable "ranges" in design reports and operating instructions. For dams with limited design data, historical behaviour patterns should be developed.

### Correlation of Inspection/Monitoring Data

The recommendation for major remedial works on a dam should not depend on uncorroborated evidence. Ideally any visible anomaly should be confirmed by anomalies recorded on associated instruments.

It is important to compare measured aspects of a dam's behaviour over identical date ranges.

Since observations cannot always be made concurrently, response factors, such as regression coefficients, should be used to determine the most probable values on the chosen comparison date, for observations that could not be made on the date. Reservoir water level, ambient temperature, and age since construction should be included among the controlling variables in these studies. In comparing the Approved Dam Engineer's predictions and the prototype's performance, regression can be an important tool in separating the effects of temperature, water load and creep, so that each may be compared in turn.

In general, those responsible for interpreting monitoring results should endeavour to make all possible logical linkages throughout the range of dam data obtained from observations and inspections and be vigilant in the detection of errors and false alarms. Familiarity with the reliability of installations and observers is a great advantage in making a judgment as to whether an "alarm" is false or real as a result of a genuine excessive change in the value of the entity being monitored. In this regard, close liaison between dam operators and surveillance personnel is critical.

## APPENDIX C - SAFETY REVIEWS

### Suggested Procedures

- Review design and design data (i.e. plans, reports);
- Review construction methods/report;
- Review operational and maintenance history, photographs and reports;
- Examine the performance and condition of the existing structure;
- Perform an survey of the dam to determine available freeboard;
- Carry out a PFMA;
- Conduct specific investigations and analyses as necessary (including Risk Assessments);
- Use PFMA to make Surveillance Plan address key PFMs;
- Use PFMA to make Emergency Action Plans address key PFMs;
- Reach final conclusions and make recommendations; and
- Prepare a report.

### Matters to be considered

#### Design

- Are design criteria and their origins documented?
- Comparison of actual performance with the intended performance;
- Was the structure constructed as designed? What changes were made and why?
- Were there any design revisions made for unusual or unanticipated conditions;
- Were the appropriate design loads considered?
- Have conditions changed, thus creating the need to change design criteria? Possible changes are:
  - Revised flood estimates;
  - Revised hazard categories;
  - Revised seismic loadings; and
  - Actual material properties

- Will the structure safely accomplish the tasks for which it was intended, both hydraulically and structurally?
- Is the original design compatible with current state-of-the-art design methods and criteria?

### Construction

- Is there the potential for the development of unsafe conditions because of:
  - Unexpected foundation conditions;
  - Presence of seepage;
  - Large grout takes; and
  - Indications of distress or movements.
- Poor construction methods leading to latent unsafe conditions.
- Inadequate materials testing or control.
- Lack of survey control during construction or repair may have resulted in zones being misaligned or being of inadequate thickness.

### Performance

- Has the reservoir been operated only within the design limitations?
- Are there any indications of deficiencies and adverse trends from the following:
  - Instrumentation observations and interpretations;
  - Changes in operating criteria;
  - Maintenance reports;
  - Other historic records; and
  - Observations during operating activities.

### Current Conditions of Visible Features

During the inspection of the dam, appurtenant structures and mechanical equipment the following aspects should be investigated:

- Regions of distress.
- Unexpected movements.
- Unusual seepage.

- Mechanical and electrical equipment malfunction.
- Gradual deterioration.
- Erosion.
- Other observations relating to safety such as inappropriate vegetative growth, animal burrows, erosion and vandalism.



## APPENDIX D: DAM SAFETY VEGETATION MANAGEMENT

### Purpose

The establishment, maintenance, and control of vegetation pose engineering, as well as routine maintenance considerations. This guidance establishes minimum requirements for maintenance/control of vegetation at dams, abutments, spillways, inlet/outlet channels, and other appurtenances.

### Background

Vegetation is much more than an aesthetic consideration. Proper vegetation management is necessary to preserve the design functionality of critical project features. Requirements for mowing and eradication are documented in the project specific Operations and Maintenance Manual. Changes in vegetation management practices to promote project benefits such as recreation and environmental enhancement must be carefully evaluated from a dam safety perspective and coordinated with dam safety experts. Vegetation that adversely impacts engineered structures or inhibits inspection, monitoring, and emergency response actions is not allowed.

### Beneficial Vegetation

Beneficial vegetation, such as grass cover, can assist in preventing erosion, controlling dust, defining zones of use, and creating a pleasant environment. Uniform grass cover enhances visual inspection, allowing the detection of seeps, settlement, displacements, and other evidence of distress. Robust grass coverage along embankments and discharge channels can help deter the natural establishment of trees and other deep rooted species.

### Undesirable Vegetation

Woody vegetation and aquatic plants (e.g. cattails) can obscure large portions of the dam, preventing adequate visual inspection, creating potential seepage pathways, reducing discharge capability, and can threaten the stability and integrity of a structure.

Structural instability can occur due to falling/decaying tree/woody vegetation and root system growth. Large, seemingly stable and innocuous trees can easily be blown over or uprooted in a storm/flood and cause a large hole left by the root system. This in turn can shorten the seepage path and initiate piping, or a breach in the dam.

Root systems may undermine concrete slabs, causing erosion of foundation materials and subsidence or heave. Additionally, root systems can interfere with interior drainage systems. Trees and aquatic vegetation in channels can restrict flow volumes, or become a source of debris which blocks releases. Trees in channels can also initiate uneven flow patterns and cause erosion that may divert discharges out of bank. All of these can ultimately threaten public safety.

## Policy

The following areas shall remain free of trees and other woody vegetation such as shrubs and vines:

- The dam and dam toe area as well as an area at least 20 m downstream of the toe of the dam;
- In or around seepage monitoring systems or critical areas for seepage observation;
- Abutments and groins;
- Spillways and regulating outlet channels, including channel floors, side slopes and approaches; and
- Outlet works discharge channels.

Inspections conducted either by project personnel, or engineering personnel must always consider the potential dangers from excessive or inadequate vegetation growth. Changes in surfaces, such as cracks, depressions, and movements must also be readily observable via controlled grass cover. Any evidence of seepage or erosion must be quickly identified, monitored evaluated and controlled to prevent flows that could become detrimental to the safety of the structure. Inspection of vegetation shall be part of each annual and formal periodic inspection for each project and shall be discussed in the respective reports.

The governing criteria for maintenance of vegetation on the dams, or areas adjacent to, or immediately downstream of dams is to provide ready and adequate visual observation.

Design and construction of landscape plantings, including irrigation systems, must be carefully devaluated and reviewed from a Dam Safety perspective and approved by dam safety experts.

Trees, brush, and weeds in spillways and inlet and outlet channels shall be maintained so as not to obstruct flows, or cause any threat or potential threat to areas downstream of the dam. Specified spillway and outlet works design discharge capacities must be maintained. Tree and vegetation removal from spillway discharge areas downstream of the crest or sill is required to avoid "head cutting" or causing flow concentrations.

## Implementation

Mowing/ clearing limits for each dam shall be identified by the Approved Dam Engineer and documented on aerial photographs or plan drawings, as part of the project Operations and Maintenance Manual. The limits shall be site-specific and shall take into consideration the topography, phreatic surfaces within the structure and abutments, foundation characteristics and any historical problems with the structure.

The horizontal limits of clearing shall not be less than the entrance width of the spillway. In the vertical direction, no encroachment by woody vegetation of any kind can be tolerated up to the elevation of the inflow design flood profile. Dam safety personnel shall establish specific clearing limits for spillways based on project hydrological characteristics, and they shall be permanently and clearly marked in the field.

Riprap in all areas shall be maintained free of vegetation. This includes embankment slopes, discharge channel slopes, and emergency rock stockpiles.

### Remediation Procedures

Undesirable woody vegetation identified by the Approved Dam Engineer shall be removed. Removal of woody vegetation will require engineering judgment to determine if the root system has engaged water bearing regions of the dam and/or site specific geologic areas of special interests such as jointed rock formation which contain water at the toe or dam abutments.

Tree and woody vegetation growth on the upstream slope should be undercut to remove all stumps, root balls, and root systems. The undercut area must be thoroughly inspected to confirm that all major root systems (greater than about one-half inch in diameter) have been removed during the undercutting operation to prohibit regrowth. Suitable backfill shall be placed in the excavation and properly compacted to the dam remediation design limits. Backfill shall be similar to the in-situ embankment fill material and shall be compacted. Installing a slope protection system is recommended to reduce the potential for wave and surface runoff erosion.

Engineering judgment will be required to identify the depth and extent of stump and root ball removal, laying back the undercut slope and selection of backfill based on dam design.

Alternative methods, such as herbicide spraying, burning, or cutting trees flush to the ground surface and leaving roots in place may be considered, in consultation with dam safety experts. However, burning atop riprap is prohibited as this can weaken and degrade the rock.

The suggested dam remediation design and construction procedure suggested for complete removal of trees, stumps, root balls, and root systems consists of the following activities:

- Cut the tree approximately two (2) feet above ground leaving a well-defined stump that can be used in the root ball removal process;
- Remove the stump and root ball by pulling the stump, or by using a track-mounted backhoe to first loosen the root ball by pulling on the stump and then extracting the stump and root ball together;
- Remove the remaining root system and loose soil from the root ball cavity by excavating the sides of the cavity to slopes no steeper than 1:1 (horizontal to vertical) and the bottom of the cavity approximately horizontal;
- Backfill the excavation with compacted soil placed in relatively loose lifts not greater than about eight (8) inches in thickness. Compaction of backfilled soils in these tree stump and root ball excavations typically requires the use of manually operated compaction equipment or compaction equipment attached to a backhoe.
- Procedure for total removal of trees near the toe is more complicated. Treatment of mature tree penetrations in a downstream slope may involve installation of a subdrain and/or filter system in the tree penetration excavation and backfill with compacted soil placed in maximum loose lifts of eight inches.

### Establishment of Vegetation

All disturbed areas must be protected by seeding and mulching. Timing must be considered to allow seed to germinate and develop roots prior to winter or heavy precipitation seasons.

Waivers to allow additional vegetation or alternate remediation techniques must be submitted in writing to the Approved Dam Engineer. A multi-discipline team shall review the proposed change, assess potential dam safety impacts, and provide a written recommendation to either approve or decline by the Approved Dam Engineer.

## APPENDIX E: TYPICAL EXAMPLES OF DAM SAFETY INCIDENTS/FAILURES

This Appendix contains example dam failures or incidents of the following failure modes:

- Internal erosion failures;
- Failure of embankment dams during to seismic loads;
- Failure of embankment dams during to seismic loads;
- Seismic failure of retaining walls;
- Failure due to overtopping of spillway walls and stilling basins;
- Overtopping failures;
- Failure due to erosion of rock;
- Concrete gravity dams failures;
- Concrete arch dam failures;
- Concrete buttress dam failures;
- Landslide failures and incidents;
- Operational failure;
- Trunnion Friction Radial Gate Failure;
- Drum Gate Failures;
- Stagnation Pressure Failure of Spillway Chutes; and
- Cavitation Damage Induced Failure of Spillways.

## Internal erosion failures

### Teton Dam, USA (Engemoen & Redlinger, 2009)

Teton Dam, a 94 m high embankment dam in Idaho, USA, failed in 1976.



Figure 6: Teton Dam during failure

The failure of the Teton Dam during initial filling of the reservoir on June 5, 1976 killed fourteen people and caused hundreds of millions of dollars in property damage downstream. A thorough investigation identified the causes of the failure and suggested improvements for the design and construction of earthen dams.

Construction of the dam began in February 1972. When complete, the embankment would have a maximum height of 93 m above the riverbed and would form a reservoir of 356 million m<sup>3</sup> at full supply level. The dam was closed and began storing water on October 3, 1975, but the river outlet works tunnel and the auxiliary outlet works tunnel were not opened.

Due to these sections being incomplete, the water was rising at a rate of about 1 m/day, which was higher than the predetermined goal rate of 0.3 to 0.6 m/day for the first year, as set by the U.S. Bureau of Reclamation. However, the increased rate was expected, due to the tunnels being incomplete, and considered acceptable by the Bureau of Reclamation as long as seepage and the water table downstream of the dam were measured more frequently.

The dam failed on June 5, 1976, when the water level in the reservoir was at an elevation 9 m below the embankment crest and just 1 m below the spillway crest. Breaching of the dam crest and complete failure

was preceded over a period of two days by increasing quantities of seepage. This seepage was observed initially some 460 m downstream, and later on the downstream face of the dam. Noticeable increases in the seepage flow rate from the face of the dam adjacent to the abutment about 40 m below the crest occurred during the morning of June 5.

At approximately 10:30 a.m. dispatchers at the Fremont and Madison County Sheriffs' offices were notified that the dam was failing. The flow rate had increased to about 0.4 m<sup>3</sup>/s. This quantity continued to increase as a 1.8 m diameter "tunnel" formed perpendicular to the axis of the dam.

Between 11:15 and 11:30 a.m. a 6 by 6 m chunk of dam fell into the whirlpool and within minutes the entire dam collapsed. At 11:55 am, the crest was breached with complete failure of the dam.

An estimated 300 million m<sup>3</sup> of water headed down the Upper Snake River Valley. The towns in its path included Wilford, Sugar City, Rexburg, and Roberts.

More than 200 families were left homeless. The final toll was 14 killed directly or indirectly and an estimated 400 million to one billion dollars in property damage.

### E.1.2 Avalon Dam, USA (Engemoen & Redlinger, 2009)

Avalon Dam in New Mexico failed twice; once in 1893 from flood overtopping and later in 1904 from internal erosion. After the second failure, Avalon was taken over by Reclamation and reconstructed in 1907. Although this dam was not part of Reclamation's inventory when it failed, it was one of Reclamation's earliest dealings with an internal erosion incident. Avalon Dam was one of several dams built in the late 1800's or early 1900's that featured a rockfill downstream section which buttressed an upstream earthfill zone. It is notable that a number of failures or serious incidents occurred at other non-Reclamation dams having this similar configuration, including McMillan Dam, Black Rock Dam, and Fish Lake Dam.

In all these cases, a seepage path existed through their earthfill zone that flowed down into underlying rockfill. The exact cause of failure of Avalon Dam is unclear, but explanations included piping of the embankment due to the severe incompatibility of the earthfill and rockfill from a filtering/retention perspective, or erosion at the base of the earthfill due to flows in the upper portion of the limestone foundation.



Figure 7: Avalaon Dam after its 1904 internal erosion failure

### Fontenelle Dam, USA (Engemoen & Redlinger, 2009)

A very serious internal erosion incident occurred in 1965, when Fontenelle Dam nearly failed during first filling. Significant seepage travelled through the open jointed sandstone foundation rock, emanating 610 m downstream in a low area as well as in the right abutment near the spillway. Seepage led to the erosion of more than 7 645 m<sup>3</sup> of embankment materials before the intervention efforts of large outlet works releases and dumping of rockfill into the embankment erosion area eventually lessened the flows and the erosion.

Fortunately, the large capacity outlet works was able to lower the reservoir by approximately 1.2 m/day, quickly reducing the head at the abutment area where internal erosion was occurring. In less than 2 days of drawdown, the reservoir was lowered off of the spillway approach channel which undoubtedly was feeding seepage into the problem area. The primary cause of the near failure was thought to be inadequate grouting of the jointed sandstone and the lack of foundation treatment measures such as slush grouting and dental concrete, which led to seepage near the base of the dam that removed embankment material and led to the growth of voids and stoping.



Figure 8: View of the piping at Fontenelle Dam

Contributing factors included the presence of infilling or soluble material in the jointed rock that may have inhibited grout travel; residual or redeposited soluble salts in the rock that may have reacted with the grout causing premature set or ultimate softening; the erodible nature of the embankment core material; and a steep right abutment that created difficulties in achieving good bond or contact between the embankment and abutment, encouraged differential settlement and cracking of the embankment, and made shallow grouting difficult because low pressures were required to prevent movement of the rock.

Another factor not mentioned in early reports was the unfavourable orientation of the abutment with respect to the potential for hydraulic fracturing. In hindsight, an obvious key factor in the near failure, in addition to the lack of sufficient foundation treatment, was the lack of an internal filter and drainage zone



that would render seepage through both the foundation and embankment harmless with respect to the removal of soil particles and the build-up of pore pressures. A couple of key details are that the average zone 1 core material in the dam is reported as being a SC-CL with 13% plus No. 4 material and having a LL of 31 and a PI of 13. However, the core material remaining after the near breach in the abutment area was generally described as a well graded mixture of sandy gravel and silt. No crack in the core was noticed during close inspection of the piping channel through the zone 1. Zone 2 materials described as select sand, gravel and cobbles as well as the materials in the miscellaneous zone sloughed during this incident and an incident that occurred four months prior and were easily removed by the concentrated seepage.

#### E.1.4 Caldwell Outlet Works at Deer Flat Dams, USA (Engemoen & Redlinger, 2009)

The Caldwell Canal outlet works, with a capacity of 1.982 m<sup>3</sup>/s, is a cut-and-cover conduit located through the left abutment section of the Upper Embankment at Deer Flat Dams in Idaho, and was completed in 1908. The foundation materials in the vicinity of the Caldwell conduit consist of mostly poorly graded sand and silty sand with some gravel. Caliche layers exist in some areas of the dam's foundation as well.

A dam safety inspection in 2001 (93 years after construction) noted some sediments in the seepage from a crack in the conduit located 19.8 m upstream of the outlet portal. A large sand deposit approximately 1.8 m wide by 4.5 m long and 0.25 to 0.30 m deep was observed downstream of the outlet structure. Although speculated to be windblown materials, it was also judged possible that the observed sediments could have been materials transported into the conduit by seepage flows. Then, in 2004 sediment was observed at the base of a crack in the conduit approximately 38 m downstream of the regulating gate.

Subsequently, ground penetrating radar was utilized in the conduit, and potential anomalies were detected between 30 and 45 m downstream of the gate. Follow-up drilling through the conduit revealed voids beneath the conduit varying from 0.013 to 0.13 m in depth, presumably caused by internal erosion of foundation soils into or along the conduit. Piezometers installed below the conduit revealed consistently low pressures similar to tailwater levels beneath the conduit from the downstream portal upstream to within 6 m feet of the intake.

It was concluded that backwards erosion piping had occurred along most of the conduit, with potentially high gradients existing at the upper end of the conduit. A large upstream berm was constructed to minimize the potential for upstream breakout of the piping pathway to the reservoir, until permanent corrective actions could be taken.

In the case of Upper Deer Flat Dam, even though in general there are gravels present in the embankment fill as well as the foundation, gravel sized particles were found to be absent over a large extent of the conduit foundation during the recent re-construction. Even if coarser particles were present in the soil mass, the mechanism of a soil filtering against a crack in the bottom of a conduit can be complicated by the fact that a flow path beneath the structure will not necessarily transport coarser particles up into or against the crack in the bottom of the conduit. Any particles transported to such a crack may drop away during times of lower gradients such as under lower reservoir operating conditions. Therefore, caution against the use of liberal filter/retention criteria in such a case is advised.

### A.V. Watkins Dam, USA (Engemoen & Redlinger, 2009), (Bliss & Dinneen: 2007).

A.V. Watkins Dam (formerly known as Willard Dam) is a U-shaped (in plan view) zoned earthfill structure constructed within Willard Bay of the Great Salt Lake. Constructed from 1957 to 1964, the dam is 10.97 m high at its maximum section and slightly more than 23.3 km<sup>5</sup> miles long. Upon first filling of the reservoir in 1965, as the reservoir reached within approximately 0.6 m from full supply level, numerous wet areas (with some areas displaying quick conditions) appeared at the downstream toe of the dam.

After this discovery, filling of the reservoir was halted, the reservoir was lowered and a toe drain was constructed approximately 4.5 m from the downstream toe from 1.2 to 1.5 m deep in the foundation, consisting of 200 mm diameter bell and spigot concrete pipe with open joints and surrounded by gravel. Toe drain outfalls were constructed at approximate 300 m intervals to discharge into the South Drain; a long open ditch excavated about 40 m downstream of the dam toe to help drain farm land as well as seepage. The toe drain was apparently successful in drying up the downstream toe area and the reservoir was eventually filled to the top of active conservation water surface.

In November of 2006, A.V. Watkins Dam nearly failed at a location in the same general area that created problems during initial filling, as the result of piping and internal erosion of the foundation soils. Two days previously, a local cattle rancher working just downstream of the incident area noticed seepage and some silty material exiting from the cut slope of the South Drain. The rancher continued to observe the seepage and erosion into the South Drain until Monday, November 13, when he became concerned over the increase in seepage and the appearance of what he described as “dark clay” exiting into the South Drain. He called authorities and Reclamation began 24 hour monitoring and initiation of an emergency drawdown of the reservoir.

Piping of the foundation soils was occurring from beneath the dam below a somewhat continuous series of thin hardpan layers, and the fine-grained, silty sand soils were exiting from the dam’s downstream toe and from the base of the north slope of the South Drain. Approximately 0.53-0.72 m<sup>3</sup>/min of seepage was exiting from sand boils at the downstream toe of the embankment (but upstream of the toe drain), flowing across the ground surface and into sinkholes between the toe of the embankment and the South Drain. The seepage appeared to be re-emerging at the base of the bank of the South Drain and was depositing large amounts of sand into the South Drain.

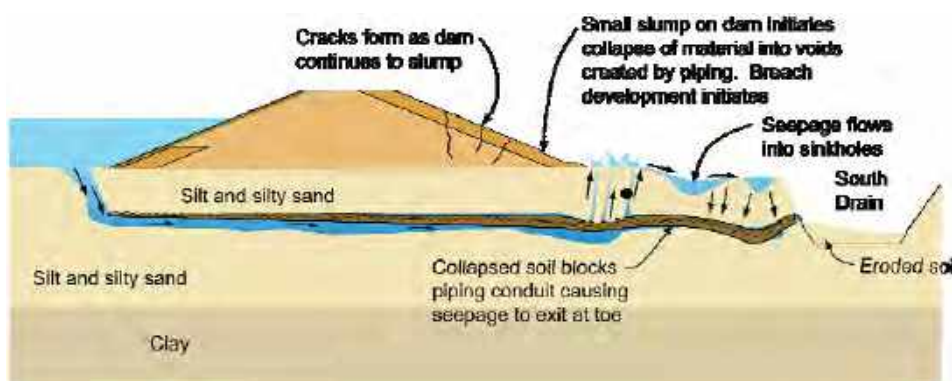


Figure 9: Failure Mode in progress at A.V. Watkins Dam (Not to Scale)

Efforts to save the dam focused immediately on transportation of filter sand and gravel materials to the site to begin placement of these soils directly over the sand boils in an attempt to stop the erosion of foundation soils. Initially filter sand was placed over the sand boils but that was quickly washed away due to the high exit velocities. Gravels were then placed over the sand boils until the exit velocities were reduced enough to allow placement of the filter sand. This reduced the flow and erosion of soil enough to allow the placement of a sufficiently large berm consisting of additional filter material, drainage material, and minus 5-inch pit-run material, to counter the uplift pressures in the emerging seepage at the toe.

On November 16, Reclamation technical staff determined the failure mode was still in progress and additional remedial action was required. It was noticed that seepage and erosion was still occurring into the South Drain. On November 17 and 18, a berm was added to the upstream slope of the embankment extending into the reservoir to stem the flow of the water into the foundation and any inlets to potential piping channels (located just beyond the upstream dam toe and within the riprap) that were postulated to be the sources for the concentrated seepage entering the foundation. These efforts were successful in stopping the foundation erosion and immediately reducing the overall seepage flows.

Some key lessons learned at this dam to consider in future dam designs and risk analysis are:

- Internal erosion can initiate, progress and nearly fail a dam with an erodible foundation at very low head to seepage length ratios, in this case generally about 0.06 (locally may have been about 0.09 due to rodent holes), if the exit point for the unfiltered seepage is nearly horizontal, the soil is highly erodible, and a roof is present.
- Rodent activity can suddenly aggravate a meta-stable seepage situation, as rodents can fairly quickly excavate a burrow and shorten a potential seepage path, compared to the more gradual particle transport caused by seepage at these low gradients.
- Construction of open trenches downstream of the toe of a dam provides a location into which materials can be eroded.
- Toe drains installed as the primary defence against foundation internal erosion, especially when the drain is installed after an occurrence of piping was observed, can be critical to the performance of the structure. Plugging of the toe drains appeared to have been occurring at this site. It is not clear that the toe drain plugging was a significant contributor to the occurrence of the incident.
- Changes to seepage conditions that occur over a long period of time can be difficult to recognize and the knowledge about the presence of buried drains can be lost. Consideration should be given to estimating risks for (or at least considering as a potential failure mode) every location that seepage or wet spots are known to exist at a dam, as well as those areas typically analysed.

### Stilling Basin at Davis Creek Dam, USA (Engemoen & Redlinger, 2009)

Davis Creek Dam is a modern embankment dam in Nebraska, completed by Reclamation in 1990. A sinkhole was reported adjacent to the outlet works on May 11<sup>th</sup>, 2007. The sinkhole was located against the left side of the outlet works control house immediately upstream of the stilling basin, and measured approximately 1.5 m along the wall, 0.6 m wide away from the wall and about 1.8 m deep.

The sinkhole was located in the structural backfill composed of fine to medium sands. The perimeter of the sinkhole was probed with a steel rod, which could be inserted with ease vertically along the wall in the sand to a depth of about 3 m below the bottom of the sinkhole or about 4.9 m below the original ground surface. Subsequent video inspections of the spillway underdrain system found sand in the drain pipes. Due to a defect in the underdrain system, whether from broken pipe or inadequately constructed filters, structural backfill and possibly foundation sands were being internally eroded into the underdrain system and then removed downstream by the action of the drains during outlet works operation.

A grouting operation was subsequently undertaken, and it took more than 15.3 m<sup>3</sup> of grout to fill voids beneath the stilling basin and surrounding areas. The precise location and lateral extent of the void system could not be defined, and it is uncertain if the erosion had progressed upstream along the outlet works beyond the limit of the upstream edge of the sinkhole. A filtered drainage system was also constructed around the sides of the basin to encourage drainage and thus reduce uplift pressures.

The underdrains were installed to assist in preventing floatation of the stilling basin structure both during dewatering of the stilling basin and during operations should the hydraulic jump move downstream. They were constructed such that during certain operating conditions outlet works discharges running by the drain outlets created low pressures thus resulting in drain flow and lowered uplift pressures. Vents were installed to ensure negative pressures did not develop. This fairly sophisticated drain system, if damaged, can apparently be very efficient in causing particle transport from the foundation. Since the operations of the outlet are intermittent, removal of soil would be intermittent and could occur over a long period of time.

The typical winter seepage regime could have primed the system with water and soil particles and then the underdrains could have nearly instantaneously removed the water and some soil from beneath the structure each year under certain operating conditions. Hydraulic connection of the stilling basin to the groundwater was potentially causing very severe transient seepage conditions and particle transport.

### Failure of embankment dams during to seismic loads

#### Lower San Fernando Dam, USA (Seed et al: 1975)

Lower San Fernando Dam is a 40 m high hydraulic fill embankment dam in Los Angeles, CA, USA that failed in 1971.

Construction of a 40 m (130 ft) high hydraulic-fill earth dam was initiated in 1912 as part of a reservoir system in San Fernando, California. Hydraulic fill was placed between 1912 and 1915. The material was excavated from the bottom of the reservoir and discharged through sluice pipes located at starter dikes on the upstream and downstream edges of the dam. This construction configuration resulted in upstream and downstream shells of sands and silts and a central core region of silty clays. A stratum of variable thickness between 3 and 5 m of reworked weathered shale (silty sand to sand size) was placed on top of

the hydraulic fill material in 1916. Several additional layers of roller compacted fill were placed between 1916 and 1930 and raised the dam to its final height of about 40 m. A roller compacted berm was placed on the downstream side in 1940. The dam created a reservoir with an estimated full capacity of about 25 million m<sup>3</sup>.



Figure 10: Lower San Fernando Dam after failure

On February 9, 1971, the San Fernando earthquake occurred with an estimated Richter magnitude 6.6. At the time of the earthquake, the water level in the reservoir was about 11 m below the crest. This reduced level was in part the result of an earlier seismic stability analysis which imposed a minimum operating freeboard criterion of 6 m. Immediately after the earthquake, a major slide involving the upstream slope and the upper part of the downstream slope occurred. As a result of the slide, a freeboard of about 1.5 m remained. Given the likelihood of further damage in the presence of after-shocks, 80 000 people living downstream of the dam were evacuated until the water level was lowered to a safe elevation over a 4 day period.

Seismic shaking triggered liquefaction of the hydraulic fill within the upstream slope of the dam, and the seismoscope records indicated that the slide occurred about 30 seconds after the end of shaking. Therefore, the slide was the result of the loss of strength in the liquefied soils rather than the result of inertia forces during the earthquake.

The earthquake shaking initiated a major failure on the upstream side of the dam and was perilously close to a catastrophe. A very steep slide head scarp and marginal freeboard remained after the event. Had the head scarp been slightly lower, the outflow from the reservoir would have quickly eroded the dam and flooded many communities downstream. Considering the extremely precarious situation, some 80 000 people over an area of 28.5 km<sup>2</sup> were evacuated while the reservoir was emptied over a period of three to four days.



## Sheffield Dam, USA

Sheffield Dam failed during the Santa Barbara earthquake of 1925. Although there were no witnesses to the breach, it was believed that the sandy foundation soils which extended under the entire dam liquefied and that a 91.4m long section of the dam slid downstream, perhaps as much as 30 m (Seed et al, 1969). The dam was located quite close to the city of Santa Barbara, and a wall of water rushed through town, carrying trees, automobiles, and houses with it. A muddy, debris-strewn aftermath was left behind. Flood waters up to two feet deep were experienced in the lower part of town before they gradually drained away into the sea. No fatalities were reported.



Figure 11: Sheffield Dam after seismic failure

## Seismic failure of retaining walls

### Austrian Dam, USA (USCOLD, 1992)

Austrian Dam is a 61 m high embankment dam that was constructed in 1949 to 1950 and is located on Los Gatos Creek, near the town of Los Gatos, California. A concrete spillway is located on the right abutment of the dam. The uncontrolled ogee crest structure is founded on moderately weathered fractured shale and the crest elevation is 4.57 m below the dam crest elevation. The spillway chute is founded on highly weathered shale, but some of the shale was replaced with shallow compacted fill during construction. Austrian Dam was subjected to the Loma Prieta earthquake on October 17, 1989. The earthquake was a magnitude 7.1 event and was centered in the Southern Santa Cruz mountains, near the Loma Prieta Lookout. It is estimated that the peak horizontal ground accelerations at Austrian Dam were up to 0.6 g.

Austrian Dam settled and spread in the upstream and downstream directions as a result of the earthquake. The maximum settlement of the dam was 0.853 m; maximum downstream movement near the spillway wall on the right abutment was 0.335 m; and, the maximum upstream movement was 0.427 m, near the left quarter point of the embankment. Longitudinal cracks up to 4.267 m deep occurred

within the upper portions of the upstream and downstream faces of the dam. Transverse cracking (to a depth of 9.75 m on the right abutment) and embankment separation from the spillway structure occurred (USCOLD, 1992).

The spillway was damaged as a result of the earthquake loading. Cut-off walls were provided along the length of the spillway walls and the cut-offs were loaded and displaced as the embankment spread in the downstream direction. The spillway structure elongated about one foot as a result of the embankment deformation. Voids up to 150 mm were created upstream of the cut-off walls. The walls of the “U” shaped chute deflected inward, which lifted the base of the structure and the adjacent portions of the chute floor slab up to 25 mm. While the spillway did not fail catastrophically, the structure was severely damaged and a potential seepage path was created along the left spillway wall, due to the separation of the wall and the adjacent embankment. Fortunately, the reservoir was low at the time of the earthquake.

### Shi-Kang Dam, Taiwan (USCOLD: 2000)

Shi-Kang Dam is a buttress gravity dam located on the Tachia River. The dam is located about 50 km north of epicenter of the Chi-Chi earthquake, which occurred on September 21, 1999. The Chelungpu fault passed underneath the spillway crest structure and ruptured during the Chi-Chi earthquake. Differential movement along the (spillway bays 16 to 18) fault was about 8.8 m in the vertical direction and 2 m in the horizontal direction. The horizontal and vertical peak ground motion of station TCU068, located at Shih-Kang Primary School 500 m away from the dam, were 0.51 g and 0.53 g, respectively. The spillway bays outside of bays 16 to 18 survived with little or no damage.

Failure of a chute wall panel in the spillway for Shi-Kang Dam however occurred. The wall is counterforted and it appears that the collapse of the wall resulted from a shear failure in the counterforts. No specific details are available regarding the failure but the failure demonstrates for the potential failure of spillway walls during large earthquakes.



Figure 12: Failed Spillway Wall at Shih-Kang Dam

## Failure due to overtopping of spillway walls and stilling basins

### El Guapo Dam, Venezuela (Villar, 2002)

El Guapo Dam was located on the Rio Guapo, 4.8 km south of the city of El Guapo, in the state of Miranda, Venezuela. The reservoir formed by the dam provided potable water for the local area, flood control, and irrigation water. The reservoir volume was 40.7 million m<sup>3</sup>. The dam was constructed from 1975 to 1980. The original spillway at El Guapo Dam consisted of an uncontrolled ogee crest, located on the left abutment of the dam, a concrete chute and a concrete hydraulic jump stilling basin. The spillway had a width of 12.192 m, a length of 281.9 m and a design discharge capacity of 101.9 m<sup>3</sup>/s.

Initial hydrologic studies were based on a similar basin but not the Rio Guapo basin. During construction of the spillway, the chute walls were overtopped, which triggered a new flood study. A tunnel spillway was constructed through the dam's left abutment, 250 m from original spillway.

On December 14, 1999, the reservoir was 0.914 m above the normal pool and 5.18 m below the dam crest. The radial gate on the tunnel spillway was fully open, both spillways were operating normally. Early on the morning of December 15 the reservoir rose quickly and was 0.762 m below the dam crest. Early the next morning the reservoir was 8 inches below the dam crest, the spillway chute walls just below the spillway crest began to overtop, and erosion of the adjacent fill initiated. By 4:30 a.m. on December 16<sup>th</sup>, cities below the dam were evacuated.

At 9:00 a.m. the dam was inspected by helicopter and the reservoir level had subsided (0.762 m below crest); people believed that flood had crested and the crisis was over. At 4:00 p.m. on December 16<sup>th</sup>, the reservoir rose again quickly; the bridge over spillway collapsed; erosion of spillway backfill accelerated and the reinforced concrete chute, basin and crest structure failed; but the concrete lined approach channel remained intact and controlled flows through the spillway.

At 5:00 p.m. the approach channel failed and the reservoir was breached through the spillway area. El Guapo Dam never overtopped. Overtopping of the spillway chute walls initiated erosion of backfill behind chute walls and undermining and failure of spillway chute. Headcutting progressed upstream and lead to reservoir breach. The spillway foundation consisted of decomposed rock, which was erodible. Figures 11 to 16 provide a sequence of photographs from initiation through completion of the spillway failure.





Figure 13: Sweepout of spillway stilling basin



Figure 14: Overtopping Along Entire Length of Chute

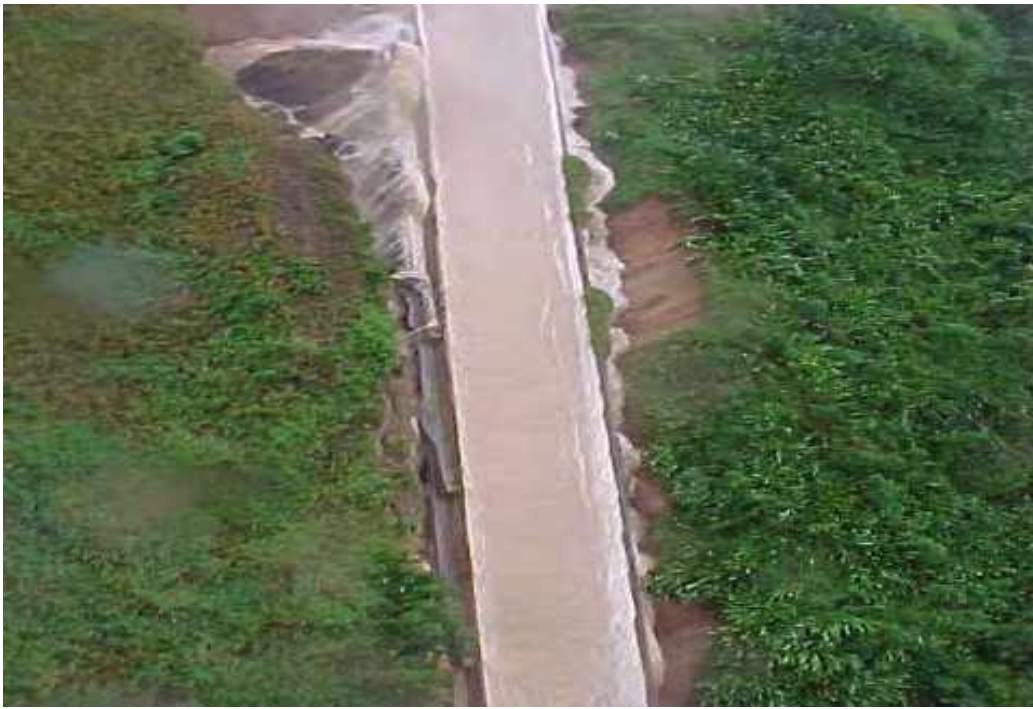


Figure 15: Overtopping of Upstream Chute Walls



Figure 16: Headcutting Progressed to Reservoir





Figure 17: Breach Formation Nearing Completion



Figure 18: Aftermath of Reservoir Breach

## Overtopping failures

### South Fork Dam (a.k.a. Johnstown Dam) (Frank, 1988)

The South Fork Dam, also known as Johnstown Dam, caused the famous “Johnstown Flood,” one of the worst disasters in United States history. The dam was located in western Pennsylvania, about 112 km east of Pittsburgh. The 21.9 m high dam was an earthfill embankment, with the original construction completed in 1852. The dam failed in 1862, due to collapse of a stone culvert running underneath the dam.

It was reconstructed from 1879 to 1881. Significant changes to the dam included the lowering of the dam crest by 0.61 m and the construction of a bridge with wooden supports in the spillway inlet channel. Screens were attached to the spillway bridge supports to prevent fish from escaping the reservoir. The reconstructed dam failed on May 31, 1889, due to overtopping failure during a large flood. Over 2 200 people were killed. Several factors contributed to the dam failure, including:

- The lowering of the dam crest reduced surcharge capacity in the reservoir and correspondingly reduced the spillway capacity;
- The bridge piers and the screens across the piers, in combination with debris that was caught on the screens reduced the spillway capacity; and
- Settlement of the dam resulted in lowering the dam crest at the maximum section by about 0.15 m.



Figure 19: South Fork Dam after overtopping failure

### Secondary (saddle) Dam of Sella Zerbino ([www.molare.net](http://www.molare.net))

The Secondary Dam of Sella Zerbino is one of two dams that were completed in 1925 to form a reservoir on the Orba River, in South Piedmont, Italy, near Liguria. The main dam is a 47 m high gravity arch dam and the secondary dam was a 14 m high concrete gravity dam. The secondary dam was added late in the design process to close off a low spot in the reservoir rim, when it was decided to increase the capacity of the reservoir. The secondary dam was designed and constructed quickly, without any geologic investigations.

The foundation for the secondary dam consisted of highly faulted and fractured schistose rock. During initial filling, significant seepage was observed downstream of the dam. A large storm occurred in the drainage basin above the dams on August 13, 1935. It was reported that 363 mm of rain fell in the Orba basin in less than 8 hours, equating to about a 1 000-year event. The inflow into the reservoir resulted in both dams being overtopped by about 2 m. The Secondary Dam of Sella Zerbino failed as a result of the overtopping, resulting in over 100 fatalities.



Figure 20: Secondary Dam of Sella Zerbino after overtopping failure

### Gibson Dam, USA (Anderson et al,1998)

Gibson Dam is a 60.6 m high concrete arch dam constructed by the Bureau of Reclamation on the Sun River on the east side of the Continental Divide in Montana. The dam was completed in 1929, and the spillway was modified in 1938. In June of 1964, a major flood developed in the area, producing 30-hour rainfall amounts from 200 to 400 mm. Overtopping of Gibson Dam began at 2:00 p.m. on June 8 and continued until 10:00 a.m. on June 9. High water marks indicated a maximum overtopping depth of 0.975 m.

The operators had left two of the spillway gates completely open, two partially open, and two completely closed. The access road was inundated by the overtopping flows, and personnel could not get to the spillway gate controls to operate them. However, even if all gates had been fully open, the dam would have overtopped. The dam survived the overtopping, with little damage to the limestone abutments.

Based on a detailed evaluation, the erodibility index of the dolomite abutment rock was estimated to be between 5 100 and 12 000 and the stream power was estimated to be between 43 kW/m<sup>2</sup> on the upper abutments and 258 kW/m<sup>2</sup> on the lower abutments.



Figure 21: Gibson Dam after some remedial work



### Banqiao Reservoir Dam, China ([engineeringfailures.org](http://engineeringfailures.org))

The Banqiao Reservoir Dam, located on the River Ru in the Zhumadian Prefecture of the Chinese Henan province, failed in 1975, killing an estimated 171 000 people (although some reports estimate that number to be as high as 230 000) and destroying the homes of 11 million people. It is considered to be the biggest dam failure in history, with more casualties than any other dam failure.

Built between April, 1951 and June, 1952, the Banqiao Reservoir Dam was designed in such a way that would allow it to withstand a large flood. This type of flood, where 300 mm of rain falls per day, is known as a "once-in-1 000-years flood." The August 1975 flood, however, was what is known as a once-in-2 000-years flood, more massive than the construction of the dam had accounted for, meaning that more than an annual amount of rain fell in only 24 hours. Records indicate that 189.5 mm of water fell every hour, which translates to 1 060 mm per day. That far exceeds the province's average annual rainfall, which is only around 800 mm.

Chances of the devastating flood happening did not go unnoticed and on August 6, a request was made to open the dam. That request was rejected due to an existing flood in those downstream areas. By August 7, the request was granted by telegrams, which failed to get to the proper authorities. Late on August 7, Unit 34450 of the People's Liberation Army telegraphed the very first warning for the dam failure, but in a matter of only three hours, the Shimantan Dam broke. Within 30 minutes, the water from that dam crested at the Banqiao Dam.

In the wee hours of August 8, 1975, the 24.5 m Banqiao Reservoir Dam was breached in the aftermath of the third typhoon that had decimated China that year. Over 700 million m<sup>3</sup> of floodwater was released over the course of six hours. The Daowencheng Commune located downstream was immediately erased from history and 9 600 people were killed instantly.

One after another, the other 61 reservoirs located in the area, including the Shimantan Dam, collapsed. This chain reaction released another six billion cubic meters of floodwater, all to an area measuring 10 000 km<sup>2</sup>.

In total, 62 dams broke and 11 million people's lives would never be the same. Anyone who survived the initial flooding was trapped without access to food or clean water and contaminated water caused illness throughout the area. 26,000 deaths were attributed to the floodwaters, while nearly 145 000 people lost their lives because of epidemics and famine. In total, around 5 960 000 structures were destroyed, converting the Chinese landscape into one filled with corpses and disease.

After years of studying the incident, researchers concluded that it was the design of the Banqiao Reservoir Dam and the other reservoirs, along with the principles pertaining to the containment of the river, which should be blamed for the failure and subsequent calamity. While many pointed fingers at the weather forecast all those years ago, researchers are citing that the tragedy was man-made and not entirely a natural disaster.

During the late 1950s, scientists warned that any given reservoir's flood control was being ignored and that the irrigation functions of those reservoirs were overemphasized during the heat of the construction frenzy. It has been estimated that China continues to have 87 000 reservoirs across the nation that were built during this low standard construction era and most of these have fallen into serious disrepair. On

top of sub-par construction standards, the country also lacked any early warning system as well as an evacuation plan that could have saved lives.



Figure 22: Banqiao Reservoir Dam after overtopping failure

### Failure due to erosion of rock

#### Ricobayo Dam, Spain

Ricobayo Dam is a 97.5 m high double-curvature arch dam constructed from 1929 to 1933 in Spain. The spillway at Ricobayo Dam is located on the left abutment of the dam and originally consisted of a 396 m long unlined at a slope of 0.0045 discharging over a rock cliff at the downstream end of the spillway. The design capacity of the spillway is 4 600 m<sup>3</sup>/s. Flows through the spillway are regulated by four 20.7 m by 10.7 m gates. The rock in the spillway chute consisted of open-jointed granite.

Five separate scour events occurred along the spillway chute, with the first event occurring shortly after the dam was commissioned. Each of the flood events lasted over a period of several months, usually from December to June. From the initial major spill in January 1934, scour initiated and began progressing upstream. Attempts were made to stabilize the spillway chute after the flood events in 1934 and 1935. The vertical face of the drop at the downstream end of the chute and the right hand slope of the plunge pool were protected with concrete after the 1934 floods.

Additional scour, about 24.4 m downwards, occurred in the base of the plunge pool during the 1935 flood. After the 1935 flood, a concrete lip was added to the end of the spillway chute to direct flows further away from the face of the plunge pool drop. The concrete lip failed during the 1936 flood, as the plunge pool deepened another 30.5 m, and the vertical face of the plunge pool experience



additional scour. During the 1939 flood event, the plunge pool did not deepen, but damage occurred at the vertical face of the plunge pool.

Even though the plunge pool did not deepen during the 1939 flood, measures were implemented in the early 1940s, in an attempt to further stabilize the plunge pool. The plunge pool was lined with concrete, and concrete protection was added to the spillway channel and the drop at the end of the spillway channel. During 1962, the flood event reached a peak discharge of 4 800 m<sup>3</sup>/s which resulted in failure of the plunge pool concrete lining that had been added in the 1940s. After the 1962 event, hydraulic splitters were added to end of the spillway channel to break up the jet prior to it plunging into the pool. Since those modifications the spillway has passed floods with discharges ranging from 3 000 to 3 500 m<sup>3</sup>/s, without experiencing additional damage.

The Ricobayo spillway is located within a granite massif known as the Ricobayo Batholith. There are two prominent joint sets in the spillway foundation rock (joint sets A & B). Joint set A is generally vertically dipping. Joint set B is more horizontally dipping about 10-20 degrees. An anticline intersects the middle of the spillway at an angle of approximately 40°. Both joint set A and joint set B are relatively planar, but joint set B appears to be more continuous. Original speculation was that joints in the spillway foundation were clay filled and that this contributed to the scour during flood events. A site visit during 2005 indicated that the gouge was more likely rock flour and no clay was observed. Joint separation was generally less than 5 mm, with a maximum separation of 10 mm at some locations near the original surface. One additional feature in the spillway foundation is a near vertical fault that trends perpendicular to the spillway. The foundation rock adjacent to the fault has experienced intense shearing.

An evaluation of the scour that occurred over the years concluded that the geology in the spillway chute greatly contributed to the scour. To the right of the anticline axis, the scour progression was in the horizontal direction, while to the left of the anticline axis the scour progression was primarily in the vertical direction. The likely cause of the change in scour direction is the joint orientations on either side of the anticline axis. It was also believed that the fault in the channel played a role in the progression of the scour. The poorer quality of the rock along the fault allowed it to be easily eroded in a vertical direction. This is reflected in the erosion that occurred in 1935 (vertical scour of about 24.4 m) and in 1936 (vertical scour of about 30.5 m).

The plunge pool did not deepen during the flood event of 1939, indicating that the rock in the floor of the plunge pool was stronger than the rock that was eroded above it. This was also confirmed during the flood event in 1962. That flood event led to the destruction of the concrete lining in the plunge pool but no significant damage to the underlying rock. This led to the conclusion that the rock was stronger than the concrete lining provided to protect it.

A quantitative analysis of the plunge pool scour that occurred historically at Ricobayo Dam was performed, using the erodibility index method. The maximum scour depth occurs when the erosive power of the jet is less than the ability of the rock at the bottom of the plunge pool to resist it. Calculated and observed scour depths were then compared. The calculated and observed scour depths from the 1935, 1936, and 1962 flood events generally were in good agreement. The analysis indicated that the calculations overestimated the scour that actually occurred in 1939, but that this was likely a function of much stronger erosion resistant rock at the base of the plunge pool after the 1936 flood.



Figure 23: Aerial view of Ricobayo Dam

#### Kariba Dam, Zimbabwe (Noret et al: 2012)

Kariba dam is a 128 m high arch, which was built across the Zambezi River between 1956 and 1959. It creates the World's largest artificial lake (181 km<sup>3</sup>). Its spillway is made of six flood sluices in the central section of the dam, with downstream caterpillar gates, having their sill 33 m below the dam crest. The gated section is 9.1 m high and 8.8 m large. Its total discharge capacity is 9 000 m<sup>3</sup>/s.

Twenty years of sustained heavy spillage created an extensive plunge pool at Kariba, with a scour reaching down to 80 m below normal tail water level. While underwater maintenance works have been carried out until 1981, there is a concern regarding the possible future continuing development of the pool that could occur in case of intense spillage due to extreme floods. Figure 22 shows a typical upstream/downstream cross section of the plunge pool through successive surveys.

It was estimated that about 150 000 m<sup>3</sup> of rock have been removed between the 1st survey (Sept. 1962) and the 19th survey (July 1981).

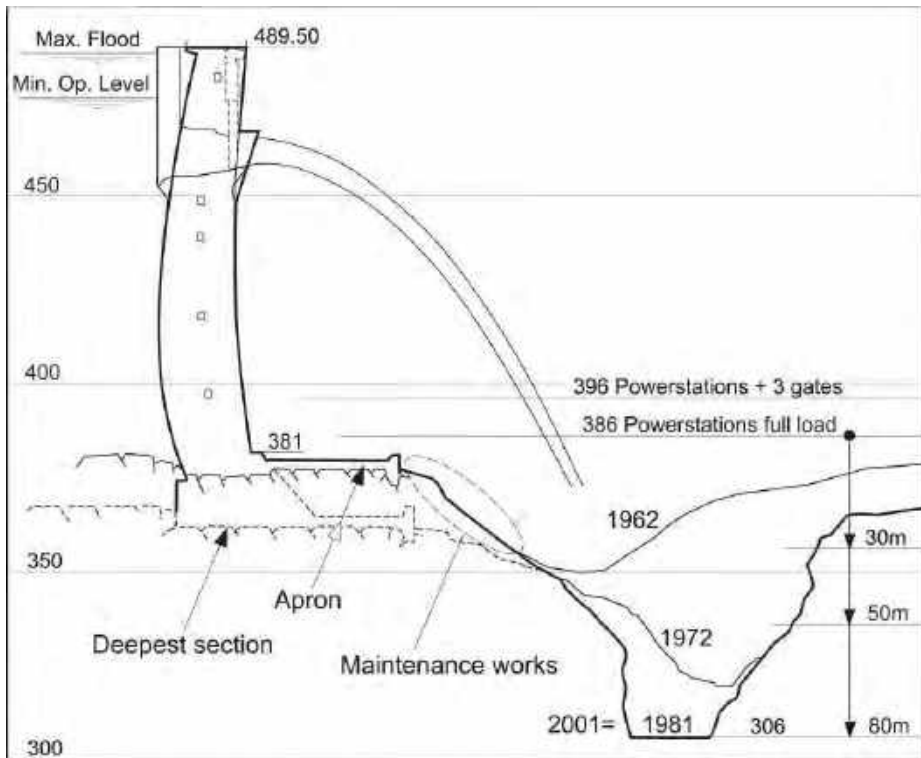


Figure 24: Evolution of the plunge pool of Kariba Dam

### Concrete gravity dams failures

#### Austin (Bayless) Dam (Anderson et al: 1998)

Austin (Bayless) Dam is a 13.1 m high concrete gravity dam in Austin, Pennsylvania, USA that failed in 1911.

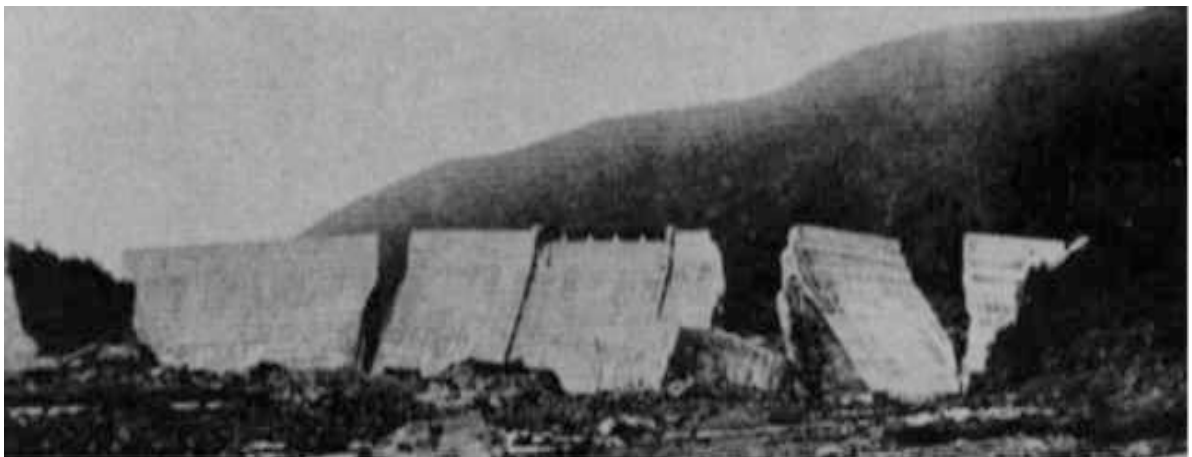


Figure 25: Austin (Bayless) Dam after failure

Austin (Bayless) Dam is a straight gravity dam made of cyclopean masonry completed on December 1, 1909 located 2.4 km upstream from Austin. The concrete dam was a major engineering feat for its time and impounded 1.04 million m<sup>3</sup> of water.

On January 17, 1910, a combination of heavy rain and snowmelt due to warm temperatures caused the reservoir to sharply raise and flow over the spillway. An undetermined thickness of ice still covered the reservoir. Heavy seepage near the toe of the dam with water bubbling up from the ground as far as 15.2 m downstream and cracks on the downstream face of the dam were observed. The dam developed six prominent vertical cracks. The dam had been built without construction joints, so the cracks divided the dam into seven separate segments. A portion of the eastern earthen embankment slid down eight feet, allowing water to bypass the dam. To prevent a catastrophe, Bayless used dynamite to blast two notches in the dam crest to lower the reservoir. The blasting had been necessary because the dam had no spillway gates to allow controlled water release. The combination of these efforts emptied the reservoir in around sixteen hours and major devastation was circumvented. The massive structure was pushed downstream an amazing 450 mm at its base and 790 mm at its crest. Superficial repairs were made to the dam after the water level dropped, and then the water level was allowed to rise to normal pool again despite leakage under the dam of about 2.3 m<sup>3</sup>/minute

Rainfall in September 1911 was unusually heavy. Water began flowing over the spillway for the first time in about 20 months. The dam failed on the afternoon of Saturday, September 30, 1911. Post-failure analysis clearly showed that the plane of sliding developed in the shale underlying the sandstone, which represented the weakest zone in the foundation. In essence, the upper sandstone layer slid downstream along with the concrete blocks comprising the dam. This was a classic foundation failure in which the dam failed by sliding.

The paper mill whistle blew but warning went unheeded due to previous false alarms. The water smashed into the town of Austin in about 11 minutes engulfing the town of 2 300 inhabitants and killing 78 people.

### Camara Dam

Camara Dam is a 48.8 m high RCC dam in Paraiba, Brazil that failed in 2004.



Figure 26: Camara Dam after failure



Camara Dam is a straight roller compacted concrete gravity dam started in 2001 and completed in February 2002, located upstream from the towns of Alagoa Grande and Mulungu. It had a crest length of 249 m, a base width of 39.6 m, and a crest width of 6.1 m. The schistosity on the left abutment dips about 30 to 35 degrees.

The reservoir filled rapidly in about 2 weeks due to heavy rains in January 2004 and then gradually increased to 10.7 m below the crest by June 17, 2004 at the time of the rupture. Some of the observations from January 2004 to the rupture included: Water noise in the gallery and carrying of material in the drains, a damp spot in the left abutment in the region of the fault, over half the drains in the gallery are clogged and those that were working had high flows leading to flooding in the gallery. A crack also developed in the drainage gallery. The left abutment failed below the concrete dam due to erosion from soil-filled discontinuities, causing a flood that killed 5 people and left 800 people homeless.

Post-failure analysis determined that during the design the assessment of the left abutment geology was not precise because some of the site geology was obtained from percussion drilling. A 300 mm thick soil fill was interpreted as being limited in depth to 3 m into the abutment. The treatment of the left abutment was not sufficient and allowed the preservation of an extensive shear zone. The inspections were sporadic and leakage was ignored. A recommendation to drain the reservoir was ignored. Flowing reservoir water washed out the foundation material to the point that drains were being plugged. As a result, high pressure gradients developed under the dam. As the flow of reservoir water increased the erosion and driving forces on the low-shear strength rock slabs, they began to slide and fail in an upstream progressive manner until a hole was piped beneath the dam. The remaining slab of rock in left abutment is essentially fracture free, therefore percolation occurred along the entire length of the fracture.

### Shi-Kang Dam (USCOLD: 2000)

Shi Kang Dam is a 21.3 m high dam close to Shi-Kang, Taiwan that failed in 1999 during the Chi-Chi earthquake.



Figure 27: Shi-Kang Dam

Shi-Kang dam is a concrete gravity control structure completed in 1997 with 18 spillway bays controlled by Tainter gates. The design was based on the traditional design concept of the pseudo static earthquake acceleration. The design horizontal earthquake acceleration coefficient was 0.15 g and the effect of the vertical motion was neglected.

The horizontal and vertical peak ground motion of station TCU068, located at Shih-Kang Primary School 500 m away from the dam, were 0.51 g and 0.53 g, respectively. A fault running underneath the dam caused enormous offsets predominantly in the vertical (over 8.8 m) and cross-stream (2 m) direction, leading to the failure of multiple bays and widespread cracking. Although sections of the dam overlaying the fault failed, the rest of the structure performed quite well and stayed intact. The reservoir was also offset and therefore only a small volume of water was released and the consequences of the earthquake were not exacerbated. The dam had supplied 50 percent of the water for the Taichung area and its failure lead to severe shortages.

#### Bouzey Dam (Anderson et al: 1998).

Bouzey Dam was a 21.9 m high masonry gravity dam constructed across the L'Aviere River near Epinal, France. Similar to Austin Dam, the dam was founded on horizontally interbedded sandstone and lenticular clay seams, with no drainage provisions, and about a 1.8 m wide by 3 m deep cut-off key constructed into the rock at the upstream face of the dam. Also similar to Austin Dam, an incident occurred during initial filling whereby the centre section of the dam moved downstream about a foot, shearing the key. Unlike Austin Dam, the reservoir was lowered and the lower portion of the dam was strengthened.

Unfortunately, the upper portion of the dam was quite thin (less than 5.5 m thick for about the upper 10.7 m), and upon refilling, the dam cracked and the upper 9 m or so was sheared off and swept away. Stability calculations indicate that cracking was likely at the elevation where the shear failure occurred, and once cracked through, the upper portion of the dam was unstable.

#### Koyna Dam, India (Anderson et al: 1998).

Koyna Dam is a 103 m high and 853 m long concrete gravity dam constructed on the Koyna River in south-western India between 1954 and 1963. During construction the decision was made to raise the dam and the downstream slope of the non-overflow section was steepened in the upper 36.5 m of the structure to accommodate the raise, resulting in a discontinuous change in slope at that location.

The dam was shaken by a M6.5 earthquake on December 11, 1967. A strong motion accelerograph located in a gallery on the upper right abutment recorded a peak ground acceleration of 0.63g cross-canyon, 0.49g downstream, and 0.34g vertical. Although the dam did not fail, deep horizontal cracks formed throughout the upstream and downstream faces near the change in slope where a stress concentration is expected to occur, requiring the installation of tendons and construction of buttresses on the downstream face to stabilize the structure. Finite element analyses indicated stress concentrations near the change in slope that exceed the dynamic tensile strength of the concrete.

## Concrete arch dam failures

### St. Francis Dam, USA (Anderson et al, 1998)

St. Francis Dam was a curved concrete gravity dam constructed in San Francisquito Canyon approximately 72 km north of Los Angeles California. The dam was 62.4 m high, 4.9 m thick at the crest, and 53.3 m thick at the base. The crest length of the main dam was about 213 m. The dam had no contraction joints or inspection gallery. The foundation was not pressure grouted, and drainage was installed only under the centre section. The foundation was composed of two types of rock; the canyon floor and left abutment were composed of relatively uniform mica schist, with the foliation planes dipping toward the canyon at about 35 degrees. The upper portion of the right abutment was composed of a red conglomerate, separated from the schist by a fault dipping about 35 degrees into the right abutment.

During reservoir filling, two sets of cracks appeared on the face of the dam that were dismissed as a natural result of concrete curing. The reservoir stood within 3 inches of the overflow spillway crest for 5 days before the failure. Large tension cracks were noted in the schist on the left abutment two days before the failure. The morning of the failure, muddy water was reported to be leaking from the right abutment, but when examined in detail, the flow was found to be clear, picking up sediment only as it ran down the abutment. Another leak on the left abutment was similarly dismissed as normal leakage. Several hours before failure the reservoir gage recorded a sudden 90 mm drop in the reservoir level. One of the caretakers was seen on the crest of the dam about an hour before failure.



Figure 28: St Francis Dam after failure

Several people drove by the dam just minutes before failure. One person reported crossing a 300 mm high scarp across the roadway upstream of the dam. The dam failed suddenly at 11:58 p.m. on March 12, 1928, as evidenced by the time the Southern California Edison power line downstream was broken. Within 70 minutes, the entire 46.8 million m<sup>3</sup> reservoir was drained. An immense wall of water

devastated the river channel for 87 km to the Pacific Ocean. It has been estimated that 470 lives were lost, but the exact count will never be known. Reanalysis of the disaster indicated that failure initiated by sliding along weak foliation planes in the left abutment, perhaps on a remnant of an old paleo-landslide.

**Malpasset Dam: 1959 (Anderson et al 1998).**

Malpasset Dam was a 65.8 m high thin concrete arch structure completed in 1954 in southern France. The dam was 1.5 m feet thick at the crest and 6.7 m feet thick at the base. Blanket grouting was performed at the dam-foundation contact, but no grout curtain or drainage was installed, and no instrumentation other than survey monuments was provided. The dam was founded on gneiss. The reservoir filled for the first time on December 2, 1959. Although earlier there had been some clear seepage noted on the right abutment and a few cracks had been observed in the concrete apron at the toe of the dam, engineers visiting the site on December 2 did not notice anything unusual. About 9:10 p.m. that evening, the dam tender heard a loud cracking sound and the windows and doors of his house, on a hillside about 1.6 km downstream of the dam, blew out. The sudden failure sent a flood wave down the river causing total destruction along a 11 km course to the Mediterranean Sea. The number of deaths resulting from the failure was reported to be 421.

The failure was attributed to sliding of a large block of rock in the left abutment of the dam formed by an upstream dipping fault on the downstream side, and a foliation shear on the upstream side. The "mold" left by removal of the block could be clearly seen following the failure. Large uplift pressures were needed on the upstream shear in order to explain the failure. Experiments suggested that the arch thrust acting parallel to the foliation decreased the permeability perpendicular to the foliation to the point where large uplift pressures could have built up behind a sort of underground dam. The uplift forces in combination with the dam thrust were sufficient to cause the block to slide, taking the dam with it.



Figure 29: Malpasset Dam during construction





Figure 30: Malpasset Dam as it looks nowadays

#### Pacoima Dam, USA (Anderson et al 1998)

Pacoima Dam is a flood control arch dam located in the San Gabriel Mountains north of Los Angeles. It is 112 m high, 3.17 m feet thick at the crest and 30.2 m thick at the base. The left abutment is supported by a 18.3 m tall thrust block. The dam was shaken by the 1971 M6.6 San Fernando earthquake, and the 1994 M6.8 Northridge Earthquake. The dam survived both events, but the reservoir was low in both cases. As a result of the 1971 earthquake, a crack formed in the thrust block, a previously grouted contraction joint opened up, and extensive cracks accompanied by displacements up to 200 mm vertically and 250 mm horizontally were found in the gunite which covered the left abutment.

Three potentially unstable rock blocks were identified in this abutment, one of which underlies the thrust block. Tendons were designed and installed to prevent movement under future large seismic events. Following the 1994 earthquake, permanent vertical offsets appeared along most of the vertical joints at the crest of the dam, with the elevation of each block dropping from left to right. The joint between the dam and thrust block opened two inches at the crest and a quarter inch at the base of the thrust block. The left abutment gunite was again severely cracked, with evidence that foundation blocks moved 400 mm to 480 mm horizontally and 300 mm downward at the surface. Elongation and overstressing of the tendons near the thrust block probably occurred. A zone in the tunnel spillway concrete lining, about 6.1 m long, was displaced and cracked along a discontinuity in the rock.



Figure 31: Pacoima Dam

### Concrete buttress dam failures

#### Gleno Dam, Italy (Anderson et al 1998)

Gleno Dam was a 50 m high multiple arch dam 48 km northeast of Bergamo in north central Italy. The dam was over 213 m long with a curved central portion and buttresses of double thickness at the tangents. A masonry gravity plug containing a 3 m wide by 9 m high outlet opening was constructed in a deep central valley gorge. The original design called for a gravity dam, but the design was changed and the dam built before the change was approved. Portions of the buttresses on either side of the masonry plug were placed directly on rock with no excavation. The masonry plug was constructed with lime mortar, even though cement mortar had been specified.

The concrete used in constructing the arches and buttresses was not of the best quality. Aggregate may have been somewhat dirty, and concrete consolidation was poor in places. Steel reinforcement consisted of scrap grenade netting from World War I.

Leakage through the masonry plug increased as the reservoir filled for the first time, reaching a maximum of 130 l/s. The pool remained full for over a month. Early the morning of December 1, 1923, the dam tender noticed a vertical crack through Buttress No. 11 near the right side of the curved section of the dam.

Large pieces of concrete fell and the buttress split in two, followed by collapse of the adjoining arches. Water surged through the opening followed by progressive collapse of the arches and buttresses in the central portion of the dam. A 30 m high wall of water swept through the Dezzo River Valley. Power stations, factories, bridges and villages were wiped out, with a reported 356 fatalities.



Figure 32: Gleno Dam before failure

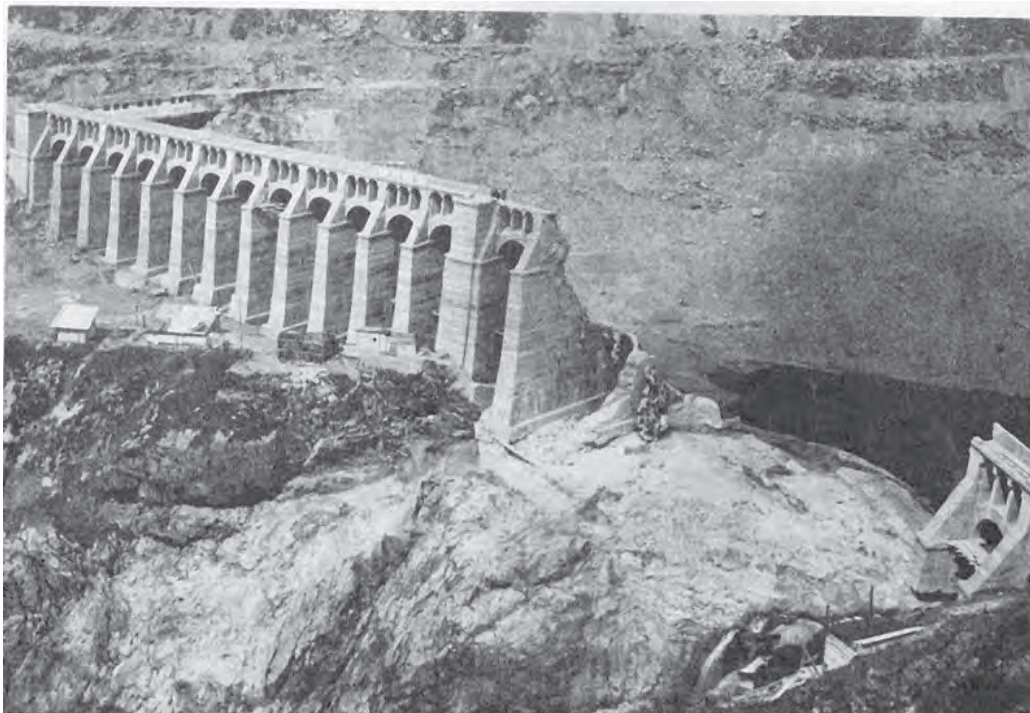


Figure 33: Gleno Dam after failure



There were various theories as to why the dam collapsed. The official report concluded that the fundamental cause was associated with the stone masonry base portion of the dam upon which the multiple arch superstructure was founded. It was concluded that collapse started as a result of settlement of the masonry plug (presumably due to leaching of the lime mortar from the leakage). This set up abnormal stresses in the superstructure which failed at its weakest point, Buttress No. 11. However, it is interesting to note that post-failure photographs show the masonry plug essentially intact. And there are no pre- and post-failure surveys to indicate the extent of the masonry plug settlement.

### Vega de Tera Dam, Spain (ICOLD: 1974)

Vega de Tera Dam was a 34 m high slab and buttress dam completed in 1957 on the Tera River in a remote region of northwest Spain. The foundation was competent quartz gneiss, the buttresses were constructed of cement mortared masonry, and the slabs were constructed of reinforced concrete. Following a winter shutdown, it was reported that little attention was paid to lift surface cleanup on the masonry surfaces. Grouting was performed in 1956 to control leakage. The reservoir filled to within 1.8 m of maximum level in February 1958, but was essentially empty by October of that year.

In January of 1959, heavy rains filled the reservoir, and the dam is thought to have failed at a joint between the concrete and masonry on a sloping portion of the foundation near the left abutment as the reservoir neared the crest. A 100 m section of the dam including 17 buttresses failed in rapid succession, stopping at the more massive spillway section near the center of the dam. The town of Rivadelago, about 4.8 km downstream and 520 m lower in elevation, was nearly completely destroyed. The failure occurred at night and rescue efforts were hampered by the bad weather, resulting in 144 fatalities.

Large-size laboratory tests conducted on the masonry indicated a low modulus value of about 0.965 GPa. The failure was officially attributed to the low modulus of the buttresses that allowed the slabs to deform and fail at the base in cantilever bending. This put additional shear load on the buttresses, which could not be resisted. However, it is interesting to note that the slabs were not sloping at a great angle. Typically, the upstream water retaining elements are sloped at close to 45 degrees. This results in a large vertically downward force from the reservoir loading, which is beneficial since the structure itself doesn't have much weight; a main advantage of a buttress dam is that the loads can be carried with much less concrete than a conventional gravity dam.



Figure 34: Vega de Tera Dam after failure

Landslide failures and incidents

Vaiont Dam, Italy (Hendron & Patton, 1985)



Figure 35: Vaiont Dam before the landslide



Figure 36: Vaiont Dam after the landslide

Vaiont Dam is an 265 m high concrete arch structure completed on the Vaiont River near Longarone, Italy. The entire left side of the reservoir was formed by steep slopes in bedded limestone with clay interbeds. The reservoir started filling in February 1960, and the dam was completed in September 1960. In October 1960 after a period of heavy rain, benchmarks installed on a suspected landslide mass began to accelerate, and a crack formed along the reservoir. The next month a slide of 700 000 m<sup>3</sup> hit the reservoir creating a 2 m high wave at the dam. The reservoir was lowered and various studies were undertaken.

Exploratory adits were driven, piezometers were installed, and a bypass tunnel was driven to connect the upper reservoir and lower reservoir in case a slide separated the two. For the next three years the level of the reservoir was adjusted to try and limit the slide movement. Then on October 9, 1963, a massive slide of 267 million m<sup>3</sup> slid into the reservoir just upstream of the dam (at a minimum distance about the height of the dam) at an estimated 20 to 30 m/s. A wave washed up the right bank more than 260 m, nearly to the town of Casso high on the abutment. A control building on the left abutment and an office/hotel 55 m above the dam crest on the right abutment were demolished and 60 staff perished. Water surged back across the canyon and up the left abutment, and a wave about 100 m high washed over the top of the concrete dam. The wall of water was still over 70 m high when it hit the village of Longarone about a mile downstream. The village was wiped clean, and about 2 600 people lost their lives. The dam survived the overtopping, but the reservoir was filled for about a 1.6 km upstream of the dam, and it had to be abandoned.

Post-failure investigations showed that low strength clay layers existed between the limestone beds. It was surmised that rainfall in the mountains above the reservoir was conveyed through solution features to the reservoir slopes where it became trapped by the impermeable clay layers. A review of the landslide survey data showed that movement accelerated with a high reservoir level following periods of heavy rain. Thus, it was the combination of high reservoir level which unweighted the toe of the slide, and heavy precipitation which increased the pore pressures in the slope, that lead to triggering of the slide on weak clay layers.

This was confirmed by limit equilibrium analyses that considered side constraint afforded by a fault on the upstream side of the landslide mass.

### Madison Canyon Landslide, USA (Barney, 1960)

A large landslide was triggered by the M7.7-7.8 earthquake that occurred near Hebgen Lake in the southwest part of Yellowstone National Park. Approximately 32.9 million m<sup>3</sup> of material slid across the Madison River canyon, downstream of Hebgen Lake Dam outside the west entrance to the park. Landslide debris traveled about 120 m up the opposite side. Unfortunately, there was a campground at this location, and 27 people lost their lives. The landslide occurred where no slide had previously existed. A “dike” of dolomite buttressed a unit of metamorphic schist and gneiss, which formed most of the mountain. The foliation in the metamorphic rock dipped about 50 degrees toward the river. The shaking was apparently sufficient to cause collapse of the dolomite, allowing large scale sliding on the weak foliation planes. A landslide debris dam, about 60 m feet high and 1 220 m wide, was formed across the river. Impervious weathered rock and debris was deposited upstream such that leakage through the debris dam was limited to about 5.7 m<sup>3</sup>/s.

Hebgen Lake was nearly full at the time of the earthquake, and Hebgen Lake Dam was damaged. Drawdown of the lake was necessary to inspect the dam and make repairs, but the volume of water in the reservoir was nearly 4 times the volume that could be stored in “Quake Lake” behind the debris dam. Even without draining Hebgen Lake, Quake Lake would fill and overflow from the natural stream flows in three to five weeks. To solve this problem, the Corps of Engineers quickly cut a spillway channel 76 m wide through the debris dam, capable of passing 283 m<sup>3</sup>/s, and armoured it with rip-rap. Later, the spillway channel was lowered, reducing the volume of Quake Lake from 98.7 million m<sup>3</sup> to 44.4 million m<sup>3</sup>.

### Operational failure

#### South Fork Dam, PA (Frank: 1988)

South Fork Dam was constructed upstream of Johnstown, Pennsylvania, forming a lake for a fishing club. The dam, as originally constructed between 1840 and 1853, was 22 m high and over 275 m feet long. It was constructed of rolled earth and puddled material, and contained a low-level stone culvert through the dam.

In 1862 the stone conduit collapsed and the dam failed through internal erosion. However, there were no significant consequences as the reservoir was low at the time. The low level outlet conduit was plugged and filled in during dam reconstruction. The spillway was 30 m wide and crossed by a bridge with supports spaced at 2 m. Iron screens were placed across the spillway to prevent fish from escaping. The crest of the dam was lowered 0.6 m to widen the roadway on top of the dam. No camber was left in the dam, and the center portion of the dam may have been lower than at the abutments. In May of 1889 a large rainstorm advanced from the west. The large inflows sent debris to the spillway area where it became lodged in the fish screens, plugging the spillway.

Overtopping erosion failure of the dam ensued. More than 2 200 people lost their lives. This was the largest catastrophe in the U.S. from a single event until the terrorist attacks of September 11.





Figure 37: Stereoscope view of South Fork Dam after failure

### Taum Sauk, USA (FERC: 2006)

The 2005 failure of Taum Sauk Dam in Missouri brought renewed attention to operational failure modes. The dam formed the upper reservoir of a pumped storage project. The dam was a concrete faced earthfill structure, forming a complete “ring” on the top of a large hill with no spillway. Water was routinely stored on a 3 m high parapet wall above the crest of the dam. After a membrane liner was installed in 2004, the instrumentation for measuring the water level in the reservoir was tied to cables in the reservoir because the warranty for the liner would have been void had holes been drilled through it to secure the instruments.

The cables, which were installed near the power intake, loosened due to the hydraulic currents. In addition, settlement of the embankment was not taken into account in re-setting the reservoir level sensors. The reservoir was overfilled due to pumping, overtopped, and failed. The instrumentation installed to detect and prevent such an occurrence did not provide accurate readings or function as originally intended. A house with five people inside was destroyed in the downstream flooding. Miraculously, everyone in the house was thrown upstream when the water hit, and no one died.



Figure 38: Taum Sauk Dam after failure



## Trunnion Friction Radial Gate Failure

### Folsom Dam, USA (USBR: 1996)

Folsom Dam is located on the Sacramento River, about 32 km northeast of Sacramento, California and was completed in 1953. The dam consists of a concrete gravity section across the river channel with a structural height of 103.6 m, flanked by long earthfill wing dams. The concrete dam has a gated overflow spillway section that is regulated by eight tainter (radial) gates: five service gates that are 12.8 m wide and 15.2 m high and three emergency gates that are 12.8 wide and 16.15 m high. The trunnion anchorage for the spillway gates consists of three steel plates (50 mm by 406 mm plates, 18.3 m long, which are welded together) covered in cork to prevent bonding to the concrete. The end anchorage for the steel plates consists of a bearing plate that is located in the mass concrete of the spillway crest concrete, below the bottom elevation of the piers.

Spillway gate No. 3 failed during a morning operation with a nearly full reservoir at about 8:00 am on July 17, 1995. Gate No. 3 was being opened to maintain flow in the river during a powerplant shutdown. As the gate was opened, it was allowed to stop at 150 mm automatically and again at 300 mm. The auto-stop function was overridden (normal procedure) with no stop being made at the 600 mm level. As the gate opening approached 730 mm, the gate operator felt an “unusual vibration” and he stopped the gate hoist motor. As the operator turned to check the gate, he saw the right side of the gate swing open slowly, like a door hinged on the left side and saw water pouring around both sides of the gate leaf. The time from the operator’s initial awareness of the vibration to observing gate displacement and uncontrolled flow of water was estimated to be no more than 5 seconds. The failed gate released a peak flow of about 1 132 m<sup>3</sup>/s.

The rated downstream safe channel capacity was 115,000 ft<sup>3</sup>/s. No injuries or fatalities occurred as a result of the failure. Nimbus Dam, the afterbay dam for Folsom Dam immediately downstream, did not overtop due to the prompt action of the dam operator at Folsom Dam. He immediately identified dispatch about the gate failure then drove 7 miles to Nimbus Dam and opened the gates there.



Figure 39: Folsom Dam radial gate failure

The gate failure started at the diagonal strut brace nearest the trunnion when the upper connection's four bolts sheared. The diagonal brace connected the bottom two struts and bracing was provided to reduce the effective column lengths and prevent column buckling of the struts. Once the original diagonal brace failed, load was transferred to the adjacent brace connections, which failed in turn. Immediately following the strut brace connection failures, the right side struts buckled downward.

More than 30 different types of tests, examinations and analyses were performed to assist a Forensic Team in determining the cause of gate failure. The cause of the failure was determined to be trunnion pin friction. The Folsom tainter gates were not designed for any trunnion friction, which was consistent with the engineering practice at the time. The gates had only a marginal factor of safety when they were installed. One unique feature of the trunnion pins at Folsom Dam was their large diameter (760 mm) which added significantly to the load imparted to the gate due to trunnion friction, since there was more area and a greater chance for higher friction coefficients. A reduced frequency of lubrication and lack of weather protection (at both ends of the trunnion pin, where gaps between the trunnion hub and the bearing housing allowed rainwater, spray and water vapor to enter) increased the rate of corrosion over the years.

### Drum Gate Failures

#### Cresta Dam, USA (Pacific Gas & Electric Company, 1997).

Cresta Dam is located on the North Fork of the Feather River, and is a key feature in PG&E's Feather River hydroelectric system. The dam forms the forebay for Cresta Powerhouse and was constructed in 1949. There are two 37.8 m long by 8.5 m high drum gates at the top of Cresta Dam. Drum gates at Cresta Dam are raised to maintain the reservoir level for electric power generation at the Cresta Powerhouse under normal operations and operated to regulate spills during high river flow conditions. On July 5, 1997, the left drum gate at Cresta Dam began to drop uncontrollably. The gate took about 20 to 30 minutes to completely lower.

The downstream water level rose from 0.48 m to 4.57 m in approximately 40 minutes. The maximum recorded downstream discharge was 428 m<sup>3</sup>/s. No injuries or fatalities occurred as a result of the gate failure.

The left drum gate at Cresta Dam dropped primarily due to a combination of failure of the drum gate drain line and leakage into the drum gate. Failure of the drum gate drain line was likely caused by crimping of the drain line at the downstream stop seal. Water accumulated in the drum gate due to leakage through the check valves as a result of failure of the drum gate drain lines and normal leakage into the drum gate through connections, hatches and the gate skin.

#### Guernsey Dam, USA (Graham and Hildale, 2001)

One of two drum gates at the south (right) spillway of Guernsey Dam inadvertently opened in 1986. A painting contractor left trash within the gate which eventually plugged the drain line. The interior of the gate filled with water and the gate lost buoyancy. The gate lowered about half way in seven hours before the problem was recognized and the trash cleared from the drain line.

Although the downstream discharge increased significantly, the downstream channel capacity was never exceeded and there were no injuries or fatalities.

### Hoover Dam, USA (Warnock, 1944)

During operation of the Arizona Spillway in the fall of 1941, there was an unexplained, uncontrolled lowering of one drum gate, resulting in a discharge spike of about 1 080 m<sup>3</sup>/s. There were no reported injuries or fatalities.

### Black Canyon Diversion Dam, USA (Internal USBR Documentation)

Extension plates were added to the gates to raise the lake level twice (in 1952 and 1998). During the week of December 15, 1998 during routine exercising of the drum gates, Gate No. 3 was lowered about 450 mm, but attempts to raise the gate failed. The gate was lowered another 150 mm, but again could not be raised from that position. The reservoir was lowered and it was found that drain line nipple had come unthreaded from the swivel joint. The gate did not sink entirely because a check valve closed or the drain line on the other end of the gate passed enough water to maintain equilibrium. In 2001, it was discovered that 13 of the 17 hinge pins in Gate No. 3 were fractured. (Only one hinge pin in each of the other two gates was found to be fractured.) The bushings were re-bored, realigned and the pins were replaced.

### Stagnation Pressure Failure of Spillway Chutes

#### Big Sandy Dam Spillway, USA (Reclamation, 1987), (Hepler and Johnson, 1988), (Hepler and Johnson, 1988)

Big Sandy Dam is located on the Big Sandy Creek, 72 km north of Rock Springs, Wyoming. The 25.9 m high rolled earthfill embankment dam was completed in 1952. The spillway is located on the right abutment of the dam and consists of an uncontrolled concrete side-channel crest structure and a concrete chute and stilling basin. The spillway has a discharge capacity of 208 m<sup>3</sup>/s at a reservoir water surface elevation 1.6 m above the spillway crest elevation. The spillway is founded on thinly bedded to massive siltstone and sandstone. The foundation rock ranges from soft to moderately hard with joints that are primarily vertical, tight and healed to open and spaced from 0.3 m to several feet apart.

A zone in the foundation below the spillway inlet structure contains open joints and bedding planes, which allowed reservoir water to seep under the spillway chute floor. The spillway chute was designed with an underdrain system and anchor bars, but waterstops and continuous reinforcement were not provided across the contraction joints. Deterioration of the concrete slab occurred shortly after the dam was put into service. Cracking occurred in the chute slabs due to excessive water and ice pressures along the foundation- concrete slab interface and some of the slabs heaved and were displaced off the foundation, creating offsets into the flow. The spillway operated from 1957 to 1983 without incident, but a chute floor slab failed in June 1983, due to uplift pressures from flows of 11.3 m<sup>3</sup>/s. The failure did not progress beyond the spillway slab failure, primarily due to the erosion resistance of the underlying foundation relative to the energy of the spillway release flows.

Calculations were performed to confirm that the failure was the result of stagnation pressures being generated under the chute slab. The Big Sandy Spillway slab failed between stations 4 + 66.87 and 4 + 85.85, during spillway discharge of 11.3 m<sup>3</sup>/s. Failure was initiated by an offset into the flow at station 4 + 66.87 (depth of flow – 0.3 ft; velocity – 31 ft/s). Assuming a 3 mm open joint and a vertical offset of 12.7 mm and anchor bars only 50 percent effective, the calculations predicted the slab would fail. The calculations also showed that with anchor bars fully effective, the slab would not have failed. The

uplift pressures assumed in the calculations were estimated from extrapolated laboratory tests. The analysis of the slab for uplift pressures evaluated a one foot wide strip of the chute slab between stations  $4 + 66.87$  and  $4 + 85.85$ , assuming that the stagnation pressures would be constant over this area. From observations after the failure, it was observed that the anchor bars exposed beneath the slab were not coated with grout, indicating that the anchor bar capacity was not fully developed.

### Hyrum Dam Spillway, USA (Reclamation, 2005)

Hyrum Dam is located on the Little Bear River, about 9 miles southwest of Logan, Utah. The 35.3 m high zoned earthfill embankment dam was completed in 1935. The spillway is located about 274 m from the dam on the right abutment and consists of a concrete lined inlet transition, a gated crest structure regulated by three 4.88 m wide by 3.66 m high radial gates, and a concrete lined spillway chute and stilling basin. The foundation of the spillway consists of Lake Bonneville sediments (described as clay and gravelly loam) to a depth of about 27.4 m below the spillway crest. The spillway chute was designed with an underdrain system (although a filter was not provided between the gravel drain envelope and the fine-grained foundation material). The spillway chute was constructed with a single layer of reinforcement that is not continuous across the joints. Waterstops were not provided at the joints.

The spillway had significant problems associated with cracking and slab movement. Long horizontal cracks developed in the sides of the trapezoidal spillway chute, and bulging of the lining was noticeable. In 1980, an inspection revealed water spurting through a crack in the left chute wall (indicating water pressure behind the wall) and open horizontal cracks. In 2003, ground penetrating radar, drilling and closed circuit television examination of the spillway underdrains and drill holes were used to identify voids underneath the spillway chute. A continuous channel, over two feet deep in places was identified beneath the steeper portion of the chute. The erosion that occurred in the spillway foundation was attributed to the introduction of flows through the cracks and joints in the slab and piping of foundation materials into the unfiltered drainage system.

### Cavitation Damage Induced Failure of Spillways

#### Glen Canyon Dam Spillway, USA (Burgi, 1987)

Glen Canyon Dam is located on the Colorado River in northern Arizona, about 24 km upstream of Lees Ferry and 19 km downstream from the Arizona-Utah state-line. The dam, completed in 1964, is a constant radius, thick arch concrete structure, with a structural height of 216 m. Spillways are located at each abutment and each consists of a gated intake structure, regulated by two 12.2 m by 16 m radial gates, a 12.5 m diameter concrete lined tunnel through the soft sandstone abutments and a deflector bucket at the downstream end. Each spillway tunnel is inclined at 55 degrees, with a vertical bend and a 305 m long horizontal section. The combined discharge capacity of the spillways is  $7\,815\text{ m}^3/\text{s}$ , at a reservoir water surface 19.2 m above the spillway crest elevation. The spillways experienced significant cavitation damage during operation in June and July, 1993 during flooding on the Colorado River system when the reservoir filled completely for the first time and releases were required.

The cavitation damage was initiated by offsets formed by calcite deposits on the tunnel invert at the upstream end of the elbow. Both spillways were operated at discharges up to about  $850\text{ m}^3/\text{s}$ . Cavitation indices of the flow in the area where damage initiated in the left spillway ranged from about

0.13 to 0.14. The cavitation indices of the deposits along the tunnel (indices at which cavitation was likely to occur) ranged from 0.64 to 0.73. Although flashboards were installed on top of the spillway gates to avoid releases to the extent possible, releases were still made through both spillways. The worst damage occurred in the left tunnel spillway – a hole 10.7 m deep, 40.8 m long and 15.2 m wide was eroded at the elbow into the soft sandstone. Extensive concrete repair work and installation of air slots was required to bring the spillways back into service and reduce the potential for future damage.



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# ONE RIVER ONE PEOPLE ONE VISION



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