Dam Safety Training Module

December, 2014

Addis Ababa, Ethiopia

Nile Basin Initiative (NBI)
Eastern Nile Subsidiary Action Program (ENSAP)
Eastern Nile Technical Regional Office (ENTRO)

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Cover Photo: Sennar dam, Sudan

FOREWORD

I am pleased to launch this Eastern Nile Dam Safety Training Module 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.

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

Eastern Nile (EN) Basin countries have made significant strides in strengthening Eastern Nile cooperation since the launch of the Eastern Nile Subsidiary Action Program in 1999, within the framework of the Nile Basin Initiative.

The water resources infrastructure of the EN Basin countries, considered herein to include Egypt, Ethiopia, South Sudan and Sudan, comprises dams with large water storage reservoirs; such as High Aswan and Merowe Dams, large irrigation systems and hydro-power plants. In addition to these, the Grand Ethiopian Renaissance Dam (GERD) and heightening of the Rosaries Dam are under construction and there are also development plans to be implemented in the basin. Many of these structures are located on the Abay/Blue Nile and Main Nile (a trans-boundary watercourse) and generate electricity, control flood, and supply water for agriculture, municipalities, industries, livestock, etc.

Dam safety is the art and science of ensuring the integrity and viability of dams such that they do not pose unacceptable risks to the public, property, and the environment. It requires the collective application of engineering, social and environmental principles.

Despite the growing number of water resource infrastructures in the EN countries, there is no regional framework or institute responsible for dam safety management. In addition, inadequate skilled manpower and budget, lack of regular maintenance coupled with population growth in downstream areas has resulted in increased risks to life, property and the environment. Hence, dam safety management has become an emerging issue of the EN region.

Therefore, to reduce the risk of dam failure and accidents caused by uncoordinated operations and varying dam safety criteria and operational strategy across the EN sub basin ENTRO has developed an EN Reference Dam Safety Guideline with subsequent technical training programs to experts, policy and decision makers, regulators, etc

The EN dam safety programs will establish regulatory frameworks which will require the adoption and implementation of the EN Reference Dam Safety Guideline in each country. **These National Guidelines will be the controlling document regarding dam safety practices.**

The objective of the ENTRO Dam Safety Training Modules to provide a supplementary, non-binding, tool for use in training programs to strengthen the capacity of dam safety management in the Eastern Nile. The training module is to be used by staff at Eastern Nile universities, to train interested students (including but not limited to Ministry staff, other professionals and degree students) in dam safety.

The dam safety training modules have the following main objectives:

- Serve as a guide for EN dam safety trainers
- provide basic checklists for dam safety management

The main objective of the short term training is to introduce and familiarize participants with the essentials of dam safety management and to enable them provide dam safety training to others responsible for dam safety at EN projects.

The following specific course objectives will enable successful participants of the short term training to act as dam safety trainers with basic knowledge, understanding and practical skills related to:

- Importance and fundamentals of dam safety;
- Application of dam safety analysis framework in executing dam safety analysis;
- Use of qualitative and quantitative tools for dam safety analysis;
- Consideration of safety in planning, design and construction of dams;
- Planning and designing of instruments for monitoring dam behaviours;
- Planning and conducting of surveillance and monitoring; and
- Preparation of Emergency Action Plans.

The target groups for the subsequent training are planners, policy makers, dam owners, regulators, consultants, dam operators, etc. responsible for the safety of dams in EN countries.

This dam safety training modules establishes a solid foundation for subsequent more detailed and targeted training courses which will be required on key technical topics.

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LIST OF MODULES

Symbol or abbreviation	Definition
EAP	Emergency Action Plan
EEAA	Egyptian Environmental Affairs Agency
EIA	Environment Impact Assessment
EN	Eastern Nile
ENSAP	Eastern Nile Subsidiary Action Plan
ENTRO	Eastern Nile Technical Regional Office
ESM	Environmental and Social Management
ESP	Environment and Social Policy
ETCOLD	Ethiopian Committee on Large Dams
FERC	United States Federal Energy Regulatory Commission
GERD	Grand Ethiopian Renaissance Dam
HAD/AHD	High Aswan Dam/Aswan High Dam
HADA	High Aswan Dam Authority
ICOLD	International Commission on Large Dams
MEDIWR	Ministry of Dams, Irrigation and Water Resources (South Sudan)
MHPPE	Ministry of Housing, Physical Planning and Environment (South Sudan)
MHUNC	Ministry of Hosing, Utilities and New Communities (Egypt)
MoWRI	Ministry of Water resources and irrigation (Egypt)
MOHP	Ministry of Health and Population (Egypt)
MEDIU	Ministry of Electricity, dams, irrigation and water resources (South Sudan)
MoWIE	Ministry of Water, Irrigation and Energy (Ethiopia)
MoWRE	Ministry Water Resources and Electricity (Sudan)
NBI	Nile Basin Initiative
NBSF	Nile Basin Sustainability Framework
NOPWAD	National Organization for Potable Water and Sanitary Drainage
O & M	Operation and Maintenance
PFM	Potential Failure Mode
PFMA	Potential Failure Mode Analysis
PMF	Probable Maximum Flood
RCC	Roller Compacted Concrete
SMP	Surveillance and Monitoring Plan
SMR	Surveillance and Monitoring Report
SSNEP	South Sudan National Environment Policy
TADS	Training Aids for dam safety
UNEP	United Nations Environment Program
USBR	United States Bureau of Reclamation
WCD	World Commission on dams

MODULE 1

Dams: Main Types & Features

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DAMS: MAIN TYPES & FEATURES

Introduction

Definition

Generally, national or state dam safety programs are responsible for developing legislations and associated regulations, including the definition of a dam.

The Reference Dam Safety Guideline for Easter Nile defines a dam as:

"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)" (Charlwood, etal 2014a).

Traditionally, in water resources development, a dam is defined as an obstruction or a barrier across a stream or a river. Through the obstruction, storage is formed, which can be utilized for various water resources development or water control purposes. **In this module, the term dam is used in this context.**

Purpose of dams

Effective water resources development and management is widely recognized as crucial for sustainable economic growth and poverty reduction in many developing countries. Large dams often play a key role in water management. Intended purposes of large dams usually include providing water for irrigation, water supply to cities, improving navigation, generating hydroelectric power and flood control. Few dams serve all of these purposes but some multi-purpose dams serve more than one.

One of the most important functions of large dams is to supply water for irrigation. According to WCD, 2000, about one fifth of the world's agricultural land is irrigated, and irrigated agriculture accounts for about 40% of the world's agricultural production. Of the 45,000 large dams, nearly 50% of the dams were built exclusively or primarily for irrigation, and an estimated 30 to 40% of the 268 million hectares of irrigated lands worldwide rely on dams. Discounting conjunctive use of ground water and surface water, dams are estimated to contribute to at most 12-16% of world food production.

Large dams are also used extensively for hydroelectric power generation. According to WCD, 2000, hydroelectric power currently provides 19% of the world's total electricity supply and is used in over 150 countries. It represents more than 90% of the total national electricity supply in 24 countries and over 50% in 63 countries. About a third of the countries in the world currently rely on hydroelectric power for more than half of their electricity needs. Hydropower has been perceived and promoted as a comparatively clean, low-cost, renewable source of energy that relies on proven technology. Except for reservoir evaporation, it is a non-consumptive use of water. Once built, hydropower, like all renewable sources, is considered to have low operating costs and a long life, particularly for run-of-river projects and reservoir projects where sedimentation is no concern (WCD, 2000).

In many parts of the world, large dams have also been built to provide a reliable supply of water to meet rapidly growing urban and industrial needs. This is especially true in drought prone regions where natural ground water sources and existing lakes or rivers were considered inadequate to meet all needs. According to WCD (2000), globally, about 12% of large dams are designated as water supply dams. About 60% of these dams are in North America and Europe.

Floods are one of the most frequent and damaging disasters in the world. According to WCD (2000), between 1972 & 1996, floods affected, on average, the lives of 65 million people which are far more than any other type of disaster, including war, drought and famine. During the same period floods left an estimated 3.3 million people homeless every year. About 13% of all large dams in the world in more than 75 countries – have a flood management function (WCD, 2000).

Major Features of Dams

According to TADS 11, structures related to dams may be subdivided functionally in to three basic components:

- The body of the dam (water impoundment),
- The spillway (water conveyance)
- The outlet works (water conveyance)

The dam

Common to all dams are the following components, TADS 11 (refer to Figure 1-1)

- **Upstream and Downstream Slopes or Faces.** The upstream slope or face is the inclined surface of the dam that is in contact with the reservoir. During normal operation, a large part of the upstream slope or face is usually under water.
  The downstream slope or face is the inclined surface of the dam away from the reservoir. Generally, the term slope is used with embankment dams, and the term face with concrete dams.

- **Crest and Shoulders:** The crest is the top surface of the dam. Often a roadway is established across the crest for traffic or to facilitate dam operation, inspection, dand maintenance. The shoulders are the upstream and downstream edges of the crest.

- **Heel & toe.** The heel of the dam is the juncture of the upstream face of a concret dam with the ground surface. The toe of a dam is the juncture of the downstream slope or face of all types of dams with the ground surface.

- **Foundation.** It is the portion of the valley floor that underlies and supports the dam structutre.

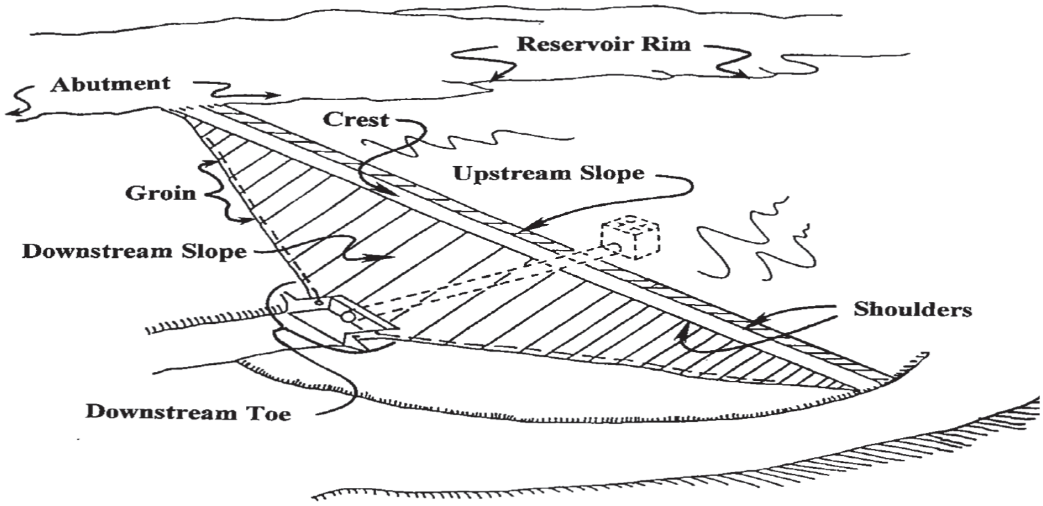

Figure 1-1: Components of a dam (TADS 11)

- **Abutments.** These are those parts of the valley sides against which the dam is construxcted. The contacts between the abutments and the slopes of an emabnkment dam are called the slope-abutment interfaces.

- **Reservoir.** It is the body of water impounded by a dam.

Water conveyance structures

The passage of water through and around the dam is accomplished by water conveyance structures including:

- **Spillway:** The spillway is the primary structure over or through which flood flows are discharged from a reservoir. If the rate of flow is controlled by mechanical means, such as gates, the structure is considered a controlled spillway. If the geometry of the spillway is the only control, the structure is considered an uncontrolled spillway. Spillways usually draw water from the top of the reservoir pool.

- **Outlet Works:** The outlet works are the structures through which normal reservoir releases are made. Outlet works can also be used to drain the reservoir. Outlet works can either be conduits which pass through the embankment or its foundation, or tunnels which are excavated through abutment rock. Outlet works usually draw water through the dam from near the bottom of the reservoir. Spillways and outlet works may be combined into one structure. A dam can have multiple spillways and outlet works structures.

- **Penstocks**: Penstocks are pipelines or pressure conduits leading from the reservoir to the power-generating turbines.

Types of Dams

Dams are numerous types and there are various ways of classifications. The most common ones are classification based on height, purpose, hydraulic design, materials of construction, & hazard potential.

Classification based on size

Dams are traditionally classified in to large dams and small dams based on their size. According to ICOLD, a dam is considered as a large dam and is registered as such in World Register of Dams if it is:

a) more than l5m in height measured from the lowest point of the general foundations to the 'crest' of the dam,
b) more than 10m in height measured as in (a) provided they comply with at least one of the following conditions:
   i. The crest is not 1ess than 500 m in length
   ii. The capacity of the reservoir formed by the dam is not less than 1 million m3
   iii. The maximum flood discharge dealt with by the dam is not less than 2000 m3/s
   iv. The dam is of unusual design

No dam less than 10 m in height is considered as large dam. Some agencies (e.g., USACE) use classification based on size in conjunction with hazard potential classification to regulate dam design and dam breach modelling.

Classification based on purpose:

Dams are classified in to storage, diversion, detention and multipurpose dams based on the function they serve (USBR, 1987, USBR DS 13, TADS 11).

a) **Storage dams:** These are dams that are constructed to impound water during periods of surplus supply for use during periods of deficient supply. These periods may be seasonal, annual, or longer. Many small dams impound the spring runoff for use in the dry summer season. Storage dams may be further classified according to the purpose of the storage, such as water supply, recreation, fish and wildlife, hydroelectric power generation, irrigation, etc. The specific purpose or purposes to be served by a storage dam often influence the design of the structure and may establish criteria such as the amount of reservoir fluctuation expected or the amount of reservoir seepage permitted.

b) **Diversion dams:** These are dams that are ordinarily constructed to provide head for carrying water into ditches, canals, or other conveyance systems. They are used for irrigation developments, for diversion from a live stream to an off-channel-location storage reservoir, for municipal and industrial uses, or for any combination of the above.

c) **Detention dams:** These are dams that are constructed to retard flood runoff and minimize the effect of sudden floods. Detention dams consist of two main types. In one type, the water is temporarily stored and released through an outlet structure at a rate that does not exceed the carrying capacity of the channel downstream. In the other type, the water is held as long as possible and allowed to seep into pervious banks or into the foundation. The latter type is sometimes called a water-spreading dam or dike because its main purpose is to recharge the underground water supply. Some detention dams are constructed to trap sediments; these are often called debris dams.

d) **Multipurpose Dams:** Although it is less common on small projects than on large developments, dams are often constructed to serve more than one purpose. Where multiple purposes are involved, a reservoir allocation is usually made to each distinct use. A common multipurpose project combines storage, flood control, and recreational uses.

Classification based on hydraulic design:

According to USBR, 1987, USBR DS 13, dams may be classified based on their hydraulic design in to:

a) **Overflow dams:** These are dams that are designed to carry discharge over their crests or through spillways along the crest. Concrete is the most common material used for this type of dam.

b) **Non overflow dams:** These are dams that are designed not to be overtopped. This type of design extends the choice of materials to include earth-fill and rock-fill dams.

c) **Composite dams**

Classification based on potential consequence / hazard classification

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. Charlwood et al, 2014b developed a five level / consequence class scheme for Eastern Nile countries, A more detailed discussion on this is given ion Module 3.

Classification according to material of construction

Dams are classified in to two major types on the basis of the materials used for the construction of the body of the dam: earthfill, rockfill (i.e., embankment dams) & concrete gravity, buttress, & arch dams (i.e., concrete dams) (USBR DS-13, 2011).

EMBANKMENT DAMS

Embankment Dams are dams constructed of natural materials excavated or obtained near the dam site. The materials available are utilized to the best advantage in relation to their characteristics as an engineered bulk fill in defined zones within the dam section (Novak et al, 2007).

Embankment dams are the most prevalent types. They represent approximately 85-90% of all dams. They possess many outstanding merits which combine to ensure their continued dominance. The more important can be summarized as follows (Novak et al, 2007):

1. the suitability of the type to sites in wide valleys and relatively steep sided gorges alike;
2. adaptability to a broad range of foundation conditions, ranging from competent rock to soft and compressible or relatively pervious soil formations;
3. the use of natural materials, minimizing the need to import or transport large quantities of processed materials or cement to the site;
4. subject to satisfying essential design criteria, the embankment design is extremely flexible in its ability to accommodate different fill materials, e.g. earth-fill and/or rock-fill, if suitably zoned internally;
5. the construction process is highly mechanized and is effectively continuous;
6. largely in consequence of 5, the unit costs of earth-fill and rock-fill have risen much more slowly in real terms than those for mass concrete;
7. properly designed, the embankment can safely accommodate an appreciable degree of deformation and settlement without risk of serious cracking and possible failure.

The relative disadvantages of embankment dams are few. The most important include an inherently greater susceptibility to damage or destruction by overtopping, with a consequent need to ensure adequate flood relief and a separate spillway, and vulnerability to concealed leakage and internal erosion in dam or foundation.

Embankment dams can be classified in broad terms as being earth-fill or rock-fill dams. The division between the two embankment variants is not absolute, many dams utilizing fill materials of both types within appropriately designated internal zones (EM-11110-2-2300)).

EARTH-FILL EMBANKMENT DAMS

Although several different definitions of earth fill dams are used by various authors and organizations, the most commonly used definition is:

it is a dam containing more than 50%, by volume, of earth fill materials (fill composed of soil and rock material that are predominantly gravel sized or smaller) (TADS 11, Novak et al, 2007).

Earthfill dams support loads by gravity and embankment stability (Sing et al, 1985). According to TADS 3, a typical earth fill dam may have the following given parts (Refer to Figure 1-2):

Core - It consists of selected soil, well compacted to provide water tightness to the dam and adequate shear resistance against slipping and also control the seepage through the body of the dam.

Shell - It is made of sand and gravel obtained from river bed and placed on either side of the core. It should be consolidated to develop shear resistance against slipping. It provides stability to the dam and helps in drainage.

Cut off - It is the extended part of the type clayey core taken up to the impervious strata to control the seepage of fine material through the previous shell, but at the same time helps in the draining of the core to relieve it from the pore pressure.

Transition Filter - It is the graded filter placed in between the clayey core and sandy shell, prevent the passage of fine material through the previous shell, it prevents of piping of dam foundation.

Rock Toe - It consists of rock fill protected by a filter on all sides. It helps to prevent sloughing of toe due to seepage flow, especially when the embankment material is relatively impervious. It also changes the seepage path and thus increases the stability of the dam.

Toe Drain - It is a perforated drain pipe laid in a trench near the toe, duly protected by a filter. It collects all see-page water and then disposes it to the down-stream river flow by means of cross drain.

Key Wall - It is a curtain wall usually of concrete, keying the core with rocky or impervious foundation. It helps in preventing the erosion of material on the up stream face due to wave action.

Earth fill dams are classified in to rolled fill earth dams and hydraulic fills dams based on method of construction. In hydraulic fill earth fill dams, the construction, excavation, transportation of the earth fill material is done by hydraulic methods. Outer edges of the embankments are kept slightly higher than the middle portion of each layer. During construction, a mixture of excavated materials in slurry condition is pumped and discharged at the edges. This slurry of excavated materials and water consists of coarse and fine materials. When it is discharged near the outer edges, the coarser materials settle first at the edges, while the finer materials move to the middle and settle there. Fine particles are deposited in the central portion to form a water tight central core. In this method, compaction is not required (TADS 3)

In rolled fill earth fill dams, the major portion of the embankment is constructed in successive, mechanically compacted layers. The material from borrow pits and that suitable from required excavations for the dam and other structures is delivered to the embankment, usually by trucks or scrapers. It is then spread by motor graders or bulldozers and sprinkled, if necessary, to form lifts of limited thickness having the proper moisture content. These lifts are then thoroughly compacted and bonded with the preceding layer by means of power rollers of the proper design and weight. Rolled-fill dams consist of three types: homogeneous, zoned and diaphragm (USBR, 1978).

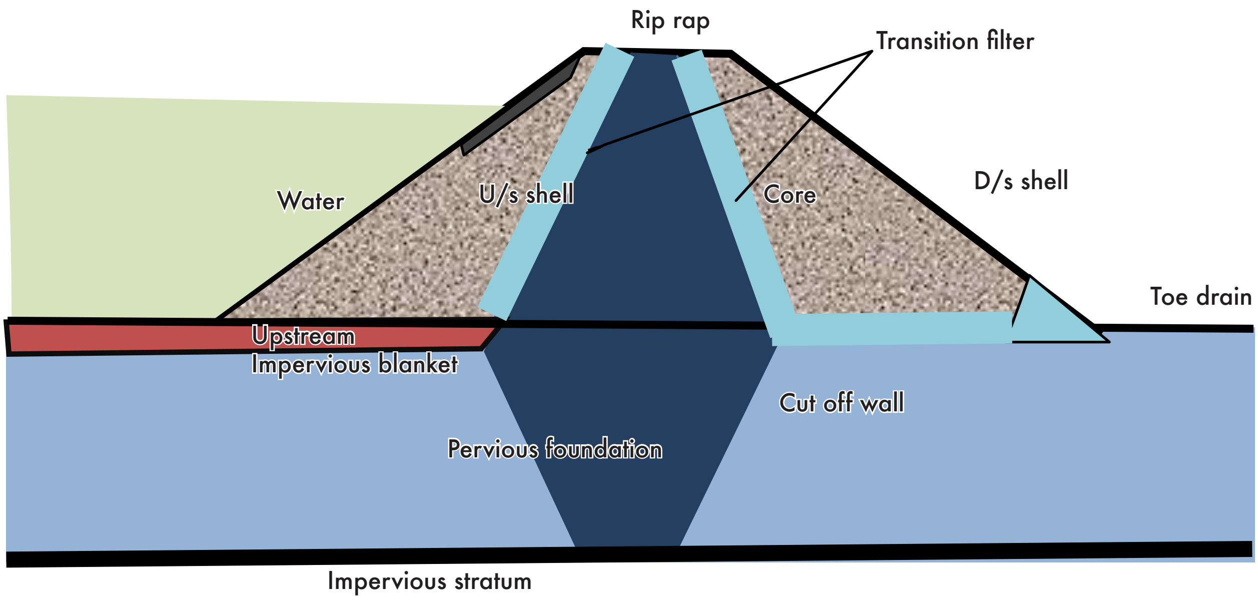

Figure 1-2: Schematic diagram of a typical earth fill dam

Homogeneous earth fill dam:

These are dams that are composed of only one kind of material (exclusive of the slope protection) (Refer to Figure1-4). The material used in such dams must be sufficiently impervious to provide an adequate water barrier, and the slopes must be relatively flat for stability and adequate dissipation of reservoir head as water seeps through the dam.

Generally, the upstream and downstream slopes of homogenous dams are relatively flat to maintain stability during sudden drawdown and steady state seepage at reservoir full or partial full conditions respectively (USBR, 1987). Although formerly very common in the design of small dams, the completely homogeneous section has been replaced by a modified homogeneous section in which small amounts of carefully placed pervious materials control the action of seepage so as to permit much steeper slopes. A homogeneous (or modified homogeneous) dam is recommended in localities where readily available soils show little variation in permeability, and soils of contrasting permeabilities are available only in minor amounts or at considerably greater cost.

Zoned Earth fill dams.-

It is the most common type of the rolled filled earth fill dams. The dam consists of a central impervious core that is flanked by zones of materials considerably more pervious, called shells. These pervious zones or shells enclose, support, and protect the impervious core; the upstream pervious zone affords stability against rapid drawdown; and the downstream pervious zone acts as a drain to control seepage and lower the phreatic surface. In many cases, a filter between the impervious zone and downstream shell and a drainage layer beneath the downstream shell are necessary (USBR, 1987).

The pervious zones may consist of sand, gravel, cobbles, rock, or mixtures of these materials. In this module, the dam is considered to be a zoned embankment if the horizontal width of the impervious zone at any elevation equals or exceeds the height of embankment above that elevation in the dam and is at least 3m. The maximum width of the impervious zone will be controlled by stability and seepage criteria and by the availability of material. Zoned earth fill dams are generally suitable when a variety of soils are readily available, because its inherent advantages will lead to more economical construction.

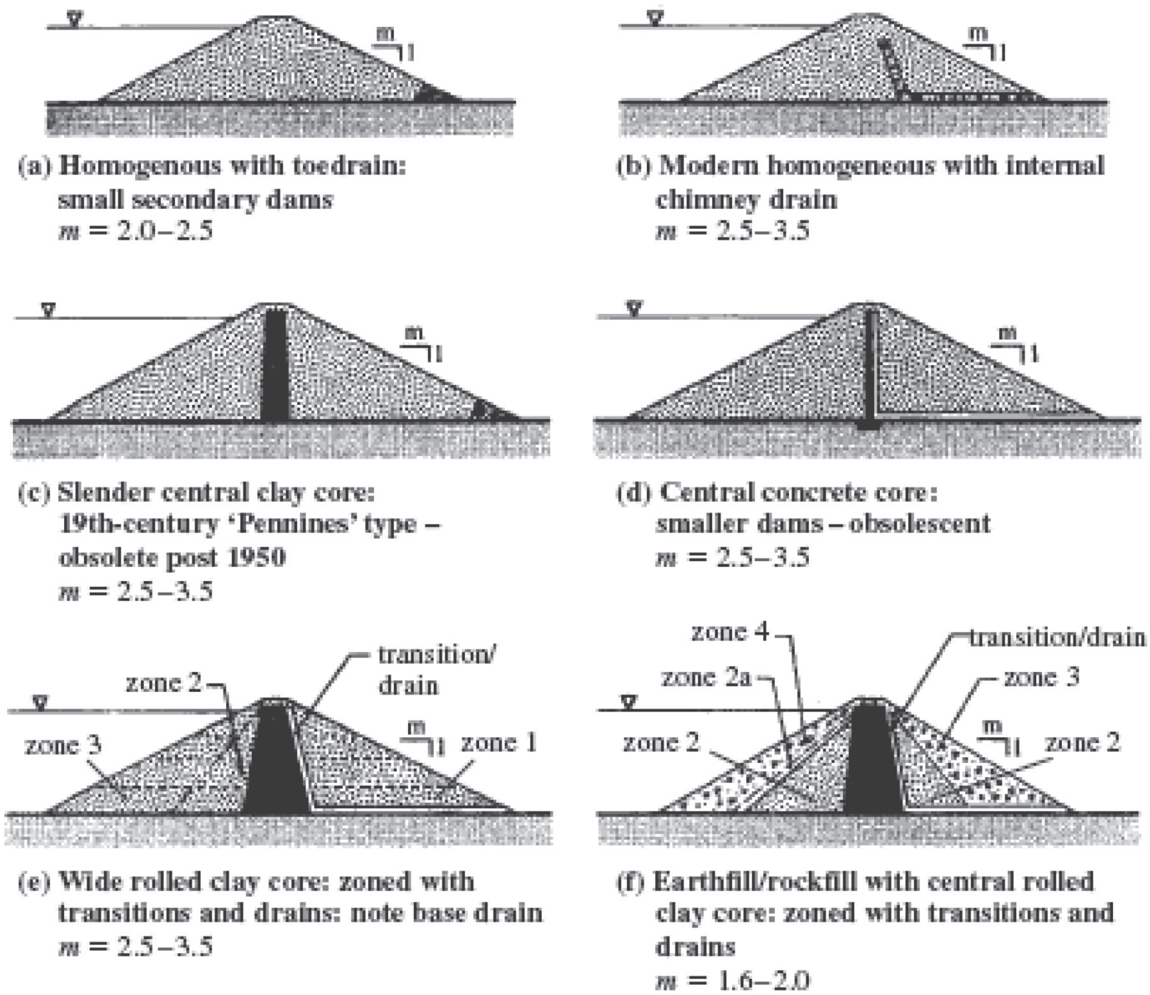

Figure 1-3: Principal variants of earth fill and earth fill-rockfill embankment dams, Novak etal 2007

Diaphragm Earth Fill Dams:

Diaphragm earth fill dams art those dams where most of the embankment is constructed of pervious (permeable) material (sand, gravel, or rock), and a thin diaphragm of impermeable material is provided to form the water barrier. The position of this impervious diaphragm may vary from a blanket on the upstream face to a central vertical core. The diaphragm may consist of earth, portland cement concrete, bituminous concrete, or other material (USBR 1987).

An earth blanket or core is considered a diaphragm if its horizontal thickness at any elevation is less than 3m or its thickness at any elevation is less than the height of the embankment above that elevation. If the impervious earth zone equals or exceeds these thicknesses, the design is considered a zoned embankment type. Design and construction of diaphragm-type dams must be approached with care. All internal diaphragms, including those constructed of earth or rigid materials such as concrete, have a potential for cracking caused by differential movements induced by embankment consolidation, fluctuating reservoir levels, and non-uniform foundation settlement. The construction of an internal earth diaphragm with the necessary filters requires a higher degree of precision and closer control than that normally used for small dams. Internal diaphragms made of rigid material such as concrete also have the disadvantage of not being readily available for inspection or emergency repair if they are ruptured by settlement of the dam or its foundation.

An earth blanket on the upstream slope of an otherwise pervious dam is not recommended because of the expense and the difficulty of constructing suitable filters. Furthermore, because the earth blanket must be protected from erosion by wave action, it must be buried and therefore, is not readily available for inspection or repair. If the supply of impermeable soil is so limited that a zoned embankment dam cannot be constructed, a diaphragm of manufactured material placed on the upstream slope of an otherwise pervious embankment is recommended for small dams.

Tailing Dams:

A unique category of earth-fill embankment dams are tailings dams used by the mining industry. Tailings dams are often constructed of coarse tailings produced by the mine but may also consist of other soils obtained near the construction site. Tailings dams often rely on the stored tailings to control seepage, but otherwise include many of the same design features as conventional water storage dams.

ROCK-FILL EMBANKMENT DAMS

Concomitant with the definition given for an earth fill dam, a rock fill embankment dam may be defined as:

a dam containing more than 50%, by volume, of rock materials (fill composed of soil and rock material that are predominantly cobble sized or larger). (TADS 11, Novak et al, 2007)

Rockfill dams have two basic structural components—an impervious zone and a rockfill zone which supports the impervious zone (Refer Figure 1-4). Rockfill dams may be classified based on the characteristics of the impervious zone into two basic types: diaphragm and central core.

Diaphragm Rockfill Dams

In a diaphragm rockfill dam, the body of the dam is constructed of rock (cobble sizes or larger), and a thin diaphragm of impermeable material is provided to form the water barrier. The diaphragm is an impervious barrier placed on the upstream face or a thin vertical core, and it may consist of earth, concrete, asphalt, or other material. (See Figure I-5). Diaphragm rockfills have several advantages. They have greater stability against downstream instability than a central core rockfill dam. If the use of the reservoir permits, the reservoir can be drawn down periodically to check the integrity of an upstream diaphragm, and repairs can be made if necessary. Uplift pressures present no problems, and benefits also arise from the fact that an upstream diaphragm can be installed after the rockfill zone has been placed and any construction settlement that could potentially rupture the diaphragm has occurred. On the negative side, because an upstream diaphragm is exposed, it is susceptible to damage (TADS 3).

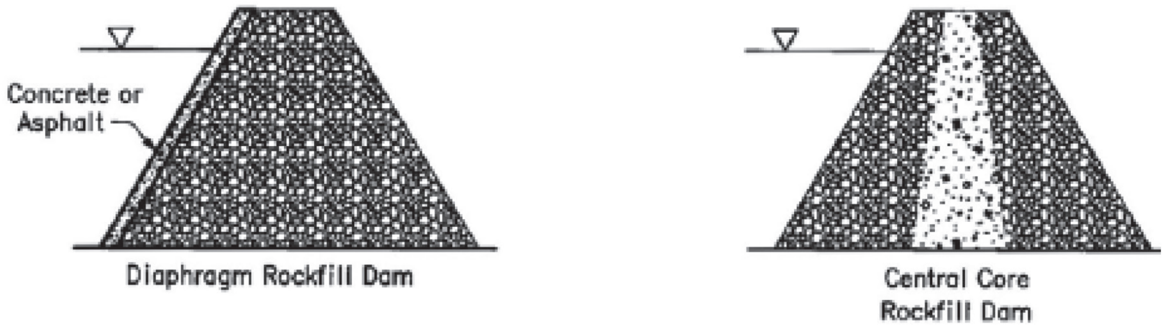

Figure 1-4: Principal variants of rock fill dams

Central Core Rock fill Dams

Central core rockfill dams are similar in configuration to zoned earthfill dams, but are constructed with outer zones of coarse, free-draining rockfill which are more stable than finer grained soils, allowing steeper external slopes, and hence an economical design because less material is required. (See Figure I-4) The central earthen core of this type of rockfill dam is placed in the same way as for a rolled earth fill dam. The shells of modern rock fill dams are compacted with large vibratory rollers, and hence little post-construction settlement occurs. However, before the advent of such equipment, the rock fill of the shells was often simply dumped into place, and as a result, settled considerably with time. Differential settlement between zones—the loose shell material and the well-compacted core—has occurred on many of these older rock fill dams. A central core rock fill dam of good design and careful construction techniques has a high resistance to deformation during earthquakes (TADS 3).

CONCRETE DAMS

Concrete dams are dams that are constructed mainly of cast in place conventional vibratory concrete (CVC) / mass concrete or roller compacted concrete (RCC) (TADS 4). These dams are hard, none yielding, and rigid structures. Loads are transmitted through the dam body and to the foundation and abutments. It requires strong and more or less uniform rock foundation. Many early dams were constructed as rubble masonry or random masonry. From about 1900, mass concrete, initially without formed transverse contraction joints, began to displace masonry for the construction of large non embankment dams. From about 1950 mass concrete increasingly incorporated bulk material additives such as slags or pulverized fuel ash

(PFA), in order to reduce thermal problems and to contain escalating costs (Novak et al , 2007).

Concrete dams are classified in to three main structural types: gravity dams, buttress dams, and arch dams.

GRAVITY DAMS

Gravity dams are the most common types of concrete dams and the simplest to design and build. Massive and triangular in cross section, they depend on their weight and shape to withstand reservoir loads and transfer the loads to the foundation (TADS 4). Conventional placed mass concrete or CVC and RCC are the two general concrete construction methods for concrete gravity dams. In earlier periods of dam design, gravity dams were built of masonry materials.

Generally, gravity dams must be sized and shaped to resist, with ample safety factor, internal stresses and sliding failure within the dam and foundation, (USBR 1987). An example of a gravity dam is shown in Figure 1-5. Typically gravity dams are constructed on a straight axis, though they may be slightly angled or curved, in an arch shape. Gravity dams may be constructed of masonry materials such as stone, brick, or concrete blocks jointed with mortar; this type of construction was typical in early dam design.

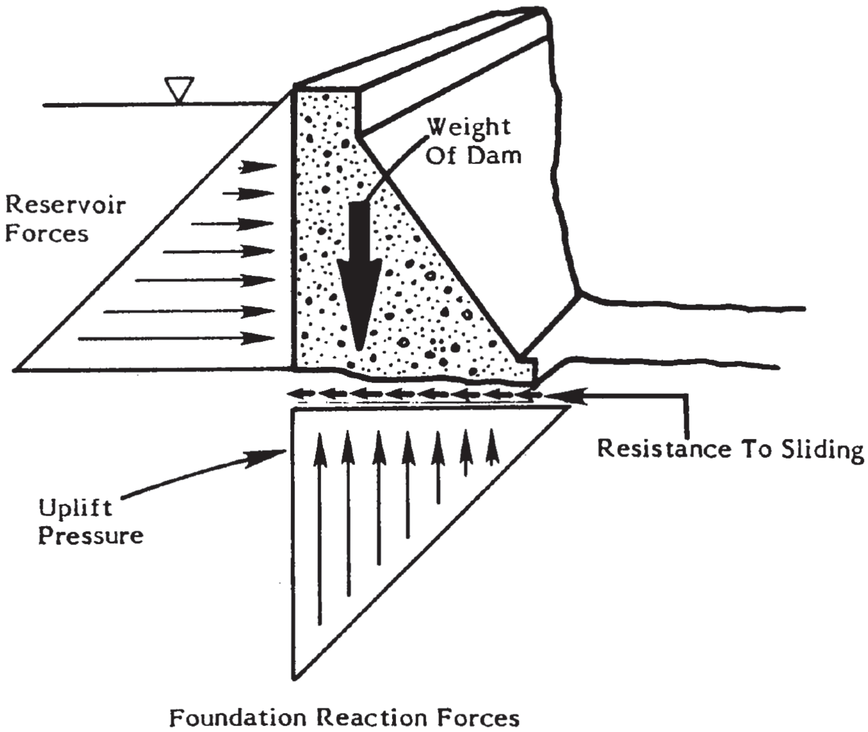

Figure 1-5: Schematic diagram of concrete gravity dam (TADS 4)

BUTTRESS DAMS

According to TADS 4, Buttress dams, a form of gravity dam, depend on their own weight and the weight of the water to maintain stability. They are comprised of two basic structural elements: a watertight upstream face and a series of buttresses, or vertical walls, that support the face and transfer the load from the face to the foundation. Buttress dams were first developed to conserve water in regions where materials were scarce or expensive but labor was cheap. Normally needs up to 60% less concrete than gravity dams of the same height, but needs more form work and reinforcement (See Figure 1-6).

Buttress dams are of three types: (i) Deck type, (ii) Multiple-arch type, and (iii) Massive-head type (FERC, 1987, Chapter 10). A deck type buttress dam consists of a sloping deck supported by buttresses. Buttresses are triangular concrete walls which transmit the water pressure from the deck slab to the foundation. They are compression members..The deck is usually a reinforced concrete slab supported between the buttresses, which are usually equally spaced. In a multiple-arch type buttress dam the deck slab is replaced by horizontal arches supported by buttresses. The arches are usually of small span and made of concrete. In a massive-head type buttress dam, there is no deck slab. Instead of the deck, the upstream edges of the buttresses are flared to form massive heads which span the distance between the buttresses.

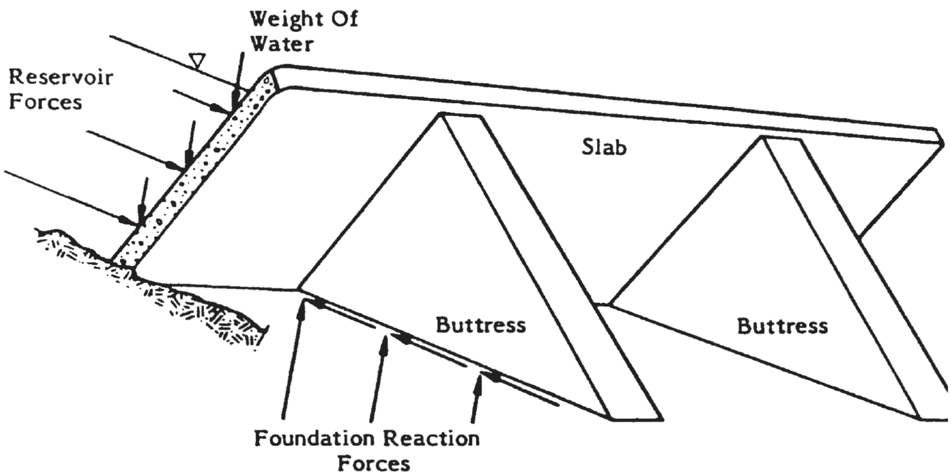

Figure 1 -6: Schematic diagram of buttress dam, TADS 4

ARCH DAMS

An arch dam is a solid concrete dam that is arched upstream and normally thinner than a gravity dam. Although arch dams transfer a small part of the reservoir load by their own weight in to the foundation, they obtain most of their stability by transmitting the reservoir load in to the abutment by arch action (TADS 4). This type is suitable in narrow gorges when the length of the crest is not more than 5 times the height of the dam. Its particular derivative is the cupola or double curvature arch dam, which is the most sophisticated concrete dams, and is extremely economical in concrete (Refer Figure 1-7).

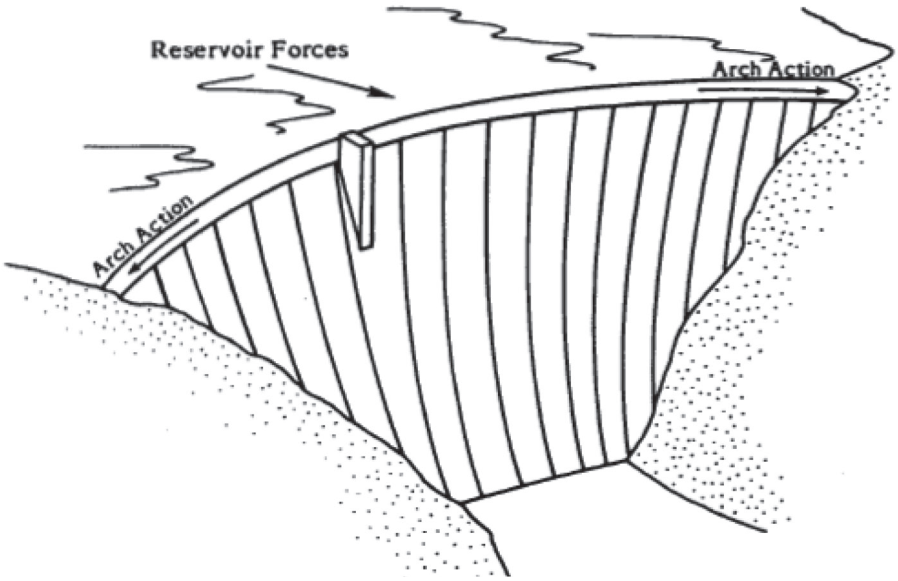

Figure1 -7: Schematics diagram of arch dams (TADS 4)

CONCRETE DAM CONSTRUCTION

Concrete dams are constructed by two different methods: Mass concrete construction (Conventional Vibratory Concrete) & roller compacted concrete construction (RCC) (TADS 4)

Mass concrete construction

Concrete is composed of aggregates held together by a hardened paste of cement and water. The thoroughly mixed ingredients, when properly proportioned, make a plastic mass that can be cast or molded into a desired shape and size. Chemical or additives are sometimes used in the mixture to enhance some characteristics of the concrete, such as workability or shrinkage control (TADS 4).

The large volume of concrete used in construction of a dam is commonly referred as mass concrete. According to American Concrete Institute, mass concrete is any volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat from hydration of the cement and attendant volume change to minimize cracking. Concrete dams are built in very large blocks, or monoliths, by placing large quantities of concrete into preset forms and consolidating the concrete by means of vibration. After the concrete cures, the forms are stripped away and used in constructing other blocks. The temperature of the concrete may be controlled during curing by means of sizing of monolith, mix design of concrete, and water spraying in curing. In cases of very large masses, cooling coils may be embedded in the concrete to minimize volumetric changes that lead to cracking (TADS 4).

Roller compacted concrete construction

According to American Concrete Institute, roller compacted concrete (RCC) is concrete compacted by roller compaction; concrete that, in its unhardened state, will support a roller while compacted. Roller compacted concrete (RCC) has been used in the construction of some newer dams and other types of structures and is potentially useful for repair work on existing dams. Using this method, a mixture of well graded aggregates with low cement content is placed in layers and compacted using heavy equipment. Because of the construction technique (similar to that used in embankment construction), the horizontal construction joints on RCC dams are significantly closer together than those in a mass concrete dam (TADS 4).

CONCRETE DAM FEATURES

According to TADS 4), the principal features of a typical concrete dam include the crest, upstream and downstream faces, heel and toe, and the abutments which are described in section xxx. Features special to concrete dams include joints, and galleries and these features are discussed below (Refer Figure 1-9).

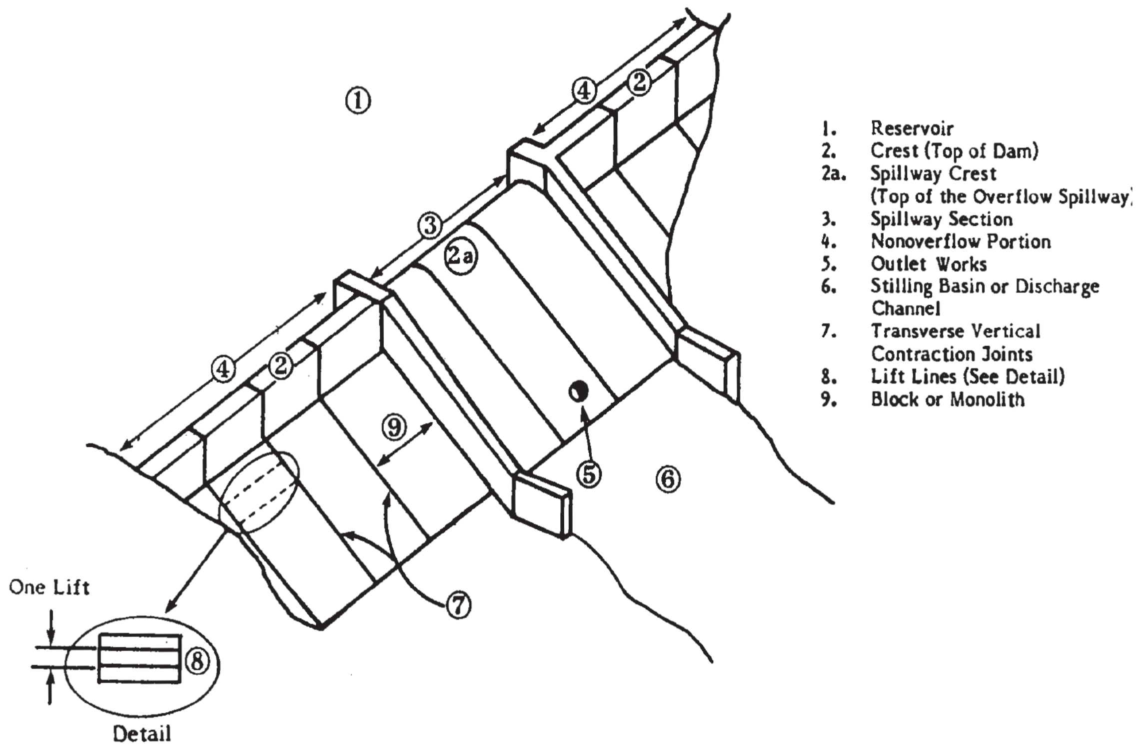

Figure 1-8: Typical concrete dam features (TADS 4)

Joints

Three main types of joints occur in the construction of a concrete dam: construction joints, contraction joints and expansion joints (TADS 4).

Construction joints

These are joints that are provided as a result of the construction process – of ending of one concrete placement and beginning of another. Concrete dams are constructed in vertical increments called lifts. Typical lift heights for mass concrete dams are 1.5 m to 3m; whereas lift heights for RCC dams are in the range of 20 cm to cm. Construction joints must be prepared and treated during construction to ensure bonding of successive lifts of concrete.

Contraction joints

As pointed out earlier, concrete dams are constructed in block or monoliths. The monolith blocks that comprise a mass concrete dam are separated by vertical joints running transversely through the structure, from the upstream face to the downstream face and from the foundation to the crest. These joints, called contraction joints, are designed to prevent the formation of tension cracks as the structure undergoes volumetric shrinkage due to temperature drop. Contraction joints are constructed so that no bond exist between the blocks separated by the joints. The opening of these transverse contraction joints could provide passage through the dam that, unless sealed, would permit water to leak from the reservoir to the downstream face. To prevent leakage, seals or water stops, are embedded in the concrete across the joints near the upstream face during the original construction. The most common types of seals are made of polyvinyl chloride (PVC), metal, or rubber.

Contraction joints may be grouted and or keyed to enhance the stability of the structure. Grouting involves forcing a mixture of Portland cement and water into the joints under pressure. The grout then binds the individual blocks together so that they act as a monolithic mass.

Expansion joints

Expansion Joints are placed in a concrete Structure primarily to accommodate volumetric expansion due to temperature rise. These joints most commonly are found in power plants and other appurtenant structures that are subjected to expansion. Expansion joints may be left open or filled with a compressible joint filler to prevent stress or load transfer.

Interior features

Two main features in the interior of a concrete dam are the gallery system and the drainage system

Gallery system

A gallery is a passage way in the body of a dam used for inspection, foundation grouting, and or drainage. Galleries may run longitudinally or transversely, may be horizontal or on a slope, and serve a variety of purposes

- Access into the dam for operation, maintenance, observation, and inspection.
- Paths for utility lines
- Sites for control equipment
- Drainage way for water within the dam
- Access for grouting the foundation and abutments.

Galleries contain drainage gutters in the floor, into which drains may empty. The gutters facilitate the flow and measurement of drainage water with in the dam.

An adit is a gallery that is used for entrance to a gallery system or that serves as a connecting passageway between galleries or other features in the dam.

Tunnels are sometimes constructed into the rock of abutments off the gallery system to provide access for grouting, drainage, and inspection of abutment rock.

Figure 1-9 shows a portion of a complex gallery system of a large dam.

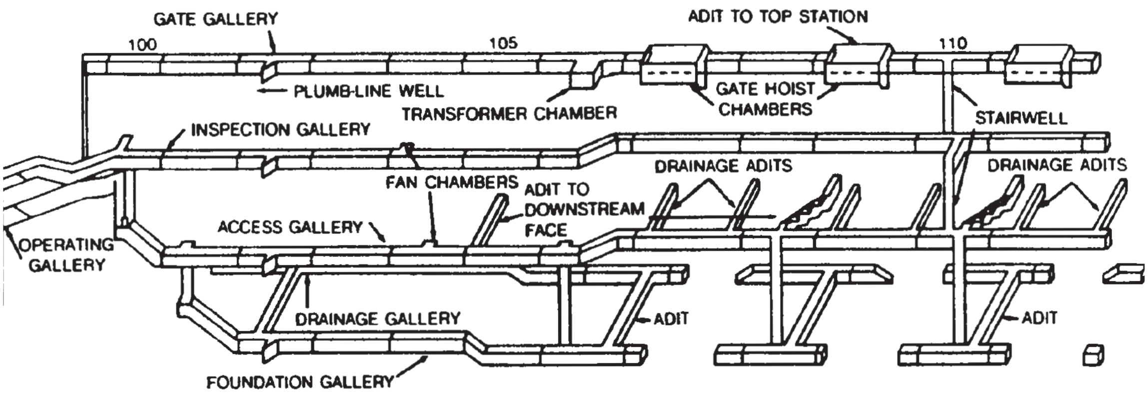

Figure 1 -9: Gallery system for a large dam (TADS 4)

A system of drains is used to control hydrostatic pressures by collecting and disposing of water that leaks in to the structure or seeps through the foundation. There are three major types of drains:

- Gallery drainage gutters,
- Formed drains (face drains)
- Foundation drains (drilled holes)

These are shown in Figure 1-10.

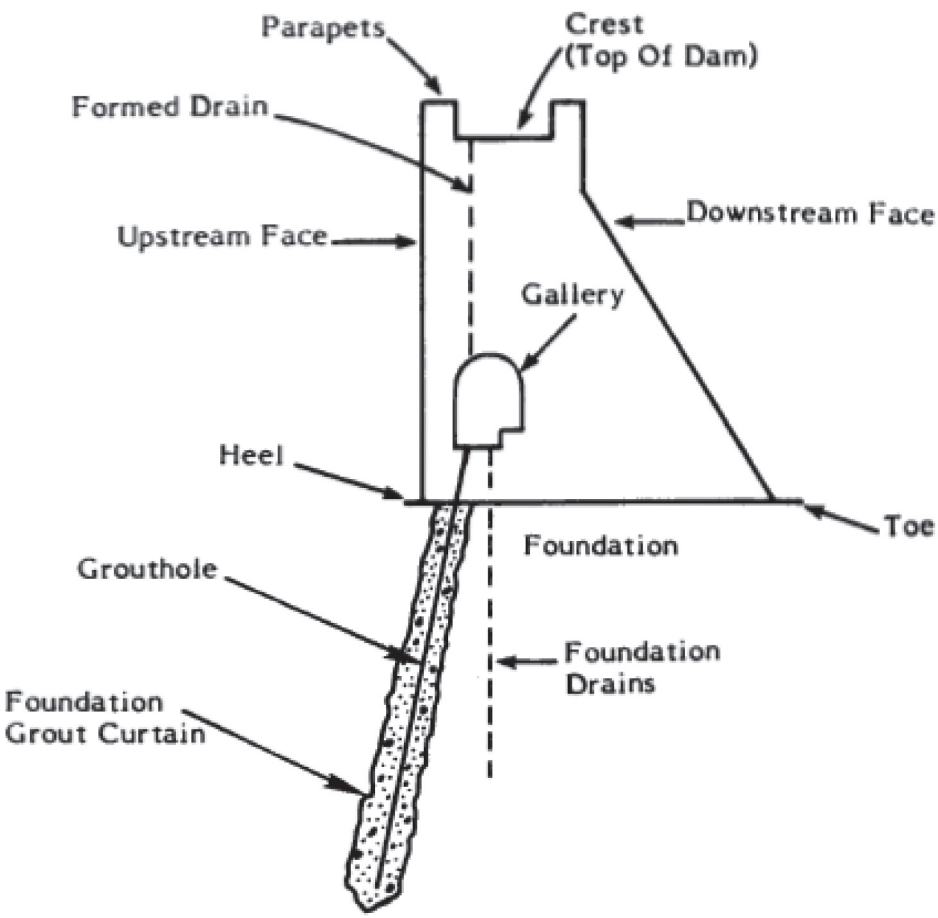

Figure 1-10: Cross-section of Gallery Showing Location of Typical Drains & Grout Curtain (TADS 4)

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TADS 4 : Inspection of Concrete and Masonry Dams

TADS 11 : Dam Safety Awareness

TADS 18 : Evaluation of Embankment Dam Stability & Deformation

TADS 19 : Evaluation of Concrete Dam Stability

USBR : 1987: Design of Small Dams

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MODULE 2

Dam Development and Safety in the Eastern Nile

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Acknowledgment

The information that is used in this module is primarily drawn from two reports

1. *Situational Assessment Report for Dam Safety Management in the Eastern Nile Sub-basin*, 2014, ENTRO
2. *Reference Dam Safety Guidelines for the Eastern Nile Countries*, 2014, ENTRO

This is duly acknowledged here.

DAM DEVELOPMENT AND SAFETY IN THE EASTERN NILE

Eastern Nile Sub Basin

The River Nile is the longest river in the world, flowing north over 6,600 km from its most distant source in Burundi to the Nile delta in Egypt (Refer Figure 2-1). The Nile and its tributaries flow through ten countries and the river basin drains over three million square kilometers (one tenth of Africa's total land mass). It is home to more than 300 million people (many of them are among the world's poorest). Because of its size and variety of climates and topographies, the Nile is one of the most complex river basins in the world.

Figure 2-1: Nile River Basin

There are two major Sub basins within the Nile basin: the Eastern Nile & the Nile Equatorial Lake. The Eastern Nile includes the countries of Egypt, Eritera, Ethiopia, South Sudan, and Sudan and encompasses the sub-basins of the *Baro-Akobo-Sobat, the Abbay /Blue Nile, the*

Tekezze-Settit-Atbara, portions of the White Nile in Sudan, and the Main Nile (Figure 2-2). The Nile Equatorial Lake is composed of mainly *Lake Victoria basins*, *sudd swamp* in south Sudan.

Figure 2-2: Eastern Nile Sub Basin

Eastern Nile is home to some of the largest dams in the world.

- The Aswan High Dam in Egypt, which impounds the River Nile and creates Lake Nasser, is the sixth biggest dam based on water storage capacity. The dam's reservoir, Lake Nasser, has a water storage capacity of 162 billion cubic metres.
- At a height of 188m, the Tekeze dam in Ethiopia, a double curvature arch dam on the Tekeze river which is one of the tributaries of Nile, is the largest dam in Africa in terms of height.
- The Merowe High Dam in Sudan, with its installed capacity of 1,250 MW is the largest hydroelectric power plant in Africa.
- The Grand Ethiopian Reniassance Dam, which will have installed capacity of 6000 MW, will be the largest hydroelectric power plant in Africa when completed, as well as the 8th largest in the world. The reservoir at 74 billion cubic meters will be one of the continent's largest dam.

Eastern Nile is also a region where some of the most populous countries in Africa is found. At populations of 86.6 million & 76.5 million (2013 est), Ethiopia and Egypt make the 2nd and 3rd populous countries in the continent. The Nile Delta is also one of the most densely populated regions in the world.

Eastern Nile Dams

According to Charlwood et al, 2014a, there are currently more than 30 large dams in the Eastern Nile, some of these are13 in Egypt, 12 in Ethiopia and 5 in Sudan. No large dams currently exist in South Sudan. 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.

Egypt

Egypt has a long history of dam building on River Nile dating as back as 4000 B.C. Currently there are two large dams and eleven (11) barrages[1] or groups of barrages in existence in Egypt (Charlwood etal, 2014a). Of these dams and barrages eight of them are more than 50 years old.

The two dams are built for irrigation, hydropower generation and flood control. The Old Aswan Dam is the first dam to be built on Nile. It was built by the British and completed in 1902. It is located 6 km from the city of Aswan. The dam wall was subsequently raised in 1907-12 and 1929-34. The dam is gravity, masonry buttress dam with a raised height of 36 meters. Its initial reservoir capacity was 5 300 million m3.
The second large dam is the High Aswan Dam. The dam is located just upstream of the Old Aswan Dam, and was completed in 1970. It is 110 m high with a storage capacity of 162 billion m3 and a hydro-power generating capacity of 2100 MW. The dam provides long term storage buffering against periods of low flow (e.g. during 1978-88) by providing sufficient water for two crops a year. It also provides flood protection for land downstream. Siltation and evaporation is two of the major issues at the High Aswan Dam.

The barrages were mainly built for irrigation, flood control and navigation. The traditional system of basin irrigation—in which Nile floods were trapped in shallow basins and a cool-season crop of wheat or barley was grown in soaked and silt-replenished soil has been replaced since the mid-1800s by a system of perennial irrigation with the help of barrages. The delta barrages, just below Cairo, built in 1862, channel water into a system of feeder canals for the delta, and other barrages at Isna, Asyut, and Nag Hammadi keep the level of the Nile high enough all year for perennial irrigation in the valley of Upper Egypt.

[1] It is barrier that is built across a river, comprising a series of gates which when fully open all the flood flow to pass without appreciable increasing the flood level upstream of the barrage.

Table 2-1 Egyptian Barrages in Eastern Nile (Charlwood et al, 2014a)

Barrage	Year
Delta Barrages	1862
Asyut Barrage	1902
Zifta Barrage	1902
Esna Barrage	1908
Nag-Hamady Barrage	1930
Damietta Barrage	1950
Edfina Barrage	1951
Rosetta Barrage	1985
Farascour Barrage	1989
New Esna Barrage	1994
New Nag-Hamady Barrage	2008

Ethiopia

Ethiopia began dam construction on Blue Nile river in 1950's. The first dam was a small dam; the Tis-abay I dam on lake Tana, which was constructed in 1954. This was followed by the first large dam, the Finchaa Dam, which was completed in 1973 on the Finchaa River that feeds into the Blue Nile, and the Amerti Dam which was completed in 1984. Ethiopia embarked on dam construction in earnest in 1990s. Four large dams were built in 1990's and another five were added in 2000's.

Curently, there are twelve large dams in operation, and three under construction. The large majority of these dams are single purpose dams. Typically the dams are used for hydropower generation, irrigation or water storage for domestic and industrial use. Only three of the dams are multi-purpose for irrigation and hydropower generation (Charlwood et al, 2014a).

According to Charlwood et al, 2014a, most of the dams are also typically embankment dams with either uncontrolled or controlled spillways. The typical potential failure modes for these dams would therefore be similar focusing on the internal erosion of the embankments and the foundations, overtopping failure of the embankments and sliding failure of the concrete structures either as a result of relative weak layers or as a result of undercutting of the downstream toe. There are one concrete arch dam with a controlled spillway, a concrete weir with a controlled spillway and the under construction Grand Ethiopian Renaissance Dam with a main Roller Compacted Concrete (RCC) gravity wall.

Table 2-2 Ethiopian dams in Eastern Nile (Charlwood et al, 2014a)

Dam	Year	Type	Height (m)	Storage (Mm3)	Purpose
Finchaa	1973	Rock fill with clay	22.2	650	Hydropower 128 MW Irrigation
Amerti	1984	Homogenous Earth fill	15	110	Irrigation
Alwero	1996	Homogenous Earth fill	14	75	Irrigation
Angereb	1996	Homogenous Earth fill	34	6	Water supply
Chara Chara	1996	Concrete Gravity	6		Hydropower 420MW
Midimar	1999	Homogenous Earth fill	33	10	Water supply
Koga	2006	Homogenous Earth fill	21.5	77	Irrigation
Nekemepte	2008	Concrete Gravity			Water supply
Tekeze	2009	Concrete Arch	189	9300	Hydropower (300MW)
Neshe	2010	Homogenous Earth fill	38	448	Irrigation & Hydropower (97MW)

Two of the three dams under construction (Arjo Dedessa Dam and Megech Dam) are solely for irrigation. The third, Grand Ethiopian Renaissance Dam will primarily be used for hydropower. This dam when completed would be 145 m high, store 74 billion m3 and have installed hydropower capacity of 6 000 MW.

South Sudan

According to Chralwood et al, 2014a, apart from small dams for water supply, there are no major dams in South Sudan due to the civil strife that continued for decades. But after the Comprehensive Peace Agreement (Sudan: 2005) several studies were done to establish the feasibility of generating hydropower from sites on the Bahr el-Jebel River, and multipurpose use on The Bahr el-Ghazal River and the Sobat River. These projects were all investigated previously by the Dams Implementation Unit at the national level in Khartoum. The greatest hydropower potential was found at Fula 1 site on the Bahr el-Jebel River, with a proposed installed capacity of 900 MW. The Government of South Sudan, and MEDWIR for that matter, has prioritized this site to be considered under the current East Africa Northern Corridor Infrastructure Project established by the Head of States Summit. Other prospective sites studied at prefeasibility level that, Bedden (570 MW), Shukoli (235 MW), and Lakki (410 MW).

Sudan

There are five large dams in operation, and one under construction in Sudan. All these dams are multi-purpose dams and the large majority were or are being built for irrigation and hydropower generation. They also have an important secondary purpose of flood control. Most of the dams also typically consist of concrete spillway sections in river section and embankment walls on either side in wide valleys with thick alluvial soils covering the underlying rock. All these spillways are also gate controlled. The typical Potential Failure Modes for these dams would therefore be similar focusing on the internal erosion of the embankments and the foundations, overtopping failure of the embankments and sliding failure of the concrete structures either as a result of relative weak layers or as a result of undercutting of the downstream toe.

Table2 -3: Sudan dams in Eastern Nile (Charlwood et al, 2014a)

Dam	Year Completed	Type	Height (m)	Storage Capacity (Mm3)	Purpose
Sennar	1925		26	930	Hydropower (45 MW)
Jebel Aulia	1937		22	3500	Hydropower (7MW)
Khashim el Gerba	1964			1300	Irrigation & Hydropower (12.5 MW)
Rosaries	1950, 2012		78	6000	Hydropower (380MW)
Merowe	2009		67	12500	Hydropower (1250MW)

The dam complex of the Upper Atbara River on the Upper Atbara River and the Setit River in Eastern Sudan are currently under construction. This dam complex are located upstream of the Khashim el Girba Dam. The dam complex will have a maximum height of 55 m and a combined storage capacity of 2 700 million m3. The scheme has an installed hydropower capacity of 135 MW.

Dam Safety Practices in EN Countries

As pointed in Section 2.1, there are 30 large dams in EN countries. This number is bound to increase as some of the EN countries, especially Ethiopia, plan to build more dams on Nile and its tributaries. According to Charlwood et al, 2014a, many of the existing dams in EN countries are high risk dams whose failure may lead to catastrophic consequences.

The starting point for any dam safety practice is the availability of a dam safety regulatory framework that clearly

- Stipulate the responsibilities of all parties involved in dam safety especially the responsibility of the dam owner,
- Identify the regulatory authority responsible for dam safety and
- Stipulate the power and responsibilities of the regulatory authority especially the power to identify and develop standards, guideline, norms etc; conduct inspection; monitor inspections ; enforce the dam safety regulation; the responsibility to register dams, inform the public, advise dam owners etc
- Identify the authority responsible for handling any emergency

Charlwood etal, 2004a carried out dam safety regulatory assessment for Easter Nile, and in the following a brief summary of their findings is given.

Egypt

According to Chralwood et al, 2014a, Egypt has several laws that address the pressing water management issues in the country such as irrigation and drainage, water quality management, electricity and energy. After the completion of the High Aswan Dam, the country has also drafted a series of water policies starting from the Water Policy of 1975 (Egypt: 1975).

Charlwood et al, 2014a noted that dam safety has not been explicitly addressed in the above mentioned legislations as well as in the policy documents. However, some elements of safety for the water structures (e.g. dams, barrages) have been considered in the Egyptian Code for Water Resources and Irrigation Works (Egypt: 2003).

The Egyptian Code for Water Resources and Irrigation Works which, was published in 2003, consists of seven volumes. While Volume No. 7 focuses on the design and maintenance of the coastal protection structures while Volume No. 3 focuses on major water structures. Volume No. 3 covers the following:

- Lined irrigation networks;
- Water crossing structures including culverts, siphons and aqueducts;
- Escapes and outlets for canals and dams including dam spillways such as over fall spillways, chute spillways, side-channel spillways and shaft spillways syphon spillways. It also deals with stilling basins;
- Weirs including e.g. sharp crested weirs, solid narrow crested weirs, solid broad crested weirs, ogee crested weirs, free flow weirs, submerged or drowned weirs. It also deals with failure due to sliding and overturning;
- Barrages. It deals with detailed design requirements for each element in the barrages, including the various types of gates;
- Dams. It deals with earthfill, rockfill, gravity and arch dams. It provides design guidelines and indicated in general the possible failure modes for earthfill and rockfill dams and addresses the settlement of rockfill dams;
- Locks. It contains detailed design and construction guidelines; and
- Hydraulic power plants. It includes fore bays, intakes, penstocks, hydraulic turbines, draft tubes, tail water pond, etc.

The Egyptian Code for Water Resources and Irrigation Works in all the above-mentioned water structures focuses mainly on two stages:-

- Design stage in which it provides guidelines on the design criteria that should be considered; and
- Construction stage in which it provides guidelines on the matters to be considered during the construction.

However, there are no guidelines on the operation and maintenance stages.

Ethiopia

At the present there is no clear dam safety regulation to be followed in design, construction and operation of dams. There is, however, one policy and two legal documents that deal with water resources management in Ethiopia:

- Ethiopian Water Resources Management Policy, 1999, prepared by Ministry of Water Resources,
- Ethiopian Water Resources Management Proclamation, Proclamation 197/2000, passed by the House of Representative,
- Ethiopian Water Resources Management Regulation, Regulation 115/2005, passed by the Council of Ministers.

The first two documents contain articles that deal with the entity that is responsible for safety of hydraulic structures including dams, and the power and duties of the entity.

In 1999, the Ministry of Water Resources issued the Ethiopian Water Resources management Policy (Ethiopia: 1999) with the general objective of enhancing and promoting all national efforts towards efficient, equitable, and optimum utilization of the available water resources of the country for significant socio-economic development on sustainable basis which is based on the principle of Integrated Water Resources Management (IWRM). The same policy is later on (2001) named as the Ethiopian Water Sector Policy (Ethiopia: 2001) while its contents remain essentially the same.

The three main categories of the policy are:

- General water resources management policy;
- Policy on cross-cutting issues; and
- Policy on sectoral issues.

As part of the cross-cutting policy issues the Ethiopian Water Sector Policy has provisions in relation to dam safety and management of trans-boundary waters. These include:

- Section 2.2.3 Technology and Engineering – (G) Dams and Reservoirs Management and Operation, Point (4):
    - "Provide guidelines concerning dams and reservoirs operations and safety procedures as well as promote community participation in the development and management of such schemes."

- Section 2.2.7 Disaster, Emergency and Public Safety, Point (3):
    - "Ensure and promote the safety of water retaining, transmission and diversion structures like weirs, barrages, dams, reservoirs and pipelines, against natural and man-made disasters for the:

        - Protection and conservation of the available water, the structures and all systems and equipment.
        - Protection of the environment, human settlements, flora, fauna, socioeconomic infrastructure."

- Section 2.2.7 Disaster, Emergency and Public Safety, Point (5):
    - "Establish preparedness and contingency plans for disasters and emergencies, in terms of:
        - Provision and continuation of services during and after emergency,
        - Plans for rehabilitation and repair of water systems,"

- Section 2.2.8 Trans-boundary Waters, Point (6):
    - "Comply with those international covenants adopted by Ethiopia, and manage trans-boundary waters accordingly.

However, the section does not directly indicate the need for safety of structures on trans-boundary rivers."

In 2000, the Parliament (House of People Representative) has passed legislative frameworks to define the water resources management issues of the country. Proclamation No. 197/2000 (Ethiopian Water Resources Management Proclamation) (Ethiopia: 2000a) vested power to the supervising body (in this case at that stage the Ministry of Water and Energy – nowadays the Ministry of Water, Irrigation and Energy) to assure the safety of hydraulic structures as indicated in the article below:

- Part II, Supervising Body, Powers and Duties of the Supervising Body, Point (1g):
    - "The supervising body shall have the powers and duties to issue directives pertaining to the safety of hydraulic structures for the prevention of damages caused by dam water to dams, persons, property and crops."

In 2005, the Council of Ministers has passed the Ethiopian Water Resources Management Regulation, Regulation No. 115/200 as a regulation for the implementation of the provisions of Proclamation No. 197/2000. However, the regulation does not include any provisions for dam safety.

The federal Environmental Protection Authority (EPA) issued the *Environmental Policy of Ethiopia* in 1997 (Ethiopia: 1997) and the policy has provisions in relation to dams, including:

- Section 3.4 Water Resources
    - Point "a" of the section states one of the policy objectives as:
        - "To ensure that the control of environmental health hazards be a necessary condition in the design, construction and use of dams …"

Further, the *Environmental Impact Assessment Guideline Document* published in 2000 by the EPA (Ethiopia: 2000b) dedicated a separate section (Section 5.5) for dams and reservoirs. However, the guideline document doesn't include dam safety and downstream risk as one of the issues to be focused on.

Sudan

As in the case of the other EN countries, there is no clear dam safety regulation in Sudan. There are, however, many laws and regulation that deal with the use and protection of the water resources system (see Charlwood etal 2014a). The issues that are dealt in these legislations include river transport, fisheries, public health, environmental health, inland river navigation, irrigation and drainage, and water development and utilization.

The main legislations currently in use are the "Water Resources Act of 1995" and the "Irrigation and Drainage Act of 1990". The Water Resources Act of 1995 mainly focuses on water allocation and efficient utilizations of the water resources of the country. The Act has provisions for dispute resolution, canal maintenance for seepage control, crop rotation & optimization of crop water application, and water use fees. The other legislation regulates irrigation and drainage.

The other important policy document is the "Sudan National Water Policy & Strategies" which was endorsed by the government in 1992. The water policy mainly focuses on management and sustainable development of the country's water resources. In 2000, an updated policy document "The National Water Policy Draft of 2000" was produced. The document included the lessons learned from the 1992 water policy. The policy document addressed an aspect of dam issue in one of its section: the "Disaster Management & Public Safety" section where it is stated

- A national "Disaster Management Plan" will be developed to enable both avoidance of disasters and effective response to disasters (which include floods and droughts which threaten the public safety and major structures such as dams and reservoirs).
- International cooperation is critical for proper and adequate response to natural and other disasters. The Sudan will seek to participate in and contribute to international efforts.
- In order to ensure adequate public protection, regulatory and administrative instruments which balance the cost of safety measures with an acceptable level of risk to public safety will be developed and implemented at national and federal level as appropriate.

According to Charlwood etal (2014), the above mentioned disaster management and public safety matters are not yet in place and not formulated in a separate legislation addressing public safety in connection to dam safety. The dam safety is addressed only in the context of securing the structure itself and facilities contained therein. The dam operators therefore struggle to maintain the functionality of the dam and they are mandatorily obliged to report to the undersecretary of the MWRE about the day to day activities in relation to gate maintenance and water releases.

South Sudan

South Sudan does not have any dam safety legislation. As a new country that comes out of long civil war, the country does not have large dams as well . However, after the Comprehensive Peace Agreement (2005), it is embarking on major dam projects. Several studies were done to establish the feasibility of generating hydropower from sites on Bahr el-Jebel, and multipurpose use on Bahr el-Ghazal and the Sobat.

Dam Safety in Dam Projects Planning, Designing & Construction

Dam Project Development Cycle

As in any other civil engineering projects, planning and implementation of dam projects follow the standard project cycle which essentially consists of four main project development phases; namely, *project planning phase, project implementation phase, project operation & maintenance phase, and project decommissioning phase (Refer figure 2-4).* The project planning phase is divided into three main study stages. These are the reconnaissance study stage, the feasibility study stage, and detail study stage. The project implementation phase consists of review and modification of the detail design, construction management and contract administration, procurement of services, construction, and commissioning.

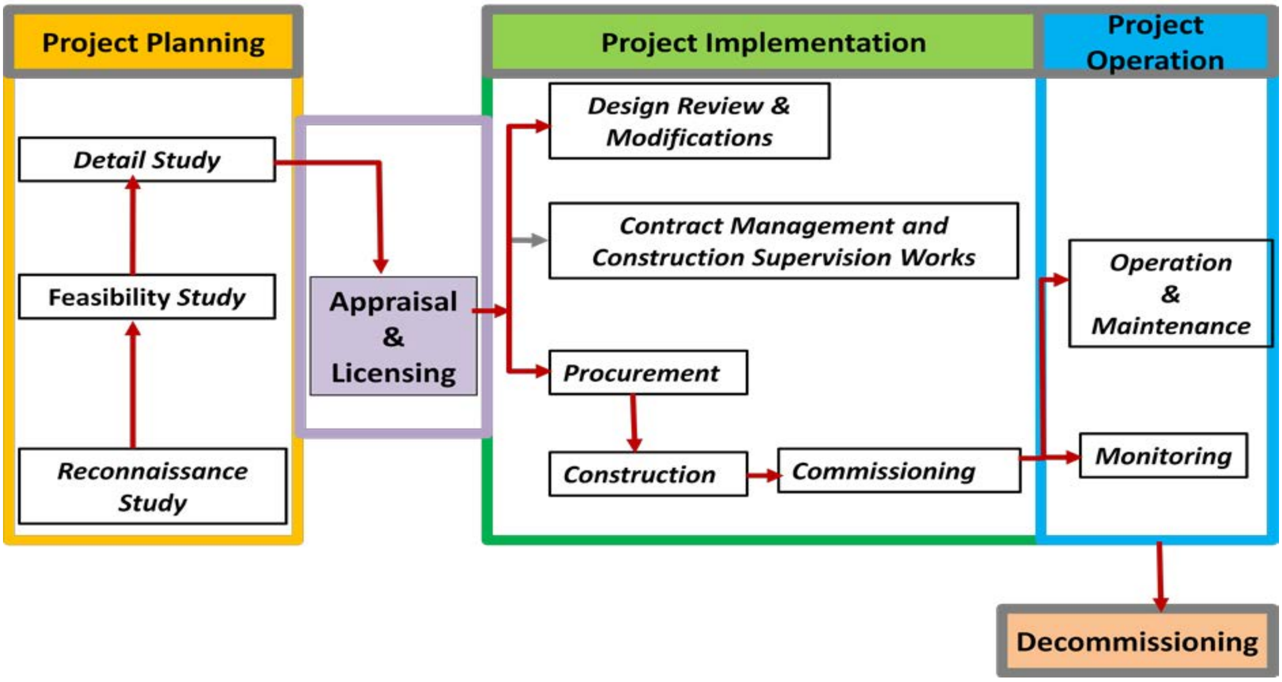

Figure 2-3: Dam Project Development Cycle

Dam projects vary in their sizes and complexity. Consequently, the time horizon for the project preparation phase may range from few months in case of small dams to several years in cases of water resources development studies at basin and trans-boundary levels. Similarly the time horizon for the implementation phase may run from few years to several. The time horizon for the operation and maintenance phase depends on the service life of the project and typically is in order of 50 to 100 years for many dam

PROJECT PLANNING PHASE

RECONNAISSANCE STUDY STAGE

It is the first stage of the project planning phase and it is preliminary in nature and general in its scope. According to Charlwood etal, 2014b, the main dam safety issues at the reconnaissance stage include:

- Assignment of an Approved Dam Engineer or an Approved Dam Engineer supported by a Team of Specialist: An Approved Dam Engineer or an Approved Dam Engineer supported by a Team of Specialist (for high consequence dam) with appropriate experience should be assigned to participate in all stages and phases of the project,
- Development of a Management Plan: A management plan should be prepared by the Approved Dam Engineer. The management plan is the blue print for conducting the feasibility stage. The plan should include sufficient detail to
    - define the design criteria to be used for all major components of the project,
    - estimate the engineering effort and its associated costs required for the feasibility stage including the initial preparation of the quality control plan portion of the Management Plan
    - identify necessary tests and model studies, and
    - prepare a preliminary cost estimate.
- Documentation: At this stage the documentation requirements should be identified, scheduled, and resourced in coordination between the Approved Dam Engineer and the Dam Safety Officer / Regulatory Body. Those documents generally include all Design Documentation Reports, manuals, plans, and reports, including the Emergency Action Plan (EAP), River Diversion (during construction), Initial Reservoir Filling Plan, Embankment Surveillance Plan, Instrumentation Plan, O&M (or OMRR&R) Plan, Turnover Plan, Water Control Plan (operational), Reservoir Control Report, and post-construction documentation of foundation, materials, and construction.
- Independent Technical Review: An independent technical review which concentrate on evaluation of the overall project plans, on the initial cost estimates and on the Management Plan should preferably held. Because the plans are largely based on experience and on extrapolation of limited data, it is essential that expert technical reviewers verify that the plan represents a reasonable solution.

FEASIBILITY STUDY STAGE

It is the second stage of the project planning phase. According to Charlwood etal, 2014b the main am Safety Items at Feasibility Stage include:

- Identification of Dam Safety Requirements: Dam safety requirements and project O & M requirements should be identified and discussed with the owner. The owner should be informed that he should be expected to comply with all dam safety requirements of the regulatory body,
- Consequence and Failure Mode Analysis and Preventative Measures. Consequences are defined as potential life loss, economic damages, and environmental damages. At the minimum estimate the consequences related to failure of the dam from a breach of the dam with the reservoir at the maximum pool – no spillway discharge, maximum pool with full spillway discharge, and overtopping of the dam. 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. Address the general potential failure modes related to dams and present the how the design for this dam prevents these failure modes from occurring.
- Downstream Lands. Land is required in downstream areas where a spillway discharge would create or significantly increase a potentially hazardous condition,
- Bottom Outlets. To respond to unanticipated such as repair or major rehabilitation of the dam, a low level outlet or bottom outlet should be provided to lower the reservoir level to a safe level within a reasonable time.

DETAIL STUDY STAGE

It is the last stage of the project planning phase and the main dam safety items during detail design stage include (Charlwood etal, 2014b):

- At this stage, the dam safety regulatory body has a regulatory role to ensure major detail design requirements (such as safety against piping, stability, flood capacity) are adequately met. The regulatory body should ensure that the design criteria include the most current dam safety requirements and that the design is properly documented for the project records,
- Design Methods & Criteria. The design methods and criteria to be used should be defined and documented. 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
- Documentation: 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 potential consequence classification of the dam,
- Construction personnel: The Approved Dam Engineer should involve construction personnel in the design phase of a project to assure the development of a technical product of the highest quality. This is particularly true on a dam safety project because of the uniqueness of the technical requirements. Experiences offered from a construction perspective regarding things such as the structuring of bid items, phasing, proper construction techniques, buildability, biddability, etc… are invaluable in assuring the project meets technical requirements while at the same time limiting contractual risk,

- Public Safety Awareness. A policy of public safety awareness shall be adhered to in all phases of design and operation of dam to ensure adequate protection for the general public,
- Downstream Land: Land is required in downstream areas where a spillway discharge would create or significantly increase a potentially hazardous condition,
- Bottom Outlets. To respond to unanticipated such as repair or major rehabilitation of the dam, a low level outlet or bottom outlet should be provided to lower the reservoir level to a safe level within a reasonable time,
- Instrumentation and Monitoring. An adequate instrumentation and monitoring system should be established following good engineering practice. The rationale for the instrumentation should be justified and thoroughly documented via the use of potential failure mode analysis. The instrumentation plan shall be prepared and documented in the Design Documentation Report.
- Operations during construction. Safe operation of the dam needs to be considered during the development of the Reservoir Operation Rule. A risk assessment should be used to inform the selection of the construction options and the results should influence the options selected,
- Initial Reservoir Filling Plan. The Initial Reservoir Filling Plan (IFP) should be prepared prior to construction, modified during construction to reflect the as built conditions, and documented in the DDR,
- Surveillance Plan. The Surveillance Plan should be prepared. The plan should address the routine and non-routine surveillance of the dam after the initial reservoir filling,
- O&M Manual. The O&M Manual should be prepared,
- Dam Brach Analysis & Inundation Mapping. Dam breach analysis and inundation mapping should be carried out,
- Emergency Action Plan. The Approved Dam Engineer should prepare the emergency action plan,
- Reservoir Operation Rule. The reservoir operation rule should be prepared at this stage.

PROJECT IMPLEMENTATION PHASE

The project implementation phase essentially consists of

- Review and modification of detail design
- Contract management and construction supervision, and
- Service procurement, construction and commissioning

According to Charlwood etal, 2014b, the main dam safety items during the project implementation phase include:

- Construction Permit: A Dam Safety Construction Permit is required before construction begins,
- Design Personnel: Similar to the importance of having construction personnel involved in the planning and design phases of a project, it is equally vital that the design team remain integrally involved and integrated throughout the entire construction period,
- Site visits and inspection: 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.

- Coordination Meeting: On dam safety construction it is imperative that constructor personnel are aware of design philosophies, intent and assumptions as to the site conditions and functions of project structures. They must also understand the designer's basis for special technical provisions in the specifications in terms of the intended risk reduction objectives of the design. To this end, the Approved Dam Engineer should facilitate a coordination meeting prior to the start of construction to ensure the entire project team fully understands the project scope, design intent, limitations, risks, roles and responsibilities of the staff, and other issues which could have an effect on the project,
- Fields Change to Design: The Approved Dam Engineer should be actively involved in the confirmation of design assumptions during construction. Frequent and mandatory inspections should be scheduled during construction to confirm that site conditions conform to those assumed for design or to determine if design changes may be required to ensure risk reduction objectives will be met. Critical changes in field conditions must be carefully reviewed and forwarded to the Approved Dam Engineer,
- 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,
- Quality Assurance Plan (QAP). The construction team should prepare Quality Assurance Plan (QAP) that is consistent with the scope and complexity of the work. The plan should ensure that the quality of the construction meets the specifications requirements and design intent. This plan should be prepared during the design phase of the project as it is important to help establish the complete project picture. It should be updated as required as the project scope is modified,
- 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,
- 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,
- Commissioning: The Approved Dam Engineer should provide a commissioning schedule for the facilities of each dam outlining to the dam owner the procedures and practices (both operational and surveillance) to be put in place to bring the dam into full operation. In addition, it is desirable that the Approved Dam Engineer provides an addendum to the dam's Emergency Action Plan (EAP) to include matters particular to the first filling of a dam. Commissioning shall be made together with independent dam experts to make sure that all precautions are made prior to hand over.
- Initial Reservoir Filling Plan: Update the IRFL prepared during the design stage. 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.
- Surveillance Plan. Update the Surveillance Plan prepared during the design stage
- O&M Manual. The Approved Dam Engineer should update the O&M Manual prepared during the design stage,
- Emergency Action Plan. The Emergency Action Plan prepared during the design stage should be updated.

- 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.

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MODULE 3

Fundamentals of Dam Safety

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FUNDAMENTALS OF DAM SAFETY

Importance of Dam Safety in EN

Dam safety can be understood as referring to the factors that influence the safe operation of the structure of the dam and the appurtenant structures, and the dam's potential to adversely affect human life, human health, property, and the environment surrounding it. This means that dam safety is concerned with two closely related but different aspects

- the safety of the dam and appurtenant structures; and
- the safety of the population, property & the environment in the vicinity of or downstream from the dam

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 Situational Assessment Report for Dam Safety Management in the Eastern Nile Sub-Basin published by ENTRO in 2014. (ENTRO, 2014)

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 of the ENTRO Reference Dam Safety Guidelines. 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.

Typically the critical risk for most scenarios is controlled by a predominant contributing factor (see Table 3-1).

Table 3-1: 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	Mis- operation, sedimentation.

Appendix E of the ENTRO Reference Dam Safety Guidelines provides an illustrative set of dam failures or incidents associated with 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.

International Practice

Dams provide enormous benefits to society. However, the vital services that they provide can also be accompanied by serious hazards. During the 1950's and 1960's there was growing international concern about the safety of dams. This concern was based on:

- Originally dams were built in remote areas far removed from population centers. This, however, has changed in recent years. As more and more people move in to vulnerable areas downstream of dams, concern about potential failure of dams becomes increasingly important.
- Some disastrous dam failures that have occurred in recent past lead to mounting concern about dam safety. Historically 1% of dams constructed have failed. These failures have resulted from a variety of causes including unpredictability of extreme floods, uncertainties of geologic setting, seepage through foundations and embankments, design and construction defects, and liquefaction under earthquake conditions.
- Many of the large dams were aging; some have passed their middle ages (over 50 years old). Weathering of foundations and construction materials, leakage and frost effects on concrete etc may all cause deterioration of the dam structure. New knowledge on hydrological conditions may render the existing spillway capacity inadequate to pass the PMF.
- Dam construction was occurring at a rapid rate. An ever increasing number of dams were being built in countries with little or no dam engineering experience. More and more dams are also built in sites less favorable for dam construction.
- Advances in science and technology allowed dams of ever increasing height and reservoir volume to be built.

These public concerns are echoed also by international organizations such as ICOLD, World Bank. In its Bulletin 59, ICOLD observed
"Debates have been going on recently in many countries about safety in technical developments and construction methods in general, which has lead to greater public awareness. The reason for this are, first, the increase in construction of structures which would cause great damage in case of failure; and second, accidents or disasters caused by failure of such structures. As a result, it has become urgent that dam safety worldwide be given the greatest possible concern, profound common understanding, and as precise a definition as possible"

These concerns prompted many countries to enact or strengthen dam safety legislations. Mention could be made of the National Dam Inspection Act (1972) in USA, the Reservoir Act (1978) in Britain, the Dam Safety Act (1978) in Australia. The public concerns also prompted professional associations, and national and international organizations to establish dam safety committees that address dam safety issues. In the following the contribution of two international organizations, ICOLD & the World Bank is reviewed.

The International Commission on Large Dams (ICOLD) is a non-governmental International Organization which provides a forum for the exchange of knowledge and experience in dam engineering. It was founded in 1928 and has National Committees from more than 90 countries with approximately 10 000 individual members. Presently, ICOLD has 21 Technical Committees that address current technical issues related to the development and management of water resources.

In 1982, ICOLD established a Committee on Dam Safety (CoDS). The Committee was entrusted with the task of defining common dam safety philosophy and principles, and developing dam safety guidelines.

After five years of work, CoDS published Bulletin 59: Dam Safety Guideline: (ICOLD, 1987), which is an excellent general reference on dam safety operations throughout the life cycle of a dam. In describing the intended purpose of the bulletin, it stated that
"The "Dam Safety Guidelines" together with the appended "Checklist on Dam Safety" are intended to offer a 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. These guides also recommend the measures, procedures, and strategies to achieve the highest, economically reasonable level of dam safety."
It further noted
"The guidelines are mainly intended to stimulate and facilitate the development of national dam safety regulations. They may be used as a model to be shaped and complemented by the specific legal, socio-economic and technological requirements of each country, taking into account its particular natural, operational, and institutional conditions and the individual character each country wants to give to its dam safety regulation."

In describing the prevailing philosophy for dam safety, Bulletin 59 stated that
"the safety of a dam manifests itself in being free of any conditions and developments that could lead to its deterioration or destruction. The margins which separate the actual condition of a dam, or the conditions it is designed for, from those leading to its damage or destruction is a measure of its safety. To be safe, therefore, a dam has to be supplied with appropriate reserves, taking in to account all reasonably imaginable scenarios of normal utilization and exceptional hazard which it may have to withstand during its life " (ICOLD Bulletin 59).

Bulletin 59 clearly recognized that the safety of dams depends on more than engineered factors, and that human error, negligence, lack of knowledge at the various stages of a dam life cycle contribute to the failure of dams. It also underlined that past incidence of unacceptable performance or damage or impairment of serviceability or outright failures are extremely valuable in dealing with safety problems during design, operation, maintenance, and surveillance of dams.

Bulletin 59 noted that failure of a dam is a complex process which normally begins with some abnormality in behavior which is not detected. Consequent deterioration, often not observed, then leads to further damage or disaster. Thus, inspection and monitoring of dams, and rapid data analysis and interpretation play a crucial role in dam safety.

Bulletin 59 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

Since the publication of Bulletin 59, the understanding of the causes of failures of complex engineered systems, such as dams, has advanced considerably. Societal demands for transparency and accountability in dam safety has also grown steadily. Significance progress has been made in the development and application of risk informed and risk based methods in the fields of safety assessment. Accordingly, the underlying dam safety philosophy and principles has seen a gradual paradigm shift. This shift has been captured in Bulletin 130: "Risk Assessment in Dam Safety Management: A Reconnaissance of Benefits, Methods and Current Applications" (ICOLD: 2005). Bulletin 130 noted that *For various historical and some technical reason, the safety of dams has been controlled by an engineering standards-based approach, which has developed over the many years, initially for the design of new dams, but increasingly applied over the past few decades to assess the safety of existing dams. Some are now asking whether the techniques of risk assessment, developed for other industries, could be adapted as an additional tool to assist in decision making for dam safety management.*

In describing what the new approach, i.e risk assessment, will add to the traditional approach, i.e., the standards based approach, bulletin 130 stated that *Risk assessment is presented in this bulletin as an enhancement to traditional practice and not in any sense as a replacement. Engineering design could essentially be seen as a process of making complicated decisions using all available data. Because the data are always limited by time, budget or physical constraints, these decisions have to be made under uncertainty. Dealing with uncertainty is such an intrinsic part of their work that many managers and designers do not give this conscious consideration. Some overlook the fact that the main part of their work is risk management.*

In the traditional approach, uncertainty is tackled by taking extreme values for the loads, conservatively safe values for resistance variables and applying safety coefficients. Alternatively, recognized defensive design measures are incorporated in dam designs. Most of this is embodied in established practice. The more subtle aspects of this approach are based on intuition, and are often referred to as "engineering judgment".

In the first place, there is the question of whether the dam will serve to generate sufficient power or will conserve the necessary amount of water. This is the dam's main function. By being present however, the body of stored water additionally poses a threat in case of failure. In both respects, the designer has to take decisions under uncertainty, partly by weighing intuitively the issues at hand and partly by taking conservative values (based on empirical knowledge) for certain variables, relying on previous work by the designer or others.

This approach has served well, as the international dam safety record shows. However, complacency should be avoided. Examples abound of new issues and new problems, where the experience of previous work does not provide an adequate guide, or where the applicability of safety margins rooted in experience may be unproven or uneconomic.

Traditional methods focus on safety and have resulted in a history of dam designs that have a great record of performance. Risk assessment methods focus on relating performance levels to consequences and thus allow an engineer to better demonstrate to decision-makers the real human and economic risks associated with investment decisions.

When use is made of probabilistic methods, the uncertainties are explicitly taken into account by expressing them as probability distributions. This approach is a way of dealing with inherent or natural uncertainty, which can be statistically analysed, as well as uncertainty due to lack of information or knowledge, where the basis for estimation of probabilities is sometimes limited to expert opinion.

The uncertainties are propagated through the system to get a quantitative estimate of the probability of failure and the likelihood of associated unwanted consequences (be it lack of water or power or a dam-break flood).

The application of probabilistic methods in risk analysis also provides an improved understanding of the unique way in which different types of structural and non-structural measures can reduce dam failure risks, thereby giving greater confidence in the effectiveness of a wider choice of risk reduction measures. Non- structural measures (see ICOLD 2001), which in the traditional approach were felt to enhance safety, but often with concerns for their reliability, can now be demonstrated, by formal analysis of likelihood, consequences and uncertainties, to have a role in reducing risk, which is distinct from that offered by structural measures.

Examples of improved opportunities for estimating the effectiveness of risk reduction are:

- *Improving the forecasting of rainfall in the catchment, will increase the likelihood that spillway gates can be operated to safely pass the flood;*

- *Monitoring will improve dam safety, if appropriate preventative action is planned and taken when observations show that there is a condition with the potential for failure. Failure will now not occur when a failure mechanism develops, AND this is observed, AND there is sufficient time for intervention that will arrest the mechanism and prevent failure occurring (see the logic diagram Fig. 2.1);*

- *The fact that a dam has already functioned safely for many years can be used scientifically in the re-evaluation of the dam's safety. It can be proven, as well as statistically shown, that most incidents and failures occur during the first reservoir filling or shortly thereafter;*

- *Reliable operation of spillway gates is often critical for dam safety. Methods to better analyse the reliability of the hardware, software and liveware aspects of spillway gate systems are now available, thereby providing greater confidence in the effectiveness of these often complex systems than can be gained from engineering judgement alone;*

- *Proper organization, staff training, reliable operating systems and adequate automation will contribute to safety by reducing the probability of human error. These dam safety management aspects must be designed, and their effectiveness maintained, with the same level of reliability in mind as for the structure itself;*

- *Planning of the inhabited areas in the downstream valley could be part of an integrated approach to managing the safety of the dam as soon as the (remote) probability of dam failure is recognised. On the other hand, in most societies, a safer dam is required if a more numerous population or a large invested value is situated downstream. Many dams have seen dramatic changes to downstream demographics, which have led to operational constraints. These changes have been caused by increases in downstream development, environmental and or water usage concerns and have resulted in reduction in the levels of protection provided at many projects, and have caused increased safety concerns;*

- *The planned warning and evacuation of downstream populations, if monitoring indicates possible failure, enhances safety (see the RESCDAM project - Finnish Environment Institute, 2001).*

In 2011, CoDS published another important document on dam safety: "Bulletin 154: Dam Safety Management: Operational Phase of the Dam Life Cycle" (ICOLD: 2011a). 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 outline is built on the principles established in Bulletins 59 (ICOLD: 1987) and 130 (ICOLD: 2005), as well as the general philosophy that informs them both.

In that respect this Bulletin is not intended to update or replace the Bulletin 59 which although written in 1987 (ICOLD: 1987) is still valid and should remain as a primary source of guidance for those professionals who are applying traditional approach to dam safety.

Bulletin 154 (ICOLD: 2012) includes the following important comments with respect to the decision-making processes involved in managing the safety of existing dams:
"Depending on the various decision-making problems which may occur during a dam's operation, the nature of this process can vary substantially. On the one hand, these decisions can be made using the approach of simply comparing the outcomes of deterministic analyzes and observed values with standards and safety requirements. On the other hand, if the risk-informed approach is to be used, then the analytic part becomes much more complex, but the resulting comparison of assessed risks provides a more complete picture of the safety status, and ensures full transparency of the decision-making process by comparing the assessed risk with the tolerable risk criteria. This Bulletin is in a way neutral with respect to which type of decision-making approach should be selected. The safety management system presented in the Bulletin allows for the use of either of the two approaches."
Bulletin 154 (ICOLD: 2012) includes a recommended set of overarching principles for dam safety management. These start with a definition of the Fundamental Dam Safety Objective:

The fundamental dam safety objective is to protect people, property and the environment from harmful effects of miss-operation or failure of dams and reservoirs.

Retaining the stored volume of water and controlling all flows through and around the dam within specified limits determined through the approvals and licensing process established by government achieve this objective. "Miss-operation" involves any departure from the design norms for safe operation of any part of the dam or its safety critical systems. The objective of protecting people, property, and the environment from the effects of dam failure has to be achieved without unduly limiting the benefits created by operation of dams and reservoirs.

To achieve the highest standards of safety that can reasonably be achieved, measures must be taken to:

Control the release of damaging discharges downstream of the dam through controls embedded in the normal operating regime of the dam;
Restrict the likelihood of events that might lead to a loss of control over the stored volume and the spillway and other discharges;
Mitigate through on-site accident management and/or emergency planning the consequences of such events if they were to occur.

The fundamental safety objective applies to all dams and dam operational activities and to all stages over the lifetime of a dam, including planning, design, construction, commissioning, operation, and either the long term sustainability of the dam or decommissioning of the dam.

The principles presented in Bulletin 154 (ICOLD: 2012) and reproduced below in the following sections then provide an overarching management framework to support achievement of the fundamental dam safety objective.

"Responsibility for Operational Integrity and Safety

The Dam Owner is ultimately responsible for assuring the safety of the public, property and environment around and downstream of dams. However, since dams are often not owned and operated by a single individual, company or organization, the term Responsible Entity is used in this Bulletin. Usually the dam owner is the Responsible Entity. Sometimes a government institution or agency is responsible for the safety of the dam and the public, either directly or through oversight over the safety management activities of the bodies that operate the dam.

The safety arrangements established by the Responsible Entity must conform to the requirements and expectations of government and the prevailing laws, regardless of how they are established and implemented. Therefore, the Responsible Entity's values and principles that govern safety management reside within the overarching legislative and regulatory value system of the country where the dam is located. In some instances for dams, the Responsible Entity may be a branch of government with significant internal dam engineering and safety management capability, and which is responsible for all aspects of the operational integrity and safety management of the dam over its entire life-cycle. Conversely, the Responsible Entity may have no engineering capability and, in the absence of prescriptive regulatory requirements, it will be the legislative and judicial arms of government where the safety of dams is implied by existing legislation and precedents, with all responsibility for meeting the intent of the law resting with the Responsible Entity.

In order for the Responsible Entity to be confident that it is meeting all obligations in relation to the safety of its dams, a systematic approach to dam safety management activities is needed. This means that the Responsible Entity is responsible, at a minimum, for:

Establishing and maintaining the necessary competencies;
Providing adequate training and information;
Establishing procedures and arrangements to maintain safety under all conditions;
Verifying appropriate design and the adequate quality of facilities and activities and of their associated equipment;
Ensuring the safe control of all inflows, outflows and stored volumes;
Ensuring the safe control of all sediments and deleterious materials that arise as a result of the dam.

Dam safety management covers the full spectrum of hazardous conditions, including dam failure, which can arise from the activities of storing and discharging water. Since dam management can span many human generations, consideration should be given to the fulfillment of the responsibilities of the Responsible Entity and the regulator in relation to both present and future operation. Provision should be made for the continuity of responsibilities and the fulfillment of funding requirements in the long term.

These responsibilities should be fulfilled in accordance with applicable safety objectives and requirements, as established or approved by the regulatory body, and their fulfillment is to be ensured through the implementation of a management system.

Role of Government

The legal and governmental framework for all industrial activities, including operation of dams, provides the overarching structures for operational integrity and safety assurance.

The role of the Government includes defending the general interest of the population and, in order to do so, it writes laws and regulations specific to protection of people, property and the environment. For activities that are hazardous, laws and regulations are often enacted to protect third parties against the harmful effects of mis-operation or failure of the specific activity.

In some cases within the general legal framework, specific laws and regulations may be established to protect against the mis-operation or failure of dams and reservoirs. The legal and governmental framework provides for the governance of dams, reservoirs and operational activities that give rise to dam breach and other inundation risks. The framework typically includes the clear assignment of Responsibility for Operational Integrity and Safety (see Section 2.2). The government is responsible for the adoption of such legislation, regulations, and other standards and measures, within its national legal system, as may be necessary to effectively fulfill all its national responsibilities and any international obligations. In terms of the modern view of safety governance this includes establishment of an independent regulatory body to assure the safety of dams.

Government authorities should ensure that arrangements are made for reduction of risks from dams, including emergency actions, monitoring of high discharges to the environment, and disposing of reservoir silt waste. This does not require that the governments establish and maintain all arrangements, although they may choose to do so. In addition, government authorities have to address the safety of dams for which no other organization has responsibility.

The government body with responsibility for dams should:

Have adequate legal authority, technical and managerial competence, and human and financial resources to fulfill its responsibilities;
Be effectively independent of the Responsible Entity and of any other body, so that it is free from any undue pressure from interested parties;

Set up appropriate means of informing parties in the vicinity, the public and other interested parties, and information media, about the safety aspects (including health and environmental aspects) of dams and reservoirs and operational activities, and about regulatory processes;
Consult parties in the vicinity, the public and other interested parties, as appropriate, in an open and inclusive process.

Bulletin 154 (ICOLD: 2011a) clearly establishes that governments and regulatory bodies have an important responsibility in establishing standards and establishing the regulatory framework for protecting people, property and the environment against dam safety risks.

In addition Bulletin 154 (ICOLD: 2011a) highlights the role of leadership and management.

Leadership and Management for Safety

In general, leadership in safety matters should be demonstrated at the highest levels in all organizations. Dam safety is no different. Safety has to be achieved and maintained by means of an effective management system. This system should integrate all elements of management so that requirements for safety are established and applied coherently with other requirements, including those for human performance, quality and security, and so that safety is not compromised by other requirements or demands. The management system also has to ensure the promotion of a safety culture, the regular assessment of safety performance, and the application of lessons learned from experience.

A safety culture that governs the attitudes and behaviour in relation to safety of all organizations and individuals concerned should be integrated in the management system. Safety culture includes:

Individual and collective commitment to safety on the part of the leadership, the management and personnel at all levels;
Accountability of organizations and of individuals at all levels for safety;
Measures to encourage a questioning and learning attitude and to discourage complacency with regard to safety.

An important factor in a management system is recognition of the entire range of interactions of individuals at all levels, with technology and with organizations. To prevent human and organizational failures, human factors must be taken into account, and good performance and good practices supported. Despite all measures that are taken, accidents may occur. Processes should be put in place for the feedback and analysis of operating experience, including initiating events, accident precursors, near misses, accidents and unauthorized acts, so that lessons may be learned, shared and acted upon."

In addition to Bulletins on general principles of dam safety management, ICOLD has also published many bulletins on specific issues including the following.

In 2012 ICOLD published Bulletin 142, Safe Passage of Extreme Floods, (ICOLD: 2012) which addresses two key issues, design floods and effects of climate change.

With regard to selection of the design flood Bulletin 142 (ICOLD: 2012) states:

"Current practice in the design of dams is to first select the design flood, which is deemed appropriate for the hazard potential for the dam and reservoir and to determine its peak flow rate and/or its entire hydrograph. Then, spillways and outlet works can be designed, or an adequate storage can be allocated in the reservoir, which could safely accommodate the flood without putting the dam and its appurtenant structures at risk and causing loss of life and property damages in areas downstream of the dam.

A survey of existing projects shows that in many modern projects the spillway (or spillways) is designed for a peak flow value based on criteria which usually consider the spillway design flood proper as well as a check flood which is taken as the maximum flood that will not cause the destruction of the dam. This approach is also the standard criterion in most countries where there is an official recommendation for the design of dams.

The selection of the design flood, which is based on guidelines established by the responsible government agency, the project sponsors and/or the project financing institutions, varies widely from country to country, according to the type of dam and the consequences of dam failure, etc.

This process is fully addressed in ICOLD Bulletin 82, *"Selection of Design Flood" published in 1992. Intrinsic to the selection process are the methods used to determine the design flood. Again, the used procedures vary greatly among the practitioners, from probabilistic approaches based on previously observed or inferred flood events to the use of precipitation-runoff models based on basin design precipitation events and assumed basin conditions corresponding to the design flood. One of the current practices is now to use the safety check floods to assess the real safety of the dam."*

In addition Bulletin 142 (ICOLD: 2012a) comments on the confidence limits of estimates and the evolution of design criteria for floods as follows:

"Reviewing the evolution of criteria and methods employed by the profession to compute the capacity of spillway facilities in dams, it is apparent that there have been great changes in the design methods and criteria. Experiences in practical applications of the dam regulations clearly indicate the desirability of a dam classification, especially for the large number of small dams, where failures can have consequences ranging from trivial to catastrophic. Design methods and criteria (ICOLD, 1987) should be in conformity with the current state of technological evolution and be compatible with the codes and standards to be used."

With regard to the impacts of climate change Bulletin 142 (ICOLD: 2012) states:

"Following IPPC 4th (IPCC Fourth Assessment Report: Climate Change 2007), climate change is expected to exacerbate current stresses on water resources. Changes in precipitation and temperature lead to changes in runoff and water availability. Runoff is projected with high confidence to increase by 10 to 40% by mid-century at higher latitudes and in some wet

tropical areas, including populous areas in East and South-East Asia, and decrease by 10 to 30% over some dry regions at mid-latitudes and dry tropics, due to decreases in rainfall and higher rates of evapotranspiration."

In 2012 ICOLD published "Bulletin 158: Dam Surveillance Guide" (ICOLD: 2012b) which addresses the key area of visual inspections and provides guidelines for the optimal organization of all components required for dam surveillance and monitoring.

Regulation of Dam Safety

The World Bank has been involved in financing dams and ancillary facilities since the 1960s, though the rate of involvement slowed sharply in the mid-l980s, with the focus shifting towards ancillary facilities. In recent years, there has been greater emphasis on promoting dam rehabilitation and safety. Thus, the Bank has a stake in dam safety.

In 1977, the Bank issued its first formal policy on "Safety of Dams"' that underscored the importance of dam safety arising from inadequate design or natural phenomena. The policy has been revised in 2001 and 2013.

In 2002, the Bank published a study entitled "Regulatory Frameworks for Dam Safety" (World Bank: 2002). The study is a comparative assessment of the regulatory frameworks applicable to dam safety in 22 countries, and aims to provide policymakers and technical experts, as well as civil society organizations, with a "tool kit" of the issues related to the regulatory framework for dam safety.

The study has three parts. The first part describes the dam safety regulatory framework in each of the 22 countries. The countries were chosen on the basis of availability of regulatory framework. The second part is a comparative analysis of the regulatory frameworks of the 22 countries. In this part, the main similarities and differences in the approaches adopted by the countries were analyzed. The third part is recommendations on what a regulatory framework for dam safety should contain. The recommendation is divided in to two:

- *Essential elements, i..e., elements that should be included in all dam safety regulatory frameworks, and*
- *Desirable elements, i.e., elements that would be desirable to include in such regulatory frameworks.*

In the recommendation part, a number of emerging trends in dam safety are identified and discussed. In this connection, this part of the study can be seen as providing a tool kit that can be used in formulating a regulatory framework for dam safety.

According to the study, there are three issues that the drafters of any dam safety regulatory scheme must consider in designing their regulatory scheme. These issues are

1. The regulatory scheme must address two closely related but different aspects of dam safety:
    a. the safety of the dam and the appurtenant structures; and

   b. public safety, particularly the safety of the population living in the vicinity of or downstream from the dam.
2. The drafters must decide whether the regulatory scheme should set different safety requirements for different categories of dam owners.
3. The drafters must decide if they want their regulatory scheme to cover all dams or only those that exceed certain size or hazard criteria.

In the following the abridged form the essential and desirable dam safety regulatory scheme recommended by the World Ban document is provided. The complete description and discussion can be found in xxxxx

Essential Elements Of Dam Safety Regulatory Scheme

Four elements constitute the essential elements of any dam safety regulatory scheme:

- The form of the regulation
- The institutional arrangement
- The power of the regulating entity
- The contents of the regulatory scheme

1. The Form of the Regulation

The regulatory framework should be clearly spelled out in publicly available documents. The precise form of the legal instruments used in the regulatory framework will vary depending on the specific characteristics of the legal and administrative traditions in each country. Such variations can be summarized in the following:

- In many cases the regulatory framework will consist of more than one legal instrument.
- The first of these instruments will be a statute or law that is passed by the legislative branch of government. Since changing such an instrument re quires legislative approval, it should be kept relatively simple and should contain only the objectives of and the general principles governing the regulatory framework.
- The details of the regulatory scheme should be contained in legal instruments, such as regulations and decrees etc that are relatively easy to change.

2. The Institutional Arrangements

The institutional arrangements of the regulating entity should address the following:

a. The regulatory authority that is responsible for dam safety should be identified, and its powers and responsibilities should be clearly spelled out in the regulatory framework. Since this is an aspect of the regulatory framework that should not be easily changed, it should be addressed in the primary statute or legislation. The authority must be independent from all those who make decisions about whether to build dams and all those who are involved in the ownership and operation of dams.
b. The regulatory authority must be provided with adequate human and financial resources to perform its functions.

3. The Powers of the Regulating Entity

The powers of the regulatory authority should include:

a. The power to identify and develop norms, standards, and guidelines dealing with dam safety.
b. A voice in decisions to issue permits or grants licenses for the construction and operation of dams.
c. The power to monitor inspections conducted by others and the power to reject the findings of the inspection either because the inspector is not qualified to conduct the inspection or because the report of the inspection is inadequate.
d. The power to conduct its own inspections when it deems it necessary to do so.
e. The power to approve the party selected by the dam owner or operator to conduct the required safety inspections.
f. The responsibility to maintain an inventory/register of all dams in the country that are covered by the regulatory scheme.
g. The responsibility to advise dam owners and other interested parties, such as affected communities and industry, about dam safety issues and developments in the regulatory framework.
h. The responsibility to make periodic and publicly available reports on dam safety issues to both higher authorities in the executive branch of government and the legislature and to advise government on dam safety issues.
i. The power to enforce the dam safety regulatory framework.

4. The Content of the Regulatory Scheme

The regulatory scheme should include the following:

a. Establishment of clear and easily applied criteria for determining which dams are covered by the regulatory scheme. It is not essential that all dams be included in the scheme, but those that are excluded should be easily identified and should be too insignificant to cause harm to anyone other than the owner if they fail.
b. Definition of the scope of the regulatory scheme. It should address dam safety issues at all stages of the dam life cycle. Thus it should ad- dress dam safety considerations that arise during the design, construction, first filling, operation, alteration, and decommissioning stages of the dam's life.
c. Clarification that it is the owner that has the primary responsibility for dam safety and can be held liable for any damage that result from a dam failure.
d. Stipulation of the dam safety standards and specifications with which the owner is expected to comply.
e. Establishment of the qualifications required of the person who does the safety evaluations for the owner.
f. Stipulation of the frequency with which the dam owner/operator should conduct dam safety inspections and reviews.
g. Stipulation that the owner/operator must maintain complete records on the dam at a convenient location.

h. Requirement of all dams to have an operations, maintenance, and supervision manual, and an adequate budget for operation, maintenance, and supervision.
i. Imposition of fees that dam owners/operators must pay to the regulatory authority.
j. Requirement of dams with a significant or higher hazard potential to have an emergency plan that is provided to the regulatory authority and to all other relevant authorities and downstream communities that could be affected by a dam failure. The regulatory authorities should provide dam owners with guidance on the issues to be addressed in the emergency plan.

Desirable Elements of Dam Safety Regulatory Scheme

The elements listed in this section are those elements, in addition to the essential elements described above, that would be desirable to include in the regulatory framework.

These desirable elements are:

1. Institutional Arrangements

a. The dam safety regulatory authority is exclusively devoted to dam safety.
b. Regulatory authorities appoint a dam safety advisory committee. The function of this committee would be to advise the authority on dam safety issues.

2. The Powers of the Regulating Entity

a. The dam safety regulatory authority is empowered, where appropriate, to coordinate dam safety regulation among all the agencies at the local, regional, and national levels that are involved in or affected by the regulation of dam safety.

3. The Powers of the Regulating Entity

a. Stipulation that the regulatory authority may make its own periodic inspections of all dams that have high hazard classifications. These inspections would be in addition to those conducted by the owner/operator of the dam.
b. Stipulation that the regulatory authority be provided with a copy of the dam's technical archives/records and, for the highest hazard category dams, be required to review these records in its periodic inspections of the dam.
c. Stipulation that, as part of a process for obtaining a dam license, prospective dam owners are required to conduct a failure impact assessment. This is an effort to determine the likely impacts of a dam failure on the potentially affected communities, property, and environment. The issuance of the license would be contingent on the regulator's approval of the assessment. Once the dam becomes operational, the dam owner would be required periodically to repeat this impact assessment and submit it for reapproval to the regulatory authority.

4. The Content of the Regulatory Scheme

a. The dam safety regulatory framework should establish a series of benchmarks that can be used to measure dam safety at all dams.
b. The regulatory authority requires the dam owner to conduct periodic safety reviews of all dams.
c. The regulatory authority is required to issue annual reports on the safety of the dams subject to its jurisdiction.
d. The regulatory authority undertakes activities designed to educate the public about dam safety.

Implementation Plan for EN

The implementation of a comprehensive dam safety program will be a multi-year program of work and training.

Regional Dam Safety Unit

An EN Dam Safety Coordinating Committee (or Regional Dam Safety Unit) that promotes and assists the development and use of dam safety regulations and guidelines as well as training programs consistent with best international practices will be established. In addition it would be a vehicle for trans-boundary coordination including ongoing exchange of operational information such as hydrological information on inflows, discharges and especially emergency situations. The terms of reference of such a unit should include:

1. Promoting the awareness of the need for and adoption of state of the art dam safety management practices within the EN. This should include organising a regional consultation and training workshop;

2. Facilitating the introduction of dam safety regulations in the EN countries;

3. Making the Reference Dam Safety Guidelines available to be adopted by each EN Country;

4. Making the Small Dams Guidelines available to be adopted by each EN Country;

5. Identifying and compiling /adopting supplementary guidelines and/or manuals for detailed application of the Reference Dam Safety Guidelines available for especially all the trans-boundary dams including the following examples:

    - Risk analysis;

    - Hydrological analysis (including design flood);

    - Geotechnical analysis;

    - Seismic analysis;

    - Design of the different types of dams including earthfill and rockfill embankments, conventional and roller compacted concrete gravity, buttress and arch dams;

- o Design of spillways and mechanical and electrical components; and
- o Dam safety and the environment.

6. Facilitate the introduction of Risk Informed Dam Safety Management Programs based on the PFMA process through the conduct of training programs and provision of support documentation. to assist in the understanding of risk issues and prioritization of risk reduction measures especially with regards to trans-boundary issues. These programs should consider a much wider range of potential failure mechanisms (PFMs) than are considered in traditional dam safety programs;

7. Maintaining and periodically updating the Inventory of Dams and the Potential Consequences Classification system (PCC) for all dams in the region;

8. Coordinating selected key regional background studies for all dams with potential trans-boundary impacts such as:

    - o PMF studies for the Eastern Nile;
    - o Dam break analyses and inundation maps;
    - o Regional seismic hazard analyses; and
    - o The potential impacts of climate change on EN region dam safety.

9. Facilitating the introduction of structured surveillance and monitoring programs (SMPs) at all dams and especially considering hydrological trans-boundary aspects;

10. Facilitating the introduction of Emergency Action Plans (EAPs) which should be coordinated for all dams with potential trans-boundary impacts based on potential dam breach scenarios and involve downstream trans-boundary agencies to provide vehicles for international cooperation to reduce the impacts of failures when they do occur; and,

11. To support the implementation of the dam safety programs and improve the current capacity and practices in dam safety there is a need to develop capacity of personnel responsible for planning, investigation, design, construction, operation and monitoring of a dam. This is especially important during construction, operation and monitoring stages to provide a reservoir of trained personnel. This may include workshops, technical training and capacity building activities.

    From the positive results of the ENTRO sponsored training PFMAs the following specific capacity building recommendations are made with regards to the RIDM and PFMA processes:

12. Develop a core group of dam safety experts as well as trained and approved facilitators in the EN. The EN countries should consider a coordinated training and certification program to establish such a group of facilitators on a regional basis; and

13. Additional training should also be provided with regards to the PFMA process for the core group of dam safety experts especially refreshing of the key concepts, detail structural and operational failure modes and dam break and inundation mapping as well as for operational staff in appropriate operation, maintenance and monitoring.

    At the international level:

14. Facilitate the establishment of national ICOLD committees in EN countries; and

15. 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.

National Dam Safety Regulations

Within each EN country the dam safety regulatory system and authority should be established for the introduction and development of regulations and oversight of the dam safety management system.

1. Establish the terms of Reference (ToR) of the regulatory authorities. The ToR 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.

2. Prepare regulations, which may be in the form of a statute or law passed by the government dealing with dam safety.

- o The precise form of the legal instruments will vary depending on the legal traditions in the country;
- o The statute should only contain the objectives and general principles governing the framework;
- o 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; and
- o The regulations may be supplemented by non-binding guidelines and/or manuals. These may take the form of recommended good practice and be developed/adopted by the EN Dam Safety Coordinating Committee and/or the ICOLD National Committees.

3. Design the regulatory scheme which should include:

- o Clear criteria determining which dams are covered by the regulatory scheme. This should be according to size and "Potential Consequences Classification" (PCC);
- o 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;
- o Clarification that the owner is responsible for dam safety and can be held liable for any damage that results from dam failure;
- o Stipulation of the dam safety standards that an owner is expected to comply with;
- o Establishment of the required qualifications of the person/team that does safety evaluations of the dams for the owner;
- o 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;
- o Stipulation that the owner/operators report any incident or failure of any component at a dam;
- o Stipulation of the frequency that the owner/operator should conduct safety inspections and reviews;
- o 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, PFMAs 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.

4. Seek Government approval and legal adoption of the regulations.

National Dam Safety Units

The National Dam Safety Units (NDSU) should be established in each country as the regulator to facilitate and monitor the implementation and ongoing development of comprehensive Dam Safety Management Programs in each country. The NDSUs should:

1. Establish ToR, management, facilities and resources for a National Dam Safety Unit as the dam safety regulatory authorities and provide it with adequate human and financial resources to perform its duties;

2. The NDSUs should each appoint an advisory committee to provide advice on dam safety issues. This advisory committee could be drawn from the National Committee of ICOLD for that country;

3. In addition, the NDSUs should be conducting training programs introducing the regulatory system to the community and establish systems to qualify and approve dam safety engineers.

4. Adopting the Reference Dam Safety Guidelines with modifications as required suiting the local conditions.

5. Adopting the Small Dams Safety Guidelines with modifications as required suiting the local conditions.

6. Maintain and periodically updating the Potential Consequences Classification system (PCC) for all dams in the country;

7. Maintain 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;

8. Maintain an archive of all the documentation submitted for each dam by the owner of each dam;

9. On going operational activities should include:

    - o Implementing the progressive use of "Risk Informed Decision Making" (RIDM) to assist in the understanding risk issues and prioritization of risk reduction measures;
    - o Review, approval and oversight of implementation of design reports and construction plans for new projects and significant modifications to existing projects.
    - o Specifying the frequency and scope for PFMAs and periodic comprehensive safety inspections and reviews by the owner;
    - o Establishment of the required qualifications and case by case approval of the persons who perform PFMAs and safety evaluations of the dams;
    - o Conducting periodic dam safety inspections of the projects including detailed review and evaluation of the owner's surveillance and monitoring reports;
    - o Observing tests of key safety equipment such as spillway gates and emergency power systems:
    - o Review, approval and oversight of project operations in the event of dam safety incidents and implementation of any required risk reduction measures;

10. Support national ICOLD dam committees and provide leadership in future for these organisations; and

11. 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.

Owners Dam Safety Programs

1. The owners of dams should 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. This should include:

    - o Clearly identifying responsibilities and authority for dam safety management by the owner's staff with adequate resources to carry out the responsibilities;

- o Implementing 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 different stages of a dam project; and
- o Incorporating dam safety into its plans for design, construction, operation, maintenance and decommissioning of their dams;

2. Carry out PFMAs for all existing dams as well as for new dams and modifications to existing dams and carry out subsequent periodic dam safety reviews on all dams;
3. Implement the recommendations of the PFMAs and dam safety reviews;
4. Establish an Operation and Maintenance (O&M) Manual at each dam for review and approval by the regulator and an adequate budget for operations, maintenance and supervision;
5. Establish a Surveillance and Monitoring Plan (SMP) at each dams for review and approval by the regulator and an adequate budget for installation, operation and maintenance of the monitoring system and data management;
    - o 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;
    - o Preparing 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;
6. At dams with any potential for loss of life or other significant consequences establish an Emergency Action Plan (EAP) 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;
    - o Carry out EAP exercises involving the dam operators and downstream entities;
7. 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:
    - o Significant damage of the dam wall or spillway caused by natural phenomena such as floods and earthquakes;
    - o Failure or unusual movements or subsidence of any part of the dam or foundation thereof;
    - o Unusual seepage or leaks which occur or which increase abnormally in the course of time or which remove material;
    - o 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;
- Serviceability of spillways and floodgates;
- Serviceability of outlet works required for lowering of the water-level in an emergency; and
- Incidents of sabotage or vandalism.

8. 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, PFMAs and Safety Reviews, SMPs, SMRs, EAPs to be available at the project and supply a complete copy of this information to the regulator.

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MODULE 4

Framework for Dam Safety for EN Countries

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FRAMEWORK FOR DAM SAFETY FOR EN COUNTRIES

Reference Dam Safety Guideline

In 2014, ENTRO published dam safety guidelines entitled "Reference Dam Safety Guideline for EN Countries" (ENTRO, 2014) that can serve as a reference for EN countries. The guidelines were prepared as part of ENTRO's dam safety program which included an updated assessment of the baseline conditions, 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.

The guidelines are intended to be a practical tool to provide procedures and promote a common approach to dam safety management across the EN countries taking into account its design, construction, and operation and maintenance phases.

The intended purpose of the guideline is stated as

"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 has become an important and emerging issue in Eastern Nile sub-Basin (ENB). This is highlighted in the guideline as

"The major concern 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. 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."

The reference dam safety guidelines for EN countries comprise of 12 basic dam safety components and a number of Appendixes. The guidelines start by establishing key dam safety objectives and then elaborate on each topic. The 12 basic dam safety components are:

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;
11. Environmental and Social Factors;
12. Trans-boundary Considerations.

IMPORTANT NOTE:

This Dam Safety Training Module is designed to assist in implementing the Reference Guidelines. Extensive quotations from the Guidelines are included with varying degrees of editing into the Module. However, in all applications, the text of the Reference Guidelines or, if adopted by an EN country, the National Dam Safety Guidelines, shall govern.

Dam Safety Objectives;

The guidelines identified 25 key objectives and organized them in to the following 8 major headings

1. Justifications for dam
   Objective 1: Dams should be constructed and operated only if they yield an overall benefit to society.

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.

   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.

   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.

   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.

   Objective 2e: The dam safety management system shall be documented and implemented according to an "Owner's Dam Safety Program".

3. Analysis & Assessment
   Objective 3a: The dam system and components under analysis shall be defined.

Objective 3b: *Hazards external and internal to the dam shall be defined.*

Objective 3c: *Potential Failure Modes, sequences, and combinations shall be identified for the dam.*

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.*

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.*

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.*

   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.*

5. Operation, Maintenance, 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.*

   Objective 5b: *Documented operating procedures for the dam and flow control equipment under normal, unusual, and emergency conditions shall be followed.*

   Objective 5c: *Flow control equipment shall be tested and be capable of operating as required.*

   Objective 5d: *Documented maintenance procedures shall be followed to ensure that the dam remains in a safe and operational condition.*

   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.*

6. Dam Safety Emergency Planning;
   Objective 6a: *An effective emergency management process shall be in place for the dam.*

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.

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.

Objective 6d: The emergency management process shall ensure that adequate staff training, plan testing, and plan updating are carried out.

7. Safety Reviews;
   Objective 7a: A safety review of the dam ("Dam Safety Review") shall be carried out periodically.

8. Management of Trans-boundary Considerations, Environmental and Social Consideration;
   Objective 8a: The dam safety management system shall include trans-boundary considerations at all stages of a dam's life cycle.

   Objective 8b: The dam safety management system shall include the management of environmental and socioeconomic issues.

Dam Safety Management

According to the guidelines, 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.

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

- 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.

The guidelines emphasized the importance of documentation and recommend that dam owners should make documents such as *planning & design reports, construction plans, standing operating procedures, O& M manuals, PFMA reports, inspection and evaluation reports, surveillance & monitoring plans, emergency action plans* available for each dam.

The guidelines also stressed the invaluable roles of competent, qualified, and experienced staffs & operators in implementing dam safety management systems. In this regard, trainings on basic principles, standard procedures, emerging approaches and new technologies in dam safety is identified as a crucial element.

The other important considerations in implementing dam safety management are the issue of quality management and public participation. The guidelines recommend that 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. As far as public consultation is concerned, the guidelines require that 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.

The management of a dam safety program should ensure that the program addresses the needs and concerns of the owner and the community. The guidelines note that this would be achieved among others by identifying the responsibilities of owners', governments' and dams' personnel, and ensuring adequate funding and resources are available for dam safety management. The guidelines specifies that

- the owner of the dam is responsible for safety of the dam; and
- the role of the government is to enact dam safety legislations (statues, proclamations, regulations etc).

The guidelines also specify the role of the Approved Dam Engineer in dam safety management. According to the guidelines, 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.

To assist with dam safety management, the guidelines introduced Potential Consequence Classifications (PCC) for EN dams. The Potential Consequences Classification 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 the guidelines, EN dams are classified on the basis of *loss of life, infrastructure & social factors, and environmental cultural factors* in to 5 consequence classes: very high, high, moderate, low, and remote.

Analysis & Assessment

In dam safety literatures and guidelines there are two approaches for dam safety analysis: formal risk assessment, and traditional standards-based approaches. These approaches could be used independently or in tandem as the overall objective in both cases is to ensure that the dam is safe to the extent reasonably and practically achievable, given the limitations of each approach. The reference guidelines treated these two approaches to dam safety in depth. In outlining the two approaches, the guidelines stressed that the setting of minimum safety levels is a matter of public policy and regulation, and engineering analyses and assessments are used to confirm and demonstrate compliance or to develop alternative measures to meet the identified requirements.

Risk is a measure of both the likelihood of an undesired event and the consequence of such event, and can be used as 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.

Considering the fact that large uncertainties are involved in dam engineering, the guidelines encourage a risk informed approach in dam safety analysis. Central to risk assessment is the issue of a balance between social equity and economic efficiency, and this is addressed in the guidelines by introducing the concept of the tolerability criteria.

The guidelines introduced the two main approaches in risk analysis: qualitative risk analysis and quantitative risk analysis. It also introduced the concepts of As Low As Reasonable Practicable (ALARP).

The document also introduced Potential Failure Mode Assessment (PFMA) which is a key component of risk informed decision making. A thoroughly developed PFM describes the progression from initiation through to failure, the probability of failure, so that the risk can be adequately understood. This can assist in implementing a dam safety surveillance and monitoring program (SMP), risk reduction measures and provide a rational basis for the Emergency Action Plan.

The second approach that is discussed is the traditional standards-based approach. This approach is a deterministic approach where the uncertainty is accounted by

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

Planning & Design

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, and the guidelines discuss the dam safety issues to be addressed in each phase.

The guidelines identified three stages in dam planning phase: reconnaissance, prefeasibility, and feasibility stages. According to the guidelines, the Approved Dam Engineer must be involved at the start of the reconnaissance stage. A preliminary dam safety management plan should also be prepared at this stage. The guidelines note that, at the feasibility stage, all dam safety requirements should be identified and discussed with the dam owner, and consequence and Failure Mode Analysis (potential life loss, economic damages, and environmental damages) and Preventative Measures should be prepared.

The guidelines further recommend that the Approved Dam Engineer should be involved during the design stage as well. Two levels of studies are identified: concept design and detail design. The guideline includes the list of items that the concept design should include. Generally, 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, and it should be submitted by the Approved Dam Engineer to the regulator for approval before proceeding with the detail design.

During detail deign, hydrologic analysis, hydraulic and structural designs, and reservoir planning are carried out. Design methods and criteria are required to be in conformity with the current state of technological evolution and be compatible with the codes and standards to be used. The Approved Dam Engineer should establish a program for prototype testing to check the hydraulic performance and operational behaviour under actual site conditions.

Construction & Commissioning

There are four main stages in this phase of the project, and the guidelines identified the dam safety issues to be addressed in these stages. The four main stages are

- Design review and modifications,
- Construction supervision & inspection
- Construction (methods & equipment)
- Commissioning

The Approved Dam Engineer has a crucial role to play in ensuring dam safety at this phase. As far as design modifications is concerned, the guidelines recommend that 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. Similarly, 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 and his consent must be obtained before going further. The Approved Dam Engineer should also provide a commissioning schedule for the facilities of each dam outlining to the dam owner the procedures and practices (both operational and surveillance) to be put in place to bring the dam into full operation.

One of the tasks that are carried out at the early stage of a dam project is river diversion. The guidelines recommend that the 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.

Operation & Maintenance

The guidelines recommend that all dams should have Operations and Maintenance Manuals that is compiled by an Approved Dam Engineer. The Manual for a dam should include the complete, accurate and up-to-date operating, maintenance and overhaul instructions for the dam and its appurtenant structures with possible associated supporting documents or other information. The purpose of the manual 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 should be prepared primarily for the dam operations staff and their supervisors who area 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.

The guidelines further recommend that a maintenance program based primarily on systematic and frequent inspections should be developed for all dams. Moreover, 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. To handle major accidents, the guidelines recommend emergency operations requirements to be clearly spelled out. In cases of incidents and accidents, their causes, and their consequences should be investigated, and 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.

Surveillance & Monitoring

The guidelines highlight that 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.

The guidelines set out surveillance and monitoring principles and recommend that a Dam Safety Surveillance and Monitoring Plan (SMP) based on these principles to be developed and implemented for all dams with a safety risk and a Potential Consequences Classification (PCC) of LOW or higher. Approved Dam Engineers, in conjunction with the Regulator, need to 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 program.

The guidelines recommend that 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.

According to the guidelines, dam safety inspections should be conducted to determine the status of the dam and its features in terms of its structural and operational safety. It recommends four general levels of dam safety inspection: comprehensive inspection, intermediate inspection, routine visual inspection, and special or emergency inspection. The guidelines discuss the inspection procedure for the specific case of first dam filling which is quite often a benchmark activity and for routine visual inspection. The guidelines also provide guidance on the frequency of inspection which is based on the dams' potential consequence classification.

Dam monitoring is one means of determining trends in structural performance. The activity involves the collection, recording, analysis and presentation of data from measuring devices installed at or near dams. The guidelines recommend that the items that need to be monitored, and the relevant associated instrumentation in the dam, should be identified by the Approved Dam Engineer undertaking the safety review of the dam. 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.

The guidelines also provide guidance on the frequency of monitoring which is based on the dams' potential consequence classification.

The guidelines recommend that 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 inspection reports and monitoring results.

Safety Reviews

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 guidelines identified three types of safety reviews, i.e., comprehensive, intermediate, special/ emergency review, and elaborated the purpose of the reviews and the personnel involved. For example, a comprehensive review is carried out to identify deficiencies by a thorough onsite inspection by evaluating surveillance data; and by applying current criteria and prevailing knowledge, and the results of a PFMA. The Approved Dam Engineer and a specialist will undertake the review. As part of the safety reviews, the guidelines recommend the Dam Safety Engineer to 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 doesn't exist.

The guidelines also provide guidance on the frequency of safety reviews which is based on the dams' potential consequence classification.

The guidelines highlight the importance of an independent audit and recommend dam owners to 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).

Emergency Action Plans

The guidelines noted that despite the best of efforts to minimize risks of dam failure, dams do fail and dam owners need to put in place a Dam Safety Emergency Action Plan (EAP). A dam safety emergency action plan 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.

and should exist for all dams where there is the potential for loss of life in the event of dam failure. The plan should be developed by the Approved Dam Engineer. In addition to the EAP, the guidelines also recommend another type of emergency plan, known as Disaster Plan, to be prepared.

The guidelines provide an outline of the activities that are carried out in developing an EAP which usually include, but not limited to, carrying out PFMA, inundation mapping, identification of parties involved in emergency actions, etc. The guidelines clearly indicate that the responsibility of preparing the dam safety EAP lies with the dam owner.

Remedial Action Plans

The guidelines noted that when a dam fails to meet an acceptable level of safety, it requires remedial actions / risk reduction. The document recommends that this process should be conducted by an Approved Dam Engineer, and 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.

The guidelines provide an outline of a remedial action evaluation for a dam, and discuss various risk reduction options which include:

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

Environmental & Social Factors

The guidelines note that there are two ways of looking at environment and social issues in dam projects

- The first is the impacts of dams on environment and society, and
- The second is impacts of environment and social factors on safety of dams.

The guidelines recommend that these two-way interactions should be considered at the early stages of project planning. This will allow planners and designers to consider project locations and design elements that will better address environment and social requirements. The guidelines discuss some of the existing and emerging environmental and social issues such as climate change, water quality, erosion and sediment transport, rare and endangered species, passage of fish etc and recommends ways to accommodate and manage these issues at the various stages of the dam's life cycle.

Potential Consequences Classification of EN Dams

A Potential Consequences Classification (PCC) system has been developed and applied to EN dams and provides a classification of dam according to their potential impacts as a result of failure. It is proposed that this classification system is the subject of training workshops and periodically reviewed for existing and new dams in each country.

In the Risk Informed Decision Making (RIDM) approach proposed for the EN Basin Dam Safety Guidelines the PCC is used in the same way as in traditional methods, as described above, but also to establish the need to carry out potential failure modes analyses (PFMA) as the first step of a risk informed approach. The results of the PCC are to be used when categorizing the risk in a "Risk Matrix" at the conclusion of the PFMA as discussed in the Reference Guidelines.

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.

The classification scheme can be used to provide guidance on the standard of care expected of dam owners and designers and used in selecting design criteria. Estimates of potential consequences of dam failure are categorized to distinguish dams where the risk is higher than others. The classification considers both national and international or trans-boundary factors.

Table 4-1 presents the 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 4- 1: Potential Consequences Classification for Eastern Nile Dams

Dam Class	Loss of life	Infrastructure, Economic and Social Factors	Environmental & Cultural Factors
VERY HIGH 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 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 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 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 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 dam classifications 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 on going 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.

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.

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.

As a part of periodic dam safety inspections, 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.

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 or 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 4-1 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, 2014).

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.

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 world-wide.

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.

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.

Dam Safety Analysis Approaches.

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.

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 4-1.

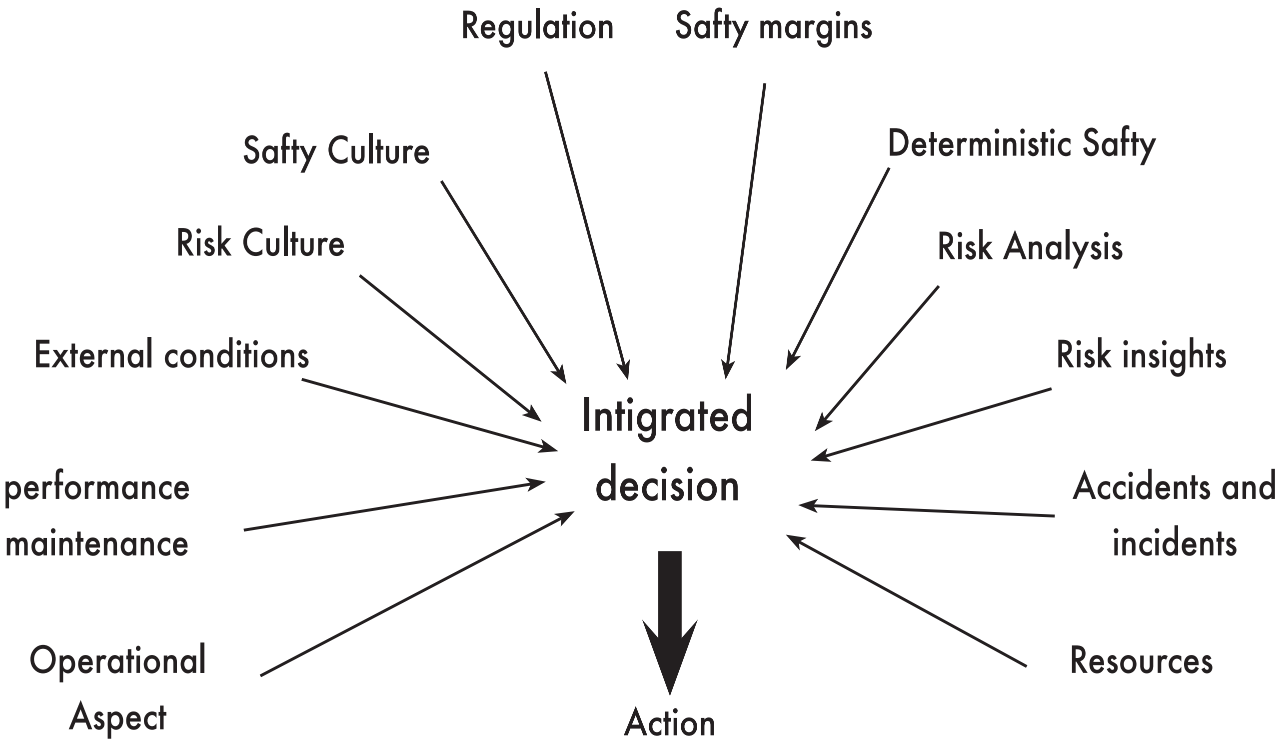

Figure 4-1: Integrated Risk Informed Decision Making (ICOLD: 2012)

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.

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 4-2, 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).

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.

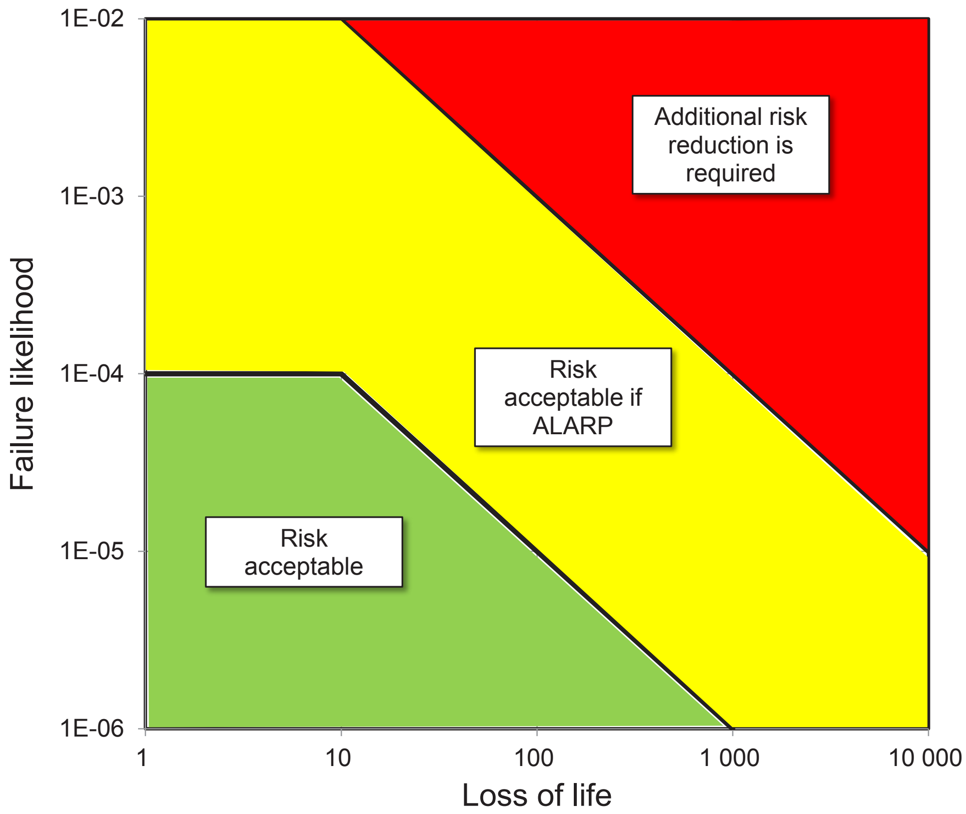

Figure 4-2 : Risk levels for Dam Safety using loss of life societal consequences

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 4-3 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 4-2: 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	1×10^{-2}	
Low	1×10^{-3}	1×10^{-4}
Moderate	1×10^{-4}	$(1/N) \times 10^{-3}$**
High	1×10^{-5}	$(1/N) \times 10^{-3}$
Very High	1×10^{-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).*

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.

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.

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.

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).

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 for PCCs. PFMAs 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 4-3.

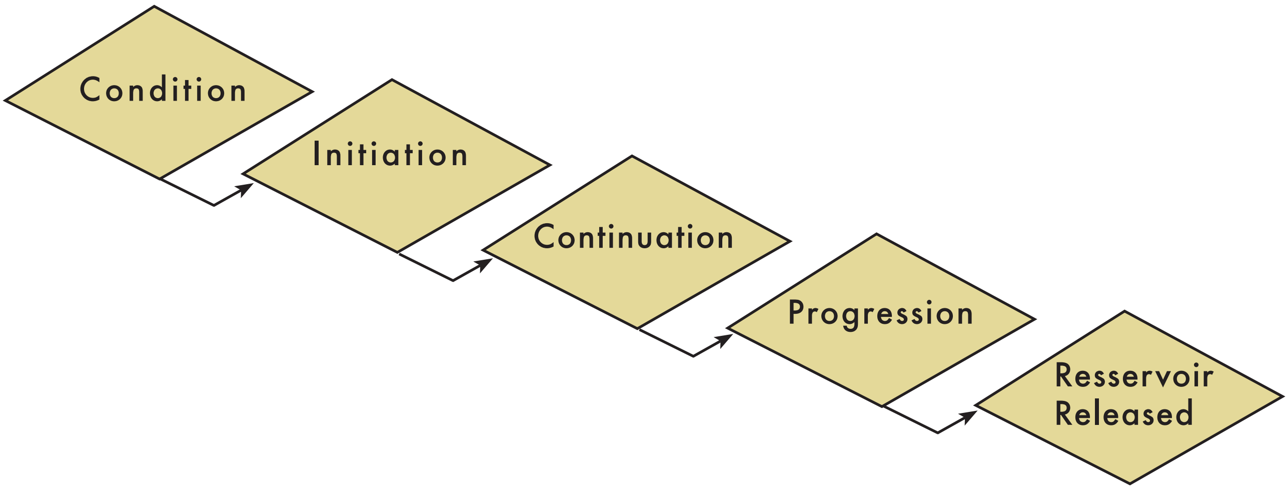

Figure 4-3: Steps in the description of a Potential Failure Mode

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.

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 4-4.

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 4.4** 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: A level of confidence is assigned to the failure likelihood category. 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 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)".

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 as shown in **Figure 4-4** 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 4-3**

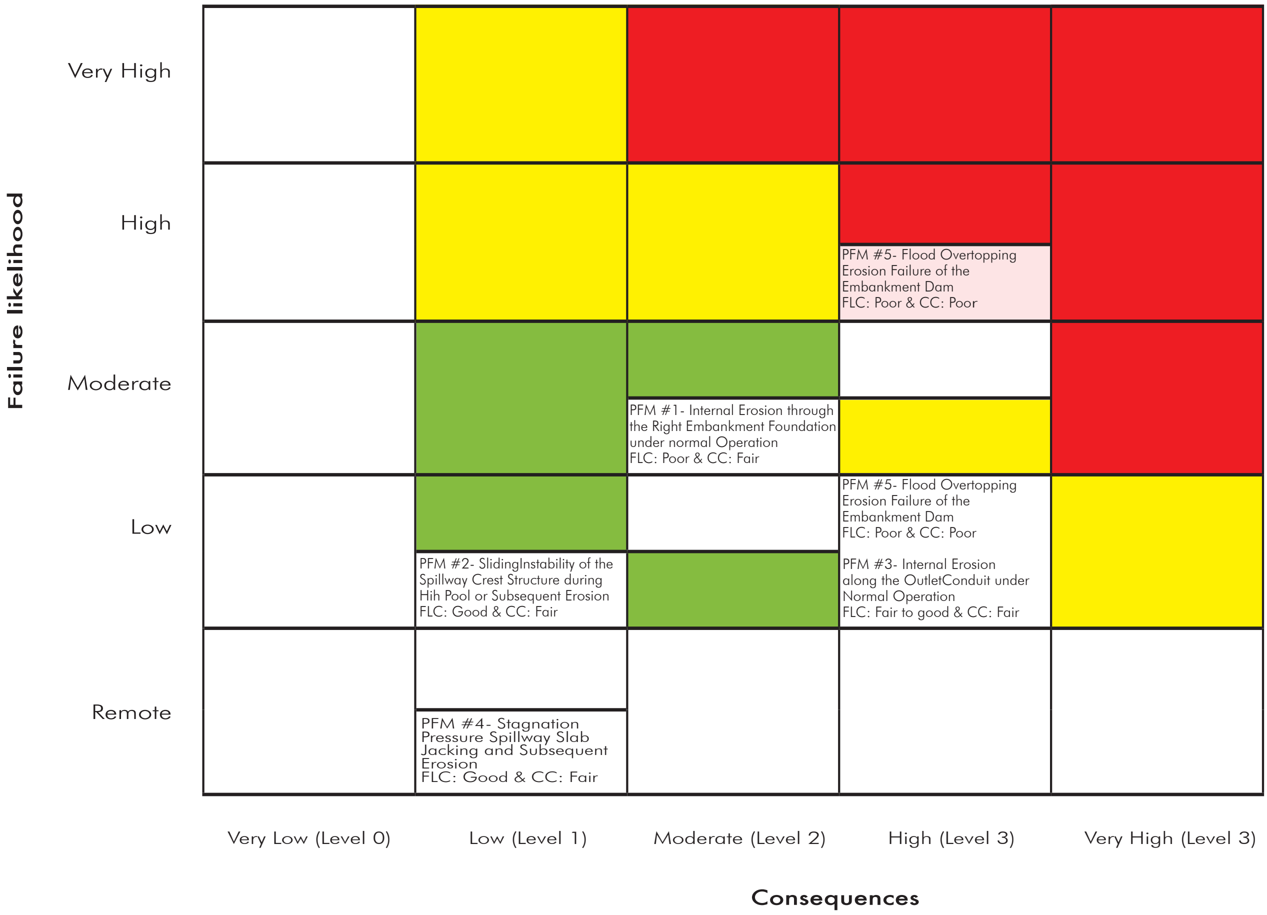

Figure 4-4: Risk Matrix

Table 4-3: 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.*

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.

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.

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.

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 4-4 suggests values for the inflow design flood (IDF) and the design earthquake based on the traditional deterministic approach to dam safety assessment.

Table 4-4 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 the guidelines.

Table 4-4: Extreme flood and earthquake hazards for the standards based assessments

Potential Consequences Category	Annual Exceedance Probability (AEP)	
	Hydrologic: Inflow Design Flood (IDF)	Seismic
Remote	1×10^{-2}	1×10^{-2}
Low	1×10^{-3}	1×10^{-3}
Moderate	PMF	MCE
High	PMF	MCE
Very High	PMF	MCE

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

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MODULE 5

Dams Breach Analysis

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DAM BREACH ANALYSIS & INUNDATION MAPPING

Introduction

General

Dam breach analysis usually relates to the process of studying a dam failure phenomenon and analyzing the resulting potential flood hazards at the downstream region. This generally deals with simulation of assumed failure for dams and analyzing the resulting consequences (Pandya & Jitaji, 2013).

The two primary dam breach study approaches that are commonly used by dam safety agencies are an event-based approach and a consequence / risk-based approach (FEMA-946, 2013). The event-based approach has been traditionally the most widely used for dam breach analysis. It is a deterministic method and based on specific precipitation and non-precipitation events for the dam breach analysis and downstream inundation mapping. In this approach, both a non-hydrologic "fair weather failure," also referred to as a "sunny day failure," and a specific hydrologic failure event, also referred as "rainy day failure", such as the Probable Maximum Flood (PMF), are usually established based on a dam's hazard potential classification.

According to FEMA-946, 2013, in the past two decades, consequence / risk-based approaches to dam breach analysis have become more acceptable for dam safety and dam design purposes. A risk-based approach is commonly used for dam design purposes to establish the spillway design flood (SDF) or inflow design flood (IDF) for a dam. For a risk-based approach, the downstream consequences for a range of hydrologic dam failure events are evaluated.

Dam breach inundation analyses include the following four elements (FEMA-946, 2013):

- estimation of the dam breach parameters,
- estimation of the dam breach outflow hydrograph;
- routing of the dam breach hydrograph downstream; and
- estimation of downstream inundation extent and severity.

Dam breach parameters, i.e., geometry and formation time of a dam breach, are routinely determined using dam breach prediction models. Typically, dam breach prediction models are based on empirical data derived from a number of mostly earth and rock fill dam failures case studies. The available empirical equations relate the dam breach parameters to properties of the dam and reservoir such as height, dam type and its erodibility, volume impounded, and shape of the reservoir.

The most common methods of dam breach outflow hydrograph routing are either one-dimensional or two-dimensional with the latter used when higher levels of accuracy are required. For most dam breach analyses, one-dimensional computer software is used. Geographic Information Systems (GIS) are the current state-of-practice for inundation mapping, especially if the dam breach analysis involves populated areas and/or other high potential consequences areas.

Figure 5-1 Teton dam failure

Purpose of Dam Breach Analysis

The way and rate at which a dam breaches can affect the timing of the breach, the rate and magnitude of the flood water released and the size of the breach itself. Therefore, breach affects the analysis of flood risk and can change the way in which flood events might be managed.

The results of dam breach analyses are typically used to develop inundation maps which can have a variety of uses including

- emergency action planning,
- emergency response,
- mitigation planning, and
- consequence assessment.

Each use has unique information requirements and may be used in different manners ranging from multi-year office-based planning efforts by mitigation planners and dam safety officials to field-based emergency responders responding to a developing or imminent dam breach (FEMA-946, 2013).

Dam Breach Analysis Approaches

As pointed out in 5.1, there are two approaches that are commonly used for dam breach analysis: an event based approach & a consequence based approach.

Event Based Approach

An event-based approach is a deterministic method. It uses a specific or series of specific non-precipitation and precipitation events for the evaluation of dam failure and downstream inundation mapping. The non-precipitation and precipitation events are also referred as non hydrologic (fair weather / sunny day) and hydrologic events (rainy day) respectively. Several non-hydrologic and hydrologic events are evaluated in a typical breach analysis.

FAIR WEATHER FAILURES

A fair weather (Sunny Day) breach is a dam failure that occurs during fair weather (i.e., non-hydrologic or non-precipitation) conditions. Establishing an initial reservoir water level and commencing a breach analysis without additional inflow from a storm event analyze the breach. A fair weather breach is typically used to model **piping failures** for hydrologic, geologic, structural, seismic, and human-influenced failure modes (FEMA P-946, 2013).

Three initial reservoir water level elevations are commonly used for fair weather breach analyses. In the first, the reservoir water level is set at normal pool level. The volume and associated discharge that would result from a failure event during fair weather condition are then estimated. For an embankment dam, this type of event is modeled as piping / internal erosion failure, whereas for a concrete dam, this event is modeled as a monolith collapse resulting from sliding, foundation instabilities, or a seismic event (FEMA P-946, 2013).

In the second, the reservoir water level is set at the invert of the auxiliary spillway (also referred to as an emergency spillway). This condition is commonly used to simulate a breach during **mis-operation** of the primary outlet works. Initiation of dam failure is typically the same as for the reservoir level at normal pool (FEMA P-946, 2013).

In the third, the reservoir level is set to the top of the dam to represent the maximum amount of volume that may be stored in the reservoir. This condition may be selected to evaluate the most conservative non-hydrologic event. In practice, dams without adequate spillways or pump storage facilities, where the water level during non-hydrologic events is maintained at the top of dam, are unique situations subject to this conservative assumption. A breach event when the water level is at the top of dam may be modeled as a **piping / internal erosion failure** or as **an overtopping failure** with the water level just above the top of dam invert (FEMA P-946, 2013).

HYDROLOGIC FAILURE

Hydrologic breaches that occur with extreme precipitation and runoff are termed “rainy day” or hydrologic failures. Hydrologic failures that cause dam breach events are generally analyzed based on the IDF established by the dam’s hazard potential and hazard size classification. Typically a PMF is used for high-hazard potential dams; whereas, values ranging from 1-percent-annual-chance flood event (often called the 100-year flood) to a percentage of the PMF is used for significant hazard dams. This condition is commonly used to simulate a breach during **overtopping** of the dam.

Consequence Based Approach

A risk-based approach to dam design and dam safety evaluations has been developed to account for the downstream consequences of a potential dam failure. The consequences evaluation is not based on the probability of failure, but instead on the potential loss of life or increase in economic losses caused by a potential dam failure.

According to FEMA P-946, FEMA 94, Federal Guidelines for Dam Safety: Selecting and Accommodating Inflow Design Floods for Dams (2004b), and the FERC document, Engineering Guidelines for the Evaluation of Hydropower Projects (1993), laid the foundation for risk-based dam safety analysis. In FEMA 94, IDF is defined as “the flood flow above which the incremental increase in water surface elevation downstream due to failure of a dam or other water retaining structure is no longer considered to present an unacceptable additional downstream threat.” Therefore, incremental hazard evaluation and the establishment of the IDF is, in essence, a risk-based approach.

The selection of the IDF is based on the evaluation of the magnitude of several flood events The incremental hazard evaluation begins with simulation of a dam failure during a hydrologic flooding condition, typically beginning with the PMF or percentage of the PMF as specified by the State hazard potential classification requirements.. The same hydrologic event is then run for non-failure conditions. The water surface elevations for both the breach and non-breach events are compared to determine the increase in the water surface elevation resulting from the dam breach. If the incremental increase in downstream water surface elevation between the failure and non-failure scenarios results in an acceptable increase in consequences, (as defined by State requirements) a smaller percentage of the PMF flood inflow or other magnitude flood is then used to repeat the process. The process is repeated until the incremental increase in consequences due to failure falls within acceptable requirements specified by the State.

Both the FEMA and FERC publications identify acceptable consequences of failure to be when the incremental effects (depth) of failure on downstream structures are approximately 0.6m or less; various other sources consider “acceptable consequences” to be 0.3m or less. FERC guidelines state that engineering judgment and sensitivity analyses are needed to make final decisions on the acceptability of consequences.

Breach Parameters Estimation

A key element for calculating a dam breach hydrograph for a specific dam involves estimating the dam breach parameters (e.g. width, depth, shape, and time of failure). It is to be noted that the shape of the peak breach outflow hydrograph is influenced by the storage in the impoundment at the time of breach, reservoir inflow at the time of breach, size of the dam, and most importantly, the dam type's erodibility and/or mode of assumed failure. For instance, a brittle concrete or structural failure will have a much faster time of breach development as compared to an overtopping failure of a large, cohesive, well compacted, and well vegetated embankment. Since the outflow hydrograph can vary widely depending upon these factors, careful consideration should be given to the dam breach modeling inputs. Ideally, dam breach analyses should be performed for a specific failure mode, so the breach scenario may be well understood.

It has been noted by several sources that the selection of breach parameters for modeling dam breaches contain the greatest uncertainty of all aspects of dam failure analysis and therefore a careful evaluation and understanding of the associated breach parameters is necessary (Wurbs, 1987; USBR, 1998; Wahl, 2004; etc.).

A number of methods are available for estimating breach parameters for use in dam breach studies. Since the selection of the breach parameters is specific to each dam, guidance is provided describing methods currently applied by dam safety professionals without recommending a standardized method.

Breach Parameter Definitions

The term breach parameters is commonly used to describe the parameters needed to physically describe the breach (breach depth, breach width, and side slope angles) as well as parameters that define the time required for breach initiation and development (Refer Figure 5-2). These parameters are key in calculating the dam breach outflow hydrograph. The following definitions are commonly accepted for use in evaluating and selecting dam breach parameters.

- **Breach depth** (h) – It is the vertical extent of the breach measured from a specific elevation to the invert of the dam breach.

- **Breach width** (B)– It is the average of the final breach width, typically measured at the vertical center of the breach.

- **Breach side slope factor** – The breach side slope is a measure of the angle of the breach sides represented as z horizontal to 1 vertical (zH: 1V).

- **Breach formation time (also time-to-failure)** – The duration of time between the first breaching of the upstream face of the dam (breach initiation) and when the breach has reached it full geometry.

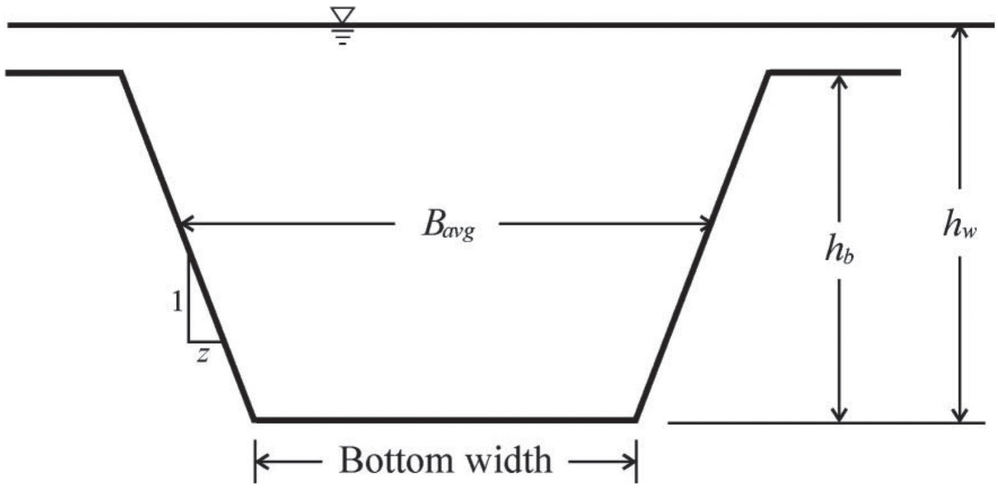

Figure 5-2 Definitive sketch for dam breach parameters

A dam breach usually occurs in two distinct phases starting with the breach initiation followed by the breach formation.

- **Breach initiation:** During the breach initiation phase, flow through the dam is minor and the dam is not considered to have failed. It may be possible to prevent a dam breach during this phase if flow is controlled.

- **Breach formation:** Breach formation (defined above) begins when the flow through the dam has increased and progressed from the upstream face to the downstream face of the dam, is uncontrolled, and will result in the failure of the dam.

Breach Mechanisms and Selection of Breach Parameters

Breach forming mechanisms can be classified into two general categories:

(1) Breaches formed by erosion of embankment material (MacDonald & Lang ridge-Monopolies, 1984), and

(2) Breaches formed by the sudden removal of all or a portion of the impounding structure as a result of some over-stressing of the structure.

Mechanism (1) addresses overtopping and internal erosion failures of embankments. Mechanism (2) describes the possible breach of a concrete or other rigid type of dam. The breach formation time for mechanism 1 may range from few minutes to 4 hours; whereas the breach formation time for concrete dam may range from few minute to a maximum of half an hour and in extreme cases it may occur instantaneously as in the case of Arch dams.

Many factors must be considered in selecting appropriate breach parameters including dam type, dam dimensions, and dam materials of construction. Other pertinent information such as historical records of seepage or foundation problems should also be considered (Gee, 2009).

Breach Mechanisms For Embankment Dams

Although breaching in embankment dams may occur for a variety of reasons, breaches in embankment dams are most often modeled as overtopping or piping failures.

OVERTOPING FAILURES

Overtopping failures can occur very differently depending on the composition of the dam. Laboratory and field investigations indicate that non-cohesive and homogeneous embankments often show a gradual and progressive breach advance. The downstream embankment face flattens progressively and is often said to rotate around a pivot-point near the downstream toe (Pickert et al. (2004)). The left part of Fig 5-3 sketches principal aspects of the breach development in case of progressive erosion. In contrast, embankments consisting of cohesive material typically show a different failure mode. The failure occurs more discontinuously and the downstream embankment erodes in vertical steps due to the impinging forces of the formed waterfalls. The erosion front hereby travels from the downstream embankment toe backwards to the crest. This erosion mechanism is also labelled 'head-cut erosion' in literature and exhibits strong 3D flow characteristics as sketched in the right part of Figure 5-3.

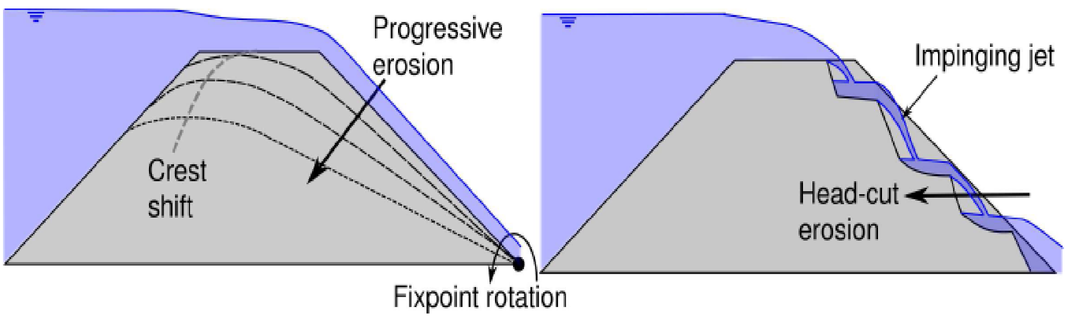

Figure 5-3 ; Progressive erosion of non-cohesive embankment (left) & head cut erosion of cohesive embankment (right). Arrow indicates the traveling of the erosion front

For cohesive embankments, the breach progress generally depends strongly on material parameters such as the degree of soil compaction and the water content (Morris et al., 2008). In contrast, progressive embankment breaches, involving mainly non-cohesive material, are said to be less dependent on the material properties. Regarding embankments made of large sized material, like boulders or blocks, which are not embedded within a sand matrix, an additional failure mode is sometimes distinguished. An 'interlocking' of the blocks is observed in such cases, which is caused by mutual and stabilizing contact interactions of the block sand can act as a surface protection for the embankment slopes (Morris et al. (2008)).

Generally, breach due to overtopping is considered to begin when erosion occurs across the width of the dam crest. After the breach initiates at the top of the dam crest, it enlarges to its ultimate extent. If there is no physical reason to believe the embankment would fail at a certain location, the breach should be modeled as initiating at the maximum section typically located at the centerline of the downstream main channel. A generalized trapezoidal breach progression is illustrated in Figure 5-4.

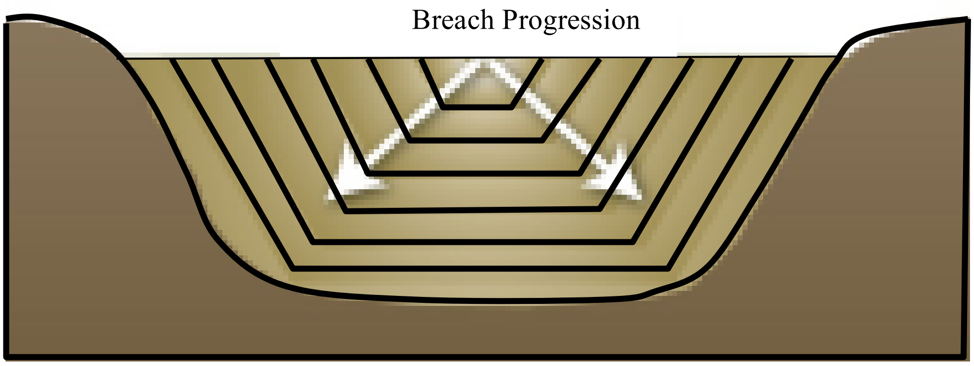

Figure 5-4 : Overtopping trapezoidal breach progression (Gee, 2009)

The breach may stop growing when the reservoir has emptied and there is no more water to erode the dam or the dam has completely eroded to the bottom of the reservoir or has reached bedrock (Gee, 2009). The breach progression may be modeled as either a linear progression or a sine wave progression:

- Linear progression: rate of erosion remains the same for the duration of erosion development)

- Sine wave progression: breach grows very slowly at the beginning and end of development and rapidly in between

In a study by the State of Colorado Department of Natural Resources, no significant difference were found between linear and sine wave progression models when comparing one overtopping case study in HEC-Hydrologic Modeling System (HMS) and HEC-RAS (2010).

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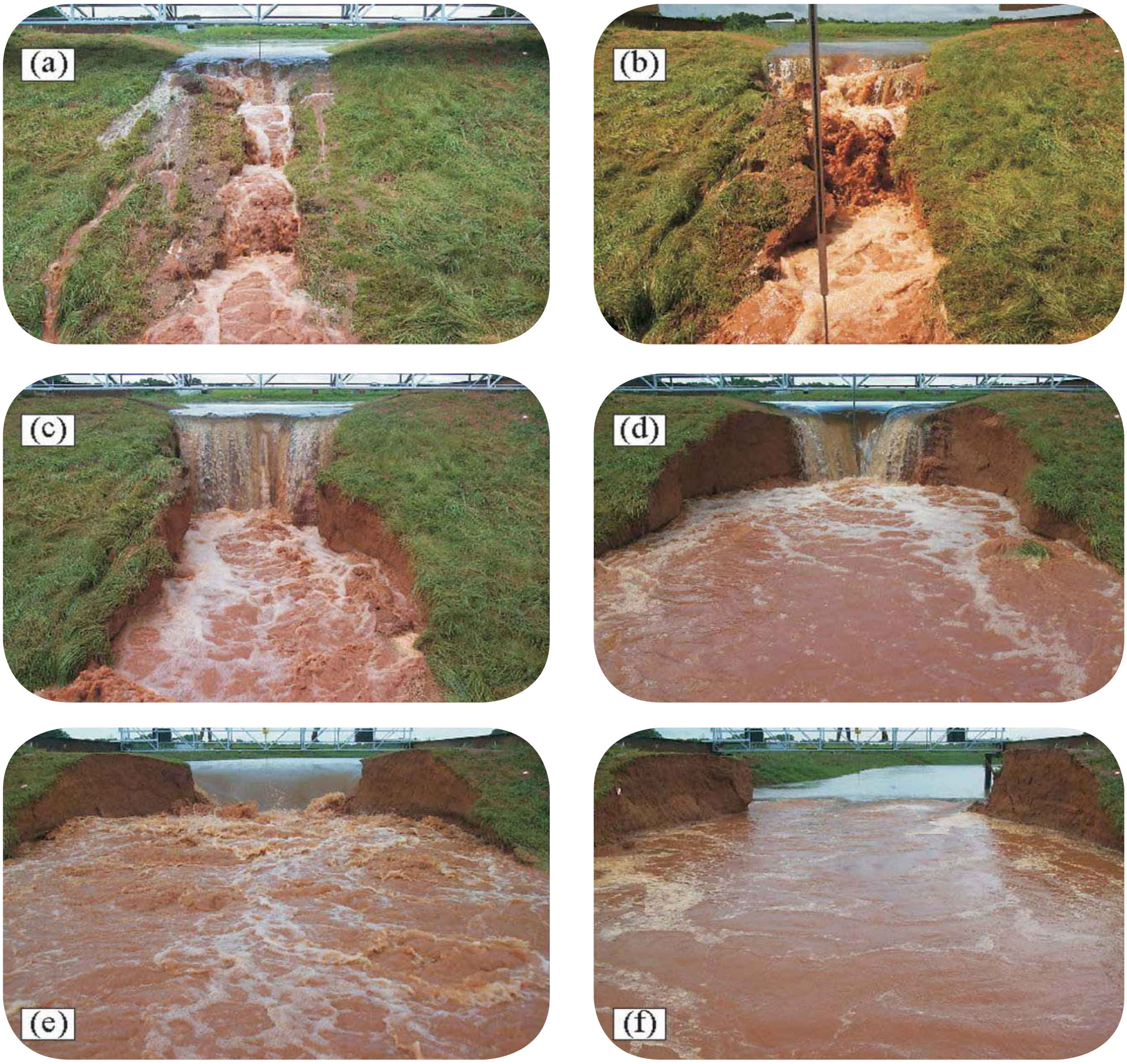
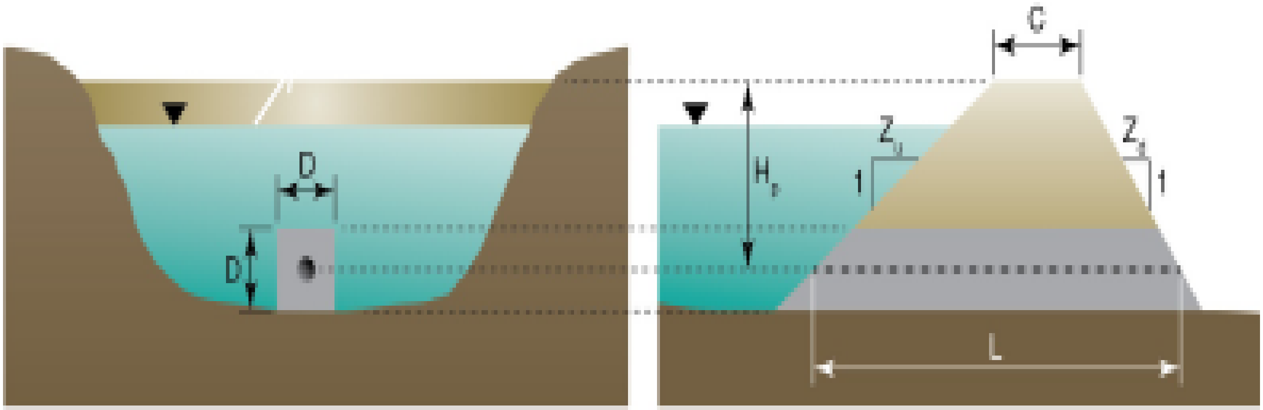


Figure 5-5 Cohesive dam breaching by overtopping (Hanson et al., 2005)

PIPING / INTERNAL EROSION FAILURES

Piping and internal erosion occurs when concentrated seepage develops within an embankment dam. The seepage slowly erodes the dam, leaving large voids in the soil. Typically, piping begins near the downstream toe of the dam and works its way toward the upper reservoir. As the voids become larger, erosion becomes more rapid. Water flow through the embankment will appear muddy as erosion increases. Once the erosion reaches the reservoir, the piping hole can enlarge and cause the dam crest to collapse. Figure 5-6 shows a schematic of a fully formed piping hole.

Piping failures are typically modeled in two phases, before and after the dam crest collapses. Water flow through the piping hole is modeled as orifice flow before the dam crest collapses and as weir flow after the dam crest collapses. For small dams constructed from cohesive soils, it is possible for the reservoir to completely empty before the dam crest collapses (State of Colorado Department of Natural Resources, 2010).



D = piping hole with/ height assumed square
H_2 = Breach depth for piping
C = dam top width
L = Length of pipe
Z = Horizontal slope of the embankment

Source: Adopted from state of Colorado department of Natural Resources, Division of Water Resourcess (2010)

Figure 5-6 Piping hole

There are several possible options to identify the breach initiation time. For breaches associated with a hydrologic event, the initiation can be considered to begin when the reservoir water level reaches a certain elevation or after the water level has exceeded a certain elevation for a specified duration. For fair weather breach analysis, an initiation time should be specified regardless of pool elevation (Gee, 2010).

Breach Mechanisms For Concrete Dams

The failure mode of concrete dams is generally characterized by some sudden structural failure (partial or complete) or catastrophic displacement of the structure. Breach analysis for rigid structures is generally straightforward. It typically involves the instantaneous removal of a portion of the structure, or, in some cases, the entire structure.

CONCRETE GRAVITY DAMS:

Concrete gravity dams are typically constructed from numerous concrete monoliths. For this type of dam, USACE suggests using an average breach width of multiple monoliths (2007), while FERC (1988) and NWS (Fread, 2006) suggest using an average breach width of less than or equal to half of the entire length of the dam (Refer Figure 5-8).

USACE, FERC, and NWS all suggest using a vertical breach side slope since monoliths are typically rectangular in shape and therefore have vertical sides. Figure 5-7 illustrates the monolith failure width (B), the breach depth (H), and the vertical side slope of 0:1. The range of possible failure times for modeling purposes is 0.1 hours to 0.5 hours.

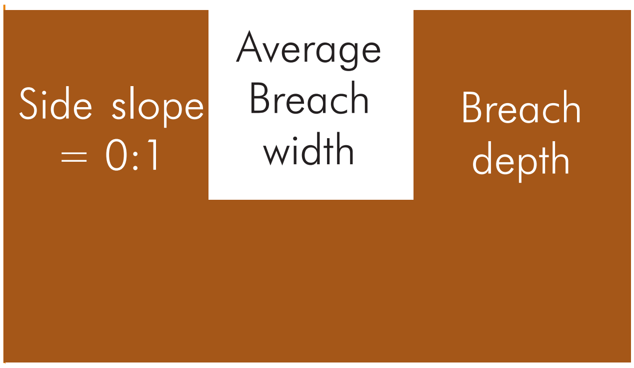


Figure 5-7 Gravity dam breach

CONCRETE ARCH DAMS:

As discussed in Section 1-, the most common location for a gravity-arch dam is in a deep canyon with steep side walls. For this reason, the breach side slope is assumed to range from vertical to the slope of the valley wall. The suggested breach widths for this type of dam range from 80 percent of the entire length of the dam to the entire length of the dam (refer to Figure 5-8). The breach formation time for modeling purposes ranges from instantaneous to 0.1 hours (USACE, 1980 and 2007; FERC, 1988; Fread, 2006).

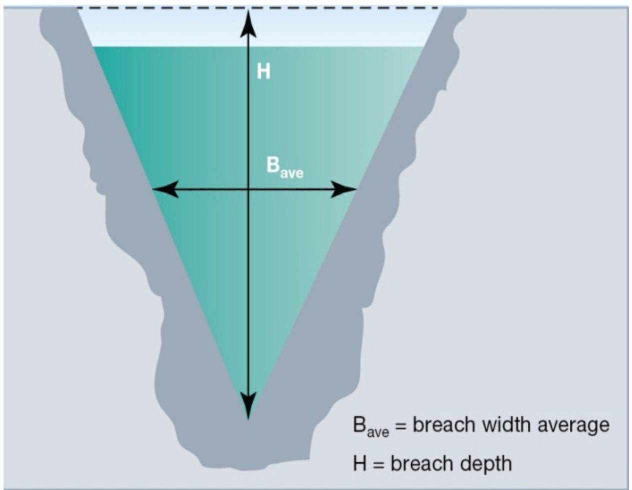


Figure 5-8 Arch dam breach

Breach Parameter Estimation Methods

A variety of methods are available in the literature to estimate dam breach parameters and the resultant dam breach peak discharge and timing. The methods could be conveniently classified in to three major groups.

Physically Based Erosion Models

These are methods that predict the development of an embankment breach and the resulting breach outflows using an erosion model based on principles of hydraulics, sediment transport, and soil mechanics (see Fread, 1988). Over the years several physically based numerical dam breach models have been developed. Mention could be made of the following model: Dam Break Forecasting Model (DAMBRK) (1977), Breach Erosion of Earth-Fill Dams and Flood Routing (BEED) (1985), and BREACH (NWS, 1988), WinDAM (NRCS,). A number of commercial models are also available.

Parametric Regression Equations

These are equations that are developed from case study information and they are used to estimate the time-to-failure and ultimate breach geometry. The breach can then be simulated to proceed as a time-dependent linear process with the breach outflow hydrographs computed using principles of hydraulics. These parameters can be used as input to a dam-failure and flood routing model such as HEC-RAS, MIKE11 to determine the breach outflow hydrograph from the dam. Such models also route the breach outflow flood through the downstream channel to predict inundated areas and downstream flood severity.

Numerous equations to predict breach parameters have been developed based on analyses of real dam failure case studies. The regression equations relate the dependent parameters such as breach width, shape, side slope, peak outflow, and failure time to the independent variables such as reservoir volume, initial water height, dam height, dam type, configuration, failure mode, and material erodibility from real failures.

The four most widely used and accepted empirically derived enveloping curves and/or equations for predicting breach parameters are: MacDonald & Langridge – Monopolis (1984), USBR (1988), Von Thun and Gillette (1990), and Froehlich (1995a, 1995b, 2008) (Table 5-1). These methods have reasonably good correlation when comparing predicted values to actual observed values.

Table 5-1 Parametric regression equations

Reference	Equation proposed	Number of case studies
MacDonald & Langridge-Monopolis (1984)	$V_{er} = 0.0261\ (V_w h_w)^{0.769}$ earthfill $V_{er} = 0.00348\ (V_w h_w)^{0.852}$ nonearthfills $t_f = 0.0179\ (V_{er})^{0.364}$ $Q_P = 1.154\ (V_w h_w)^{0.41}$	42
USBR (1988)	$B_{avg} = 3\ h_w$ $t_f = 0.011 B_{avg}$ $Q_P = 19.1\ (h_w)^{1.85}$	21
Von Thun and Gillette (1990)	Guidance for z $B_{avg} = 2.5\ h_w + C_B$ $t_f = B_{avg}/4\ h_w$ erosioon resistant $t_f = B_{avg}/(4\ h_w + 61)$ highly errodible	57
Froehlich	$B_{avg} = 0.1803\ K_o\ (V_w)^{0.32}\ (h_b)^{0.19}$ $t_f = 0.00254\ (V_w)^{0.53}\ (h_b)^{-0.3}$ $Q_P = 0.607\ (V_w)^{0.295}\ (h_b)^{1.24}$	
B_{avg}: average breach width (m); h_w: height of water above breach invert (m); h_b: height of breach (m); V_{er} =volume of embankment material eroded (m3); V_w =volume of water stored above breach inert at failure (m3); K_o: a constant with 1.4 for overtopping and 1 for piping; t_f: time to failure (hrs); Q_P: peak discharge (m3/s)		

All the four equations were developed based on regression analyses of data collected from actual dam failures. Wahl (2010) suggests that one of the main advantages of using empirical parametric regression equations is that the user can exhibit some control over the breach parameters used in the model, and thus account for site-specific factors.

Predictor Regression Equations

These are empirically developed equations used to estimate peak discharge based on actual case study data. These equations are used as a prediction method to determine a reasonable outflow hydrograph shape.

Table 5-2 presents the empirical relationships developed by various authors for predicting peak breach discharge. These equations are based on case study data used to develop empirical equations relating peak breach outflow to dam height and/or reservoir storage volume. The predictor regression equations provide an alternative method of computing the dam breach discharge; they can be used instead of determining breach parameters and then using a hydrologic-hydraulic model to compute the breach hydrograph.

Table 5-2 Predictor regression equations

Reference	Case studies	Relations proposed
Soil & Conservation Service (1981)	13	$Q_p = f(h_w)$
Reclamation (1982)	21	$Q_p = f(h_w)$
MacDonald & Langridge-Monopolis (1984)	42	$Q_p = f(V_{out} * h_w)$
Costa (1985)	31	$Q_p = f(h_d)$ $Q_p = f(S)$ $Q_p = f(d)$
FERC (1987)		Guidance for B, Z, tf
Froehlich (1995a)	22	$Q_p = f(V_w h_w)$

Summary of Typically Used Breach Parameters

The selection of breach parameters for a dam is specific to the dam and therefore guidance is not provided for one method or set of breach parameters. The following guidance presents a summary of breach parameters or range of parameters covering both overtopping and piping breach situations referenced in State and Federal dam safety guidelines and used for dam breach modeling (Table 5-3).

Table 5-3 Typical range of parameters

Earth Fill Dams	
Average breach width	½ to 5 times the dam height
Side slope of breach	0:1 to 1:1
Breach formation time	0.1 to 4 hours
Concrete Gravity Dams	
Breach width	A multiple of monoliths
Side slope of breach	0:1
Breach formation time	0.1 to 0.5 hours
Concrete Arch Dams	
Breach width	Entire dam width
Side slope of breach	0:1 to valley wall slope
Breach formation time	Nearly instantaneous, < 0.1 hours

Dam breach parameter selection guidance published in Chapter 2, Appendix II-A of FERC's Engineering Guidelines for the Evaluation of Hydropower Projects (FERC, 1993) is widely referenced as an acceptable method by regulating authorities and is provided in the following table.

Table 5-4 FERC suggested breach parameters

Parameter	Value	Type of Dam	
Average Width of Breach	BR= Crest length BR= Multiple slabs BR = Width 1 0r more Usually $\overline{BR} \leq 0.5W$ $HD \leq \overline{BR} \leq 5HD$	Arch Buttress Gravity Earth fill, rock fill	Definitions HD = Height of Dam Z = Horizontal component of side slope of brach BR = Average width of breach TFH= Time to fully form the breach W = Crest length
Horizontal Component of Side Slope of Breach	$0 \leq \mathrm{Z} \leq \text{slope of valley walls}$ Z=0 $\frac{1}{4} \leq Z \leq 1$	Arch Gravity, Buttress Earthen	
Time to failure (TFH) in hrs	$\mathrm{TFH} \leq 0.1$ $0.1 \leq \mathrm{TFH} \leq 0.3$ $0.1 \leq \mathrm{TFH} \leq 1$	Arch Gravity, Buttress Earthen	

Dam Breach Modelling

As pointed out in section 5.1, dam breach analysis is basically carried out to predict flooding conditions and resulting loss of life downstream of a dam in the event of breach. Consequently, the focus of dam breach modelling has traditionally been on the tools that produce the predictions of flood inundation.

According to Wahl (2010), three principal strategies for dam-breach flood modelling have emerged since the 1970s.

- The first strategy was to predict the breach outflow hydrograph directly and then use one of the available flood routing models to route that flood downstream so that flooding consequences could be determined.
- The second approach was to parameterize the breach so that its evolution through time could be described in relative simple mathematical terms, allowing the breach outflow hydrograph to be determined by combining the description of the breach development with a weir equation or other appropriate model for simulating the hydraulic performance of the breach opening.

Typical breach parameters determined were the maximum breach size, rate of breach development (or total time needed for full breach development), the shape of the breach, and a mathematical model for how enlargement takes place (e.g., linear increase of breach dimensions through time). In this second approach, breach parameters could be determined by several different means externally to the flood routing model, but determination of the breach outflow hydrograph took place in the routing model.

- The third approach is to use a combined model that simulates specific erosion processes and the associated hydraulics of flow through the developing breach to yield a breach outflow hydrograph. Early models that took this approach were run separately from flood routing models, with the breach outflow hydrograph provided as input to the routing model. There is work being done now to integrate breach modelling and flood routing capabilities into a single model.

In essence, dam breach modelling, therefore, can be divided into two categories, each of which has a number of models, tools, or equations, ranging from simple to advanced:

1. Tools that generate the dam breach peak discharge and hydrograph only; and
2. Tools that perform downstream flood routing using a one- or two-dimensional

   Hydraulic model.

Dam Breach Peak Discharge and Hydrograph Generation Tools

The first major task in dam breach modelling is the determination of the outflow hydrograph in the event of dam breach. A dam breach outflow hydrograph represents the sudden release of water from the impoundment due to a breach, followed by the draining of the reservoir. The volume represented by the hydrograph is the storage volume of the reservoir released during the breach. Factors that affect the shape of the breach include: size and shape of the breach, breach formation time, depth of water at the dam, volume of stored water, surface area of reservoir, shape of reservoir.

The essential characteristics of the breach outflow hydrograph that affect loss of life in a dam failure event are the

- magnitude of the peak discharge, which affects inundated area, and
- the time required for the flow rate to rise to the peak, which relates to available warning time (Wahl, 2010).

Several models have been developed over the years that relate dam breach outflow hydrograph (or breach peak flow) to simple reservoir characteristics such as reservoir volume and dam height. According to Wahl (2010), these models may be grouped in to five categories:

- **Regression Models for Peak Outflow:**
  These models rely on formulas that directly estimate the peak outflow discharge as a function of dam or reservoir properties. The formulas are developed by regression analysis of case study data from real dam failures. These formulae offer means to estimate the complete breach hydrograph if one assumes a hydrograph shape and know the volume of water to be released through the breach. The most commonly assumed hydrograph shape is triangular.

  The most widely applied peak-flow prediction equations include those of MacDonald & Lang ridge- Monopolies (1984), Costa (1985), and Froehlich (1995a). An analysis by Wahl (2004) found the Froehlich (1995a) equation to have the lowest uncertainty of the peak flow prediction equations available at that time.

  Advantages of this approach are its simplicity and quickness which makes it useful as a screening tool for analysing large dam inventories and offers a quick way to check the reasonability of results from other methods. Disadvantages of this approach are the fact that none of the equations include factors related to material edibility, and the time parameters predicted by these equations help define the shape of the hydrograph but do not fully answer the question of how much warning time is available prior to the release of peak outflow.

- **Analytical Models to Predict Peak Outflow:**
  These models are based on an equation or set of equations derived from the physics of dam breach erosion and hydraulics. An early example of such a model is the work of Cristiano, which can be argued to be the first physically based dam breach model. The model related the rate of erosion of the breach channel to the discharge through the breach, using an equation that accounted for the shear strength of soil particles and the force of the flowing water. Key assumptions were a trapezoidal breach of constant bottom width, side slopes of the breach determined by the angle of repose of the material, and bottom slope of the breach channel equal to the internal angle of friction. An empirical coefficient was critical to the model's performance (Fread, 1988).

- **Regression Models for Breach Parameters:**
  The breach formation process and the analysis of the flow through the beach are separated. This allows the flow problem to be handled analytically (e.g., treating the breach opening as a weir control), while the breach development problem, which is not as well understood, is handled with empirical regression models. The regression models are developed using case study dam failure data and predict parameters characterizing the breach development as a function of other dam and reservoir characteristics. This approach saves the dam break model from actually simulating the erosion processes by which the breach develops. The parameters describing a breach are typically taken to be the breach depth, width, side slope angle and formation time. As discussed in section. The four most widely used and accepted empirically derived enveloping curves and/or equations for predicting breach parameters are: MacDonald & Lang ridge – Monopolies (1984), USBR (1988), Von Thun and Gillette (1990), and Froehlich (1995a, 1995b, 2008).

  Advantages of the breach parameter approach to dam break modelling are that the analyst can exert some control over the breach parameters used in the dam break model, taking into account site specific factors such as an upper limit on breach width due to erosion resistant abutments. Weaknesses of the breach parameter approach are primarily the uncertainties of the predictions, which arise from a multitude of factors.

- **Erosion Models Leading to Parametric Breach Descriptions:**
  This approach to dam failure analysis uses a dam breach model that simulates specific erosion processes to define the development of the breach. The first widely applied and most well-known model of this type is the National Weather Service BREACH model (Fread 1988). Since the erosion processes are related to the flow through the breach, models of this type by necessity also predict the breach outflow, but they do so without incorporating some of the features of a dam-break flood routing model, such as tail water effects on the flow through the breach and dynamic effects on the flow within the upstream reservoir (most breach models have used level-pool storage routing through the reservoir). If these effects might be significant, then a hybrid modelling approach is possible. The erosion-based dam breach model is used to simulate the breach development and its results are used to construct a parameterized representation of the breach development process (i.e., to determine ultimate breach width, breach formation time, etc.). These breach parameters are then provided as input to the dam-break flood routing model, which can determine the breach outflow hydrograph itself, accounting for dynamic effects in the reservoir and downstream tail water effects.

- **Process-Based Dam Breach Models Integrated with Dam-Break Flood Routing:**
  The next step in the development of dam-break modelling technology is the integration of models that simulate embankment erosion and breach processes with the models used to route the resulting flood and determine downstream consequences. Wahl et al. (2008) described some of the erosion models being considered as part of one such effort. Just as previous advancements in dam-break flood modelling occurred when the process for determining the breach outflow hydrograph was subdivided into breach development and analytical hydraulics, the breach development process is being refined further by subdivision. The models under development now (Mohamed 2002; Temple et al. 2005) recognize different phases in the breaching process and also incorporate quantitative estimates of material erodibility into the modelling of each phase.

Dam Breach Flood Routing

General

The second major task in dam breach modelling, i.e., next to the determination of dam breach outflow hydrograph, is the routing of the breach outflow hydrograph downstream to evaluate the potential consequence of dam failure.

The routing of large floods is a well developed science. Great progress is also being made in this field, as geographic information technology and computing resources continue to improve, making more sophisticated flow modelling possible, and making it easier to integrate flow information with geographic information to simulate dam failure consequences.

Flood routing may be classified in to two broad classes: lumped and distributed (Fread D. L., 1992; Fread D. L, 1985). In lumped flow routing or hydrologic routing, the flow is computed as a function of time t at one location along the water. Hydrologic routing methods employ essentially the conservation of mass equation and flow/storage relationship. Typical examples of such methods include the Level Pool Reservoir Routing and the Muskingam River Routing methods. In distributed flow routing or hydraulic routing, the flow is computed as a function of time simultaneously at several cross-section along the water course. Hydraulic routing methods employ both the conservation of mass and moment balance equations. Typical examples include all those models that are based on de St Venant's & Shallow Water Equations.

In the literature a wide variety of lumped and distributed routing models are available. Selection of a particular model for a particular application depends on several factors including the accuracy of the model; accuracy required in the flow routing application; the type and availability of required data; available computational facilities and costs; familiarity with a given model, extent of documentation, range of applicability, availability of packaged routing model; complexity of the mathematical formulation if the routing model is to be totally developed from the scratch. In the following, hydraulic flood routing methods, applied to dam breach modelling is discussed.

Hydraulic Flood Routing

Generally, there are two different approaches to simulate hydraulically the flood inundation caused by a dam breach: one-dimensional (1-D) and two-dimensional (2-D) flood routing models.

One-Dimensional Modeling

The 1-D approach to flood inundation modelling only considers one dimension of the flood flow in the direction of x axis (the downstream direction). The unidirectional flow is best represented by the St-Venant equation used for calculating the 1-D dam break flood wave. With x as location measured from the dam section, t as time measured from the beginning of break, Q as discharge, v as cross-sectional average velocity, h as flow depth, A as cross section, So as bottom slope and Sf as friction slope, these equations are

$$\frac{\partial A}{\partial t} + \frac{\partial (Q)}{\partial x} = 0$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial h}{\partial x} = g\left(S_o - S_f\right)$$

The first equation is an equation for conservation of mass: while, the second represents the momentum balance equation. The first three terms in the momentum equations represent advective acceleration, convective acceleration and pressure respectively. The last term in the equation represent gravity (So) and frictional resistance.

The 1-D St-Venanat equation is also known as the **dynamic wave equation**. When the flow is assumed to be uniform and the friction slope is taken to be approximately equal to the bed slope, the 1-D Saint-Venanat equation simplifies to

$$\frac{\partial v}{\partial t} + v\,\frac{\partial v}{\partial x} = 0$$

This equation is referred as the **kinematic wave equation** and it is valid when the inertial acceleration is much larger than the other forms of acceleration. The dynamic wave model is used for modelling unsteady flood flows in modelling software including HEC-RAS, and Mike 11 HD; whereas, the kinematic wave model is used in such software as HEC-HMS.

The 1-D St Vennant equation or its simplified form is a hyperbolic partial differential equation. It is usually solved numerically subjected to appropriate initial and boundary condition. The two primary unknowns in these equations are the velocity v and flow depth h as functions of location x and time t. Finite difference, finite element, finite volume methods are commonly employed to numerically solve the equations.

1-D models have traditionally carried out Dam break routing. The modelling of the downstream river conditions requires knowledge of the lateral and longitudinal geometry of the stream and its frictional resistance. This determines how the peak of the flood wave is reduced as it moves downstream (attenuation), the travel time of the flood peak between points of interest, the maximum water stage at points of interest, and the change in shape of the hydrograph as it moves downstream. These effects are governed by factors such as: the channel bed slope; the cross-sectional area and geometry of the main channel, overbank, and backwater areas; the roughness of the main channel and overbank; the existence of storage of floodwaters in off-channel areas from active water conveyance areas; the shape of the flood hydrograph as it enters the channel reach, and the computational solution scheme.

Generally, 1-D models are best suited to geographic regions with moderate to steep slopes. In such regions, the floodwaters are contained or confined within a relatively narrow floodplain and generally the floodwater flow in the direction of a single stream line without major or frequent divergence of flow. Thus, the one-dimensional assumption is valid and may yield meaningful results.

One-dimensional models only provide a depth and discharge at computational cross-sections along the river. Although this process may be appropriate for confined alluvial floodplains/channels, errors in the unsteady simulation may be introduced in unconfined flat areas. In such cases, two-dimensional models, and coupled one- and two-dimensional models, which have the capability to route both channel flow (one-dimensional) and overland flow on flat terrain (two-dimensional) give better results.

Geographic regions with flat to mild slopes, areas of depressed terrain, poorly defined flow paths, alluvial fans, and fluvial areas typically exhibit unconfined floodplains whereby floodwaters are not contained within a well-defined floodplain and generally flow in multiple directions, often with frequently diverging and converging flows.

Several 1-D hydraulic models are available for dam breach flood routing. Table 5-5 lists some of the most widely used one-dimensional hydraulic models for dam breach simulation and downstream hydraulic routing of the flood wave. The table also provides a summary of the application, strengths, limitations and governing equations, of each model.

Table 5-5 One dimensional hydraulic models (FEMA P-946, 2013)

Model	Application	Strength	Limitations	Governing equations
USACE HECRAS	Recommended for detailed analysis and routing of the breach hydrograph	Considers effects of downstream obstructions such as backwater effects Output data can be input into GIS to produce inundation maps Allows dynamic reservoir routing	Labor intensive and time consuming Instability problems may arise	Governing equations vary depending on the assigned function. HEC-RAS can perform four functions: Steady flow routing Unsteady-flow routing Movable boundary flow for sediment transport analysis Water quality analysis
Win DAM B	Analysis of erosion in an earthen and vegetative spillway to determine the discharge capacity of the principal and auxiliary spillway Analyzes overtopping erosional breach using physical parameters	Erosion estimation based on geotechnical input parameters and condition of vegetation	Does not consider breach flow through erosion/failure of the auxiliary spillway	Routing Does not route breach hydrograph downstream and uses level pool routing for dam breach simulation.
NWS FLDWAV	Breach analysis for fair weather piping/internal erosion and overtopping breaches Can analyze flows in mixed-flow regimes in a system of interconnected waterways	Considers effects of downstream obstructions such as backwater effects	Calibration is time consuming Not adequate for all complex river conditions	Routing One-dimensional St. Venant equations User selects implicit dynamic wave, explicit dynamic wave, implicit diffusion wave, or level pool solutions of the St. Venant equations of unsteady flow

FEMA Geo-Dam BREACH Toolset	Simplified method to be used in initial analysis and non-regulatory studies	Simple and quick to use	Only conducts fair weather breach analysis	Uses principles established in the NWS SMPDBK Routing Dimensionless curves distinguished by the ratio of the volume in the reservoir to the average flow volume in the downstream channel governed by the Froude number Travel time of the peak flow Kinematic wave (steady-state) velocity
NWS SMPDBK	For use in emergency situations	Fast and easy to use	Not a nationally accepted, FEMA-supported hydraulic model Neglects backwater effects	Routing Dimensionless curves distinguished by the ratio of the volume in the reservoir to the average flow volume in the downstream channel governed by the Froude number Travel time of the peak flow Kinematic wave (steady-state) velocity

Two-Dimensional Modeling

One-dimensional models include mathematical simplifications related to the assumption that flood depth remains uniform over the entire cross-section. This assumption is not accurate for wide and flat floodplain areas. Two-dimensional models, use full dynamic or simplified forms of two-dimensional shallow water equations (SWE) to solve both one-dimensional channel flow and two-dimensional overland flow and are more appropriate for flat and wide floodplain areas.

In the 2-D approach, there are no cross-sections, as with 1-D modelling. Instead, the riverbed is defined by a network field, single grids or mesh, in which the shape can be square (cell based with regular elevation intervals) or polygonal (with irregular intervals) where each individual element has an associated elevation. The single grid has square fields (cells) with constant size, for example, 10 x 10 meters. The flexible mesh has an irregular representation that can be square, rectangular, triangular, or a combination of these shapes; also, the size of the shapes can vary. Typical modelling software used for calculating two-dimensional flood flows would include FLO-2D, Mike 21 HD, Mike Flood.

Within the 2-D computer model, water propagates by a cell to cell evaluation basis. In contrast to the 1-D model, the Manning coefficient can be variable and applied at every element location (cell). For example, if the element sizes are 5 x 5 meters, and if some elements have dense foliage, where others not, it is possible to define different Manning coefficients for the separate elements at as much as a 5 x 5 meter interval.

The 2-D modelling method is not constrained by the same limitations as the 1-D approach. The limitation to a horizontal water surface at the cross-section locations and the lack of exchange of momentum between the main channels and flooded areas, doesn't exist in the 2-D approach. Although the water surface is horizontal within an individual cell, when propagating from cell to cell along a cross-section, the water surface can oscillate according to the dynamics of the model. Also, the exchange of impulses between cells is possible, and therefore, the momentum exchange between the main channel and the flood area is possible.

Boundary Conditions

As partial differential equations, the 1D & 2D hydraulic routing models have to be supplemented with initial and boundary conditions in order to obtain unique solutions. Boundary conditions are generally required at each boundary node for the duration of the simulation. For 1D hydraulic models where flow conditions on the boundary are subcritical, two boundary conditions are required at the upstream (inflow) and downstream (outflow) boundaries. For supercritical conditions, two boundary conditions are required at the upstream boundary. Boundary conditions can be values of discharge or stage (water level) obtained from measured data, hydrological analysis, or others models, such as an embankment breach modelling.

The upstream boundary condition can be defined by a stage-storage relationship, or as a series of cross-sections cut through the reservoir. The downstream boundary conditions are not usually an important assumption because routing for risk informed decision-making should be continued far enough downstream where impacts are no longer significant. This point could occur when:

- There are no habitable structures, and anticipated future development in the floodplain is limited,
- Flood flows are contained within a large downstream reservoir,
- Flood flows are confined within the downstream channel, or
- Flood flows enter a bay or ocean.

Initial Conditions

Initial conditions consist of values of predicted variables (water level and velocity) at each node on the computational grid at the start of the simulation. The assumptions used for the initial reservoir water surface can either be specific to the failure mode being studied, consider a range of possible elevations or annual exceedance probabilities, or for preliminary or screening applications begin with the reservoir at the normal maximum pool elevation especially if there is no allocated or planned flood control storage (e.g. run-of-river). In risk informed decision-making, the best estimate should be used for the dam breach scenario being evaluated.

Inflow hydrograph, project discharge and concurrent flows

The inflow hydrograph is a straightforward assumption used in the model that is defined by the study's purpose. In risk informed decision-making, a range of inflows is usually considered in the analysis. The same can be said of the base flow condition assumed in the river reach being studied.

The dam's spillway and/or project discharge operations should be modelled as most realistically anticipated for the study's purpose. Debris loading or other spillway blockage situations may require artificially modifying the dam breach model's project discharge rating curve to compensate for the diminished spillway capacity. Gate operations should be modelled depending on normal and flood operation procedures in place at the project, or as described in the failure mode being investigated.

When routing a dam breach flood wave through the downstream floodplain, appropriate local inflows should be considered in the computations, as concurrent floods in a river system may increase the area flooded and also alter the flow velocity and depth of flow as well as the rate of rise of flood flows. These assumptions ultimately affect the estimation of downstream consequences and the levels of effort in determining these assumptions should be requisite to the level of detail required and include sensitivities as appropriate. This is an important issue that should be discussed in the scoping phase of the modelling process, so that all the parties are agreed on what assumptions are reasonable.

If historical records are available and the records indicate that the downstream tributaries are characteristically in flood stage at the same time, then concurrent inflows based on historical records should be adjusted so they are compatible with the magnitude of the flood inflow computed for the dam under study. For screening level and sunny-day EAP inundation mapping dam breach applications, the concurrent inflows may be assumed equal to the mean annual flood (approximately bank full capacity) for the channel and tributaries downstream from the dam. The mean annual flood can be determined from flood flow frequency studies. As the distance downstream from the dam increases, engineering judgment may be required to adjust the concurrent inflows selected.

Domino Failure Consideration

The possibility of a domino-like failure of downstream dam(s) resulting in a cumulative flood wave large enough to cause adverse impacts should be considered. If one or more dams are located downstream of the dam site under review, the dam breach failure wave should be routed downstream to determine if any of the downstream dams would breach in a domino-like action. While the flood routing of inflows through the dam being studied may be either dynamic or level pool, the routing through all subsequent downstream reservoirs should be dynamic. Tail water elevations should consider the effect of backwater from downstream constrictions.

Much like concurrent flows, described above in section 5.5, the introduction of downstream dam(s) to the model creates the need for numerous additional variables. If the downstream dam(s) is managed by a different entity than the one performing the dam breach analysis, these variables could be hard to estimate without consultation. This is an important issue that should be discussed in the scoping phase of the modelling process, so that all the parties are agreed on what assumptions are reasonable.

Dam Breach Inundation Mapping

Introduction

Dam breach inundation maps are maps that are produced to show geographical areas, which could be flooded in the event of dam breaching. The maps generally show the water depth or the water levels, and as appropriate flood arrival times & the flow velocities.

Although many dam safety regulatory bodies have produced important guidance on dam breach modelling, they have limited guidelines for developing inundation maps reflecting dam failure incidents. Where guidelines are available they are inconsistent in how a dam breach is modelled and how the results are shown on a map. In the following, the FEMA guidance for dam breach inundation mapping is summarized

Uses of Inundation Mapping

Inundation maps can have a variety of uses including emergency action plans, mitigation planning, emergency response, and consequence assessment.

Emergency Action Plans (EAP)

According to FEMA, an EAP is a formal document that identifies potential emergency conditions at a dam and specifies preplanned actions to be followed by the dam owner in coordination with emergency management authorities to minimize property damage and loss of life. The EAP usually includes inundation maps to assist the dam owner and emergency management authorities with identifying critical infrastructure and population-at-risk sites that may require protective measures and warning and evacuation planning. Since EAP maps are intended to be used in an emergency, it is critical for these maps to be easily reproducible without loss of critical information.

Emergency Response

Emergency response embodies the actions taken in the immediate aftermath of an incident to save and sustain lives, meet basic human needs, and reduce the loss of property and the effect on critical infrastructure and the environment. Actions may include warning and evacuating the population at risk. Given the short warning times typically encountered with dam failures and incidents, dam emergency evacuation plans should be developed before the occurrence of an incident. It is recommended that plans be based on a worst case scenario and address the following elements, including identifying the roles and responsibilities for all action items:

- Identification of critical facilities and sheltering
- Initiating emergency warning systems (who is responsible and what is the method)
- Specific evacuation procedures, including flood wave travel time considerations (for example, evacuation of special needs populations and lifting evacuation orders)
- Distance and routes to high ground

- Traffic control measures and traffic routes
- Potential effect of weather or dam releases on evacuation routes (for example, identify whether portions of the evacuation route may be flooded before the dam incident occurs)
- Vertical evacuation/sheltering-in-place
- Emergency transportation
- Safety and security measures for the dam perimeter and affected areas
- Re-entry into affected areas

Since inundation maps included in the EAP may help in developing the warning and evacuation plans, they should be shared with emergency management authorities.

Hazard mitigation Planning

Mitigation is the proactive effort to reduce loss of life and property by lessening the effect of disasters. This is achieved through identifying potential hazards and the risks they pose in a given area, identifying mitigation alternatives to reduce the risk, and risk analysis of mitigation alternatives. The result is the selection of proactive measures, both structural and non-structural, that will reduce economic losses and potential loss of life when implemented. In the case of dam failures and incidents, hazard mitigation planning involves identifying the population at risk and identifying actions to reduce their vulnerability.

Hazard mitigation planners need digital data that defines the dam breach hazard. Information needed includes the breach inundation zone boundary, depth of flooding, velocity, and timing.

Dam Breach Consequence Assessment

Dam breach consequence assessment includes identifying and quantifying the potential consequences of a dam failure or incident. While hazard mitigation planning focuses on specific projects to reduce flood risk, consequence assessment focuses on the economic and social impacts of a potential disaster and the organizational and government actions needed in the aftermath of a dam breach to respond and recover. Data compiled for a consequence assessment can also be used in risk assessments. Consequence assessment requires the same basic data as used in hazard mitigation planning, with the addition of data related to communicating the hazard to community elected officials and the public. Advanced mapping products that allow state-of-the-art visualization is key to communicating the hazards and consequences of a potential dam failure.

Mapping guidance

Recommended Inundation Map Elements

Map Collar Information

Latitude and longitude coordinates can be referenced at the corners of the neatline. Other useful information displayed on the map collar8 can be horizontal reference grid ticks (e.g., Universal Transverse Mercator or State Plane) to help orient map users to real world coordinates. Adjacent map panel numbers should also be listed along the neatline borders that correspond with adjacent map panels.

Base Map Data

Base map data provide the background from which inundation hazard information is overlaid and interpreted. Clear, easy-to-interpret base maps are critical for the effective use of an inundation map.

Inundation Polygons

The key information on an inundation map is provided by one or more inundation polygons that define the horizontal limits of the inundated area for one or more breach events. The inundation polygons show the intersection of the peak water surface elevations from the dam breach model with the ground elevations from the terrain source. If multiple breach events will be shown on the inundation map, the polygon representing the event that would result in smallest inundation area should be displayed on top of those representing events with larger inundation areas.

Inundation Elevations

Inundation elevations can be annotated at key locations along the inundation polygon if desired. The inundation elevations can be extracted directly from a dam breach model. Elevations are not always a critical element for an inundation map. Emergency responders are primarily interested in the extent and depth of inundation rather than the elevation of flooding. Elevations may be important for flood warnings, however, particularly if early warnings are possible.

Flood Wave Arrival Time

Flood wave arrival times can be annotated at key locations along the inundation polygon if desired. The flood wave arrival time is the time (usually in minutes) from dam breach initiation until the leading edge of the inundation arrives at a specific location.

For a fair weather failure, the arrival time can be considered the first time that a notable change in the base flow is observed. For a hydrologic failure event, the arrival time is best determined by comparing two simulations for the same hydrologic event. The first simulation would be a non-breach hydrologic event, while the second simulation would be the exact same hydrologic event but with the dam breaching. The downstream hydrographs of both events can be overlaid to identify what time the effects of the dam breach would be first observed. The separation of the two hydrographs at the point of interest indicates the effects of the dam breach at that location. The arrival time for hydrologic events is normally defined as the time lapse from breach initiation until the differential stage for with- and without-failure simulation for the river or creek to exceed a defined depth, typically 0.3 or 0.6m.

Table 5-6 shows the recommended intervals for flood arrival times that should be included on inundation mapping, although judgment should be applied when selecting mapped intervals and should be commensurate with the population at risk and map scale.

Table 5-6 Time intervals to include on inundation maps

Time after Breach	Mapped Arrival Time Intervals
0-30 minutes	5 minutes
30-90 minutes	10 minutes

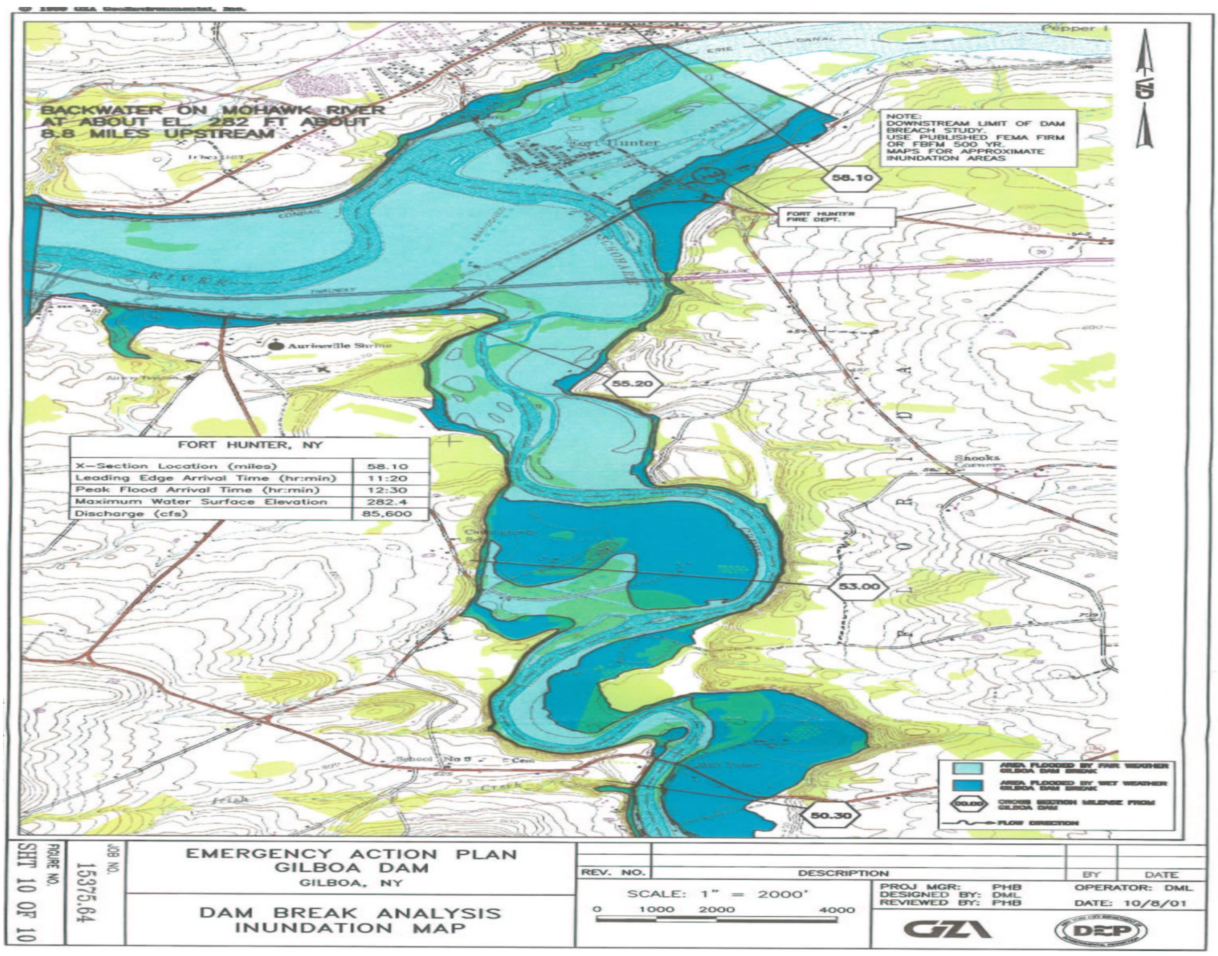


Figure 5-9 Sample Inundation map

Recommended Format of EAP Inundation Maps

EAP inundation maps must be developed with the anticipation of being widely used in the field by emergency responders in the event of an EAP being activated. Hardcopy maps are typically preferred by emergency responders; inundation maps should always be printed when creating an EAP to avoid relying on power and printing technology that may not be available to print the maps in an emergency situation.

Printing Considerations: Hardcopy maps should be uncluttered and easy to read. Only the most relevant information for field use should be provided on the maps. Although maps of larger size can be created, 8½×11 inch or 11×17 inch sizes provide a map that is easily reproduced by most modern photocopy machines. Since most EAP activations occur as a result of hydrologic events, lamination of hardcopy maps can make them more resistant to water and general wear and tear when being used in severe weather conditions.

Maps can be printed in colour, allowing an emergency responder to see the most detail; however, maps should also be tested using black and white copiers to ensure the maps still communicate the same information if only black and white copiers are available. To ensure that orthophotographic base maps can be easily reproduced in black and white without overpowering overlaid features such as inundation polygons, the brightness of the base map should either be increased or alternatively, the imagery should be made approximately 50% transparent.

Mitigation planners may use EAP maps, but they may wish to overlay additional features such as political boundaries, population data, or zoning information. Additionally, mitigation-planning discussions often require large-sized maps suitable for workshops and presentations. In these cases, digital inundation maps or hardcopy maps printed on full size (24×36 inch or larger) sheets are typically preferred.

Title Block Information: an index map to allow the user to know the location of the panel in relation to other map panels should link every map. The title block on each map panel should contain the following information:

- Title of the map referencing the EAP and inundation scenario
- Index map for all multi-panel map schemes
- North arrow
- Map scale bar
- Legend identifying all critical map features
- Vertical elevation datum reference (if elevations are
- Date of map creation

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MODULE 6

Safety Considerations in Planning, Design, Construction & Operation

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SAFETY CONSIDERATIONS IN PLANNING, DESIGN, CONSTRUCTION & OPERATION

The purpose of this Module is to provide insights into potential failure modes that should be considered in safety evaluations of EN dams. The discussions refer mainly to conditions in constructed dams but these should be applied in all stages of dam planning, design, construction and operation.

This section presents summary reviews of several of the most frequently occurring dam safety issues in terms of potential failure modes. These summaries are extracted from the USBR/USACE Best Practices Manual as indicated in the heading to each section of this module as BP XX and are for the purposes of general training guidance only. A recent set of chapters in the full manual are listed as References at the end of this Module and included in full in the References on the DVD accompanying this Module. These full manual sections include more details of the selected safety issues as well as other safety issues which should be considered in any applications to safety assessments.

Potential Failure Modes Analysis (BP 01, 02)

Key Concepts

Identifying, fully describing, and evaluating site-specific potential failure modes in the framework of a Potential Failure Modes Analysis (PFMA) are usually the most important steps in conducting a risk informed dam safety assessment. This forms the basis for risk evaluations and event tree development should that be utilized.

PFMAs should be performed at critical stages of design, construction, operation and/or modification of dams.

An adequate job of identifying potential failure modes can only be performed after thoroughly reading all relevant background information on a dam, including geology, design, analysis, construction, flood and seismic loadings, operations, dam safety evaluations, and performance and monitoring documentation. Photographs, particularly those taken during construction or unusual events, are often key to identifying issues related to potential failure modes. It is essential that the records be diligently collected and reviewed, even if those involved have familiarity with the project, as something might have been missed in previous reviews.

A site examination should also take place. The examination team should be looking for clues as to how the dam and facilities might be vulnerable to uncontrolled reservoir release. Operations personnel should be involved in the examination, and queried as to how they handle flood operations and other unusual incidents. They should also be asked their opinion as to where the vulnerabilities lie.

More than one qualified person should take part in the data review and examination activities, as one person might uncover something that another might miss. The interaction of disciplines often reveals vulnerabilities that would otherwise be missed.

First hand input from operating personnel is essential to the process of identifying and understanding potential failure modes. This usually occurs at the examination and initial meeting. For team facilitated risk analyses, operating personnel are typically part of the risk analysis team.

It is important to include, but also think beyond the traditional "standards-based" analyses when identifying potential failure modes. Some of the more critical potential for uncontrolled reservoir release may be related to operational issues.

Identifying and Describing Potential Failure Modes

Identifying potential failure modes is done in a facilitated team setting, with a diverse group of qualified people. The facilitator must be a senior level registered engineer with many years experience in dam design, analysis and construction. The facilitator must have participated in several failure mode and risk analysis sessions before facilitating a session. It is important to take a fresh look at the potential failure modes, and not just default to those that may have been previously identified.

The facilitator elicits "candidate" potential failure modes from the team members, based on their understanding of the vulnerabilities of the dam and project from the data review and field conditions. It is often useful to "brainstorm" potential failure modes, then go back and evaluate each one.

The first step following the brainstorming session is to identify those potential failure modes that are not expected to contribute significantly to the risk associated with the dam. The team should discuss and agree on those that potentially contribute the most to the risk. These are often referred to as "risk-driver" potential failure modes. It should not be just one person's opinion, nor should the team just accept the previous failure mode screening.

Once the risk-driver potential failure modes have been identified, it is the facilitator's role to ensure the potential failure modes are completely described. It is important to put scale drawings or sketches up on the wall, and sketch the potential failure modes during the discussions.

The potential failure modes must be described fully, from initiation to breach and uncontrolled reservoir release. There are three parts to the description:

The initiator: For example, this could include increases in reservoir due to flooding (perhaps exacerbated by a debris-plugged spillway), strong earthquake ground shaking, malfunction of a gate or equipment, deterioration, an increase in uplift, or a decrease in strength.

Failure progression: This includes the step-by-step mechanisms that lead to the breach or uncontrolled release of the reservoir. The location where the failure is most likely to occur should be also be highlighted. For example, this might include the path through which materials will be transported in a piping situation, the location of overtopping in a flood, or anticipated failure surfaces in a sliding situation.

The resulting impacts: The method and expected magnitude of the breach or uncontrolled release of the reservoir is also part of the description. This would include how rapid and how large the expected breach would be, and the breach mechanism. For example, the ultimate breach from a piping failure mechanism adjacent to an outlet conduit might result from progressive sloughing and unraveling of the downstream slope as a result of flows undercutting and eroding the toe of the dam, until the reservoir is breached at which point rapid erosion of the embankment remnant ensues, cutting a breach to the base of the conduit.

The reasons for completely describing the potential failure modes are: (1) to ensure the team has a common understanding for the follow-on discussions, (2) to ensure that someone picking the report up well into the future will have a clear understanding of what the team was thinking, and (3) to enable development of an event tree or other means of estimating risks, if warranted.

Evaluating and Screening Potential Failure Modes

Adverse and Favorable Factors

After the team has completely described a potential failure mode, it is then evaluated by listing the adverse factors that make the failure mode "more likely", and the favorable factors that make the failure mode "less likely". These are based on the team's understanding of the facility and background material. The facilitator captures these in bullet form on a flip chart. However, these must also be fleshed out in the documentation so that someone picking up the report in the future will understand what the team was thinking. It is the facilitator's job to review the report and ensure that this happens.

Consequence Review

Although a detailed consequence evaluation will be performed as part of the risk analysis (see Section on Consequences of Dam Failure), an initial review is performed to get a general sense of how significant the downstream hazard is. This is done in two parts.

The first part is the downstream impacts of the given potential failure mode; the second part relates to factors specific to the potential failure mode in terms of how quickly it might progress, whether a partial or full breach is more likely, or other site specific attributes. The following paragraphs illustrate these two components.

Risk Screening Of Potential Failure Modes

Once all the adverse and favourable factors that the team can think of have been collected, and the consequences have been reviewed, each potential failure mode is screened to determine its potential contribution to the risk. It is helpful to use the semi-quantitative matrix approach (described later in this manual) to get a sense of the risks associated with each risk-driver potential failure mode. This can be useful in identifying risk reduction actions, monitoring improvements, and additional data or analyses that could be useful in better defining the risks. In addition, quantitative risk analyses can be quite expensive and time-consuming, and such a screening exercise will help focus any quantitative risk analyses on only the failure modes potentially critical in terms of risk guidelines.

Potential Failure Modes Considerations

A list of issues related to potential failure modes that have been identified in past potential failure mode analyses is provided below. It is not an exhaustive list, nor have the descriptions been fleshed out to the extent needed in the documentation. This must be done on a case-by-case basis. However, the list provides food for thought in conducting a potential failure mode analysis.

- Discharge capacity is reduced during flooding by flows that take out power plant transformers (eliminating the ability to generate and discharge through the units), power supplies to gates, or access to open gates, leading to premature overtopping.
- High tail water floods the power plant and leads to loss of release capacity through the units, resulting in premature overtopping.
- Loss of power or communications due to lightning, earthquake shaking, or other causes leads to gate misoperation, and overtopping or life-threatening downstream releases.
- Binding of gates (possibly due to ASR concrete expansion) or mechanical failure can lead to inability to open gates and premature overtopping.
- Spillway discharge capacity is reduced when the reservoir rises to levels not envisioned in the original design and impinges on the bottom of open gates, transitioning from free flow to orifice flow, leading to overtopping.
- Opening the gates in accordance with the Standard Operating Criteria rule curves would flood people out downstream and there may be reluctance on the part of the operators to do this, which in turn could lead to a delay in releases and premature overtopping of the dam.
- Faulty instrumentation could indicate reservoir levels and flows are within normal ranges, but dangerous inflows, outflows, or water levels are developing.
- Overtopping of concrete dams may be acceptable and advisable. The quality of the rock on which the flows impinge must be evaluated.
- Careful attention must be paid to the flood routings. In some cases the dam crest may lower than assumed or shown on the drawings, crest elevations may vary between reservoir impounding structures, or the elevation of a single structure may vary, creating a flow concentration possibility.

Consequences Assessment (BP 09)

Introduction

Flood water can be one of the most destructive forces on earth, especially if caused by an event that unexpectedly overwhelms an existing flood defence infrastructure or by catastrophic breach of a dam or levee. Recent events, such as flooding caused by Hurricane Katrina in the USA and the tsunami in Japan, have caused thousands of people to lose their life and unknown billions of dollars in damages.

By the same token, dozens of floods (some from similarly unexpected events like a dam or levee breach) occur every year with no resulting loss of life and relatively minimal property damage.

Although flooding can have many types of severe consequences, including economic, social, cultural, and environmental, the primary objective of dam safety programs are to manage the risk to the public who rely on those structures, and to keep them reasonably safe from flooding.

Thus, reducing the risk associated with loss of life is paramount. The safety program treats life loss separately from economic and other considerations.

Decisions as to whether invest in dam or levee improvements are based primarily on risk to life by applying the concept of tolerable risks. Since informed decisions based on tolerable risk require estimates of loss of life for potential flood events, the focus of this chapter is on estimating loss of life.

Estimation of the magnitude of life loss resulting from a flood requires consideration of the following factors:

- The potential failure mode for the dam or levee
- The assumed breach parameters
- The intensity and extent of downstream flooding
- Flood wave travel time
- Assumptions of warning and evacuation
- Estimation of the downstream population at risk
- Estimation of fatality rates

The full consideration of all these factors is a complex problem that requires detailed modelling of the physical processes (breach characteristics and flood routing), human responses, and the performance of technological systems (such as warning and evacuation systems, transportation systems and buildings under flood loading).

This chapter describes a range of practical approaches to this complex problem that can provide life-loss estimates for use in risk informed decision-making.

Consequences Methodologies and Perspectives – USACE and Reclamation

Both the U.S. Army Corps of Engineers (USACE) and the Bureau of Reclamation (Reclamation) perform risk analysis for the dams or levees (USACE only) contained within each agency's portfolio. While the basic concept of using life loss estimates to help quantify risk is similar, the methodologies employed by the two agencies have agencies, and is structured in a way that presents general information on life loss estimation, followed by agency-specific subsections.

Life loss estimation models currently in use by USACE include the LifeSim model and HEC-FIA, which contains a simplified version of LifeSim. Importantly, since the simplified LifeSim methodology in HEC-FIA is derived from the LifeSim approach, a specific application of HEC-FIA can be scaled up to a full LifeSim application by developing and gathering the necessary supplemental data.

LifeSim is a simulation model that tracks the movement and severity of flooding through time. It includes an integrated transportation algorithm to model the evacuation process, and evaluates loss of life based on location of people when the water arrives and important factors related to building, vehicle, and human stability. Grouping people into one of three "zones" estimate fatalities. Each zone has a corresponding fatality rate, which were developed based on an extensive review and analysis of historic flood events.

HEC-FIA includes a simplified version of the LifeSim methodology. Applicability of HEC-FIA depends on the goals of the assessment as well as the characteristics of the study area. The main differences between the simplified LifeSim methodology applied within HEC-FIA and the LifeSim methodology include simplifying assumptions related to evacuation simulation, influence of velocity on loss of life, and how flood wave arrival times are determined. Grouping of persons into zones and application of fatality rates is similar to the full LifeSim model.

More details on the difference between LifeSim and HEC-FIA life loss methodologies are described in the USACE Loss of Life Estimation Methodology section later in this chapter.

Reclamation currently uses the DSO-99-06 method for the vast majority of life loss assessments. DSO-99-06 is based on case history data and judgment. Fatality rates are developed using key parameters including warning time and flood severity. The method is relatively simple to apply. Reclamation has also been developing capability with the Life Safety Model. Similar to the LifeSim model used by USACE, the Life Safety Model is a simulation model which tracks movement of water and movement of people. Fatalities are estimated based various factors including building destruction, vehicle toppling and drowning. The Life Safety Model has an integrated transportation model, but does not use empirical-based fatality rates.

All flood disasters are unique in many ways. However, there are a few commonalities that are consistent across most flood scenarios when it comes to how many people lose their life. These common factors include the intensity of the flooding and the time available for warning and evacuation.

Estimation of Downstream Population at Risk

Life loss estimates are based on some assumption of the number of people that are present in the flood zone. There are different life loss estimation methods that take various approaches to how they develop fatality estimates, but one thing these methods all have in common is that they require an initial estimate of PAR. At a very basic level, the development of a PAR estimate can be as simple as visiting a site below a dam or levee and counting houses in the inundation zone.

One of the online map services such as Google Maps, Google Earth or MapQuest can also be used to count inundated houses.

Typically in the USA PAR is estimated using the U.S. Census data. Often, PAR estimates are based on residential PAR. The most accurate data for residential PAR estimation is at the level of the census block. The flood inundation boundary can be overlaid with the census block data in a GIS, and the number of inundated PAR households can be calculated. Partially inundated census blocks must be treated separately. If the residences are evenly distributed within the partially inundated block, a percent-inundated estimate can be applied to the total number of households within that block. If the distribution of residences within a partially inundated block is more concentrated in specific locations, then an approach would be to manually count the houses in the inundation zone. Finally, the total number of inundated residences is multiplied by an average household size that is specific to the area of interest, to obtain the estimated residential PAR.

The use of residential PAR for life loss estimation is a simplifying assumption. If more detailed information is known about where people may be located during daytime hours, must be taken though, not to double count PAR when looking at non-residential PAR distributions. A good example of this is a Reclamation Dam that has a mill operation located immediately downstream. The mill has maybe 400 employees present during daytime hours. The proximity of the dam to these employees puts them at the highest level of risk in the event of dam failure. It is unknown however, where the residences of these employees are located. Some may live in the flood zone at locations further

downstream, and because of this they may be double counted. In this case though, the fatalities close to the dam can be assumed to be high and persons living downstream in the floodplain are assumed to have much more time to evacuate, so that the issue of potentially double counting is not considered to be introducing major errors. Double counting of PAR when considering non-residential situations should be evaluated on a case by case basis to avoid the possibility of overestimating fatalities.

Another type of PAR that is frequently estimated is recreational or transient PAR. This would include persons occupying campgrounds, fishing, boating or hiking along a river, etc. Recreational PAR estimates can be obtained through site visits and/or by consulting with land use and recreation management groups who oversee these areas. In some cases, visitation numbers data may be available, or in other cases, campground hosts or park rangers may have a general idea of user numbers. Typically, recreational PAR will vary by time of year and day of week, with great numbers in the summer months and on weekends. Day use areas will of course have higher PAR during daytime hours, with low or no PAR present during the evening.

Warning and Evacuation

In the most ideal situation, a dam breach in progress would be detected, well in advance of the beginning of catastrophic outflows, warnings and a strong evacuation order are issued to downstream PAR without delay, and all of the PAR moves safely out of the flood zone by the time flooding arrives in downstream areas. Unfortunately, dam failure and flash flood case histories have shown that things don't always go that smoothly. The sequence of events that takes place is often a mix of physical and social phenomena, combined with a dose of luck or chance.

The issuance of warning and the decision of downstream PAR are critical factors that impact the potential for life loss. Flood wave travel times provide an estimation of arrival time for flooding and can be used as a basis for warning time assumptions in cases where warning is issued after the beginning of flood releases.

Past dam break flood instances show that, in general, the number of fatalities decreases as the distance downstream increases, but increasing distance by itself is not what decreases the life loss potential. Potential life loss decreases when the travel time begins to exceed the amount of time required to warn and evacuate the population at risk. A combination of breach development rate and flood wave velocity determines the flood wave arrival time for a given distance. Then, the distance to a safe haven, the escape route capacity, and various human perceptions and choices determines who might be caught within inundation boundaries when the flood arrives. Another attribute of increasing distance is the attenuation (reduction) in flow that occurs. However, flow depths and velocities can increase downstream if the flood plain transitions from a wider valley to a narrow canyon.

Warning time is broken into stages: detection of the threat, decision to issue warning, notification of the downstream PAR, and warning dissemination. Detection of a developing dam failure situation could be by automated instrumentation or by routine visual inspection by project personnel. Quite often, in seepage-related incidents, a hiker or fisherman raises the initial alarm. After the unusual situation is noticed, some time is required before project and emergency preparedness personnel assess the situation and decide that there is a reasonable chance it will develop into a condition that cannot be controlled. Then, the notification of those responsible for spreading the warning can take some time. The actual warning to the population at risk can be transmitted many ways, each with its own degree of effectiveness. The wording of the warning message can itself be important, either giving people a strong perception of the danger or not. Warning can also spread by word-of-mouth through friends, family, neighbours, and concerned citizens. People who are at risk, but are not warned verbally, can still perceive danger by hearing an unusual sound or seeing a rapidly rising flow.

Estimation of the warning and evacuation process may include consideration of the following issues:

- Failure of the dam or its impending failure may need to be verified before warning is issued.
- The decision to order evacuations must be made. There can be issues related to public trust or potential liability that may delay issuing an evacuation order.
- People may receive warning or an order to evacuate, but may delay evacuation or may choose not to leave at all. The timeliness of evacuation has been found to be related to how serious the risks are perceived by the public. To some degree, this perception of the seriousness of risk has been tied to the quality or forcefulness of the warning that is received.
- Persons who do not attempt to evacuate or who attempt to evacuate at the last minute can be placed in critical situations where a number of factors may influence their survival. The flood depths, the intensity of flooding (often quantified as depth times velocity, DV), the strength of a shelter, and a person's physical condition will influence the survival chances of PAR exposed to flooding.
- Some people may not receive warning.

- Some people may choose not to evacuate. Reasons for this include: warnings may not be taken seriously; elderly persons or disabled persons may have too much difficulty attempting to evacuate; people may not evacuate for fear of looting; people may not believe that the flood impacts will be severe enough to endanger them; people delay evacuation to protect personal property such as pets or livestock.
- Densely populated urbanized areas need more time to evacuate. These are special situations where traffic congestion may play a role in the ability to evacuate. Persons attempting to evacuate in advance of flooding may get stuck in traffic, resulting in exposure to flooding. In many situations, evacuating to a large, sturdy building, or staying in one's home may be safer than attempting to leave the area in a vehicle. The existing body of case histories from dam failure and other types of flooding does not contain a contemporary case where evacuation was hampered by traffic congestion. Note that life loss simulation models such as address traffic congestion issues during flood events.
- Economic demographics can play a role in whether people will evacuate - During Hurricane Katrina many of the poorest people did not leave New Orleans simply because they did not have a car, had no money and/or had no place to go.

Case history data provides some examples of human behaviour in relation to flood risk and evacuation:

- The failure of the Macchu II Dam in India in 1979 killed as many as 25,000 people. Once warned, some people didn't leave because they lived above the highest flood levels that had occurred during their lifetime.
- Teton Dam failure in 1976 (11 fatalities) and Lawn Lake Dam failure in 1982 (3 fatalities) both contained fatality incidents where people who had safely evacuated re-entered the flood zone to retrieve possessions, thinking that they had more time before the arrival of flooding.
- The eruption of the Nevado del Ruis volcano and the deadly lahar mudflow flood at Armero, Columbia in 1986 killed about 22,000 people. Most residents of Armero didn't evacuate because the severity of risk was downplayed by local officials.
- St. Francis Dam failed in 1928, killing more than 400 people. Some who heard the approaching flood waters could not conceive of a dam failure flood and thought the sounds to be due to a windstorm.

Experience indicates that there is sometimes a reluctance to issue dam failure warnings. The operating procedures or emergency actions plan that may be available for a dam or levee should provide some guidance regarding when a warning would be issued. There is no assurance, however, that a warning would be initiated as directed in a plan. A study investigating loss of life from dam failure can be used to highlight weaknesses in the dam failure warning process and provide some guidance on how improvements in the process would reduce the loss of life. Sensitivity analysis should be used to provide information on how significant warning issuance is to the uncertainty in a life-loss estimate.

For most breach mechanisms where the breach progression is observable prior to catastrophic failure of the dam or levee, the time when a warning is issued should be determined by first estimating the time when a major problem would be acknowledged relative to the time of dam failure. The major problem acknowledgment time for these failure modes is the time when a dam owner would determine that a failure is likely imminent and they would decide that the dam breach warning and evacuation process should be initiated by notifying the responsible authorities. The time lag between major problem acknowledgement and when an evacuation order would pass from the dam owner to the responsible emergency agency (EMA) and then from the EMA to the public should be estimated based on the judgment of dam operations personnel and emergency management personnel who have jurisdiction in the areas of each downstream community.

The amount of time it takes from when the evacuation warning is issued by the responsible agency (warning issuance) until the population at risk receives that warning is dependent on the warning system or process that is used to disseminate that warning. A typical warning would be received by the population through various means. For example, the first group of people would typically receive warning through the primary warning process (e.g. Emergency Alert System), but then a secondary warning process would begin that includes emergency responders and the general population spreading that warning via word of mouth.

Hydrologic Failures/Overtopping (BP 07, 16)

Flood Overtopping Failure of Dams and Levees

Historically, dam and levee design and analysis methods have focused on selecting a level of protection based on a particular frequency or loading event. Traditionally, the protection level for dams is based on the Probable Maximum Flood (PMF) (Cudworth, 1989; FEMA, 1998) for High Hazard Potential Dams; the design level for levees used various methods including the Standard Project Flood (SPF), the historical flood of record, or a return frequency.

Risk informed decision making is currently used to assess the safety of dams and levees, recommend safety improvements, and prioritize expenditures in more recent years risk analysis has started to be implemented on the nation's levees. Risk estimates, from a hydrologic perspective, requires an evaluation of a full range of hydrologic loading conditions and possible failure mechanisms tied to consequences of failure.

The flood loading input to a dam safety risk analysis is a hydrologic hazard curve (HHC) that is developed from a Hydrologic Hazard Analysis (HHA). Hydrologic hazard curves combine peak flow, reservoir stage, and volume probability relationships plotted against Annual Chance Exceedance (ACE) or the equivalent Annual Exceedance Probability (AEP). These terms are used in lieu of the "100-year flood"; see Stedinger et al. (1993) and Holmes and Dinicola (2010) for definitions. The range of ACEs or AEPs that is displayed will depend on the data available for the study location, and the needs of the risk team and agency.

Overtopping flow is a component event of many or even most potential failure modes resulting from floods. Dams and levees have been overtopped by a few inches to more than a foot without breaching, but other structures have failed quickly. Overtopping is a failure mode of concern since Costa (1985) reported that of all dam failures as of 1985, 34% were caused by overtopping, 30% due to foundation defects, 28% from piping and seepage, and 8% from other modes of failure. Costa (1985) also reports that for earth/embankment dams only, 35% have failed due to overtopping, 38% from piping and seepage, 21% from foundation defects; and 6% from other failure modes.

Key Concepts and Factors Affecting Risk

Type of Dam or Levee

Materials for dams and levees range from earthen and/or rockfill embankments to various types of concrete dams. Embankment dams typically cannot withstand any significant amount of overtopping, due to limited erosion resistance of the soil material used in their construction. The amount of erosion is dependent on the quality and type of vegetation cover, material in the embankment, depth, and duration of the overtopping flow.

Concrete dams are generally perceived to be more resistant to overtopping failure, due to the durability of the dam itself as well as the erosion resistance provided by a rock foundation. However, weak and fractured rock may be susceptible to significant erosion during overtopping flows, and if foundation support is lost due to overtopping erosion, the dam could be lost.

Levees typically are earthen embankments constructed from a variety of materials ranging from cohesive to cohesionless soils. The factors influencing the erosion are similar to those for earthen dam embankments.

For floodwalls the factors influencing the overtopping are similar to concrete dams but a much smaller scale in terms of head for wall stability, under seepage and energy of overtopping flows.

Type of Overtopping

Dams and levees can be overtopped with a continuous flow when the pool elevation or river elevation exceeds the low portion of the dam or levee. For these cases the computation of the depth and duration of flow can be relatively easy depending on the information available for the specific project.

For overtopping by waves, the water surface elevation approaches but does not exceed the low point in the elevation profile. Instead waves driven by wind produce waves that run-up and overtop the top of dam or levee. The wave action can form an “equivalent” discharge per liner foot of the structure and can lead to the erosion and potential failure of the structure. Waves are influenced by wind speed, wind direction, bathymetry, open water distance, and embankment slopes. (USACE, 2002)

Erosion Process

The erosion process is described in the chapter for Erosion of Rock and Soil but items specific to embankments will be included here. In general, the most erosive flow occurs on the downstream slope, where the velocity is highest and where the slope makes it easier to dislodge particles and move them away. On embankments that have been overtopped by floods, severe erosion has often been observed to begin where sheet flow on the slope meets an obstacle, such as a structure, a large tree, or the groin; a break in slope occurs; a change in material type, or vegetation is not uniform or soil is bare creating local turbulent flow. Based on the four phase erosion process in the chapter for Erosion of Rock and Soil, areas where vegetation has been removed or sparse, the erosion will proceed to attack the soil directly until a “headcut” or overfall is formatted. Erosion generally continues in the form of "headcutting," in an upstream progression of deep eroded channel(s) that can eventually reach the reservoir. For embankments made from cohesionless material a headcut may form or concentrated flow will erode a gully more uniformly.

In the case of an embankment dam, erosion of the soil comprising the embankment can ultimately lead to dam failure. For cohesive soils, the failure mechanism is typically headcut initiation and advance. A small headcut is typically formed on the downstream slope of the dam and then advances upstream until the crest of the dam is breached. For cohesionless soils, the failure process typically initiates as a result of tractive stresses from the flow removing material from the downstream face, but then progresses as headcut advance once a surface irregularity is formed. Predicting whether breach initiation and formation will occur can be a complicated procedure.

Pavement on the crest may be of some value in slowing uniform erosion of cohesionless materials once the gullies reach the crest, but should not be expected to affect initiation. Depending on the depth of the headcut, the headcut can actually undermine pavement leading to a mass wasting of the pavement material as cantilevered section collapse into the headcut.

In the case of a concrete dam, the erosion resistance of the foundation rock is typically the key to the likelihood of failure. The likelihood of rock erosion can be estimated using the methods described in the section on Erosion of Rock and Soil. If various weathering horizons or rock types exist in the abutment or foundation, the evaluation will need to be done for each. If significant depth of erosion is needed for undermining, it may be necessary to re-compute the erosion potential for various depths of erosion to obtain an indication of how deep the erosion is likely to go. If significant abutment erosion occurs, support for the dam may be compromised. It would be necessary to evaluate the potential for enough erosion to occur such that support for the dam would be lost for each pool loading.

If a parapet wall is provided on the embankment dam crest across the entire length of the dam, dam overtopping will initiate when the reservoir water surface exceeds the elevation of the top of the parapet wall. Parapet walls are typically designed to contain waves that might overtop the dam and may need to be evaluated for a sustained water load (considering instability of the wall and blowout at the toe of the wall for loads part way up on the wall). If a parapet wall overtops, the impinging jet from overtopping flows of the wall fails, the depth of flows overtopping the dam crest will be significant and breach may occur quickly.

Dam Overtopping

Flood Frequency

Flood frequency is an important factor in the risk from overtopping and dam failure. The procedures for determining the frequency is in the chapter on Hydrologic Hazard. Items that may influence the frequency are spillway discharge capacity, debris blockage, and spillway and gate configuration. Determining the impacts from these factors will typically require multiple routings of inflowing hydrographs to determine their potential impacts on the pool elevation and ultimately the overtopping depth and duration.

Spillway Discharge Capacity

Spillway discharge capacity is usually determined based on the Inflow Design Flood (IDF) and determined in conjunction with routing of the inflow flood hydrograph through the reservoir based on the operations outlined in the Water Control Manual (USACE) or Standing Operating

Procedures (Reclamation) . When the reservoir has significant volume, the spillway capacity may be significantly less than the peak inflow discharge.

When the reservoir has minimal storage volume, the spillway capacity may equal the peak inflow discharge. Variations on this occur when the dam is designed to pass the IDF using outlets works and/or hydropower units to help pass the IDF. In cases where the outlet works or hydropower units are critical to safely pass the IDF; these features need to be closely examined. For example, if overtopping would take out a switchyard, the release capacity of the turbines would likely be lost at that point. If the outlet works were not designed to safely pass their contribution, their use may cause embankment or outlet damage and/or contribute to other failure modes.

For High Hazard Potential dams, when the dam safely passes the PMF and the PMF meets current guidance, overtopping is usually not an issue as explained in the chapter
Hydrologic Hazard. If the PMF overtops the dam, the dam would be subject to erosion of the foundation and/or embankment. If the PMF approaches close to the top of the dam (typically three feet for embankment), the dam may be subject to erosion from over topping from waves.

Spillway and Gate Configration

The spillway configuration can affect the reliability and the ultimate discharge capacity \of a spillway. Uncontrolled, overflow spillways are generally reliable with predictable discharges. Gated spillways can have inherent reliability concerns, due to the potential for mechanical and power failures, and the potential for operations to differ from planned operations as a result of the inability of an operator to access the gate controls or an operator decision to delay opening the gates due to downstream flooding concerns.

Fuseplug spillways may have some inherent uncertainty regarding when they will operate.

For dams where the IDF has significantly increased and the spillway is gated, the new spillway flow may impact the gates and significantly reduce the capacity as the flow will switch from weir flow to orifice flow

Potential for Reservoir Debris to Block Spillway

If the full capacity of the spillway is not available, dam overtopping can occur under more frequent floods. Some watersheds produce large amounts of debris during rainstorms. Sturdy log booms may be able to capture the debris before it reaches the spillway, but if not, the debris may clog the spillway opening. As a rule of thumb, spillway bays with a clear distance less than 40 feet (less than 60 feet in the Pacific Northwest) are vulnerable to debris plugging. If a spillway is gated and the gates are being operated under orifice conditions or if the bottom of the raised gate is less than 5
feet above the flow surface the spillway openings will be further restricted, compounding the potential for debris blockage. References on debris potential in reservoirs are provided by the Federal Highway Administration (2005) and Wallerstein, Thorne and Abt (1997).

Depth and Duratiion of Overtopping

The depth and duration of overtopping and the erodibility of the embankment materials are the key parameters to determine the likelihood that dam failure will occur as a result of overtopping. The estimated probability of an embankment dam failure due to overtopping will be site specific and will also be a function of the zoning and details of the dam. Heavily armored downstream slopes and highly plastic embankment materials are more erosion resistant

Once erosion initiates at the toe of an embanlment dam, a headcut forms at the toe and then advances upstream until the crest of the dam is breached. Note that the breach does not initiate until the upstream crest begins to erode.

The likelihood of concrete dam failure for a given overtopping depth and duration is primarily a function of the erosion resistance of the abutment and foundation rock. The ability to accurately predict the allowable threshold for depth and duration of overtopping is still limited, but there are tools in the Erosion of Soil and Rock to assist with these estimates.

Top of Dam Profile

Some embankment dams were built with camber, meaning the portion of the dam near the maximum section was built higher than at the abutments, to allow the embankment to settle after construction without the crest dropping below the design crest elevation. However, in most cases, the embankment settlement has been less than the camber, so the embankment crest is still lower at the abutments. Embankment dam crests may also have low spots, due to localized settlement, which are areas where overtopping will initiate and flow concentrations may occur. Actual profile surveys of the embankment crest should be used when estimating the overtopping flow for embankments and where overtopping will initiate. These surveys should be used to determine the minimum elevation of the top of dam and this elevation should be used in lieu of the "design" top of dam elevation.

Wave Overtopping

When the water surface elevation is below the top of dam elevation, wave overtopping of the embankment may be a concern along coastal areas, larger lakes, etc. Typically a significant surface area would need to be present to allow winds to develop waves that would be directed towards the embankment and overtop it. For wave overtopping the wind and wave direction, levee slope, and the local bathometry are critical components for determining how the wave runs up the levee leading to overtopping. While there is currently no rigorous method for evaluating overtopping failure due to wave action, it of the dam.

The Coastal Engineering Manual (USACE 2002) describes ways to calculate setup (increase in water surface from wind/water friction) and runup for various geometries and calculate an "equivalent" or "average" overtopping discharge per unit width. The estimate of the average overtopping discharge is strongly influenced by the distance between the still water level and the top of the embankment. Using estimated average overtopping discharges, (Table VI-5-6 CEM, 2002) the likelihood of erosion and failure can be estimated from existing allowable guidance. Note the data is for specific sea dikes and results will vary with variations in material and vegetation cover.

Subsequent studies have indicated that erosion from wave overtopping cannot always be described by the overtopping discharge. In fact larger volume, less frequent waves tend to cause more erosion than smaller volume, more frequent waves when both have the same calculated overtopping discharge (Van der Meer, 2010).

Potential Failure Mode Evaluation

An initial conservative assumption should be made that breach is initiated with any overtopping of an embankment dam or levee. If this shows that risks are above agency risk guidelines, or if allowing a small depth of overtopping could change the conclusions
for this failure mode, a more refined approach can be considered (see the section on Erosion of Rock and Soil). If refinement is needed a risk analysis team may consider developing fragility curves to relate the depth of overtopping to the probability of dam failure due to erosion and breach of the dam crest. If the team elects to do this, careful
consideration should be given to the development of the fragility curve. For a given depth of overtopping, a range of failure probabilities and a best estimate should be developed. The following items should be considered in the development of the fragility
curves:

- Depth of overtopping
- Duration of overtopping
- Potential concentration of overtopping flows at dam crest due to camber or low spots
- Potential concentration of overtopping flows on the dam face, along the groins or at the toe of the dam
- Erosional resistance of materials on the downstream face and in the downstream zones of the embankment
- Whether a parapet wall is provided and the potential for the wall to fail before or after it's overtopped

WinDAM or NWS-Breach may assist in determining erodibility. Empirical breach equations assume the embankment has breached, these programs will help determine a range of flow conditions that may or may not lead to full breach. In the past, fragility curves have typically been developed through a combination of simplified analyses, judgment, and team consensus. The development of physically based dam breach computer models such as WinDAM B (released in late 2011) makes it possible to develop fragility curves through a dedicated modeling effort. Even if such tools are used, it is still important to develop a range of failure probabilities and a best estimate, since the dam failure process is highly non-linear and sensitive to variable input parameters. Repeated WinDAM B simulations can be made using a range of input data

Internal Erosion Potential Failure Modes in Embankment Dams (BP 26)

Key Concepts

The number one cause of dam failures in the United States is from internal erosion of embankments (or their foundations). Unfortunately, this is a potential failure mode that cannot be completely analyzed using numerical formulae or models. However, valuable information on dam and soil behavior is available to help in assessing internal erosion risks. The term "internal erosion" is used herein as a generic term to describe erosion of soil particles by water passing through a body of soil. "Piping" is often used generically in the literature, but actually refers to a specific internal erosion mechanism (described below).

It is recognized that risk estimating procedures, although quantitative, do not provide precise or accurate numerical results. The nature of the risk evaluation should be advisory and not prescriptive, such that site specific considerations, good logic, and all relevant external factors can be applied in decision making, rather than reliance on a "cookbook" numerical approach

(Von Thun, 1999). Thus, although the numbers are important, the more important aspects of a risk analysis are to: 1) develop an improved understanding of the dam's strengths, weaknesses and vulnerability to potential failure modes; and 2) to "build the case" for the numbers that are presented and the resulting recommended action (or inaction). As such, one of the primary objectives of the risk analysis/assessment[1] is to understand and "build the case" for the risk estimates that are developed and the resulting recommended actions. Prior to the risk assessment, the risk team should review and discuss available information, and some analyses may be necessary (e.g. filter compatibility, internal instability, vertical exit gradient, etc.). The risk team should also review pertinent case histories. A few are summarized at the end of this chapter as a good starting point.

According to Sherard et al. (1963), "there remains a wide variety of opinion and practice among engineers working in the field. Many aspects of designing and constructing large earth dams will probably always fall within the group of engineering problems for which there are no universally accepted or uniquely correct procedures. In spite of advances in related technology, it is likely that the building of earth dams will always remain an empirical process." This assessment certainly applies to risk estimating procedures as well. This chapter on internal erosion risks "has been prepared in an attempt to present the main elements of current practice, experience, and opinion. It is being published with full recognition that the content will not gracefully withstand even a short period of time."

General Categories of Internal Erosion

Internal erosion failure modes can develop in response to a loading applied to the embankment dam or its foundation. The loading is generally characterized as either:

- Static/normal operation (i.e., reservoir level at or above a threshold elevation that would cause initiation of internal erosion) – Reclamation only

- Hydrologic (i.e., related to a flood or reservoir level higher than the normal operating reservoir level)

- Seismic (i.e., earthquake causes deformation and/or cracking that would cause initiation of internal erosion)

Internal erosion potential failure modes can be categorized into general categories related to the physical location of the internal erosion pathway. Case histories of dam failures can be related to four general categories of internal erosion:

- Internal erosion in the embankment (Figure 26-1)

- Internal erosion in the foundation (Figure 26-2)

- Internal erosion of the embankment into the foundation (Figure 26-3a), including along the embankment-foundation contact (Figure 26-3b)

- Internal erosion along or into embedded structures such as conduits or spillway walls (Figure 26-4)

- Internal erosion into drains such as toe drains, stilling basin underdrains, etc.

The stilling basin case history described at the end of this chapter is an example of internal erosion into drains. It is important to note that no large dam failures have occurred as a result of internal erosion into drains. This is most likely because this potential failure mode would take a long time to develop and case histories indicate intervention through early detection has been successful in stopping the internal erosion process.

The categories of internal erosion identified here are not potential failure mode descriptions. The potential failure mode should be identified in detail based on site-specific information and clearly described from initiation to breach. It is important to identify where the concentrated seepage path will likely form, where erosion first initiates, where the soil particles will be carried, how the erosion will progress, opportunities for detection and intervention, and how the dam will breach.

Conceptual Framework for Internal Erosion Process

The process of internal erosion is generally broken into four phases: 1) initiation of erosion; 2) continuation of erosion; 3) progression of erosion; and 4) initiation of a breach.

A generic sequence of events has been developed for internal erosion failure modes that is based on the four phases of internal erosion shown above. In addition, a threshold reservoir elevation (or several different ranges of elevations) and the likelihood of unsuccessful detection and/or intervention are assessed.

- Reservoir at or above threshold level
- Initiation – Erosion starts
- Continuation – Unfiltered or inadequately filtered exit exists
- Progression – Continuous stable roof and/or sidewalls
- Progression – Constriction or upstream zone fails to limit flows
- Progression – No self-healing by upstream zone
- Unsuccessful detection and intervention
- Dam breaches (uncontrolled release of reservoir)

Depending on how the potential failure mode is envisioned, it might be appropriate to decompose the initiation event into two events: 1) flaw exists; and 2) erosion initiates given the flaw exists. Reclamation generally (but not exclusively) considers one event because historical rates of initiation within Reclamation's inventory (discussed later) can be estimated, whereas historical rates of a flaw existing where erosion has not initiated are unknown.

USACE has chosen to decompose initiation into two events in the event tree to identify scenarios where the likelihood of a flaw may be a primary factor in the risk estimate, and if so, focus investigations and study in an attempt to gain a better understanding of the likelihood of a flaw or reduce the uncertainty in the risk estimate. Many USACE dams are designed for flood risk management and have not been fully loaded.

- Reservoir loading (at or above threshold level)
- Flaw exists – Continuous crack, high permeability zone,zones subject to hydraulic fracture, etc.

- Initiation – Particle detachment (erosion starts)
- Continuation – Unfiltered or inadequately filtered exit exists
- Progression – Continuous stable roof and/or sidewalls
- Progression – Constriction or upstream zone fails to limit flows
- Progression – No self-healing by upstream zone
- Unsuccessful detection and intervention
- Dam breaches (uncontrolled release of reservoir)

This sequence of events can be illustrated as an event tree. The risk team should develop specific event trees for their identified potential failure modes.

Concrete Gravity Dams (BP 20)

Key Concepts

Within the context of this section, massive concrete spillways or other gravity-type concrete water retention structures are also referred to as concrete gravity dams.

Historically, the leading cause of concrete gravity dam failures (for those founded on rock) has been related to sliding on planes of weakness within the foundation, most typically weak clay or shale layers within sedimentary rock formations. A few failures have also occurred along weak lift joints within masonry (and buttress) dams. This section focuses on risks associated with sliding instability of concrete gravity dams. For concrete gravity dams founded on alluvial soils, the leading cause of failure is piping or "blowout" of the soil material from beneath the dam. Therefore, the reader is referred to the section on Internal Erosion and Piping Risks for Embankments for evaluating this potential failure mode, considering "backward erosion piping" of the foundation soils.

The heel of the dam is a location of sharp geometry change and as such is a point of singularity and stress concentration. Thus, the dam-foundation contact is typically the focus of most of the stability analysis. However, this typically is not the weak link in the dam-foundation system, unless the dam is founded on the foot wall of smooth discontinuity surfaces such as faults or bedding planes. The rough surface that results from blasting the dam keyway excavation typically provides a significant roughness or "dilation" component to the shear strength on this surface, which should be taken into account to the extent possible based on construction photographs and other information.

If the surface clean-up is good, significant cohesion and tensile strength can result (as with lift joints). When surface cleanup of lift joints is not good, weaker horizontal planes may occur within the dam body. For gravity dams constructed in blocks, the weaker planes may not "line up" across contraction joints, and if the joints are constructed with keys, considerable stability can result from load transfer to adjacent monoliths. This should be considered when evaluating the risks.

A line of functioning drainage holes in the foundation or dam body adds significantly to the sliding stability of concrete gravity dams by reducing water pressures (typically referred to as "uplift") along potential sliding surfaces. A decrease in water pressures increases the effective normal stress and frictional resistance. Research shows that drains remain effective even if a crack or open surface extends downstream of the drainage curtain as noted in nonlinear analysis guidelines (Mills-Bria et al, 2006), based on the Electric Power Research Institute (EPRI) research results (Amadei et al, 1991).

However, drainage systems can become plugged over time if they are not maintained, and the drainage curtain can be offset under significant seismic displacements, thus becoming less effective beneficial in that they can facilitate load transfer between monoliths. This could be important if one monolith or series of monoliths contains an unbonded lift joint or weak foundation conditions, whereby load in excess of the weak monolith(s) capacity could be transferred to adjacent stronger monoliths. Not all gravity dams contain shear keys within the contraction joints, but many do.

When a potential sliding plane is formed by a partially bonded and partially unbonded surface, care must be taken in assigning the shear strength to each portion. That is because the peak shear strengths may not be mobilized at compatible displacements. It may take much less shear displacement to mobilize the shear strength of a bonded joint than an unbonded joint, in which case it may not be appropriate to simply add the peak strengths determined from testing. Test results could be examined and new strength curves developed at compatible displacements.

A special discussion on tensile strength of concrete and the so called "cracked base" analysis is provided here, as estimating risks requires a somewhat different approach than that currently provided in design criteria documents. As opposed to designing a new dam, where conservative assumptions and criteria are appropriate to ensure that the dam does not slide for the design loads, estimating risks for an existing dam requires attempting to establish the most likely behaviour.

Tensile Strength of Concrete

The tensile strength of concrete has been somewhat controversial over the years. Jerry Raphael published an often cited paper on the subject (Raphael, 1984). His basic conclusions were that:

- Direct tension tests are unreliable, and can be in error by as much as 50 percent (attributed to moisture gradients during drying which caused surface micro cracking and an effective reduction on cross-sectional area in these types of tests – Cannon (1995) noted that the drilling process can also induce strains capable of causing micro-cracking of the core surface).
- Splitting tension tests are the most reliable means of determining tensile strength (potential zone of micro-cracking is loaded in compression). · Tensile strength determined by static testing (from splitting tension tests) should be increased by 50 percent when used with seismic loadings, based on rapid loading tests where the samples are taken to failure in a fraction of a second representing one load cycle during an earthquake.

Raphael supported the fact that splitting tensile tests best represent tensile strength by converting strengths from modulus of rupture (flexural) tests results to tensile strength based on an evaluation of the stress and strain distribution in the samples, which shows the tensile strength should be about ¾ the modulus of rupture value. The results, suggest that both splitting tension tests and modulus of rupture tests produce a consistent pattern. Raphael indicated that an apparent tensile strength can be used when performing linear elastic analyses to account for the non-linear strain that occurs prior to failure. The apparent strength is estimated as the failure tensile strain multiplied by the Modulus of Elasticity used in the analysis. It can be determined directly from modulus of rupture (flexural) tests, or can be estimated from equations he provides (which result in approximately a factor of 1.35 applied to the static strengths). However, this typically has not been used in practice due to discomfort with using the high strengths it produces, particularly for static loading. However, for dynamic loading, it can be considered, especially if it is taken that only one spike in the stress time history is sufficient to crack the concrete (considering that it represents a rapid load cycle similar to that experienced under dynamic testing).

Slightly over a decade later, Bob Cannon published additional information in a Corps of Engineers Engineering Pamphlet (Cannon, 1995). He examined direct tension and splitting tension test results for a variety of conventional concretes, and concluded that:

- Splitting tensile strengths can be used as a starting point. If these strengths are not available, then: (1) for compressive strengths less than 3,000 lb/in2 the tensile strength is expected to vary between 10 and 15 percent of the compressive strength, or (2) for compressive strengths greater than 3,000 lb/in2, the equations 1.7(fc')2/3 (Raphael's equation) or 7(fc')1/2, which are based on splitting test relationships, can be used to estimate tensile strength.
- The tensile strength values should be reduced by 10 percent if the maximum size aggregate is larger than 1½ inches (based on 6-inch x 12-inch cylinders).
- The strengths should be reduced by an additional 20 percent to adjust for direct tensile strength (particularly for examining vertical or "cantilever" stresses).

Cannon also gave recommendations for roller-compacted concrete (RCC) indicating that:

- Parent material tensile strength should be no higher than about 75 percent of the splitting tensile strength value, reduced by 10 percent if based on wet-screening of aggregates larger than 1½ inches.
- Joint tensile strength is similar to conventional concrete when properly cleaned, cured, and covered with a suitable mortar or bedding mix.

Cannon supported Raphael's conclusions that:

- The dynamic tensile strength of concrete is about 1.5 times the static tensile strength.
- For linear elastic finite element analysis, the apparent tensile strength of concrete is about 1.35 times the tested strength.

The intent of reviewing these important pieces of work is not to dictate the tensile stress parameters that should be used in a risk analysis. These need to be determined on a caseby-case basis using available information. However, the work by Cannon is important and often overlooked in estimating tensile strength. It is always preferred to have tested material properties from extracted core from the dam. The direct and splitting tensile strengths can significantly vary from dam to dam at shown in the Non-Linear Practices Manual (Mills-Bria et al, 2006).

Lift line strength is not only a function of the concrete strength but is greatly influenced by construction methods. Experience suggests that tensile strength across lift joints for modern concrete construction with good joint clean-up averages about 85 percent of the parent concrete strength. Good clean-up usually involves water curing the top of new concrete lifts, then "green cutting" or water blasting (sometimes sandblasting) the laitance from the top of a lift prior to placing the overlying concrete. Sometimes a layer of mortar or richer concrete with smaller aggregate is placed first to bond to the underlying lift. Lower strengths could be present for concrete where lift clean-up and material quality control was questionable.

Seepage on the downstream face of a concrete dam is not a reliable indicator of lift joint bond. Friant Dam has many large seeps on the downstream face along the lift lines but extracted core indicated bonded lift surfaces. It appeared that the bottom of the concrete lifts were not consolidated as well and were more porous than the overlying concrete, forming a seepage pathway, but that enough paste and contact was maintained to bond to the underlying lift. In contrast, Stewart Mountain Dam has a dry downstream face, but extracted core showed 16 of 23 lift joints unbonded. Failure to thoroughly clean the laitance from the lift surfaces resulted in weak bond, but there were sufficient fine particles at the interface to limit seepage along the joint. Therefore, it is important to locate as much information as possible about the methods and specific conditions encountered during construction, which are often keys to the strength of lift joints. If insufficient information can be located to make a judgment on lift joint strength at the time of the risk analysis, best practice is to perform some analysis results with poorly or unbonded lifts to judge the stability implications if this condition exists. It only takes one poorly bonded lift to create a potentially high risk situation.

It should be noted that any empirical relationships between concrete compressive strength and tensile strength do not apply to concrete that has been affected by alkali aggregate reaction (AAR). AAR results in formation of a gel around the aggregate particles. Therefore, while the compressive strength of the concrete may remain at a fairly high level, the tensile strength is often greatly reduced. Site specific testing is typically required in this case.

Cracked Base Analysis

The "cracked base" analysis has found its way into most concrete gravity dam design criteria, based on the "gravity" method of analysis, which assumes plane sections remain plane, and thus the distribution of vertical stress is linear. It is often applied without thoroughly evaluating the reasonableness of the results or the analysis assumptions relative to actual conditions. In a risk context, these must be considered.

Several important points in this regard include:

- There is often confusion in how to deal with total stress and effective stress in carrying out the calculations. *Design of Small Dams* (1987) indicates that "Uplift from internal water pressures and stresses caused by the moment contribution from uplift along a horizontal plane are usually not included in the computation of σZ." This is the total stress method, which is endorsed by Water Meyer (2006), who states that the "reactive stress equations [which include the contribution from uplift] are erroneous and can lead to erroneous conclusions when uplift reducing drains are incorporated into the base of a gravity dam." That is not to say that uplift is not considered in the analysis, only that the moment contribution from internal uplift forces are not included in the stress calculations.
- The effective stress is determined by subtracting the pore water pressure (often equated to the "uplift pressure") from the total stress. If the effective stress is tensile and exceeds the tensile strength, then it is assumed that cracking can initiate. At that point, the water force in the crack becomes an "external" force which is included in the total stress calculations, and the base length is assumed to be shortened to only that portion downstream of the crack tip. The effective stress

at the crack tip is subsequently calculated as the difference between the total stress and effective stress at that location. It should be noted that the crack the tensile strength.

- At the base of the dam, the potential for full reservoir pressure at the crack tip is controlled by the permeability of the foundation. Concrete gravity dams are typically founded on fractured and jointed rock. Thus, full reservoir pressure cannot develop at the tip of a crack along the foundation contact unless the foundation rock is massive and un-fractured, or the foundation joints are much tighter than the base crack. This is because water entering the crack will flow out through fractures at the base of the dam, and head loss will occur due to this flow. Thus, full uplift in a crack tip at the foundation contact may not be reasonable.
- Drains remain effective even if penetrated by a horizontal crack, although the drain efficiency may be reduced somewhat. This is demonstrated by the research sponsored by the Electric Power Research Institute at the University of Colorado (Amadei et al, 1991). Thus, analyses which consider full hydrostatic reservoir pressure in a crack tip downstream of the line of drains are typically not used for risk analyses.
- In the limiting case, if a crack is judged to propagate completely through the structure, the uplift pressure distribution along the crack is that which is appropriate for the post-cracking conditions, including the effects of drains in reducing the pressures, and pressures no higher than tailwater at the downstream face. It should be noted that there is very little guidance currently available concerning the effects of drains if the section cracks all the way through. If the aperture of the crack is thought to remain relatively tight in comparison to the drain diameter, the drains should retain some effectiveness. If the aperture is thought to be large in comparison to the drain diameter, then there may be more flow than the drains can handle, and their effectiveness would be questionable.
- If a crack is shown to exist, cohesion is presumed to act only on the portion of the intact potential sliding plane that is in compression. It is expected that intact concrete in tension will exhibit a smaller cohesive strength component, and since this is difficult to quantify, it is typically ignored.

Risks under Normal Operations

Concrete gravity dams that have performed well under normal operating conditions will likely continue to do so unless something changes. Changes could result from plugging of drains leading to an increase in uplift pressures, possible gradual creep that reduces the shear strength on potential sliding surfaces, or degradation of the concrete from alkali-aggregate reaction, freeze-thaw, or sulfate attack. These may be difficult to detect. A review of instrumentation results can be helpful. For example, if piezometers or uplift pressure gauges indicate a rise in pressures, and weirs indicate a reduction in drain flows, the drains may be plugging leading to potentially unstable conditions. If conditions appear to be changing, risk estimates are typically made for projected conditions as well as current conditions.

Reliability analysis for sliding on near horizontal foundation planes and/or potentially weak or cracked horizontal lift joints, typically using two-dimensional analysis sections, is the primary tool used for estimating risks posed by concrete gravity dams under normal operating conditions. This involves performing a probabilistic stability analysis using the Monte-Carlo technique. It requires an assessment of the likely range in input parameters, such as drain efficiency, cohesion and friction coefficient along the potential sliding surface, percentage of potential sliding surface that is intact, orientation of the potential sliding surface, and unit weight of the material(s). For potential foundation sliding planes, the influence of a downstream passive rock wedge should be considered, where appropriate.

The shear strength of rough surfaces is nonlinear as a result of "riding up" over asperities at low normal stress and shearing through them at high normal stress. A straight line fit through such data points can result in overestimating the shear strength, particularly at low normal stresses. Therefore, strength parameters should be selected for the appropriate normal stress range of interest, or other means used to account for the nonlinear shear strength envelope.

Probabilistic stability analyses are typically performed at various reservoir water surface elevations, and combined in an event tree, such as that shown in Figure 20-1. See the sections on Event Trees and Reservoir Level Exceedance Curves for information on calculating reservoir load range probabilities. Note that in the limit, if small enough reservoir elevation increments are selected, a curve, referred to as a "fragility curve", results. The calculations are essentially the same whether larger discrete ranges or a fragility curve is used, and the results are similar as long as care is taken in selecting the
discrete ranges. Therefore, either method can be used in estimating risks.

For the probabilistic stability analyses, it is important to examine the sensitivity rank coefficients and perform parametric studies, varying the parameters that affect the results the most. These parametric studies are used to estimate an appropriate range in
conditional failure probabilities for the node titled "Sliding Instability". If there are significant three-dimensional effects, the two-dimensional sliding model may not be appropriate, and three-dimensional analyses may be needed to get a handle on how significant these effects might be if risks estimated from the two-dimensional models exceed the public protection guidelines.

Risks under Flood Loading

The approach for estimating risks due to structural instability under flood loading is essentially the same as for static loading, except that reservoir water surface elevations above the normal operating range, assigned the appropriate flood frequency, are used in the analyses and event tree. If flood routing information is not available, a conservative initial assumption is that inflow is equal to outflow, and the level of the reservoir is determined by that needed to pass a given peak inflow through the spillway and/or other release facilities (see also the section on Dam Overtopping). If the risks using this method are in an area where risk reduction actions are justified, then flood routings may be needed to get a better handle on the probability of attaining various reservoir elevations.

As the reservoir rises during flood loading, there may be a level at which the heel of the
dam goes into tension (based on effective stress), in which case the potential for cracking along a lift joint at that elevation may increase. At some point, the estimated tensile strength of the concrete may be exceeded. Typically, a separation in the event tree reservoir load ranges occurs at these reservoir elevations. Stability analyses should be performed at these reservoir water elevations to judge the impact on the dam. Make sure the tailwater and uplift conditions correspond to the given reservoir elevation. In the case of an overflow section, care must be taken when assuming nappe forces (forces due to water flowing above the spillway) and tail water forces act on the dam. Stilling basins can "sweep out" at high flows, and nappe pressures can become sub atmospheric, reducing the stabilizing forces. Forces generated by water flowing through a flip bucket can also affect the results. A hydraulic evaluation is typically performed to determine whether it is appropriate to include these forces. A reliability model with the proper

formulation for a cracked base analysis (see Water Meyer, 2006) is important in examining conditions where tension exceeding the tensile strength develops.

Risk evaluation associated with overtopping erosion of the abutments or foundation is discussed in the sections on Flood Overtopping and Erosion of Rock and Soil. However,
another potentially significant issue involves cases where a concrete gravity dam serves as a spillway section. If erosion occurs at the downstream toe of the structure during spillway releases, weak bedding planes or foundation discontinuities in the underlying foundation rock might be exposed, day lighting into the erosion hole. This could remove passive resistance from the downstream rock mass, and result in a much more unstable condition. See the section on Erosion of Rock and Soil for guidance on how to estimate the potential for erosion. Figure 20-2 shows how this might impact the event tree. The potential for failure of stilling basins is discussed in the section on Overtopping of Walls and Stilling Basin Failure.

Risks under Earthquake Loading

Under earthquake loading, concrete gravity dams will respond according to the level and frequency of the shaking, and the reservoir level at the time of shaking. Therefore, sufficient analyses need to be performed to evaluate conditional failure probabilities at various levels of shaking and reservoir elevation.

For each reservoir and seismic load range that is established for the estimating process, the likelihood of cracking through the dam body at this location must be estimated. The
best approach for this is to perform a nonlinear dynamic finite element studies, modelling the potential weak plane with a contact surface that can be assigned a tensile strength value. As the tensile strength is exceeded near the faces during seismic response, the nodes will separate. If the shaking is severe enough, complete separation of the contact surface may propagate through the structure.

Varying the tensile strength within reasonable parameters and monitoring the percentage of the joint that separates can make a range in the likelihood of complete separation.

It should be noted that this is a total stress analysis, and pore pressures are not considered. Pore pressure behaviour in concrete under dynamic loading is a subject of much uncertainty. Therefore, it is typically assumed that the total stress analysis provides a reasonable approximation of the potential for cracking through the section.

If the dam only cracks partially through, the probability of post-earthquake instability in the estimated cracked state is determined using static reliability analysis, as previously described. The estimated crack length from the nonlinear analysis of the seismic shaking is used as the starting point for a cracked base analysis. It is very difficult to estimate the amount and depth of cracking from a linear analysis. Linear analyses only help determine if and where cracks might initiate (high stress areas) but cannot model crack development or the sudden release of kinetic energy when cracks form.

If the section cracks all the way through, the likelihood of shearing the drains is next estimated. Information typically used to make this assessment includes calculated displacements from the finite element study assuming frictional resistance only on the potential sliding surface, as shown in Figure 20-5. In this case, very small values of damping, only enough to keep the model stable as the loading is applied, need to be used.

If the model is over-dampened, the displacements will be under-estimated. Although this type of analysis assumes the section is cracked at the beginning of the earthquake and thus are somewhat conservative, they can be used to estimate the likelihood of drains, where present, being sheared. The post-earthquake instability could be considerably different whether the drains are still functioning after the earthquake shaking or not. It is possible that the drains could be sheared off, or opening of pathways in the foundation could lead to increased flow that overwhelms the drainage system. Therefore, two estimates are made, using reliability analysis, to account for these two conditions (drains functional or not).

Seismic risk analysis of concrete gravity dams typically relies heavily on finite element analyses to evaluate the dynamic response, and the "gravity method" analyses to evaluate post-earthquake stability. The finite element analyses described above are not routinely performed. Although more uncertain, if analyses that include a contact surface are not available, it may be necessary to make judgments on cracking from traditional linear elastic finite element analysis results, by examining the magnitude and duration of the vertical tensile stresses at the upstream and downstream faces. Judgments must be made concerning how load is redistributed if cracking begins at the face, and how far toward the center of the dam it will progress, which is not an easy task. It is also important to examine the three-dimensional effects and, for example, whether excess driving load can be transferred to adjacent monoliths through shear keys. This is particularly true if all analyses are based on two-dimensional sections.

Spillway Gates (BP 30)

Key Concepts and Factors Affecting Risk for Radial Gates

Load Carrying Mechanism

Spillway radial gates (sometimes called tainter gates) transfer the reservoir load to the trunnion pin through compression of the relatively slender gate arms.

Pin friction represents a special loading case for a radial gate under hydrostatic loading. An increase in pin frictional moment will increase the combined arm stresses, which can lead to a greater probability of arm buckling failure. This potential failure mode will only apply when the spillway gates are operated and frictional resistance is developed between the trunnion pin and trunnion bearings. Gate operation would typically occur during a flood but could occur when the gates are being routinely exercised. For this reason, flood load probabilities are typically not considered in estimating the risks. This is not a ductile failure (it involves buckling of the steel gate arm members) and can occur suddenly.

Spillway radial gates are most vulnerable to this failure mode when they are initially opened, as the loading on the gate will be the highest at this time. Fortunately, for most radial gates, trunnion pin friction has not been found to be a problem for arm overloading. Either the pin frictional moment has been accounted for in the gate design; or it represents a relatively small and manageable load that can be carried by the reserve buckling strength of individual arm members. When reviewing suspect radial gates which are capable of developing excessive pin friction, one should consider as candidates the larger, older-designed radial gate installations having obvious lubricant deficient pin design, and a lack of hub stiffening and/or arm bracing.

Trunning Pins and Bushings

When a spillway radial gates is operated, friction at the trunnion pin is transferred as an axial compressive force and bending into the gate arms. Lubrication at the trunnion pin is critical to ensure that the trunnion pin friction is minimized. If lubrication is not provided or if the trunnion has inadequate seals that allow moisture to access the trunnion pin, corrosion can occur which will increase the trunnion pin friction over time. Unless measured on a regular basis (for example using a laser pointer attached to the gate arm and measuring the bending of the arm during operation), trunnion pin friction should be assumed in the analysis of spillway gates. Based on studies at Folsom Dam, the assumed trunnion pin friction coefficient should be at least 0.3. For large trunnion pins, this failure mode will be more critical because trunnion pin friction will result in more resistance to the gate being opened.

Size of Radial Gates

Spillway radial gates come in all sizes. Large radial gates, 50 feet or more on a side, are common. Larger gates are not necessarily more prone to failure but failure of a large gate will result in a large breach outflow and likely greater consequences than the failure of a smaller gate.

Mechanics of Pin Friction

All radial gate arm assemblies are subjected to a bending moment induced by pin frictional moment. Whenever radial gates (a.k.a. tainter gates) are operated, the pin friction develops at the interface of the surfaces of the fixed pin and the inside surface of the bushing.

Pin friction loading means the pin frictional moment which develops and acts in a direction opposing the motion of the gate. Pin frictional moment is generally at its peak when a gate is loaded under full reservoir head and is in its closed position. As the gate begins to rise and first begins to break free through its static coefficient of friction, the pin frictional moment develops and loads the hub end of the arm assembly. The frictional moment, which lies in a vertical plane, is a function of the three parameters. The first is the hydrostatic load carried in axial compression through the arms to the hub, the second is the diameter of the pin acting as a lever arm to produce the friction, and lastly is the coefficient of static friction between the pin and the bushing.

Over the years, radial gates have utilized several types of pin bushing configurations. For old and small radial gates, the pin/bushing design may have been as simple as a small cantilevered steel pin passing through an oversized hole in a steel plate used as a and hub without any bushing. For large, new radial gates, the arrangement is more likely a self-lubricating bushing rotating around high strength, stainless steel pin. Beyond the simple arrangement without a bushing, there are four likely historical pin/bushing configurations.

Plain Bronze Bushing - A simple bronze bushing and either a steel trunnion pin, SAE 1020 cold-finished steel trunnion pin, or a stainless steel trunnion pin.

Lubricated Bushing. – A bronze bushing with a means to inject lubricating grease to the pin/bushing interfaces. In some instances, the injection point provides an inadequate single point of lubrication. In major gate installations, the inner surface of the bronze bushing has been machined with grease grooves to allow a better and more even distribution of lubrication.

Graphite-Insert," Self-lubricating Bushings" – In the latter half of the 1940s, the bearing industry had developed so-called self-lubricating journal bearings. However, the lubricant used for the bushings was a graphite plug that was inserted into recesses on the inside of the bronze bushing. The graphite proved to be a bad choice for hydro applications because of the galvanic cell that it set-up with the steel pin that promoted corrosion, pitting, and increased coefficient of friction and greater pin frictional moment.

Self-Lubricating Bushings. – In the 1970s, self-lubricating bushings were often specified that utilized propriety lubricants formulated without the addition of graphite or molybdenum.

Reservoir Water Level

The reservoir water level on the gates is a key parameter since it affects the loading on the gates (stresses in gate members and normal force on trunnion pin which determines the frictional resistance) and also the consequences of gate failure (due to the effect on the breach outflow). It is most likely that the reservoir water surface elevation will be at the top of the gates when this potential failure mode is triggered, unless the gates are being operated as part of a routine exercise operation and the reservoir is down for some reason. This is because spillway radial gates are typically only operated under flood conditions and flood releases are typically not made until the reservoir exceeds the top of active conservation pool or the top of joint use pool, which is usually located near the top of the spillway radial gates when they are in the closed position.

Reservoir Operations

This potential failure mode requires operation of the radial gates to initiate the failure. If the gates remain in the closed position, trunnion pin friction will not be mobilized and the gate members will not be loaded by this mechanism. Reservoir operation levels will only be a factor if the spillway is operated at levels below the top of the gate elevation (or below a level within a foot or two of the top of the gates). If the reservoir level is typically at or near the top of the gates on an annual basis when the gates are likely to be operated or tested, this is a more hazardous situation than if the reservoir frequently does not reach the top of the gates on an annual basis, or the gates are typically tested when the reservoir is low. The likelihood of various reservoir levels at times when the gates will be operated can typically be estimated from the historic reservoir exceedance curves.

Combined Stress Ratio

The key parameter for evaluating this potential failure mode is the combined stress ratio which accounts for both axial and bending stresses, and can be used to estimate the likelihood of buckling in steel members. Combined stress ratios can be related to failure probabilities using a response curve. For radial gate arm buckling, the combined stresses are the axial compressive stresses and the vertical and horizontal bending stresses which act at the extreme fibbers at the same cross section of the arms wide flange (or other) beam.

Multiple Spillway Gates

For spillways with multiple radial gates, failure due to trunnion pin friction is most likely to result in only one gate failing, since the gates are typically operated one at a time, and failure of a gate would likely result in an evaluation, or at least extreme care in operating the other gates. However, there is more of a chance that one of the gates will suffer problems with trunnion friction if multiple gates are present, and failure of one large gate could exceed the safe channel capacity or surprise downstream recreationists with life threatening flows.

Maintenance of Spillway Gates

Gates that are well maintained can usually be relied upon to have their original design capacity at the time they are operated. A key maintenance item for this failure mode is lubrication of the trunnion pin. If the pin is lubricated frequently, the pin friction will be reduced and the probability of this failure mode will also be reduced. Some trunnions have self-lubricating or graphite bearings. The condition of these should be evaluated and the trunnion friction measured periodically to ensure they continue to perform as intended. Also, if gates are not maintained and the gate members corrode, the original design capacity may be reduced. A recent examination is usually needed to determine the condition of the gates and trunnions. Finally, exercising of the gates at least annually helps to ensure that the trunnion pin lubrication is uniformly distributed around the trunnion pin and verifies that the gate is performing as expected. If any of these attributes are questionable, the potential for higher failure probabilities exists.

Hoist Ropes and Chains/ Gate Binding

This section focuses on failure of spillway radial gates due to trunnion pin friction, but there are other mechanisms that could lead to inoperable spillway gates. These mechanisms include failure of wire hoist ropes or hoist chains and gate binding. While these mechanisms may not lead to gate failure and an uncontrolled release of the reservoir, they could result in inoperable gates during a large flood, which could initiate other failure modes, such as dam overtopping or internal erosion failure modes. If gates are well maintained and exercised, the chance of an inoperable spillway gate during a large flood will be significantly reduced. Inspections of the gates should focus on wear or corrosion of wire ropes and chains and connections of the ropes and chains to the gates and the hoists. Exercising of the gates will verify that the gate can travel freely within the gate bay, at least for smaller gate openings. The walls and piers in the area of the gate wall plates should also be inspected for plumbness, to identify if there are any potential problems with larger gate openings.

Consequences

Consequences are a function of the reservoir level at the time of failure (which determines the breach outflow). Loss of life can be estimated from these breach flows (typically resulting from the failure of one spillway gate) and the estimated population at risk that would be exposed to the breach outflows using the procedures outlined in the section on Consequences of Dam Failure.

When spillway gates are operated, they typically are opened slowly to ramp up the flows. Failure of a spillway gate due to trunnion friction would likely result in a sudden large increase in spillway flows. While the flows may be within the "safe channel capacity," they may be large enough to endanger recreationists, especially during sunny day testing of the gates.

If a spillway with multiple gates is being operated during flood conditions and the spillway capacity provided by more than one gate is needed to pass the flood, it may be possible that multiple gates would fail due to trunnion pin friction. The scenario would be that one spillway gate is initially opened to pass flood inflows and the gate fails suddenly due to trunnion pin friction. The increased discharge through the failed gate bay would likely be enough to match incoming flows for a while. At some point, the inflows would increase to the level that discharge from a second spillway gate would be needed to prevent the reservoir from rising to the level that dam overtopping would be possible. The decision would likely be made to open the second gate, recognizing that it too may fail due to trunnion pin friction. Mitigating this situation is the likelihood that the initial gate failure would evacuate the channel of the recreation populations and the fact that there would some delay in between the first gate failure and the time when a second gate would need to be opened. This would allow for downstream warning and evacuation. If conditions are such that incremental loss of life would occur with successive failure of spillway gates, and if the probability of a flood that would require more spillway capacity than that provided by a single gate is large enough, this scenario may need to be considered.

Seismic Risks for Embankments (BP 27)

Key Concepts

Case histories indicate there are very few instances where an earthquake has damaged an embankment dam enough to result in the uncontrolled release of reservoir water. Many embankment dams are exposed to earthquake shaking each year, but either the damage caused by the earthquake was not extensive enough, or in the rare cases where damage was extensive, the reservoir was far below the damage and uncontrolled releases did not happen. The failure probability estimation procedures described below are built upon standard analysis techniques used to predict responses of soil to dynamic loading and upon observations from case histories of embankments that have been exposed to earthquakes.

Dynamic loading from an earthquake changes the stress states within an embankment, causing permanent damage if the stress changes cause shear or tensile strength to be exceeded. Loose, saturated, cohesionless soils, when subject to earthquake shaking and initial shearing, can contract as the soil particles are rearranged. Since the water within the pore spaces is virtually incompressible, this results in an increase in pore water pressure. If the pore pressure increase is enough to reduce the effective stress to nearly zero, the soil is said to have liquefied, and the soil experiences a significant reduction in shear strength. Extensive shear strength reduction beneath an embankment slope can trigger a flow slide which, in turn, can result in a very rapid dam failure. In dense, saturated cohesionless soils, large shear displacements may not occur. Instead, the temporary occurrence of excess pore water ratios of 100 percent (or initial liquefaction) is accompanied by the development of limited strains, resulting in progressive and incremental lateral spreading of slopes.

Whether or not the soil of an embankment or its foundation liquefies completely, pore pressure increases can still result in a decrease in shearing resistance. If enough reduction occurs, over a sufficient extent, large deformations can result. A translational failure can occur if the entire foundation beneath an embankment liquefies and the reservoir pushes the embankment downstream far enough to create a gap in the vicinity of an abutment.

Overtopping erosion failure can occur if crest deformations exceed the freeboard at the time of the deformations.

If the deformations do not result in an immediate release of the reservoir, the embankment can be cracked or disrupted to the point where internal erosion can occur
through the damaged remnant. This failure mechanism can occur with or without liquefaction. There are many ways in which cracking can occur due to seismic shaking, such as differential settlement upon shaking, general disruption of the embankment crest, offset of a foundation fault, or separation at spillway walls. Internal Erosion and Piping may make a particular dam more susceptible to transverse cracking and subsequent internal erosion.

Compacted embankments are typically not considered susceptible to liquefaction upon shaking and initial shearing. Dense, cohesionless soils tend to dilate upon shearing, which increases the pore space between soil particles and reduces the pore pressures. Most Reclamation and USACE embankment dams are compacted, so the focus of liquefaction studies tends to be related to loose foundation soils.

However, hydraulic fill embankments may be susceptible to liquefaction or pore pressure increases. Fine-grained soils, while not strictly "liquefiable," may be susceptible to strength loss during an earthquake. Two aspects of a fine-grained soil's shear strength behavior can require investigation: 1) the anticipated peak magnitude of earthquake induced shear loading when compared to a soil's undrained shear strength determined from monotonic loading; and 2) sensitivity, which is the potential for a reduction in the undrained shear strength due to the effects of many shearing cycles or very large monotonic strain.

If active faults or faults capable of co-seismic displacement cross an embankment dam foundation, the potential exists for foundation displacement that cracks or disrupts the dam core or water retaining element as well as transition zones or filters. The cracking can initiate concentrated seepage, and the translational movement can create locations
Where there would be unfiltered exit points for the seepage. Both conditions would increase the likelihood for failure from internal erosion or piping. Shearing of a conduit passing through an embankment dam as a result of fault displacement can result in transmission of high-pressure water into the dam, leading to increased gradients and potential for internal erosion. At the time of the 1906 San Francisco Earthquake, Upper
and Lower Howell Creek Dams were located on the San Andreas Fault and holding water. Lower Howell Creek Dam, which had a conduit through it, failed, but Upper Howell Creek with no conduit did not. The presence of the conduit *might* have made the difference.

Seiche waves can be generated by large fault offsets beneath the reservoir, by regional ground tilting that encompasses the entire reservoir, or by mass instability or slope failure along the reservoir rim. "Sloshing" can lead to multiple overtopping waves from these phenomena.

Steps for Risk Evaluation

- Develop detailed site-specific potential failure modes
- Develop event trees to assess the potential failure modes
- Establish loading conditions for earthquake PGA and associated magnitudes, as well the coincident reservoir level
- Evaluate site conditions and develop representative characterization of the embankment and foundation materials
- Perform a screening by evaluating the load combinations and site characteristics to determine if seismic potential failure modes will be significant risk contributors

If the potential failure mode can't be screened out, then perform the following for each selected earthquake and reservoir load combination

- Estimate the likelihood of liquefaction of any foundation or embankment materials
- Calculate the likelihood of no liquefaction
- Estimate the residual strength of the materials that may liquefy
- Estimate the deformation of the embankment given liquefaction
- Estimate the deformation of the embankment given no liquefaction occurs

For overtopping, assess the estimated deformation, and estimate a probability of overtopping. Different estimates are made for the various reservoir (freeboard) and earthquake combinations represented in the event tree. Complete the event tree nodes following procedures similar to flood overtopping failure modes.

For cracking, assess the estimated deformation, and determine the likelihood of developing transverse cracks. Estimate the depth and width of the cracks, and complete the event tree similar to the failure mode of internal erosion through cracks.

The probability for each node in the event will be determined by team elicitation considering all of the more likely and less likely factors associated with that node.

Seismically-Induced Potential Failure Modes

The following are generic descriptions of how a dam might fail due to these potential failure modes. For a specific dam, additional details would be needed in the descriptions, as described in the Chapter 6.1 on Potential Failure Mode Analysis.

Deformation and Overtopping

Severe earthquake shaking causes loose embankment or foundation materials to contract under cyclic loading, generating excess pore water pressures (i.e., liquefaction occurs).

The increase in pore water pressure reduces the soil's shear strength. (This could also occur as a result of loss of strength in sensitive clay.) Loss of shear strength over an extensive area leads to slope instability and crest settlement. Crest deformation exceeds the freeboard existing at the time of the earthquake. The depth and velocity of water flowing over the crest are sufficient to erode materials covering the downstream slope.

Head cutting action carves channels across the crest. The channels widen and deepen.

Subsequent human activities are not sufficient to stop the erosion process. The embankment breaches and releases the reservoir. This failure mode can also be initiated without the requirement for liquefaction. If the seismic deformation is great enough for the crest to settle below the reservoir level, overtopping can be initiated. This mostly pertains only to dams that have a small amount of freeboard at the time of the earthquake.

Deformation and Transverse Cracking at the Crest

Severe earthquake shaking causes loose embankment or foundation materials to contract under cyclic loading, generating excess pore water pressures (i.e., liquefaction occurs).

The increase in pore water pressure reduces the soil's shear strength. Loss of shear strength over an extensive area leads to slope instability, deformations, and crest settlement. However, crest deformation does not exceed the freeboard existing at the time of the earthquake.

Open and continuous transverse cracks form across the crest and through all zones of the dam deep enough to intersect the reservoir. The depth and velocity of water flowing through the open cracks are sufficient to erode the materials along the sides and across the bottom of the cracks.

Material from upstream zones is not effective in sealing the cracks (by being transported to a downstream zone or constriction point where a filter would begin to form).

Head cutting action carves channels across the crest. The channels widen and deepen. Subsequent human activities are not sufficient to stop the erosion process. The embankment breaches and releases the reservoir.

This failure mode can also be initiated without the requirement for liquefaction. If the seismic deformation is great enough for cracking to extend to the below the reservoir level, internal erosion can be initiated. Again, this mostly pertains only to dams that have a small amount of normal freeboard, such as a water supply dam that is kept full most of the time.

Liquefaction and Sliding Opening Gaps

Severe earthquake shaking causes loose embankment or foundation materials to contract under cyclic loading, generating excess pore water pressures (i.e., liquefaction occurs).

The increase in pore water pressure reduces the soil's shear strength. (Again, this same outcome could occur if there is sensitive clay in the foundation.) Loss of shear strength occurs in a layer that is continuous upstream to downstream. Reservoir loading exceeds the shearing resistance remaining in the layer, and the entire embankment slides downstream.

Downstream deformation opens a gap at the crest deep enough to intersect the reservoir. The depth and velocity of water flowing through the gap are sufficient to erode the materials along the sides and across the bottom of the gap. Material from upstream zones is not effective in sealing the gap (by being transported to a downstream zone or constriction point where a filter would begin to form).

Head cutting carves channels across the crest. The channels widen and deepen. Subsequent human activities are not sufficient to stop the erosion process. The embankment breaches and releases the reservoir. It is believed that Sheffield Dam failed by this mechanism in the 1925 Santa Barbara CA earthquake.

Deep Cracking

Severe earthquake shaking causes differential settlement over stiffness discontinuities, at near-vertical embankment-foundation contacts, or at contacts between the embankment and concrete.

Continuous transverse cracks of sufficient width form through the core, and concentrate seepage flow through the cracks below the reservoir level occurs.

The seepage quantity and velocity are sufficient to erode core material and transport it beyond the downstream shell material. Upstream zones are not effective in sealing the cracks (by a mechanism whereby material from upstream zones would be transported to a downstream zone or constriction point where a filter would begin to form).

Subsequent human activities are not sufficient to stop the erosion process. The embankment breaches and releases the reservoir.

Dam/Reservoir Operational Potential Failure Modes (BP 33)

Key Concepts

In recent years, many dam failures and levee incidents have been attributed to operational failures, such as the failure of Taum Sauk Dam in Missouri in 2005.

These can result from equipment, instrumentation, control systems (including both hardware and software), or processes failing to do what they were intended to do. This, in turn, can lead to uncontrolled reservoir release, inundation of the leveed area, or inability to get people out of harm's way. Examples of these types of failure modes include:

- Failure of a log boom allows reservoir debris to drift into and plug the spillway, resulting in premature overtopping of the dam.
- Gates fail to operate as intended resulting in premature overtopping of the dam. This could result from mechanical or electrical failure, control system failure, or failure of the decision process for opening the gates.
- Gates open inadvertently sending life-threatening uncontrolled releases downstream. This could result from control system failure, operator error, or in the case of drum gates (which drop to release the reservoir), mechanical failure. Position sensors or limit switches could fail, resulting in gate openings greater than intended.
- Insufficient pump capacity or inoperable pumping systems prevent evacuation of interior drainage from the leveed area leading to inundation.
- Excess seepage overwhelms interior drainage facilities leading to inundation of the leveed area.
- Inability or failure to close conduit gates or valves allows backflow into the leveed area leading to inundation.
- Inability to warn and evacuate people in advance of life-threatening downstream flows. This could result from inability to detect the flows or a breakdown in the communication process to

get people out of harms way; for example power and phone lines may be cut by a large earthquake or flood.

- Loss of access to operate key equipment during a flood leads to overtopping of the dam or other uncontrolled releases.
- Loss of release capacity leads to overtopping of the dam. For example, if releases through the powerplant are a major component of the release capacity and the switchyard is taken out during a flood or earthquake, that release capacity will be lost. Mechanical equipment failure due to changes in operation without a corresponding change in maintenance. For example, if river re-operation equires frequent gate opening to enhance fisheries without a corresponding increase in the frequency of gate lubrication, component failure could occur when the gate is needed to pass a flood, resulting in premature dam overtopping.

Event Trees or Fault Trees

Event trees allow the analysts to visualize the progression of events that lead to failure. Since this is how potential failure modes are typically described, most geotechnical, hydraulic, and structural failure modes are evaluated using event trees. Indeed, even relatively simple operational failure modes can be described using event tree logic. However, in some cases there may be an operational failure mode involving complex interaction between mechanical and electrical systems. This could result in an event tree with an unmanageable expanding array of branches.

In such cases, a fault tree would be a more manageable tool for estimating risks. A fault tree starts with the assumed failure, and works backwards to look at the causes of the failure. It has the advantage of using “and gates” and “or gates” to link the basic events. For example, failure could result from one basic mode “or” another. But each mode might require conditions 1, 2, “and” 3 to occur. This allows the use of “Boolean” algebra for calculating risks.

REFERENCES

The following USBR/USACE Best Practices Manuals are referred to in this Module. Digital copies of these are provided with tis Module.

00 Cover 26 Nov 2013

01 Risk Guidelines 5 Nov 2012

02 Potential Failure Modes 5 Nov 2012

03 Qualitative and Semi-Quantitative 10 Nov 2012

04 Building the Case 16 Nov 2012

05 Basic Probability and Statistics 7 Oct 2013

06 Seismic Hazard 6 Sep 2012

07 Hydrologic Hazard 26 Nov 2012

08 Water Level Exceedance Curves 26 Nov 2012

09 Consequences 26 Nov 2012

10 Engineering Geology 16 Nov 2012

10 Geologic Drawing Examples compressed 26 Nov 2012

11 Event Trees 22 Nov 2013

12 Reliability Analysis 31 Oct 2012

13 Subjective Probability 16 Nov 2012

14 Reinforced Concrete 28 Sep 2012

15 Erosion of Rock and Soil 9 Apr 2013

16 Flood Overtopping 26 Nov 2012

17 Seismic Spillway Pier Failure 26 Nov 2012

18 Seismic Failure of Walls 26 Nov 2012

19 Buttress Dams 9 Oct 2012

20 Concrete Gravity Structures 21 Sep 2012

21 Arch Dams 9 Oct 2012

22 Stagnation Pressure Failure 3 Oct 2012

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26 Internal Erosion Tables

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29 Seismic Failure of Spillway Radial Gates 21 Nov 2012

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MODULE 7

Instrumentation, Surveillance & Monitoring

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INSTRUMENTATION, SURVEILLANCE & MONITORING

This section is based on the Reference Dam Safety Guidelines Chapters 8 and 9 which should be referred to for more details and specific requirements.

Inspections, Surveillance & Monitoring

Principles

Continuous surveillance and monitoring of the performance of dams to minimize 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 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
- Performances monitoring procedures and principles for a number of common adverse responses or conditions that typically are indicators or contributors to potential failure modes.

Section 7.2, presents principles and procedures for periodic and special safety reviews.

These basic principles and procedures provide general guidance that 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 (e.g. 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.

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 7-1**).

"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 of the Reference Guidelines.

Experienced people, trained to recognize deficiencies in dams, should carry out inspections. Inspections, requiring technical evaluations, should generally be carried out by an 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 7-1** summarizes the main types and purposes of inspections.

Table 7-1 Dam Safety Inspections

Type of Inspection	Personnel	Purpose
Comprehensive	Approved Dam Engineer and Specialists[1](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. 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. 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 Specialists1	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.)

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 7-2. 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 7-2 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 & REMOTE	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.

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. Reference Guideline 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.

Inspection Reports

All dam safety inspections should be fully documented by the inspecting personnel to provide an on going 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 Reference Guideline 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)

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 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 indicators 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.

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 7-3** are a guide for dams that are "in service" and have no known deficiencies.

Table 7-3 **Guide for "In Service" Dam Monitoring Frequencies**

Monitoring	Potential Consequence Classification (PCC)		
	LOW & REMOTE	MODERATE	HIGH & VERY HIGH
Meteorological data	Monthly	Twice Weekly to Weekly (TC)[2]	Daily (TR)[2]
Storage Level	Monthly	Twice Weekly to Weekly (TC)[2]	Daily (TR)[2]
Seepage	Monthly	Twice Weekly to Weekly (TC)[2]	Daily (TR)[2]
Chemical analysis of seepage[5]		Consider	Consider
Pore pressure[3]	Consider	3-Monthly to 6-Monthly	Monthly to 3 Monthly
Surface movement, control[4]		Consider	5-Yearly
Surface Movement, Normal	Consider	Consider	Yearly
Internal movement/stresses[3]		Consider	Yearly
Seismological[3]		Consider	Consider (TR)[2]
Post tensioning[6]		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.

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 Reference Guideline Appendix B.

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.

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. An Approved Dam Engineer or appropriate specialist with the relevant experience should prepare these reports. 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 7-4.

Table 7-4 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 & REMOTE	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.

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. An Approved Dam Engineer who is independent of the on-going surveillance program should undertake the audit.

Safety Reviews

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 Table7-5.

Table 7-5 **Dam Safety Reviews**

Type of Safety Review	Personnel	Purpose
Comprehensive	Approved Dam Engineer and Specialists[1](where relevant)	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: • Current criteria and prevailing knowledge. • The results of a PFMA Equipment should be test operated to identify deficiencies. For a Safety Review consider: • Draining of outlet works for internal inspection. • Diver inspection of submerged structures.
Special / Emergency	Approved Dam Engineer and Specialists1	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.

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.

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 7-6.

Table 7-6 **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 & 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.*

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.

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.

Reference Guidelines 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.

MODULE 8

Emergency Action Planning

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EMERGENCY ACTION PLANNING

This section is based on the Reference Dam Safety Guidelines Chapter 10 which should be referred to for more details and specific requirements.

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.

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.

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.

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 outdate, 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 outdate and useless.

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.

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.

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.

Sabotage

Sabotage is a possibility in the Eastern Nile region. Ill planned 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

MODULE 9

Environmental & Social Considerations

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ENVIRONMENTAL & SOCIAL CONSIDERATIONS

Environment and Social Factors that may affect the Safety of Dams

The following factors that may affect dam safety should be incorporated into the National Dam Safety Guidelines. The treatment of environmental and social issues generally should be addressed in separate Environmental and Social Guidelines.

Climate change

The sudden or unplanned release of impounded water in the event of a dam failure can cause much destruction of life and property. 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. However there is no proper understanding or 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.

Land stability

There are evidences that landslides have caused overtopping of dams. The sudden plunge of mass of rocks and soil in to a reservoir can displace the water causing overflow over the dam. This may result in dam failure and can also harm power houses downstream. Proper assessment of slopes and geological characteristics of land masses in the perimeters of the reservoir is necessary to ensure stability of abutments, islands within a reservoir and land around reservoirs and dams.

For reservoirs in very mountainous regions, it is considered important to analyze the possibility of dam failure or severe damage caused by the failure of a big slope along the reservoir border, and the big waves caused by it when hitting the dam.

Debris and vegetation

Floating debris and vegetation or large trunks of tress may obstruct gates and outlets that may endanger the safety of dams due to blockage of gated spillways.

"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."

This may be countered through a proper environmental assessment studies which usually address issues of vegetation clearing, soil and land stability studies.

Water quality

Severe water quality degradation in reservoirs may affect the integrity of gates and upstream dam facing material. In warm humid areas when trees and heavy vegetation are left in the reservoir area they decompose to produce hydrogen sulphide. This is a considerable nuisance in the vicinity of the dam and can cause corrosion of hydraulic machinery.

Reservoir Induced Seismicity (RIS)

Reservoir induced seismicity (RIS) is usually associated with large reservoirs, but has also been observed at a number of smaller water storages with lower heads of 60 to 40 m and less. It is recognized that RIS is an issue which is not fully understood but nevertheless should be considered in the design of dams.

Sabotage

Sabotage is a possibility in the Eastern Nile region. planned 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 dam owners should conduct security assessments, using established risk assessment methodology and dams should have physical security plans.

Environmental Dam Safety Factors Management Plan.

The Reference/Generic Dam Safety Guidelines include reference to environmental and social issues as they related to dam safety. It may be beneficial for ENTRO to develop separate complementary environmental dam safety factors guidelines.

Trans-boundary Considerations

Trans-boundary or Regional dam safety is an important aspect of trans-boundary agreements and conventions. Dam safety is not normally specifically mentioned in such international agreements, but can be inferred from various principles. The implementation of the regional dam safety program, will examine aspects of a regional dam safety regulatory body or other institutional arrangements. In follow-up to this Assessment Report it will be useful to ascertain the need for such an organization based on the preliminary information as described above. Discussions prior to and during the Workshop with delegates from the EN Basin Countries should assist in this regard to determine the regional factors relating to dam safety.

It will also be helpful to understand the functioning of the various organs of the Nile Basin Initiative in greater detail such as the Technical Advisory Committee and the Nile Basin Council of Ministers. However, it will be important to be particularly aware of any country sensitivities in respect of regional dam safety issues. Once the country information on dam safety has been gathered it should be analysed to ascertain whether there are any major imbalances between countries or differences of approach and to recommend a way forward.

A key initial activity which should be implemented at an early stage is the exchange of relevant dam safety information. This activity has in fact already commenced during the scope of this study and should be expanded upon in time. The exchange of information should be carefully considered and restricted to that which is absolutely necessary for regional cooperation.

On going activities should include:

- The Regional dam safety unit, in collaboration with national units, needs to organize and lead the dam safety management on Transboundary Rivers.
- An independent Dam Safety Panel of Experts should be appointed to review and comment on the design, construction, operation and maintenance of each dam with trans-boundary aspects.

- Catastrophic dam failure of the cascade development would pose a significant risk to populations in downstream areas living along the banks of the river. . Due consideration shall be given for such large dams safety scenarios.
- A Dam Safety Monitoring and Emergency Response Plan should be prepared in consultation between the riparian countries.
- The downstream population should be informed of the emergency response plan and the required action in the event of a dam break

Appendix A –

LIST OF DAMS

Country name	Name of Dam	Year of Completion	Year of change 1	Change type 1	Year of change 2	Change type 2	Year of change 3	Change type 3	Planned year of completion	Design or construction	River	Basin	Dam Type	Detailed type	Sealing	Height of Dam (m)	Length of Dam wall	Reservoir Capacity (103 m3)	Purpose	Catchment area (km2)	Potential Consequences Classification
EGYPT	Assiut Barrage	1902									Nile	Main Nile	BM	Masonry	fm	16.0	800	NA	IHN	-	HIGH
EGYPT	Delta Barrages	1862									Nile	Main Nile	BM	Masonry				NA	IC	-	
EGYPT	High Aswan	1970									Nile	Main Nile	ER/PG	Rockfill		111.0	3 830	162 000 000	IHC	2 200 000	VERY HIGH
EGYPT	Esna Barrage	1908									Nile	Main Nile	BM	Masonry	fm	16.0	865	NA	IC	-	
EGYPT	Damietta Barrage	1950									Damietta branch	Main Nile	TE/BM			15.0	360	NA	IC	-	
EGYPT	Rosetta Barrage	1985									Rosetta branch	Main Nile	BM			15.0	483	NA	IC	-	
EGYPT	Nag-Hamady Barrage	1930									Nile	Main Nile	BM	Masonry	fm	16.0	825	NA	IC	-	
EGYPT	New Esna Barrage	1994									Nile	Main Nile	ER/BM	Concrete		17.5	532	NA	ICNH	-	HIGH
EGYPT	New Nag-Hamady Barrage	2008									Nile	Main Nile	TE/BM/TE	Concrete		17.0	330	NA	ICNH	-	HIGH
EGYPT	Old Aswan	1902	1912		1933						Nile	Main Nile	CB	Masonry	fc	36.0	1 950	5 000 000	IHC	2 200 000	
EGYPT	Zifta Barrage	1902	1954								Damietta branch	Main Nile	BM	Masonry				NA	IC	-	
EGYPT	Farascour Barrage	1989									Damietta branch	Main Nile	ER/BM	Concrete				NA	INX	-	
EGYPT	Edfina Barrage	1951									Rosetta branch	Main Nile	BM	Masonry				NA	NX	-	
ETHIOPIA	Alwero	1996										Baro-Akobo-Soba	TE	Homogenous	he	14.0	4 100	75 000	I		HIGH
ETHIOPIA	Amerti	1984									Amerti	Blue Nile	TE	Homogenous	he	15.8	740	110 000	IH		VERY HIGH
ETHIOPIA	Angereb	1996									Angereb	Tekezze-Atbara	TE		he	34.0	420	6 000	S		VERY HIGH
ETHIOPIA	Chara Chara Weir	1997									Tana	Blue Nile	PG		hc	4.6	670		H		VERY HIGH
ETHIOPIA	Finchaa	1973									Finochaa	Blue Nile	ER	Rockfill with central cla	ie	22.2	543	650 000	IH	2 500	VERY HIGH
ETHIOPIA	Grand Ethiopian Renaissance Dam									C	Blue Nile	Blue Nile	PG	RCC	hc	145.0	1 780	74 000 000	H		
ETHIOPIA	Koga	2006									Koga	Blue Nile	TE	Zoned	ie	21.5	1 855	77 000	I		VERY HIGH
ETHIOPIA	Midimar	1999									Maria Shewito	Tekezze-Atbara	TE	Zoned	ie	33.0	380	10 000	S		VERY HIGH
ETHIOPIA	Nekempte	2008										Blue Nile	PG	Masonry	hx				S		
ETHIOPIA	Neshe	2010										Blue Nile	TE	Homogenous	he	38.0	1 010	448 000	IH	330	VERY HIGH
ETHIOPIA	Tekeze	2009									Tekeze	Tekezze-Atbara	VA	Double curvature arch	hc	188.0	420	9 310 000	H	30 390	VERY HIGH
SUDAN	Jebel Aulia	1937									White Nile	White Nile	PG/TE	Zoned+Masonry+Zone	he	39.0	5 000	2 540	HC		VERY HIGH
SUDAN	Khashim el Girba	1964									Atbara River	Tekezze-Upper At	TE/CB/TE	Zoned+RCB+Zoned	he	50.0	3 850	600	IH		VERY HIGH
SUDAN	Merowe	2009									Nile River	Main Nile	TE/ER/PG/TE/ER	Zoned+CFRD+RCPG+EC	he/fc/ie/fc/h	67.0	9 300	12 400	H		VERY HIGH
SUDAN	Roseires	1966	2012	H							Blue Nile	Blue Nile	TE/CB/TE	Zoned+RCB+Zoned	ie	78.0	25 125	6 000	IH	250 000	VERY HIGH
SUDAN	Dam Complex of Upper Atbara								2015	C	Setit, Upper Atbar	Tekezze-Upper At	TE/CB/TE	Zoned+RCB+Zoned	ie	54.0	13 000	3 700	IH	100 000	VERY HIGH
SUDAN	Sennar	1926									Blue Nile	Blue Nile	TE/PG/TE	Zoned+Masonry+Zone	he	39.0	3 025	375	IH		VERY HIGH
SUDAN	Kajbar									D	Nile River	Main Nile	ER/PG/ER	Zoned+RCPG+Zoned	ie	31.0	2 930	678	H		
SUDAN	Sheraik									D	Nile River	Main Nile	ER/PG/ER	Zoned+RCPG+Zoned	ie	44.0	3 065	2 687	H		

The following ICOLD terminology is used to describe details in the table above.

DESIGN OR CONSTRUCTION

- C : under construction
- D : in design but not yet under construction

DAM TYPE

- CB: buttress dam
- BM: barrage
- ER: rockfill dam
- MV: multiple arch
- PG: gravity in masonry or concrete
- TE: earth
- VA: arch
- XX: unlisted

When a dam is composed of several types of structures, they are described from the right bank to the left bank with various types separated by a slash. For example TE/PG/TE is a dam with a central part as a gravity dam and two wings in earth.

PURPOSE

- C: flood control
- I: irrigation
- H: hydroelectric
- F: fish farming
- N: navigation
- R: recreation
- S: water supply
- X: others or unlisted

When a dam has several purposes, these purposes are indicated with a combination of these letters without any separator, beginning with the most important purpose of the dam and ending with the least important purpose. For example "HIS" is for a dam used for hydropower and secondary purposes in irrigation and water supply.

ENTRO is an autonomous organ established to implement the Eastern Nile Subsidiary Action Program within the framework of Nile Basin Initiative

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