Dam Safety Management:

Pre operational Phases of the Dam Life Cycle

Committee on Dam Safety
International Commission on Large Dams (ICOLD)

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Foreword

In 2011 the ICOLD Committee on Dam Safety (CODS) submitted a report aimed at complete characterization of processes supporting the identification, tracking and effective addressing of all potential and actual problems that can impact the safety of the existing dams. The report approved as ICOLD Bulletin 154 Dam Safety Management: Operational Phase of the Dam Life Cycle recognized that within the complete life cycle of a dam (concept - feasibility - design – construction – commissioning – operation – rehab/decommissioning), the operational phase was the longest and required that the organization responsible for the dam had a process in place that was fully capable of addressing all aspects of dam safety.

In the early stages of Bulletin 154 development, Working Group preparing the document and the entire CODS came to the conclusion that the management of dam safety in the operational phase was possibly the most challenging, and, taking into account the sheer number of existing dams, was also the most urgently needed. However, CODS also recognized that another document addressing all aspects of development and implementation of the modern safety management approach to other phases of the dam life cycle should be considered as a priority task for the CODS in the future.

This document extends the general approach and concepts presented in Bulletin 154 to all phases of dam life cycle preceding the operational phase. Its importance cannot be overstated if one recognizes that many risks associated with the operation of existing dams have their origins in other phases preceding the actual operation. Although there are numerous ICOLD Bulletins addressing mostly technical aspects of planning, design, construction and commissioning of dams, there is not a single Bulletin which covers the subject in a comprehensive manner. The current document is the first attempt to capture all relevant dam safety aspects in all preoperational phases by systematically characterizing the actors involved, their roles, the activities and complex interactions present in different phases of the dam lifecycle.

Committee on Dam Safety members hope that the ideas developed and presented in the document will provide a better guidance and help in identifying and eliminating potential sources of dam safety issues, before they actually happen when the dam has been already built and is being operated.

Przemyslaw A. Zielinski
Chairman, Committee on Dam Safety

Acknowledgments

The Committee on Dam Safety and the ICOLD Executive gratefully acknowledge the contribution of members of the Committee's Working Group and the support provided by their sponsoring organizations. The final text of the Bulletin is the result of the collective effort of the entire CODS which continued providing general guidance and valuable input during the period of 2013 to 2018. The task of converting this guidance into guidelines for managing dam risks rested with the Working Group. The Group not only acted as a forum for exchange of ideas but was also instrumental in reviewing comments from CODS members. A workshop was held at the 2017 Annual Meeting in Prague, where the draft of the Bulletin was presented to a broader audience and initiated valuable comments and remarks from the participants.

The task of writing the drafts and preparing the final text was carried out by:

1. Mr. M. Balissat, Working Group Leader, Senior Consultant at Stucky Ltd., Switzerland - financial and in kind assistance provided by Stucky Ltd;
2. Dr. D.N.D. Hartford, Principal Engineering Scientist, BC Hydro, Canada – financial and in kind assistance provided by BC Hydro;
3. Mr. M. Poupart, previously Dam Safety Advisor at Electricité de France, presently Independent Consultant, France ;

It needs to be stressed that the effort provided by the members of the Working Group was extensive and its work was instrumental for completion of the task. Working Group members had a substantial knowledge and experience of dam safety issues. This breadth of perspective on regulatory, organizational, managerial and engineering aspects of dam safety management can hopefully provide the readers of this Bulletin with the help in conceiving and implementing a modern comprehensive management system for designing, building and commissioning dams.

Przemyslaw A. Zielinski
Chairman, Committee on Dam Safety

Chapter 1 - Introduction

1.1. Why this bulletin?

Dams are massive structures retaining large water bodies able to cause substantial or even catastrophic damages downstream of their location. As such they represent a potential hazard in case of uncontrolled release of water due to overtopping by flood or by submergence caused by a sliding earth mass in the reservoir. Obviously structural failure of the dam body or its foundation or malfunction of water releasing structures constitute also potential hazards. Although many risks associated with dams are linked to the operation of these structures some of them are imbedded in the phases preceding operation. They can be found at the preliminary planning of the dam scheme, during the detail design of the structures, as well as during the construction and commissioning phases. Identifying the risk factors and trying to minimize them are essential to structural safety and to (planned) operational safety. Dam safety has to be adequately managed from the onset of a project development until its construction and commissioning. It shall be pursued during the whole operation of the scheme. This means that how dam safety is to be pursued in the operational phase of the life-cycle must be developed in the design phase of the project.

Until present no bulletin of ICOLD was directly addressing this situation. Bulletins (see list in Appendix B) are either purely technical or describing risk evaluation methods from a theoretical point of view. The present Bulletin addresses the pre-operational phases of a dam project and links them to the guidance of the previously issued Bulletin 154 which presents recommendations for safety management during the operation of the dam (see Fig. 1.1).

In phases preceding operation of a dam scheme (going from preliminary studies to commissioning) attention has to be given to the implementation of engineering and construction measures (best practice) excluding or, at least, minimizing the risk of failure of the dam. They encompass both structural (retention of water) and operation (conveyance of water) oriented safety measures. Several factors (human and technical) tend to affect the safety aspects of a dam. Whereas technical aspects are relatively easy to identify in design, human factors covers a broad range of interfering and less strictly defined aspects going from personality conflicts within a working team to deficient communication and organizational flaws. Therefore management of the steps leading to the realization of a dam scheme and its operation should be aware of these possible drawbacks and should put all necessary efforts into identifying and controlling them.

1.2. Importance of dam safety at all development stages

A decision to invest in the development of a dam is a very significant matter that can be of national and even international importance from multiple perspectives. The investment involved is generally so large that it is imperative that the development fulfil all of the intended objectives and other objectives as might be determined after construction, or as determined over the economic evaluation period of the dam and beyond (the whole life-cycle). It can be taken as a premise that the investment must be secured at the outset in such a way that the principle that development of the dam results in a net positive contribution to society is realised. Dam Safety considerations have a pivotal role in securing the investment over the whole life-cycle of the dam.

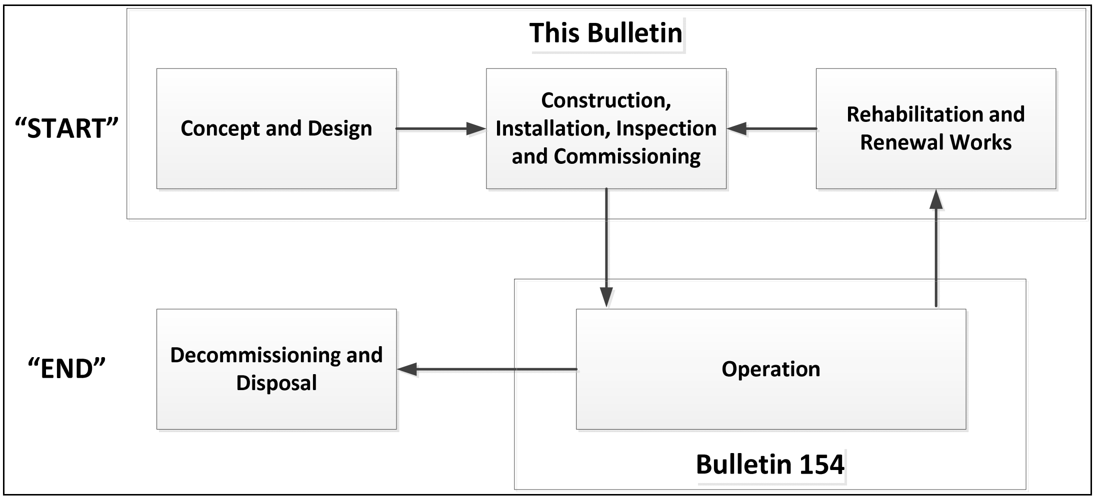

Figure 1.1 Extent of this bulletin

In the modern context, Dam Safety considerations which include all aspects of safety management over the whole life-cycle contribute to a great deal more to securing the investment than previously considered when dam safety pertained to structural safety (ICOLD B59, 1987):

> *The safety of a dam manifests itself in being free of any conditions or developments that could lead to its deterioration or destruction. The margin which separates the actual conditions 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 into account all reasonably imaginable scenarios of normal utilization and exceptional hazard which it may have to withstand during its life.*

By way of illustration, how dam safety is considered in the design phase influences construction costs and safety during construction, and later on operational safety, costs, constructability and safety of modifications, improvements and renewal, and finally decommissioning.

For instance, the choice of spillway type, a matter that is identified at the conceptual design or feasibility stage can significantly influence whole life-cycle operational costs and the effectiveness of operational safety. Life-cycle operational costs that can be influenced at the conceptual design stage go far beyond the physical components and include surveillance and monitoring costs, staffing costs, maintenance and repair costs and ultimately repair/upgrading/renewal costs prior to the end of the life-cycle.

In addition to the physical and operational justifications for including whole life-cycle safety considerations at an early stage of the design process, there are sound financial reasons for the dam Investor to consider early investment in dam safety for financial efficiency and for insurance reasons. The financial efficiency dimensions relate to the economics of the project over the whole life-cycle from the perspectives of asset value, operational costs and refurbishment/renewal costs whereas the insurance dimensions relate to the overall protection of the investment. The investment in the dam is "at risk" from the initial stages of the investment up to the end of the economic evaluation stage with the investment most "at risk" initially from first filling to approximately 5-years into the service life, and again at the end of the service life of the dam. The relatively long pay-back period for the capital investment in a dam means that the total financing and operational costs of a dam will not become net-positive until well into the economic evaluation life-cycle. During this time, the effects of ageing will begin to manifest themselves, and safety expectations can be expected to increase. A robust design that considers these issues at the outset can significantly influence the repair and replacement costs at the later stages of the economic evaluation process. In straightforward terms, securing safety contributes to securing the investment and vice-versa.

1.3. Overarching Principles

ICOLD Bulletin 154 defines nine overarching principles for dam safety that are sufficiently general to be applied directly or with minor alteration over all phases of the life-cycle of a dam. These principles are as follows:

a) Justification for dams: Dams should be constructed and operated only if they yield an overall benefit to society.
b) Fundamental Dam Safety Objective: The fundamental dam safety objective is to protect people, property and the environment from harmful effects of misoperation or failure of dams and reservoirs.
c) Responsibility for Operational Integrity and Safety: The prime responsibility for operational integrity and safety of a dam should rest with the Dam Owner.
d) 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.
e) Leadership and management for Safety: Effective leadership and management for operational integrity and safety should be established and sustained over the life cycle of the dam.
f) Balancing of Protection across Competing Objectives: Protection should seek to achieve a balance across competing objectives to provide the highest level of operational integrity and safety that can reasonably be achieved.
g) Limitation of Risk to Individuals and Society: Measures for controlling risks from dams should ensure that no individual bears an unacceptable risk of harm, and that the risks to society do not exceed the risk tolerance levels of society.
h) Sustainability of Dams and Reservoirs: In order to secure the societal value, dams and reservoirs must be sustained in the long term. To ensure sustainability of dams, all reasonably practicable efforts should be made to prevent and mitigate failures and accidents.
i) Emergency Preparedness and Response: Appropriate arrangements should be made for emergency preparedness and response for dam failures and accidents.

Clearly, one of the objectives of the pre-operational phases is to ensure that the dam conforms to all of these principles when it goes into service. Importantly, for most dam constructions, the dam enters in operation as soon as impoundment begins and often before the construction has been handed over to the Investor/Owner.

Of the 9 overarching principles the following apply directly without any alteration to the pre-operational phases:

- Justification for Dams
- Fundamental Safety Objective
- Balancing of Protection across Competing Objectives
- Limitation of Risk to Individuals and Society
- Sustainability of Dams and Reservoirs
- Emergency Preparedness and Response

The remaining three, Responsibility for Operational Integrity and Safety, Role of Government and Leadership and Management for Safety, can be modified and made specific to the pre-operational phases in a way that there can be a smooth transition to the operational phase when the dam is handed over to the Investor/Owner.

The Investor/Owner has the continued full responsibility to maintain leadership and management for safety during all phases of a project (planning, design, construction, quality control) including transitioning to the operation phase, and subsequently through the operational phase and then into either renewal or decommissioning.

The three revised Pre-operational Safety Principles are provided as follows:

Responsibility for Integrity and Safety in the Pre-Operational Phases:

The prime responsibility for the overall integrity and safety of a dam should rest with the Dam Owner. The Owner is responsible for the third party liabilities. Responsibility for meeting safety objectives of the design should rest with the Designer, but the Owner has to make sure that he is fully understanding and accepting the design of the project. He further carries full responsibility for implementing an adequate quality control system during design and construction. Responsibility for safety of the works during construction and commissioning should rest with the Construction Supervising Engineer as determined by the contractual arrangements established by the Investor/Owner.

Role of Government:

The legal and governmental framework for all industrial activities, including licensing, development, operation, and alteration of dams, provides the overarching structures for pre-operational and operational integrity and safety assurance, and for safety during renewal or retirement from service. The Government through its regulatory agency requires a number of policies and design criteria to be satisfied. But the Owner has to be even more conservative for reducing potential risks to a level satisfactory for the protection of the public and its own assets.

Leadership and Management for Safety in the Pre-Operational Phases:

Effective leadership and management for pre-operational integrity and safety should be established in a way that deals with all aspects of safety including first filling and provides for a smooth and uninterrupted transition to the operational phase of the life cycle of the dam.

1.4. Bulletin Structure

The Bulletin is mainly intended for dam owners and investors but also for all other actors intervening in the development of dam projects. It concerns not only development of new dam schemes but also heavy rehabilitation or upgrading of existing dams. The term "dam" or "dam scheme" is not limited to the dam structure itself but encompasses the appurtenant structures (spillway, bottom outlet, water intake, etc.) and the surrounding environment (reservoir, downstream area). In case of hydropower development it concerns also the power intake, headrace tunnel or canal, penstock and powerhouse. Thus the dam has to be understood as a *system* that, as many other undertakings of mankind, is exposed to risks during its development and its operation.

- Dam development phases and role of the various actors are presented in a first section (Chap. 2) of the Bulletin. Contractual relations and interdependency of the actors are also briefly described and commented.
- In the following section (Chap.3) the various risks involved in design and construction of dams are described. The influence of nontechnical (human) factors is stressed and the importance of uncertainty in dam design and construction is discussed. The need to improve knowledge of the prevailing conditions by investigation is also presented. General rules for minimizing risks in the development of a dam project are proposed.
- The need of defining an overarching safety management system for all actors is presented in Chap. 4. Starting from safety objectives their transformation in implementable actions is described. The roles of the different actors within this framework are presented. As the Owner/Developer shall be considered as the main driving force in the development of a dam project this responsibility is especially stressed. General organization and policies of the Owner/Developer's management system are presented. Management of changes is an important issue in the development of dam projects is also discussed.
- Finally engineering principles to be applied not only to design of new dams but also to the preservation of the asset function during the lifetime of a dam are presented and commented in Chap. 5.

Chapter 2 - Dam development phases and Actors

2.1. Dam as a prototype

Developing an hydraulic scheme including a dam as the key impounding structure is usually a long and difficult process, because it implies many aspects and often involves compromises between competing interests.
Once the size of a reservoir has been selected according to hydrological conditions and economic considerations the layout and type of a dam will depend essentially upon the topographical and the geological conditions, as well as the availability and supply of building materials. Flood discharge facilities setup during construction and those used later on in the operational phase can also be decisive in selecting the type and layout of a dam. Furthermore any dam project has to be developed in accordance with its future use (water supply, irrigation, flood control, energy production, etc.) and has to be in agreement with environmental and public safety considerations. This indicates the uniqueness of each dam scheme.
It is thus obvious that design and construction of dams is not a standardized industrial process such as the production of consumer goods or even the manufacturing of cars or planes. The majority of issues at dams are very much site dependent and can be approached only by using general technical principles, state of the art and state of the practice rules. Safety requirements are more difficult to grasp as they are spread across different project stages from the very first studies to the construction stage and commissioning.
It is therefore justified to consider dams as *prototypes* which are different from most other standardized industrial structures or products.

2.2. Related development phases

Development phases of dam projects can differ from a country to another especially regarding the procedures linked to tendering of the works, construction permit and licensing. Also the way a project is being tackled by the Owner and/or the Investor from the first studies to the construction and commissioning phase can have an impact on development phases.
Development of a dam project takes usually several years or even decades as it requires identifying the need for and demonstrating the profitability of a given scheme, setting up the financing and last but not least complying with the environmental requirements.
Starting from the earliest point in the dam life the successive development phases can be summarized as follows:

- Preliminary studies (conceptual design)
- Feasibility study
- Detail design*
- Tendering*
- Construction (construction design)
- Commissioning

(* Tendering is usually based on the detail design, can be also on a reduction thereof called "tender design").

2.2.1. Preliminary studies

Developing a dam scheme usually originates from a primary demand in terms of drinking or industrial water, agricultural use, flood-control, hydropower production, or several of these demands considered together. Further purposes such as flood alleviation are often also considered in conjunction with the -primary purposes or independently from them. It is inevitable that the construction of a dam will result in alteration of the hydraulic regime of the river, the agricultural capacity of the upstream and downstream river reaches, river flood characteristics, human habitat and life quality, and the environmental performance of the river. At an early stage the studies focus on alternatives for water storage in one or several reservoirs. The emphasis is deliberately put on the hydrology of the river (or rivers) to be impounded and the general topography of the project area. Regional

and site geological conditions are also considered at this stage and dam sites roughly estimated based on their geometrical (or topographical) characteristics. Dam costs are derived from bulk prices and experience with previous schemes. The same applies to headrace tunnels and powerhouses.
In the *preliminary studies* different options for reservoir size and dam location are envisaged and compared. Only general geological information is usually available at this stage that does not allow to develop the layout of the dam and appurtenant structures in much details. Construction costs and potential benefits in terms of energy production or water supply are estimated in a coarse but comparable way for each alternative. They are then compared to find out the most suitable solution. A preliminary financial analysis to determine the return on investment is usually performed at this stage.
Development of dam projects requires time and long term investments, they are difficult to establish and to manage in large part because economic and political conditions are changing nowadays faster than it used to be a couple of decades ago. A typical example is the development of pumped storage schemes in Central Europe (Alpine countries) which was supposed to supplement the production of energy from alternative "green" sources (wind, sun) when these sources were not delivering power. “Green sources” have however been developed with governmental subsidies to such an extent that presently (as of 2016) enough cheap energy is always available on the European continent. Design of several pumped storage schemes has been therefore put back in the drawer and the future of existing schemes or schemes under construction is uncertain.

2.2.2. **Feasibility Studies**

At the *feasibility study* level for new dams more detailed investigations are required especially regarding foundation conditions and hydrological aspects (flood study). Typically, one or two prime alternatives (sometimes more than two) are examined and layout of dam and appurtenant structures is established based on the results of the field investigations. Recommendations are drawn for further investigations at the next stage. The technical and financial feasibility of the best alternative is established at this stage. It forms the basis for a decision of the Owner to go ahead with the project.

2.2.3. **Detailed design**

At the *detail design* stage complementary field investigations are usually performed to clarify or improve some design issues. Design of the dam and appurtenant structures is carried out with a degree of accuracy that should be sufficient to apply for a building permit and all further administrative authorizations, as well as for tendering the construction works among interested contractors. As the design is significantly more detailed and comprehensive than at the feasibility level the cost estimate might also substantially increase and the realization of the project could be put at stake. It is therefore not unusual to have a time break at the end of this phase to re-evaluate the project feasibility. In the meantime application for the building permit can be initiated.

2.2.4. **Tendering Stage**

At the *tendering stage* description of the works should be sufficiently precise in quality and quantity for allowing well elaborated proposals from prospective contractors. It is essential that the successful tender has properly considered the logistical and constructional issues, and that the Designer has carefully and completely considered all aspects of the successful tender in the context of the design assumptions and expectations.

2.2.5. **Construction stage**

The *construction stage* is the phase which involves most probably the largest number of actors during the lifetime of the dam, i.e. Investor/Owner, Designer, Contractor, Subcontractor(s), and Regulatory Agency. A key role is that of construction supervision. It is usually set up of professionals from both the Investor/Owner and the Designer. The construction supervision has to ascertain that the construction drawings prepared by the Designer are correctly implemented by the Contractor, it has also to make adjustments in case of difference between drawings and in situ conditions. The management of these adjustments (changes) requires considerable attention and often requires deep involvement of the Designer as changes in the design may have significant safety and performance implications on top of cost and schedule implications.

2.2.6. **Commissioning**

Commissioning of the scheme requires a first impounding of the reservoir to be performed. A reservoir fill plan has to be developed (including instrumentation and surveillance), reviewed and authorized before reservoir filling can begin. Preparation of the plan shall be done early enough to properly plan and install necessary instruments to monitor specific features of the dam as determined through the design.

Closure of the diversion facility (tunnel or channel) is a critical task as it requires lowering of bulkheads in flowing water to block the flow. It shall be done therefore during a low flow (dry) season. The reservoir level shall be maintained at several staged levels according to dam height to create permanent seepage conditions and allow for observation of the dam behaviour. The essential part of the commissioning phase is related to testing and first operating of the hydro-mechanical and electrical equipment (gates, valves, pumps, instrumentation, control system, etc.)

2.3. Typical activities at each of the pre-operational phases

Over the several project phases activities can be grouped in different categories. The Table 2-1 gives an overview of typical activities linked to

- project design (desk activities)
- site activities
- economic aspects

The third category might be surprising. It is however proven that economical or financial conditions are (too) often dictating the choices made at the design, tendering and/or construction stage and that these choices will ultimately affect the safety of the dam and its appurtenant structures.

Phase	Project Design	Site activities	Economical aspects
Conceptual ideas	Reservoir sizing, preliminary site selection	Fly-over	Needs and benefits
Preliminary studies	Hydrology, site selection (geology)	Site reconnaissance	Preliminary cost estimate, comparison of alternatives
Feasibility study	Type of dam, material sources, foundation interpretation, construction scheme	First site investigations (drilling campaign, etc.)	Cost estimate, selection of "best" alternative
Detail design	Load cases, structural analysis, materials	Detailed site investigations	Detail cost estimate, project economics
Tendering / contract awarding	Technical support	--	Procurement costs, market conditions
Construction	Construction (application) drawings	Diversion scheme, material borrow areas, construction delays, quality checks	Additional costs, cash flow
Commissioning	Performance analysis	Surveillance, Inspections	Possible additional costs

Table 2-1 Typical activities for different phases

2.4. Definition and role of the different actors

2.4.1. The Investor / Owner

Per definition an Investor is an individual or a corporate entity who commits money to industrial products or services with the expectation of financial and other returns. The primary concern of an Investor is to minimize risk while maximizing returns. Investors can be single persons, banks, funds (institutional or private), governments or other types of entity.

An Owner is a party (individual or corporate entity) that possesses the exclusive right to hold, use, benefit from, transfer and otherwise dispose of an asset or property. In this sense the Owner has a broader role than the Investor, but as both terms often describe the same entity they can be used jointly.

An Investor/Owner is mainly interested in getting a maximal return on investment (RoI) for the partners and/or shareholders, while meeting the needs of the stakeholders who will include the public at large (an overarching principle). On the other side the Investor/Owner bears the long term economical risk especially in the case of hydropower schemes (case of non-profitable energy retail and of non-amortizable assets) which can be adversely affected by volatility in the electricity market. The Owner/Investor relies on the skill and experience of his engineer and the applicable design codes and standards (if any) to have a state of the art project. In the construction phase the quality of the services provided by the Contractor and the Suppliers will further be decisive in correctly implementing the design of the engineer.

The Owner/Investor bears the *ultimate responsibility* for the safety of the dam from the early design concept to commissioning and later on during the operational phase of the dam. The Owner/Investor has to establish rules for the Designer in terms of reporting including explicitly the safety issues.

The Owner/Investor might compromise the quality of the work by having a too tight budget or a unrealistic time schedule (concerns both design and construction phase). The Owner/Investor is responsible for obtaining the several authorizations (concession, environmental permit, construction permit, operating license, etc.) and satisfying the requirements of the licensing (state) regulatory agency. The Owner shall further consider the land use downstream of the planned dam scheme and ascertain the possible impact of extreme flow releases in case of existing habitations or other human activities (see also Chap. 4). Last but not least the Owner/Investor shall communicate with the public at large and especially with the stakeholders (population living upstream and downstream of the dam, on the reservoir shores, fishermen associations, etc.).

2.4.2. **The Designer**

The Designer is acting during all phases preceding operation on behalf the Investor/Owner and is bound to the Investor/Owner by several successive contracts or (exceptionally) by a long term contract (initial studies, preliminary design, detail design, tender documents, assistance at tendering phase, construction supervision, commissioning). As such the Designer usually represents the Investor/Owner toward third parties on technical matters. The Designer has to apply the best technical knowledge (state of the art/state of the practice) to respect the regulations (building code, standards, environmental aspects etc.). The Designer has to make sure that all technical and safety aspects of the design are properly interpreted and that the totality of the design meets the objectives of the project. The Designer shall make use of his previous experience on similar designs while identifying well the particularities of the project he is working on. As far as possible he has also to envisage the possible problems that could be encountered during refurbishment or upgrade works of the dam.

The Designer has to serve the interests of the Investor/Owner at best. As such the Designer should apply value engineering to the main components of the project and propose to the Owner the economically and technically best solutions. Whatever the case the safety aspects of the design should not be compromised.

Design contracts are usually on a time basis with a financial cap. They can include lump sum parts for some standards and/or well defined design activities. If the Designer is not able to carry out his tasks within the negotiated budget an attempt might be made to perform sloppy work

In case of a design mistake the financial liability of the Designer can be contractually limited to the amount of the fees. But this is often not possible due to the prevailing legislation on professional liability and for this reason design firms must keep up liability insurances.

2.4.3. **Board of Consultants**

For large projects and for smaller dams with complex conditions it is advisable for the Owner to appoint a Board of Consultants for the period of the development. The Board shall provide recommendations as early in the detail design stage, especially at the feasibility level. At the construction stage the Board shall be entrusted with the required authority to guarantee towards the Owner that all appropriate technical and constructional measures have been taken for ensuring the proper operational and structural safety of the project.

2.4.4. **Site supervisor**

Site supervision is usually provided by the Investor/Owner (if they possess a sufficient technical capacity) or by the Designer or by a combination of both. In any case the Site Supervisor reports directly to the Owner and informs the Designer either directly or through the Owner. The Site Supervisor has a decisive impact on the quality of the work performed by the Contractor.

The Supervisor shall be fully informed by the Designer on "why and how" design solutions have been adopted. On the other hand the Supervisor shall also regularly inform the Designer of any problem requiring a design change or adjustment and be responsible on site for the management of design changes. Important design modifications shall be submitted to the Regulator and the Board of Consultants (if any) and no changes shall be made until all agree.

The Supervisor has to manage the construction works within given contractual prices (bill of quantities) and an overall budget and is responsible for the temporary and final acceptance of construction works

The Supervisor represents the Ownership on site and, as such, shall initiate and keep good relationships with the local people and the authorities.

2.4.5. **Contractor**

The Contractor is a key entity in the realization of a dam project as this organization usually provides the construction machinery, the materials and the workforce in charge of the construction.

Several forms of contract can be used to bind the Contractor to the Investor/Owner. The most common types are

- Building contract (either lump sum or unit price contract or combination of both)
- Design-build contract (general contractor agreement)
- EPC (or turnkey) contract
- EPCM contract (with construction management)

In the first case the Contractor is bound to provide only construction services paid on the basis of unit prices and lump sums. This is the most common form of construction contract. In the second case the engineering design is included in the package of the Contractor. This has the advantage for the Owner to handle all matters with a single interlocutor. For dam projects standard construction contracts or design-build contracts have proven to be effective in managing construction activities although they do seldom contain incentives for the Contractor to share with the Owner the benefit of a shorter construction time or of a faster concrete placement. It is usual for the Owner to keep a Designer at his side (so called Owner's Engineer) for checking and approving the construction drawings provided by the Contractor.

Under an EPC (Engineering Procurement Construction) contract the Contractor is supposed to deliver a complete project within a fixed budget and a predetermined time schedule. At the scheduled date of delivery the project shall be ready to go into operation. This is the reason why this type of contract is called turnkey contract. EPC contracts seem to be a general trend in the international construction business. They are however not well adapted to dam projects, as several unknowns, such as the effective foundation conditions, have to be supported by the Contractor. This leads most of the time to disputes with the Owner and can end up with arbitration procedures.

Under the EPCM model the Contractor does no building or construction, rather he develops the design and manages the construction process on the Owner's behalf. In this case the work force has to come from a third party (a construction company or supplier) and work contracts are passed between the Owner and the construction entities. The liability of an EPCM contractor is limited to his own services. This type of contract is well adapted to non-conventional or complex structures where several specialized firms are involved.

Another form of contract which has been used sometimes for special works is the cost plus contract, where the Contractor is paid for all expenses plus a fix percentage. In this case the Owner is assuming all risks of cost overruns. This type of contract is justified only when the works to be carried out are non-conventional or there is an urgent need to complete the works.

Several professional organizations (FIDIC, ICE, ASCE, etc.) have developed contract books and forms, which include the basic contract types cited above.

Many factors can influence the final difference between the offered unit prices and lump sums and the effective cost prices. Too low unit prices in the proposal of a Contractor will lead to sloppy work and/or to attempts to renegotiate prices later on (claim management). Independently of the design quality good workmanship is essential for a successful construction work.

In general the professional liability of the Contractor extends to all flaws caused by poor workmanship of their own construction team and of their subcontractors and he must be prepared to repair these defaults at their own costs and without loss for the Owner.

2.4.6. **Supplier**

Under the general term of Supplier one understand all providers of hydro-mechanical and electro-mechanical equipment, monitoring instrumentation and control system in the dam, the appurtenant structures and in the case of hydropower schemes, the power headrace and the powerhouse. Supply and installation are included in the overall package of a general contractor agreement or in single contracts directly with the Owner.

The installation of equipment is to be coordinated with the Contractor. Provisions shall be made in the Contractor's work contract for any service provided to the Supplier, including waiting time, and vice-versa.

The responsibility of the Supplier is limited to the supply package as awarded. This can lead to interface problems. Therefore a larger electrical and mechanical package is often delimited under the lead of one (major) supplier.

Following the site installation and the preliminary testing of equipment, the commissioning phase is the crucial period for the Supplier, as its equipment has to prove its proper functioning under real operating conditions (first wet test for the hydro-mechanical parts, etc.). Early defects of pieces of equipment can have a substantial impact on commissioning schedule and safety of a dam in the first years of operation.

2.4.7. **On Site Operator**

At new dam schemes the future On Site Operator, if already known, can be called in at the detail design phase to review arrangements made by the Designer in terms of ease of operation and operational safety. Later on the On Site Operator will be directly involved at the commissioning phase together with the Suppliers to become fully acquainted with the operating modes of the various equipment.

In case of major rehabilitation projects the dam operation is usually modified (lower operating level, increased discharge through bottom outlet, etc.). The On Site Operator has to strictly follow the modified operating rules and must make sure that safety prevails over production targets or other economic goals. Critical situations (sudden flood, plugging of discharge openings, etc.) have to be anticipated and provisions established to overcome or (at least) mitigate their impact.

2.4.8. **Licensing agency**

Dam projects because of their important impact on the environment require a comprehensive licensing process involving many aspects. The licensing process is conducted by a state agency or, in some countries, directly by an entity of the Ministry of Water Resources. Other governmental entities are usually involved, such as the Ministry of Environment or the Ministry of Energy. The Licensing Agency is usually at the National level, but in case of a decentralized (federal) type of structure also at the State or Province level.

Basically the water resources development licensing progress involves consultation between national and local agencies for reaching terms and conditions to protect and enhance water quality, fishery resources, public recreation, renewable energy production and other public interests. A water resources development license concerns essentially the water use, but specifies also the safety requirements. In this sense licensing should consider the downstream area of a dam scheme and include provisions, if necessary, for restricted land use because of potential damages in case of large flow releases.

2.4.9. **State or National regulatory agency**

A State or National regulatory agency is in charge of the high-level oversight surveillance of dam safety. It issues rules concerning the design and the operation of dams and regularly checks whether the Owner meets the safety requirements. The regulatory agency can also fulfil both functions of licensing (in the pre-operational phases) and of high-level oversight surveillance (in the operational phase).

State or National regulatory agencies should establish and enforce legislation that requires periodic inspections and subsequent reporting by qualified dam safety experts. Also requirements for preparation of EPP's and EAP's for the dam scheme should be included in the legislation (see 3.2.5).

Not only new projects, but also major rehabilitation or modification works have to be approved by the regulatory agency.

> *Examples of regulatory agencies from different countries can be found in the ICOLD Bulletin 167:* "Regulation of Dam Safety: An overview of current practice worldwide"

2.4.10. **Public**

The public shall be involved from the onset of a project development, whereas a distinction shall be made between stakeholders, i.e. the population living around the reservoir or downstream of the dam, and the public at large (power consumer, beneficiary of water supply, etc.). These two groups require different types of communication.

Already at preliminary project stage opposition from the public can arise for different reasons (ecology, water use, safety, financial aspects, etc.). Special interest activists will put a given water resources development project in the light of their views on general society development and this can completely hinder the development. Public opposition (even if factually and correctly countered by the Investor/Owner and the Authorities) can last during construction and until commissioning of the scheme.

People are more and more confronted with technical issues in their personal life and the reliability of technical components. From this point of view it can be assumed that they understand that any technical activity entails a *residual risk* (even very low) and, as such, a dam project cannot be 100% safe for all possible conditions, but that design and organizational measures are being taken to mitigate the negative impact of such conditions.

The public living downstream of dams shall be informed about the existence of emergency (evacuation) plans in case of a loss of control of flows or problems with the structural integrity of the dam. Joint training of dam scheme personnel, police, local civil protection and/or army units shall be organized at regular time interval and should include the public under some circumstances (see also chap. 3.2.5)

2.5. Involvement of the actors during a dam project development

In the course of a project development the several actors will be involved to a various degree (Table 2-2). As the development of the project might take several years or even decades it is obvious that rarely the same persons will be in charge at each function. Knowledge of the conditions related to the project will be spread over numerous people with various levels of knowledge according their respective position.

It is also usual that some activities will require a "back and forth" process until the aimed results are achieved. This is the case at the feasibility stage, where the whole project concept might be re-questioned and set anew. A similar situation might also arise at the detail design phase where more in depth investigation could indicate that the solution issued from the feasibility study has to be modified or even abandoned.

During the construction phase adjustments of the detail design have usually to be performed to take into account the particular site conditions (bedrock level, limit of weathering depth, etc.). In some cases resizing of the scheme or change of the dam type has been decided when construction had already started leading to ambiguous contract situations.

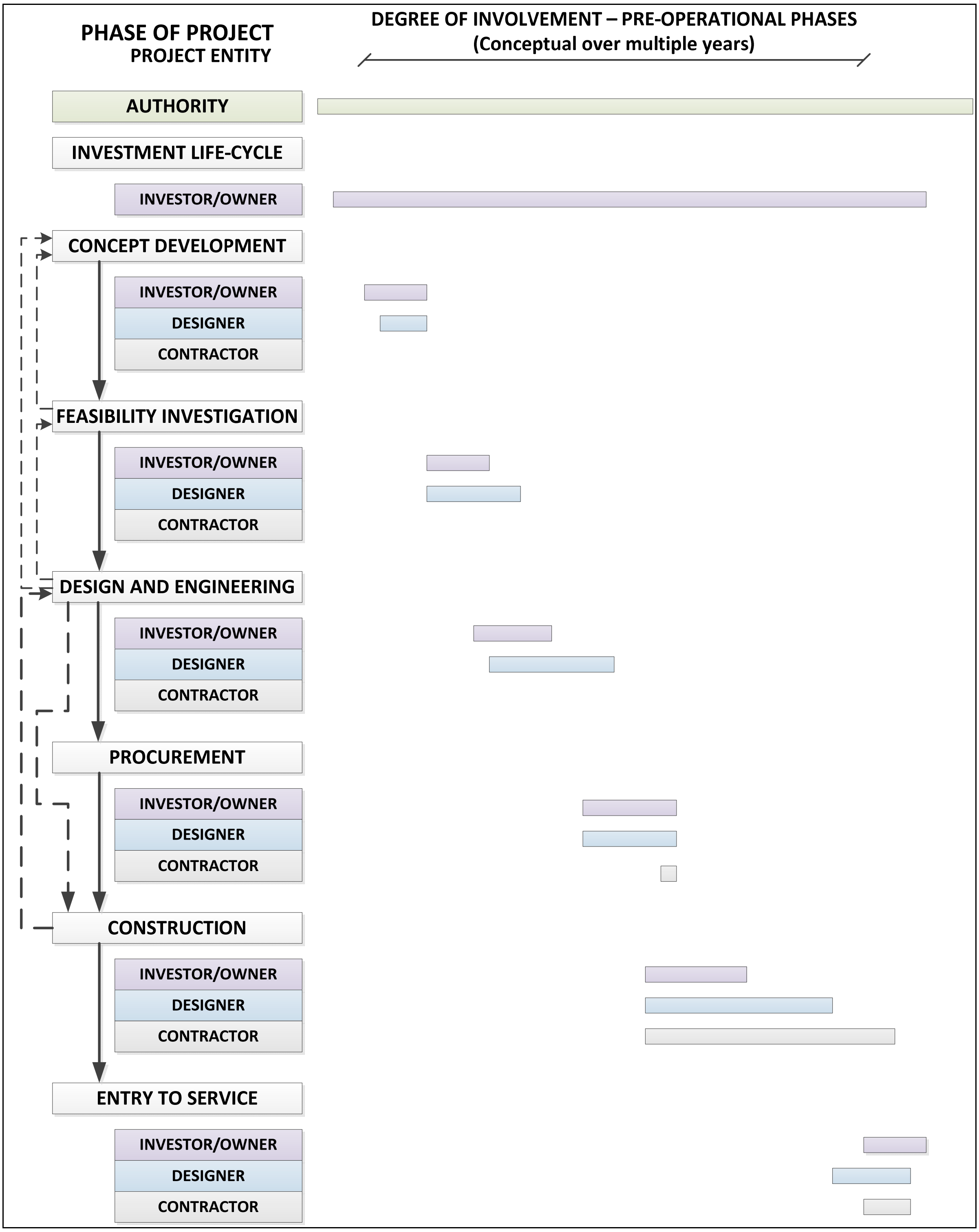

Table 2-2 Pre-Operation Phases of a Dam Development

Chapter 3 - Key Issues to be addressed

Risks associated with the development of a new dam project (or new dam scheme project) are of multiple nature. Within the present context only risks affecting the safety of the dam during its subsequent lifetime are considered.

It is essential that any critical pre-operational activity in the sense of bearing a potential risk for the safety of the dam being identified and classified according to the level of risk it might induce. For each player involved safety management during the pre-operational phases of the dam lifetime shall focus on this issue. While having identified the critical aspects in any of the activities the players shall take appropriate measures to reduce to an "acceptable" level the potential risks incurred.

3.1. Risks involved in design and construction of dams

3.1.1. **Non-technical aspects**

A number of nontechnical factors can affect the quality and the safety of the works (IFT Report on Oroville Dam Spillway Incident, 2018). Nontechnical causes of shortcomings can be found on many dam projects which are more numerous and more serious than the technical causes (R. Peck in Casagrande Volume, 1973). This statement was originally issued for earth and rockfill dams, but can easily be extended to other types of dams. The shortcomings may infringe only slightly on the nominal factors of safety assigned to the structures. But in some instances they may lead to costly maintenance or even large-scale remedial measures, if not properly detected and/or discarded during construction.

Human and organizational (non-technical) factors are not always easy to properly recognize, mitigate or even discard by the dam safety management. Whereas omissions, misunderstandings, computational errors or other defects can be recognized and corrected, when identified early enough, it is sometimes more difficult to track and rectify errors caused by uncooperative or adverse attitudes in an Investor/Owner or in a design or a construction supervision team.

Furthermore when numerous actors are involved their respective liability is not always clearly defined. There is a risk of overlapping, but also of dilution in responsibility, of overconfidence on each other ("the other guy will do it"). Misunderstandings can happen, especially when decision making is not properly developed and documented. This leads usually to a lack of continuity and loss of knowledge on specific issues.

Some nontechnical factors (from R. Peck, Casagrande Volume, 1973)

The unrealistic Owner

- Reasonably enough the Owner wishes to obtain his facility at minimum expense. (...) Preliminary (cost) estimates must be made at a time when there is a minimum of information. (...) An unrealistic Owner has a predilection forever after to consider the lowest preliminary estimate as "the cost of the dam". He is likely to discount the importance of the allowance for contingencies or even to ignore it completely. (...) He is likely to regard all increases above the lowest preliminary estimate as money out of his pocket.
- If the Owner has made inadequate allowance for the time required for appropriate and necessary exploration and design, the finished product inevitably suffers. (...) Many Owners regards the cost of exploration as a waste. They see no tangible benefit from the time or money spent in drilling holes and performing other operations in the subsurface materials.
- Once a job is under construction (...) the Owner sees his scheduled completion date approaching more and more rapidly and fears that construction will not be finished on time. He may then exert great pressure to expedite the work. Under these circumstances he may seriously hamper the effectiveness of the inspection forces who are attempting to safeguard the quality of the construction.

The uncertain designer

- The uncertain designer is likely to be one who has taken the job too cheaply. He may find that he cannot afford either the time or the money for adequate investigations.(...) The consequences of an inadequate exploratory program persist and are compounded throughout the construction period and possibly throughout the life of the facility.
- (...) He may also be one who is willing to accept an assignment to design without the concomitant authority for supervision of the construction. (...) No earth or rockfill dam should be supervised during construction by a different organization or group of people from the designers. If the construction supervisory forces are not intimately familiar with the bases for design, unanticipated field conditions may lead to serious blunders.

The overly optimistic designer

- The overly optimistic designer assume that "this project" will be a normal one and therefore that the allowance for the contingencies can be reduced.(...) He assumes that the subsurface conditions will correspond to the best ones compatible with the findings from the exploratory program. (...) He further assumes that the contractor will be happy to take care of the deficiencies (and) that instrumentation will make up for deficiencies in the design. He trusts that the weather will be at least normal during the construction period.
- (...) If the subsurface conditions do involve unexpectedly unfavourable features, or if the working season is unusually short and wet, additional time may be needed to complete the job. The pressure to complete the work on schedule may lead to inferior workmanship under relaxed inspection, to the detriment of the final product.

The designer inexperienced in construction

- The designer of an earth or rockfill dam, if inexperienced in the building of such structures, fails to recognize the inherent difficulties of certain operations and is likely to establish unrealistic requirements in the specifications.
- (...) The benefits of construction experience are legion, but they are rarely appreciated by designers, especially those who lack such experience.

The ineffective inspector

- The problems of inadequate inspection are by no means peculiar to earth and rockfill dams. The inspector is often the least experienced and lowest paid man on the job. The combination of a neophyte inspector and an experienced contractor, and its consequences with respect to the quality of the finished product, are well known.

- (...) Even the inexperienced inspector may recognize that a certain construction operation does not lead to results that are in accordance with the contract documents. If he takes a strong stand and his superiors fail to support him, he will conclude that violations of the specification are not considered serious , and any defects thereafter are likely to go unreported.
- (...) Inspection and supervision are sometimes delegated (...) to a separate organizational division not associated with the designers. This practice almost always lower the quality of the dam.

The loophole contractor

- The contractor has a right to a profit if he bed the job correctly and carried out the work satisfactorily. He has no right to expect a profit that he realizes solely on the basis of technicalities or loopholes in the contract.(...) If a contractor at the very outset looks at the job from the point of view of finding loopholes to exploit, he sets up antagonisms that influence the tone of the entire job. In a climate of antagonism between contractor and supervisory forces, quality and progress suffer.

The unqualified contractor

- The degree of qualification of the contractor is reflected by his representative on the job, the superintendent. A poor superintendent is an insuperable obstacle to scheduled completion of a dam of high quality. The superintendent's personal characteristics may play a significant role in the nature of the final product. (...) The foremen are just as important as the superintendent. They are the men who must have the intimate know-how and on whom all parties depend for the execution of the work.

The construction of many dam projects has been affected by nontechnical aspects and these dams have been eventually completed under such conditions. They often bear uncontrolled or hidden risks that might affect later on their safe performance in the operational phase. Some classical examples are:

- A long interruption of construction works due to financial problems of the Owner or withdrawal of the main Contractor
- Abandonment of a construction site because of political decisions or belligerences and restart of construction activities years later, often with another design and construction team.
- Withdrawal or insolvency of the key subcontractor or unique supplier of specially designed equipment.

Decisions on changing the construction or the operation mode of the dam before completion of the works can also induce risks which have to be properly assessed. An often encountered case is the necessity of selecting other material sources (embankment material, concrete aggregates, cement) during the course of works because of scarcity of the original source or change in delivery conditions.

3.1.2. **Technical aspects – Major influence of uncertainties**

Technical risks can be defined as those risks which are linked to uncertainties in the determination of external loads acting on the structure or of the strength of the dam itself, its appurtenant structures and their foundation.
Incorrectly applying the loads in a stability analysis or using incorrect strengths (or strengths not properly determined in the laboratory) will also induce risks. Therefore one can speak from external technical risks (resulting from external actions) and from internal technical risks (structural or operational deficiency) that arise within the project arrangements.

To these two types of risk one has to add non-technical aspects as already mentioned.

The following diagram (Table 3-1) gives a short overview of some common risks encountered at dam projects.

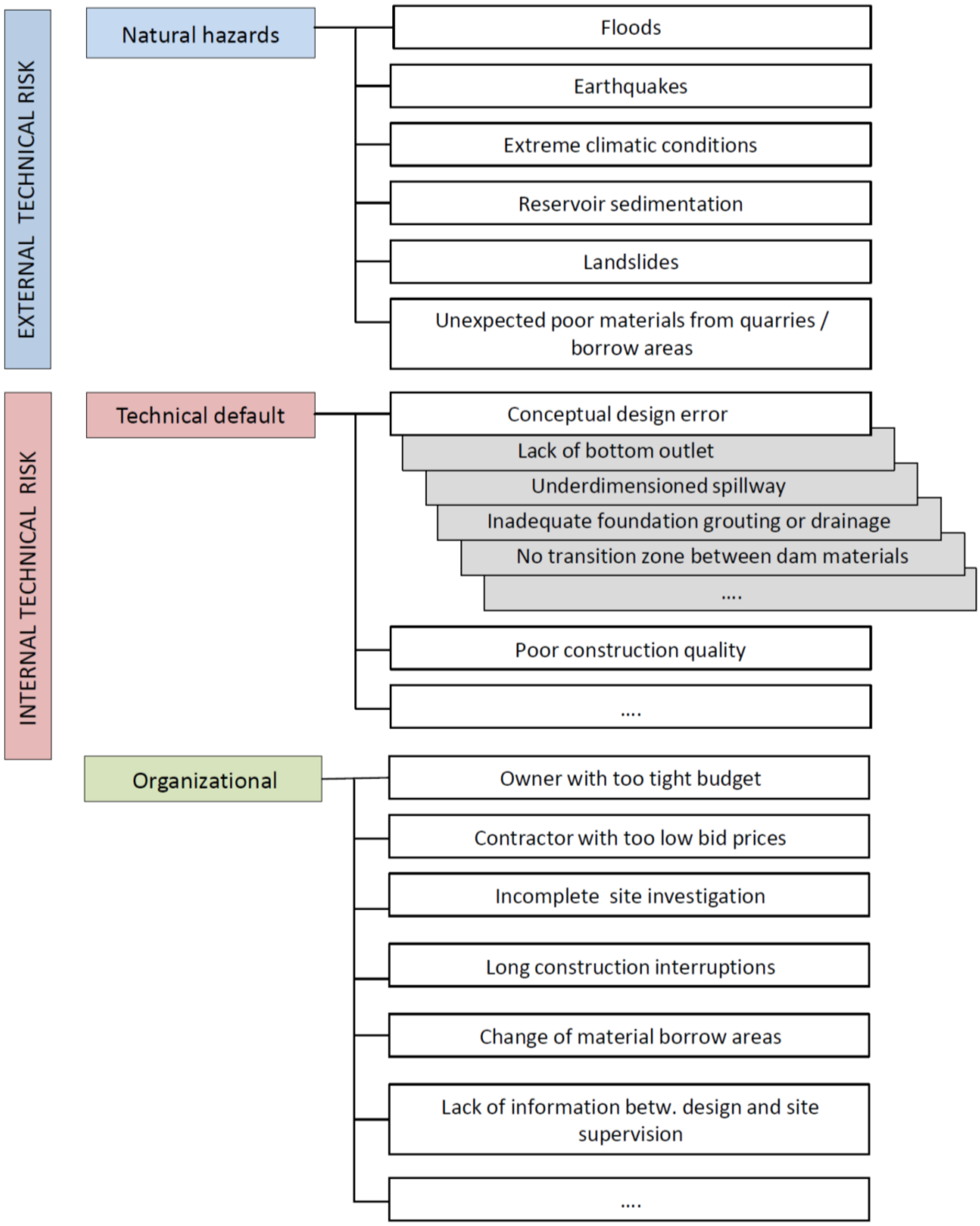

Table 3-1 Typical risks encountered during design and construction of dams

Uncertainty accompanies the whole development process from the preliminary studies to the construction phase. It concerns not only the technical aspects, but also the economic and financial ones.
The foundation is very often the critical element in the whole dam system because of its heterogeneity and of its not always predictable behaviour under loads and seepage forces. Foundation investigation is therefore one of the main issues in dam design. In many countries the most favourable dam sites from a geological and topographical point of view have already been built. New sites to be developed are often more problematic and require an additional investigation effort. The question of how tight the foundation shall be treated by grouting and/or drainage has two different aspects: one technical (reduction of the uplift pressure in the foundation, but also prevention of internal erosion from the core into the foundation at an earthfill dam) and one purely economic (how much seepage water can be released without major financial consequences).
Another important issue are the hydrological conditions. Statistics clearly show that floods, particularly inadequacy of the spillway structure accounts for the largest percentage of dam failures. This is especially true where the hydrological conditions are not sufficiently known (e.g. too short period of records) or too low values for the design and check floods have been considered by the Designer. It is therefore advisable to exert caution in selecting flood values for both the construction and the operation phases. At the operation stage the uncertainty regarding high floods can be covered by complementing the main spillway with an auxiliary or emergency (ungated) spillway facility.

On the other hand uncertainties in dam design might lead to adopt too high safety levels (conservatism) and to increase costs unnecessarily. It is therefore of utmost interest for the Owner and the Designer to estimate the amount of uncertainty by applying reliability type of analyses to the design data and to try to obtain better or more consistent data by increasing the amount of investigation.
Assuming a given level of potential hazards implies that the dam features shall be designed in such a way that they can accommodate these hazards but at the same time that a residual risk remains. The selection of dam design features will thus imply the willingness of assuming a residual risk.

A conservative design can allow covering the margin of uncertainty and overcoming the problem of residual risk, but it will also entail higher construction costs for the Owner as the structures have to be dimensioned with a larger margin of safety (e.g. wider spillway openings, flatter embankment slopes, higher cement content for concrete dams, etc.). On the opposite a too optimistic or slender design might lead to a higher or even excessively high residual risk and potential future costs for risk reduction.

3.1.3. **Need for monitoring**

Surveillance of a dam is fundamental and therefore the monitoring system must be designed from the start of the project. It concerns all stages of the life of the dam, construction, impoundment and operation. Of course, the phenomena to be measured and the modalities of the monitoring vary during these different phases: in general, more parameters are measured during construction and filling, and at a higher frequency. However, it is extremely important to have a continuity of the measurements between the construction phase and the operation phase. This makes it possible to better understand the behaviour of the dam and in particular to ensure that its behaviour is in line with the expectations of the project.

The design of a monitoring device - determination of phenomenon to be measured and choice of location - must be made to achieve two objectives: understanding of dam behaviour and detection of abnormal behaviour. For achieving this second objective an analysis of failure modes is required: the sensors must then be arranged so as to detect the measurable and precursory signs of a failure mode. Analysis of the failure modes is also required to set the frequency of measurements: the anticipated failure rate is the main parameter so that the readings frequency must be scheduled in such a way that a significant physical occurrence is not missed between two measurements.

Finally one must keep in mind that a badly designed monitoring system can have an impact on the safety of the dam. A classic example is the presence of a benchmark vertical tube in a clay core which implies that the area around the tube is not well compacted with an ultimate risk of triggering internal erosion. A tight collaboration between monitoring sensors suppliers, contractor and consultant engineer is necessary to anticipate these potential flaws.

3.2. Development stages and need for investigation

The main purpose of feasibility and preliminary studies is to check the size of investment costs and of benefits for a given scheme. It is expected that the level of *accuracy* is rather low at this preliminary stage and that a large amount of *uncertainty* prevails regarding essentially site and reservoir conditions, as well as hydrology, especially when records of river discharges are scarce.

Accuracy concerns the precision with which figures of technical or economical nature are established, whereas *uncertainty* is the non-determination of occurrence or of magnitude for a given natural event or for physical characteristics. To reach a certain level of confidence in designing a dam (as is the case with any built structure) investigation of the prevailing conditions in the reservoir area or at the dam site is required. As dam design is progressing over the various phases of the project, *uncertainty* regarding material and foundation parameters, flood magnitude and frequency will be reduced as the amount of investigation effort tends to increase. And as the design of the dam becomes more detailed the level of *accuracy* will be also improved.

The question is often raised of the *optimal investigation effort* required at each project phase. The general answer is that it should be as large as is required to reduce the uncertainty to an “acceptable” level. This level will depend upon the willingness of the Designer and ultimately of the Owner to assume a residual risk. In most countries consideration is being given to potential hazards to the public and guidelines and/or regulating documents are established by a regulatory authority restricting this risk to some generally agreed level.

Investigation shall be scheduled in sequences going from the general foundation characteristics of a dam site (rock type, major faults, overburden) to more specific details such as geotechnical parameters (deformation moduli, strength, permeability, etc.). Uncertainty about site characteristics will be progressively reduced as more investigation is performed, provided that the investigation is well targeted on the critical issues for the dam project.

Nevertheless one has to take into account that field and laboratory data, even for the same type of rock or of loose material, can exhibit a substantial amount of scatter. Generally parameters are selected based on the expertise of the Designer, Board of Consultants and regulations. Several techniques are available at the design stage such as parametric studies or, more recently, semi of fully probabilistic approaches (as an example, see the AFS concept (Adjustable Factor of Safety / *Kreuzer H., Léger P., 2013*) to evaluate the influence of material data scatter on the structural safety of the dam. The later techniques can help also in determining the appropriate effort of investigation to be applied.

Design proceeds usually by drawing up *alternatives*. They encompass the dam site, the dam type and finally the layout of the dam and the appurtenant structures. Each alternative is examined essentially from a point of view of construction costs and operating expenses, but also under other aspects, such as conformity with environmental legislation, accessibility, operating ease, etc. Applying established good practice from the onset of design activities is an important step towards a well designed and structurally safe dam.

Even when based on the same return period for extreme load cases and on identical material properties, alternatives will present different levels of *risk* related to the construction period and to the subsequent operation of the dam.

3.2.1. **Dam Design**

At the design stage uncertainties affect the external actions on dams (flood, earthquake, temperature, ice) as well as material properties (deformability, permeability, strength, etc.).

- External actions are described by a probability function that links their size or intensity to a return period. Their application may be described in the national legislation on dams or in standards issued by a regulatory authority.
- Material properties vary from site to site and have to be determined by investigation. Properties are mostly based on in-situ tests, laboratory test results and the expertise of the Designer to select rather conservative parameters for use in the analyses. Standards prescribe only minimum values to be applied for concrete and other materials.

The different levels of risk will arise from:

- Construction schedule and methods
- Type and size of river diversion
- Operation and maintenance facilities (e.g. existence or not of an inspection gallery)
- Anticipated long term behaviour

Often Designers believe that by driving a tunnel for the river diversion and transforming it later on in headrace for the powerhouse (case of an underground powerhouse close to the dam) they can generate substantial cost savings. By doing this they tie together the construction programs of both structures and lose any flexibility for the river diversion scheme. The resulting risks can result in delayed scheduling and extra expenses for time extension. Risks of poor workmanship are also to be considered as the headrace (often partly lined) will be done under extreme time pressure.

Methods of construction have to be envisaged by the Designer during the detail design stage as this will ease the performance of the Contractor later on and should be considered as part of an optimal design. This concerns accesses (temporary and definitive), scaffolding for high structures, material transport, placement of material, installation of dam instrumentation, etc. The Contractor can choose other means of construction but this should be approved by the Designer and the Owner, as well as the Board of Consultants (if any). The quality control inspection program may need to be adapted accordingly.

Size of the river diversion is dictated by the duration of the construction period and the return period of the peak discharge considered for the diversion flood. Effective costs of the diversion tunnel can be balanced against the random costs of rebuilding the cofferdam (in case of overtopping) and of cleaning the construction site. Risks are evidently different when considering an embankment dam or a concrete dam. In many countries rules have been established by the Regulatory Authority concerning diversion floods for these two types of dam. In such a case one has to comply with the specific regulation. Risk of overtopping increases as the construction duration is extended. It is not unusual that because of financial or political problems the construction of a dam is halted for months or even years. Very rarely the capacity of the river diversion is increased in such a case and this for obvious reasons (cost of an additional tunnel), although the level of risk is undoubtedly higher.

Dam design shall be rather defensive and shall consider all major external hazards and requirements for smooth and efficient operation activities later on. Provisions for a grouting and drainage gallery in the lower part of the dam will reduce the risk of not being able to intervene in case of high uplift pressure or excessive seepage in the foundation. Also appropriate accesses to hydro-mechanical and electrical devices will ease their maintenance and operation and can be decisive in case of emergency situations.

Dams are designed to function for decades and even centuries. Every effort has to be made to have them performing well over their entire lifetime. Insufficient foundation grouting or swelling of concrete caused by alkali-aggregate reaction will affect their long term behaviour. This can be the case also with accumulated sediments at the upstream dam toe, floating ice exerting an additional pressure on the dam face or slides affecting abutments just upstream of the dam. The fact of not taking into account these load cases will not only alter the behaviour of the dam but also impair its overall safety.

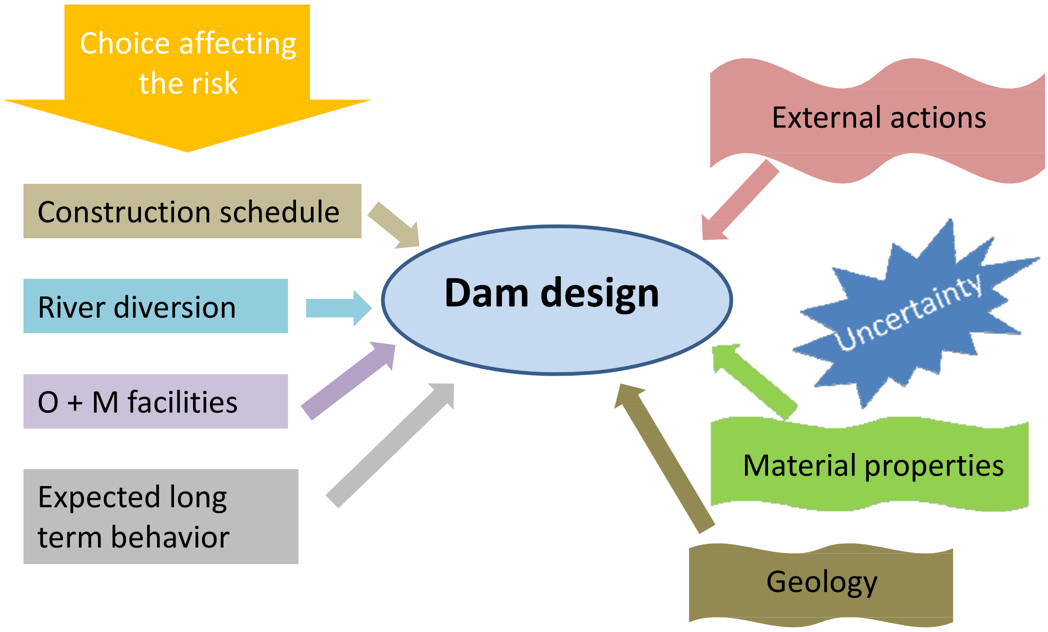

Figure 3.1 Uncertainty on dam environment and design factors susceptible of influencing the risk of dam failure

Current *codes and guidelines* to ensure the structural safety of buildings, bridges, nuclear power plants and offshore platforms contain formulations reflecting the uncertainties in load and resistance parameters. These codes comply with the advance of reliability analysis and they respect the increasing public consciousness concerning uncertainty and risk as a reality in stochastically experienced environment *(Kreuzer H., 2005)*. Although design codes cannot be applied directly to dams as dams are massive structures different from other (much more slender) load bearing structures the technique of reliability analysis for load and resistance parameters could be used for dams too. An approach such as the AFS concept already mentioned above could be a valuable help in determining the level of uncertainty and trying to reduce it as far as possible in order to obtain a less conservative design.

Experience with modification, rehabilitation and renewal of existing dams gained in recent years points to the value of the designer considering the future functional and operational expectations of the dam scheme and also to consider how inevitable ageing effects can be ameliorated. Further, advances in science and technology together with ever increasing societal expectations means that a dam scheme should be designed with adaptive asset management considerations embodied in the design philosophy to ensure that the dam scheme remains of societal value over the exceptionally long life-cycle of the dam structure.

3.2.2. **Construction phase**

The construction phase involves certainly the highest number of actors during the dam lifetime as it encompasses the Regulatory Authority, the Owner, the Designer, the Site Supervision, the Contractor and often further Subcontractors and individual firms. The interdependence between the different actors is described and regulated in a number of contracts and contract clauses (see 2.4). It is essential to maintain a good overview of the respective responsibilities in terms of work quality and liability towards third parties.

The main critical issue during construction is the *river diversion*. Usually the Contractor bears responsibility up to a given flow discharge (called the diversion flood) and the Owner for higher discharges. The return period of the diversion flood should depend upon the duration of the diversion stage and the reliability of the river flow records (i.e. the length and quality of the record series). Also the consequences of an overtopping of the cofferdam for the construction site and for the downstream area should be weighted up while determining the diversion flood.

As excavation for the dam and the appurtenant structures is proceeding, significant differences with the anticipated conditions can be encountered. These "surprises" are usually more frequent when the field investigation has been of limited extent and/or a comprehensive geological interpretation has not been performed. The occurrence of such a risk clearly demonstrates the need for performing in-depth field and laboratory investigation at the design stage. Extended field and laboratory investigation does not completely preclude the possibility of encountering surprises during excavation works, as demonstrated by some cases, but it will substantially reduce this risk.

3.2.3. **Construction supervision**

Construction supervision provides the critical link between the Designer and the Contractor including the skilled workers who perform construction tasks. Construction supervision is normally carried out by a team of engineers and site inspectors who develop strong working relationships with the Designer and with the Contractor. Construction supervision might be carried out by the Designer (the company responsible for the design as opposed to the individual who is responsible for the design), or by an independent Construction Supervision company.

The Construction Supervision Company is responsible for the quality acceptance of the constructed project. Typically, the Construction Supervisor will establish a quality control and assurance program that is independent of the Contractor's quality control and assurance program.

The Construction Supervision Company should be fully familiar with the philosophy of the design and the detailed design, including the Designer's expectations of the constructability aspects of the works.

Site supervision during the construction phase is usually focused on monitoring the quality and progress of the works and ensuring that the contractor's working methods are in line with the design assumptions. Unlike most other forms of construction, in dam construction it is either very difficult or impossible to check the construction works once completed as they are usually buried in the ground or in the body of the dam. Problems with dam construction are likely to come to light at a much later stage in the project, for example in the form of cracking which may only become apparent at later stages of the pre-operational phase or during the early operational phase. In some cases it may be several decades before construction flaws become apparent (e.g. in some cases of internal erosion). Investigation of problems and the subsequent remedial works are usually expensive and time consuming with resulting in claims, disputes and general dissatisfaction. While the presence of a supervising engineer on site cannot be expected to ensure that all defects are eliminated, proper supervision during construction phase provides a valuable check on workmanship and constructability.

Construction supervision is a very important project risk control measure as the management of changes to the works takes place through the supervision process. It is important that the lead supervising engineer (sometimes called the Resident Engineer) is suitably prepared and supported throughout the construction by the client or by the designer depending on the conditions of engagement of the Construction Supervision company.

Regardless of the terms of engagement of the Construction Supervisor it is important that the designer properly briefs the supervising engineer of the details of the design in advance of the commencement of construction. The Designer should be available to advise the Construction Supervisor during the construction of the works. It is important for the Designer to appreciate that the Construction Supervisor must be in a position to make sensible judgements and to have the capability of taking decisions quickly as needed if deviations from the design are required. At the same time it is important for the Construction Supervisor to fully understand the nuances of the design and to make every effort to accommodate these factors should deviations from the design be required.

Essential tasks that the Construction Supervisor is typically responsible for include but are not limited to:

- Providing an independent check on quality
- Ensuring compliance with technical requirements
- Ensuring that design-related issues are raised and promptly resolved
- Contract administration
- Providing an effective communication link between the Designer and the Contractor

The Construction Supervisor shall also ascertain that the Contractor is establishing as built drawings and that they correctly reflect all changes occurred during construction. In some contracts preparation of as built drawings is a task assigned to the Construction Supervisor and/or the Designer based on the documentation provided by the Contractor. A complete construction report has also to be prepared by the Site Supervisor. The essential point is that both sets of documents become established and that they are kept permanently in the documentation of the Owner. As built drawings and construction records shall serve as reference for subsequent operation, maintenance and rehabilitation works.

3.2.4. **First impounding / Commissioning**

Hydrology is usually the major risk at first impounding as a too fast rise of the water level might impair the safety of the dam. A too slow rise on the contrary will lead to delayed returns on investment. An optimum balance has to be found in the *impounding program* between the testing requirements for the operations equipment and some limited rising speed of the reservoir level. It is usual on high dams to have two or more stages at constant reservoir level to check the behaviour of the dam under nearly permanent pressure and seepage conditions.

Closure of the diversion may involve some risks related to the installation of the bulkheads. When a diversion has been under operation for a longer time erosion of the sill at the entrance of the diversion structure is not uncommon and the remaining gap between the lowest edge of the bulkheads and the sill hinders a watertight closure while the reservoir level continues to rise.

First impounding can also initiate *landslides* at the reservoir banks. Landslides will start during impounding if there are pre-existing unstable zones and the toe of these zones become saturated, or they may be deferred to the first drawdown following impounding because of the saturation of the apparently stable slopes. Further risks involve *reservoir induced seismicity* (ICOLD Bulletin 137). Also devices which get their first “wet” test (gates, stoplogs, control devices, instrumentation, etc.) can exhibit a *defective functioning*.

The first (usually five) years of operation following commissioning are somehow critical and a number of dams (small and large) have exhibited problems leading in some cases to failure affecting the dam and/or one of the appurtenant structures. Most of these failures were induced by an inappropriate treatment of the foundation (lack of drainage, ineffective grouting, etc.) or, in case of earth dams, by a poor contact between fill material and an adjacent concrete structure.

3.2.5. **Operational documentation**

Setting up operational documentation is an important requirement before starting operation of a dam scheme. It has to be established in agreement with requirements from the Regulatory Agency and shall essentially encompass three types of documents:

- Operating, Maintenance and Surveillance (OMS) Manual

- Emergency Preparedness Plan (EPP)
- Emergency Action Plan (EAP)

The OMS manual shall describe the procedures to operate, monitor the performance of, and maintain the facility to ensure that it functions in accordance with its design, meets regulatory and corporate policy obligations and links to emergency planning and response. It should further define and describe the roles and responsibilities of personnel assigned to the facility as well as the procedures and processes for managing changes.

The *Emergency Preparedness Plan* is an overarching document that deals with the arrangements made by the downstream civil protection authorities to mitigate the consequences of dam failure and the arrangements at the interface between the Owner's responsibilities and those of the civil protection authorities. The Owner will be required to establish arrangements to inform the downstream responders of an impending dam breach flood or other large release, the characteristics of the outflow flood, the flood arrival time at various locations downstream, and the expected forcefulness of the flood waters (depth x velocity). The Emergency Preparedness Plan may be initiated by the authorities, either on the advice of the Owner or based on their own assessment of the situation (The actual terminology used for this activity might be different between countries depending on the prevailing legislation).

The *Emergency Action Plan,* sometimes referred to as *Emergency Response Plan* is typically a set of arrangements developed by the Owner with the purpose of defining the actions that the Owner will implement to respond to incidents and to prevent failures. In cases where the intervention plan includes emergency releases through the spillway, the Emergency Action Plan will include notification of the downstream civil protection authorities of an impending high outflow flow, and possible activation of the Emergency Preparedness Plan.

Both OMS and EAP have normally to be prepared and submitted to the Regulatory Agency at the start of the construction works, exceptionally before first impounding of the dam. Preparation of the documents is under the responsibility of the Owner with major contributions from the Designer and from the hydro-mechanical and electromechanical suppliers (essentially for the spillway and outlet gates).

Training personnel for the operation of the new dam scheme shall be done sufficiently in advance and critical situations shall be simulated to test and improve reactions of the personnel. Capacity building and capacity development of the operating personnel has to be clearly defined (training units, frequency, tests, etc.) and integrated in the OMS Manual.

3.3. Rehabilitation works and performance enhancements

Rehabilitation of dams to account for all manner of changes since construction as well as projects to enhance the original design capacity (e.g. reservoir raising to increase storage capacity) are increasingly common especially in the developed economies where most dams are now over fifty years of age and have exceeded their economic evaluation period. Enhancement of original capacity could become more common in response to climate change either to permit safe handling of increased design floods or to improve the storage capacity. These projects can be exceptionally challenging and since they are carried out while the dam remains operational, great care is required in their design and execution. Unlike the design of a new dam where uncertainties become reduced as the construction proceeds, there may be significant uncertainties in rehabilitation and enhancement projects that remain unresolved throughout the project.

In addition to technical challenges, rehabilitation and in many cases performance enhancements bring management challenges associated with determining the degree of urgency of the rehabilitation or enhancement, financing the works, and safety management of the works and the public, including determination of the extent of any reservoir drawdown. As is the case for new dams, careful planning and quality engineering are pre-requisites for the success of such projects.

3.3.1. **Introduction**

Dams and their appurtenant structures require rehabilitation when

- their structural or operational function is no longer guaranteed as originally designed and has to be restored (case of restoring capacity). This includes errors or omissions in the original design, deviations from the design during construction to account for unforeseen conditions that are not functioning as expected, and deviations from the design due to pressures of schedule and or budget during construction. It also includes deterioration of functional elements such as dam and foundation constitutive materials (e.g. concrete swelling) drains, corrosion or loss of tension of anchors, chemically induced deterioration, etc. Deferred maintenance can cause deterioration that ultimately requires rehabilitation.
- new requirements in terms of reservoir volume, flood discharge capacity, bottom outlet discharge, etc. are issued. Such changes in functional demand are often necessitated by increases in the extent of development downstream and the associated consequences of dam failure, changes in the upstream or downstream environmental demand and changes in the production (power generation cycle or irrigation regime), or
- changes in the underlying science become imposed on the dam and can result in requirements to improve and increase its structural or hydraulic functionality (case of increasing capacity). Such changes include improved understanding of seismicity and or seismic performance analysis, changes in the way design floods are calculated, advances in the understanding of the behaviour of dams, and advances in understanding of organisational failure causes that can be addressed through physical improvements to the dam system.

Many defects, usually caused by ageing and operational wear and tear, can be treated and eliminated during normal maintenance. There are parts of dams or their components that cannot be maintained (e.g. filters in earth dams, embedded anchors in concrete dams, etc.) and such issues can be exceptionally difficult to address. Occasionally, rehabilitation may be required early in the life-cycle including after first filling if the dam is found not to be performing as intended. In this case the capacity of the scheme is just maintained (case of maintaining capacity before there will be any significant loss of capability or capacity). Rehabilitation involving restoration of the original capacity concerns more serious and extended issues. It requires development of a new project to be integrated in an existing operating dam structure.

Rehabilitation usually concerns the dam body, its foundation, and the appurtenant structures (spillway, bottom outlet, power or water supply intake, gates, and penstocks). The reservoir might be involved when the quantity of sediments accumulated impair the live volume with purging or dredging of the sediments being required.

The upper part of the generalized “Fault Tree” as presented in ICOLD Bulletin 154 provides a starting point to identify possible inadequacies in performance (Figure 3.2). This “Fault Tree” when coupled with “Failure Modes and Effects Analysis” and “Bow-Tie” analysis provides a useful means of identifying functions that should be considered for remediation. Fault Tree Analysis (ICOLD Bulletin 130) when coupled with Failure Modes and Effects Analysis provides a “top-down” – “bottom-up” approach to determining what can go wrong and why things might go wrong, including the initial identification of interdependencies between failure modes and failure mechanisms.

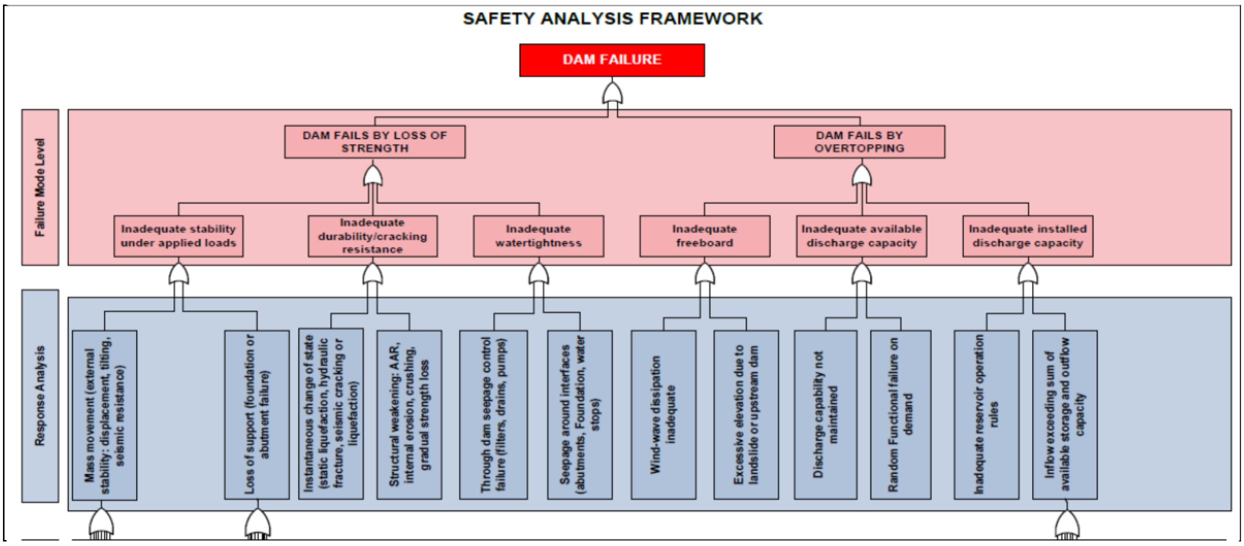

Figure 3.2 Safety Analysis Framework (from ICOLD Bulletin 154)

This type of analysis when combined with inspections together can guide the engineer in determining the need for remedial measures.

- *Restoring capacity*

  The structural or operational causes requiring rehabilitation can be multiple (Figure 3.2)
  - excessive settlement of an embankment dam (partial loss of freeboard)
  - excessive uplift under a concrete (gravity) dam
  - excessive seepage through or under a dam
  - loss of strength in the foundation causing differential settlements and cracks in dam body
  - alkali aggregate reaction (AAR) at concrete dams or structures (e.g. spillway)
  - gate jamming at spillway, bottom outlet or intake (can be caused by AAR)
  - loss of discharge capacity due to obstacle (sediments, landslide) at the entrance of outlet
  - damage to the spillway structure due to rock falls, freeze-thaw effects and deterioration of waterstops and joints
  - internal erosion in earthfill dams and their foundations
  - drain restoration and installation of new drains to replace degraded drains
  - ...
- *Increasing performance capacity*

  In this case changes are required to bring the dam to a new safety standard or new performance demand dictated by the Supervising or Licensing Authority or changes that result from an optimisation of the scheme operation by the Owner. Changes will also result from, advances in science, changes in safety requirements or because of economic considerations. Requirements of this nature involve changes to the “Key Capability Requirements” and Capability Requirements” described in 4.4 below. These projects can involve increasing:
  - the height of the dam
  - the discharge capacity
  - the physical strength of the dam
  - the performance of the foundation
  - the configuration and type of discharge facilities including the installation of a low-level outlet

Typically the general rules for the design of a new scheme will apply to increasing the performance capacity of an existing scheme. A rehabilitation project can be expected to conform to the general rules of a new scheme and will also require a specific management system with a detailed planning of the works and allocation of resources to ensure that the existing performance capabilities of the un-remediated section are properly matched with those of the rehabilitated section.

Regarding site conditions a distinction shall be made between works required at a hydraulic structure that are vital for the release of reservoir water and works at the dam body itself. In the first case, the discharge capacity will be reduced during a given period of time, whereas in the second case any work at the upstream face of the dam will require lowering of the reservoir level to some extent. It is therefore advisable to plan rehabilitation works in such a way that they match the natural discharge and flood conditions. Also at dams with multiple sluices or openings (e.g. at river dams) flow during rehabilitation should be balanced ranging from a limited number of openings at a particular time to a larger number according to the probability of occurrence of a flood and the corresponding discharge.

Reservoir level lowering capacity can range from some m^3/s to values of the river diversion discharge (100-500 m^3/s or even more). In some cases (especially at schemes on rivers with large mean annual flows) lowering of the reservoir is not possible. Special measures have to be taken as indicated in the Figure 3.3.

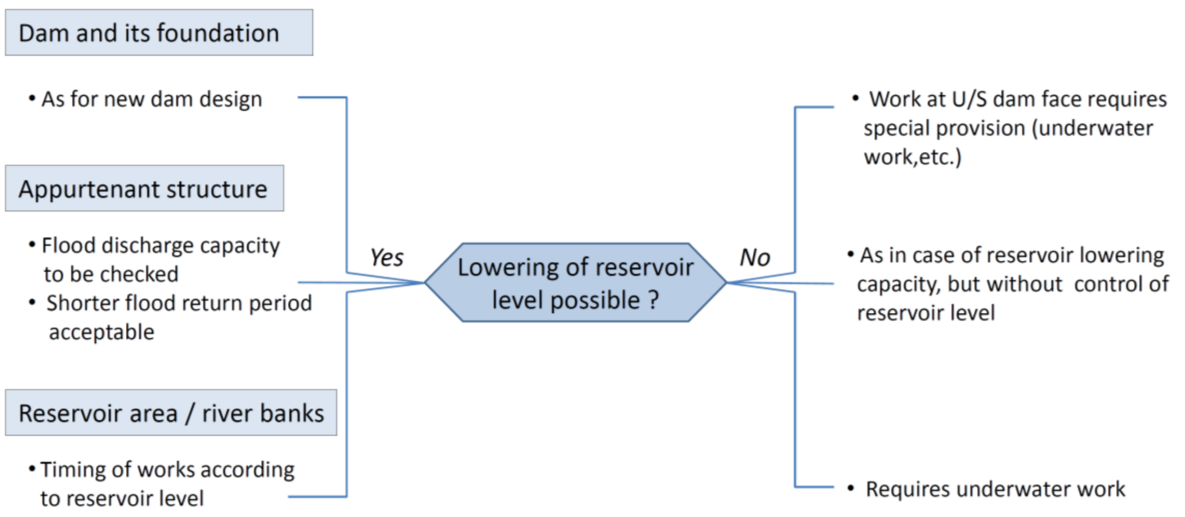

Figure 3.3 Impact of reservoir level lowering on rehabilitation works

Reservoir lowering to permit rehabilitation works may have to be balanced against maintaining the functionality of the system. It may be physically possible to implement a large drawdown, but not operationally possible because of production, social or environmental requirements and objectives. In such circumstances, a re-balancing of the Key Capability Requirements and the Capability Requirements may be required including a re-balancing of upstream community reservoir needs against the safety of the dam during rehabilitation. In some cases it may be necessary to maintain full hydraulic functionality while performing the rehabilitation of improvement works. Often, rehabilitation needs lead to both restoration and enhancement of performance.

3.3.2. **Planning rehabilitation works**

Rehabilitation works should be planned as if it is a new project sitting on or next to an operating dam. The main difficulties arise from the fact that operation of the dam usually has to continue (reduced or fully) while the risk level resulting from the combination of simultaneous construction works and operation has to be kept at the same level as during normal operation. Effective management of the water is a vitally important activity that must be given due consideration at all stage of the rehabilitation process. Special operation instructions will often be required for this purpose.

The intervening actors are basically the same as for a new design. The Owner's organisation has a decisive role to play as it knows the scheme best and has an interest in minimising the interference by the works with the on-going operation of the scheme. Typically, the Owner is either undertaking a major repair or improvement of some part of the dam or with the replacement of hydro-mechanical devices at an appurtenant structure or with both. The Owner will hire a Designer to develop the plans. This person or firm will not necessarily be the original designer and typically will have to first become acquainted first with the technical features of the existing project. The Owner should provide the Designer with comprehensive documentation on the dam, its history and its operation. Additional investigation is also usually performed to determine the actual condition of the dam and the foundation in terms of material deformation, strength, permeability, etc.

In the case of major repair or improvement of a dam the Designer can be expected to develop a range of solutions which will differ by the extent of the work to be undertaken. More radical and complete rehabilitation measures will be more expensive but will usually provide a longer term solution to the problems encountered. The Designer will have to draw the attention of the Owner to this aspect of the possible approaches. As in all design endeavours a compromise must be found between "the desirable" and "the pragmatically achievable". The Designer shall be concerned not only by the structural aspects of the rehabilitation design, but also by the constructional ones (access, temporary structure, disposal site, crane location, etc.) to demonstrate the complete feasibility of the work to be undertaken. The Designer and the Owner/ Operator will have to agree on the operational regime of the facility during the rehabilitation process. The tendering design shall leave the possibility for the Contractor to modify or optimize some of the issues according to their own experience and approach to the works. Nevertheless key safety issues such as the reservoir discharge during the works or the timing of critical construction phases shall not be compromised.

Tendering of the works can be done in separate single packages, but in case of very comprehensive and complex rehabilitation works it might be advantageous for the Owner to entrust a general contractor with all works to be performed, including special works, such as grouting or asphalt lining, and the renewal or installation of hydro-mechanical and electrical parts.

Considerable care and attention should be given to analysis and management of rehabilitation project risk as slippage of the schedule may result in a dangerous situation developing. This dangerous situation is a case of "risk from the project" that arises from the occurrence of a "risk to the project" and causes an increase in the total "risk of the project" for the Owner (refer to 3.5 below).

The degree of risk depends on a number of factors related to the management of water flows, the nature of the rehabilitation process, the timing of the particular work tasks, the extent to which features of the facility that are important to safety are out of service, and the time taken to restore sufficient functionality to manage the flows.
Simulation of the project activities, the reservoir hydrology and the operational conditions provide a means of analysing all possible combinations and permutations of scenarios that might develop. These possible scenarios can then be analysed stochastically to estimate the probability of occurrence of any individual scenario and to also

estimate the associated risk. Contingency plans can be developed to account for many scenarios, especially the scenarios with the higher probabilities of occurrence. For those situations where contingency plans cannot be developed, consideration should be given to designing the rehabilitation works in a way that the risk can be absorbed by the structure without threatening the safety of the dam and it's retaining and discharge functions.

3.3.3. **Performing rehabilitation works**

In most cases operation of the reservoir and the dam has to be pursued during the rehabilitation works. An interference between operational and building or installation activities cannot be avoided. Interference has to be minimized while separating as far as possible the areas of construction work and that of regular operation. It is important to have a Safety Officer in charge of ensuring that all safety procedures are respected by the Contractor workers. On site personnel shall be also entrusted with the authority to check workers if they do not respect operational safety provisions.

Inflow forecasting coupled with an understanding of the time that it would take to restore a minimum level of service for the part of the dam undergoing rehabilitation provides an important means of controlling the risk. The rehabilitation work should be designed and the schedule implemented in a way that the rehabilitation works can be interrupted, flow control functionality restored in part or in full to permit passage of the outflows as temporarily required, followed by resumption of the rehabilitation when the danger has passed.

In case of heightening or strengthening of a dam an appropriate site installation is required for the rehabilitation works. According to the importance of the works an aggregate crushing plant and a concrete batching plant may have to be installed. It may be also necessary to have a welding plant in cases where large steel structures are to be replaced or new steel structures installed. At remote dam sites access and temporary installation can constitute major issues. Transportation of material and equipment has been done in some cases by helicopter but the capacity of such means is limited. In mountainous regions heavy aerial cableways have been also used. Obviously it is an essential advantage when the major amount of construction material can be found in the vicinity of the dam and does not require a long hauling way. In ideal cases the same source of material as for the original construction can be used.

During and after rehabilitation the behaviour of the dam has to be monitored by an appropriate surveillance program. If instruments are moved during the works, e.g. the attaching point of a plumbline, a set of readings immediately before and after movement of the instrument shall be made to have the exact difference between the pre- and post- project situations.

3.3.4 Dam safety management during rehabilitation works

The situation of the safety of the system during the rehabilitation and enhancement works is potentially more complicated than in the case of the construction of a new dam where the contractor is in full control of the site and the safety of the works until handover of the dam scheme to the owner is complete. In the case of rehabilitation and enhancement works, and unless the dam scheme can be effectively taken out of service, responsibility for the safety of the scheme remains largely with the Dam Owner/Operator with specific aspects of the safety of the scheme such as the safety of temporary works, and works interruptions plans and schedules being the responsibility of the Contractor. The Designer must design the proposed works in a way that is readily constructible given the constraints of the operation of the dam and construction capabilities. Throughout the whole process, effective control of the stored volume, the inflows and the outflows are of paramount importance.

In the case of rehabilitation of part of the dam body it may be appropriate to construct a temporary upstream cofferdam to perform the water retention function while the works are carried out. The type and arrangement of such a cofferdam will be dependent on a range of factors including the layout of the dam scheme and the operational requirements (Figure 3-4). While there are many aspects of the design of a cofferdam for remedial works that are similar to those required for a new dam, the interface between the existing dam and the cofferdam will require careful design and construction to ensure that the interface is watertight and that the construction of the cofferdam does not adversely affect the performance of the existing dam.

Figure 3.4 Temporary upstream cofferdam to protect low level modification works (courtesy of BC Hydro)

The approach to the design of a temporary cofferdam must properly account for the whole life-cycle of the cofferdam with the design of the removal process being given appropriate attention to avoid damaging the repaired dam during its removal. Because of system interactions, construction works at one part of a dam can usually be expected to have an effect on the rest of the dam by virtue of proximity and dependency. Similarly operational activities such discharging flows may have an adverse effect on the construction conditions during remediation works.

Rehabilitation of spillways can be particularly challenging as in many schemes there is only one spillway, and therefore no redundancy in the essential hydraulic safety features. Spillway rehabilitation may well temporarily adversely affect the performance or safety of the dam scheme as a whole and as such the rehabilitation works represent a dam safety hazard. In some cases it might be possible to partition the spillway and carry out the works in such a way that some percentage of spillway capacity is available throughout the remediation works as illustrated in Figures 3.5 and 3.6.

Figure 3.5 Partitioning of spillway discharge function during spillway modification (courtesy of BC Hydro)

In the case of the rehabilitation of a spillway that cannot be completed during the dry season, and where partitioning is not possible or not appropriate there will be a requirement for close co-operation between the dam owner/operator and the contractor to ensure that in the event of a demand for spillway discharge, the works can be safely interrupted to permit the passage of the flows. In such circumstances, the works as constructed to date may be damaged by the spill, and the design should account for this by making provisions for repair of any damages and resumption of normal construction after the spill.

Consider for example the works on BC Hydro's WAC Bennett Dam where the spillway has been taken out of service to permit construction to proceed (Figure 3-7). This situation would be considered to be a temporary case of "Inadequate Available Discharge Capacity" as set out in the safety analysis framework of Figure 3-2. Under such circumstances, plans may be required to return the spillway to service during the construction process in the event of a need to pass inflows.

Figure 3.6 Reservoir level control during spillway modification with reduced spillway capacity (courtesy of BC Hydro)

Figure 3.7 Sectioned spillway works to ensure “return to service” with “t” days of notice (courtesy of BC Hydro)

Management of the construction risk (risk to the project) requires a determination of the “probability of demand” for the conveyance function throughout the duration of the remedial works and a determination of the time required by the contractor to return the spillway to service. In the case of a reservoir with seasonal inflows and significant annual operational fluctuations of the reservoir, this problem can be reformulated in terms of exceedance of an “operationally safe” reservoir elevation that will prompt an interruption of the works with sufficient time to return the spillway to service thereby permitting the spill to occur (see Figure 3-8). This requires a limit the extent of the works that the Contractor can perform at any time, as determined by the time that would be required for the ongoing element of the works to be completed and the spillway returned to service pending a spill.

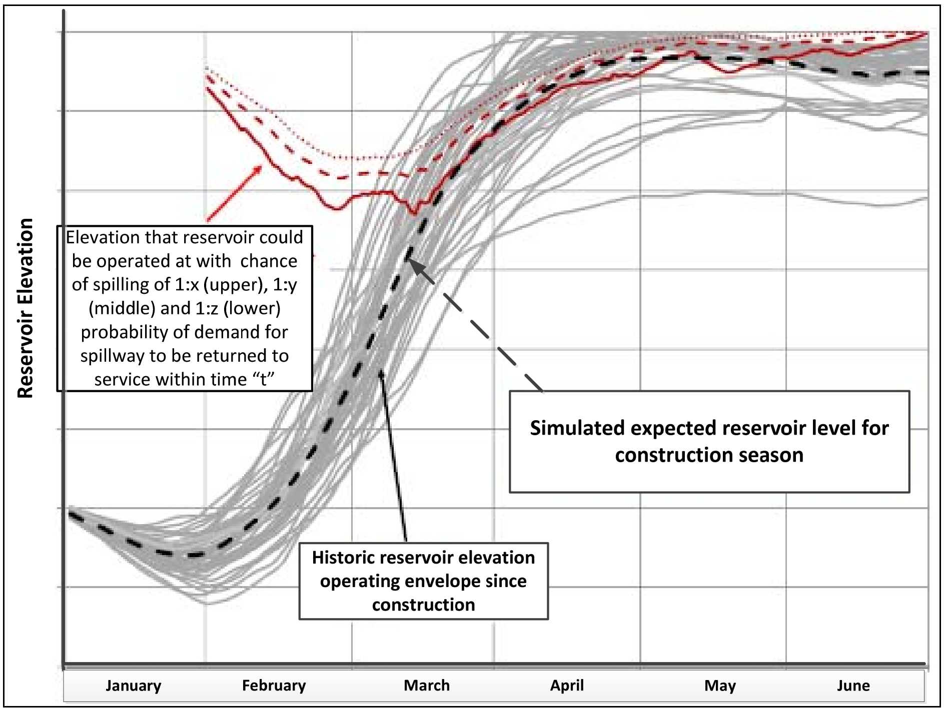

Figure 3.8 Notional target reservoir elevation with return to service in "t" (days)

Clearly, there is a chance that the spillway works will not be completed in time for return to service within time "t", or that an unusually high inflow occurs which necessitates an early release of water. A suitable contingency plan should be established for such an eventuality, and this eventuality might include loss of the works completed to date. However, loss of previously completed work due to an unavoidable spill through ongoing construction, while highly undesirable should be managed in a way that will not endanger the safety of the dam.

Whatever the purpose and nature of the works, effective control of the stored volume, the inflows and the outflows are of paramount importance in ensuring dam safety during rehabilitation and enhancement projects.

3.4. Dam scheme development as a continuous process

Developing a dam scheme consists in proceeding in terms of alternatives starting from the basic layout up to the detail design of technical components. At each step options shall be compared for their technical adequacy (both structural and operational) and for their costs (investment and maintenance). At each step also the remaining uncertainty on natural hazards, as well as foundation and material parameters, shall be reduced by field and laboratory investigations.

Dams are subjected to extreme loads compared with some other engineered structures. Their design should be rather on the (reasonably) conservative side, i.e. that they should be provided with some strength or size (e.g. height) reserve. It is therefore not advisable to go systematically to the limit on dam design.

Risk analyses will be useful in assessing the potentially weak points of a dam design. Such analyses are required in several countries by the Regulatory Authority to check the incidence of a dam overtopping or dam failure in the downstream area. Attention is usually paid to the water discharge devices (outlets and sills) and the probability of non-functioning of these features. Probability of local failure or extended internal erosion due to inadequate foundation conditions is also examined. Such analyses shall be discussed and agreed upon between the Owner, the Regulatory Agency and all stakeholders.

A set of simple rules will help in enhancing the consistency and quality of the design process. They are usually included in quality management systems: the three basic principles are *continuity, independent checking* and *traceability*.

- *Continuity* means that the Designers in charge should follow the project from the very beginning (or at least from the feasibility study on) to the construction. It is understood that due to various time and organizational constraints this is often not possible. In this case a complete internal documentation, that includes also "hidden" facts or items, should be established at the end of each phase to be available in the next project phase.
- *Independent checking* means that every technical aspect shall be reviewed by a team of competent people. This function of quality control is implemented nowadays in all engineering organizations. It is the duty of the Owner to make sure that the quality control is effective and not carried out only as a low priority routine task
- *Traceability* means that all decisions regarding design and construction modifications (see below) shall be recorded and adequately documented for the posterity.

On large projects it is recommended to have a *Board or Panel of Independent Consultants* to insure that the right technical options are selected and implemented. This does not mean that the internal quality control can be neglected or abandoned. Since it is acting on detail aspects which are not treated by the Board of Consultants its function remains essential.
During the construction phase the adequacy of the works relative to the design specifications shall be thoroughly checked by the site supervision. In dam construction site adjustments are usually required depending upon foundation conditions and quality of the local materials that can depart from the original specifications. It is therefore essential to

- have the Designers check and formally authorize these adjustments (*continuity principle*)
- document the modifications and keep records for the subsequent operation and monitoring of the dam (*traceability principle*)

On large projects involving several technical departments or even different engineering firms the project management shall have a comprehensive overview of the design of the entire scheme to rapidly detect incompatibilities between project parts and to avoid interferences.

3.5. Risk management

Dam development projects involve a great deal of risk and uncertainty. In fact, risk arises because of uncertainty and unpredictability. In the case of dam developments, all of the principal actors; Investor/Owner, Designer and Contractor take the "risk of ruin"; specifically bankruptcy, professional liability or personal liability and also almost instantaneous destruction of reputation earned over many years. Further, since risk from dams involves risk to society (people, property and the environment), the Investor/Owner is also responsible for the control of the risk to society. Therefore prevention of failure of the dam both during and after construction, which could bring one or all of the aforementioned risks, is imperative for all actors.

These risks can be grouped in terms of a set of risks termed the "risk of the project"; "risk from the project"; and, "risk to the project". These different categories of risk are not completely separable as risk in one category can be transferred to (or migrate to) another category. This said, responsibility for control of these categories of risk as they pertain to the dam can be broadly apportioned as follows.

- The "risk of the project" refers to the total risk that the Investor/Owner is exposed to and the societal risk that the Investor/Owner is responsible for controlling on behalf of society when undertaking a dam development project. This includes the risk of loss all or part of the investment and the benefit stream that is anticipated to arise from the investment over its economic evaluation life should the dam fail during or after construction. Depending on the type of construction contract, it may include much of the risk associated with the planning, feasibility, design and construction processes.

- The "risk from the project" refers to the risk associated with the way that the project is conceived, planned and implemented. Much of the "risk from the project" pertains largely to the Designer, and the Designer is responsible for controlling this risk within limits set by the Investor/Owner. However, should the dam fail due to errors or omissions in the design of the works, the societal element of the risk and much of the cost associated with the loss of the asset will revert to the Owner. The Designer will typically limit its liability for "risk from the project" but this does not mean that the designing organization is fully protected from adverse effects of this class of risk, which includes reputational risk.
- The "risk to the project" essentially refers to the scope, budget and schedule risks associated with dam developments and importantly includes all risk associated with the management of unforeseen conditions and the management of changes. "Risk to the project" is partly the responsibility of the Site Supervisor and partly the responsibility of the Contractor. How these responsibilities are apportioned forms an important part of the contract negotiations.

The above categories of risks are general and apply to all actors to varying degrees depending on the type of contract. The Designer and the Contractor are actually exposed to some elements of all categories of risk from an internal perspective although to a significantly lesser degree than the Investor/Owner.

Notwithstanding how financial liability for these risks is apportioned, all actors have a moral responsibility for the effective control of these risks, and in particular all of the dimensions of the societal risk.

The two following chapters describe how to identify and mitigate these risks for all actors involved. This can be done by an integrated management concept involving all actors (Chap. 4). Out of this overarching management system the role of the Investor/Owner and his own management system are especially relevant as the Investor/Owner is (or should be) the driving force and the central pivot in implementing the dam project.

General engineering principles are also required to reduce residual risks at all stages of the dam development project. They are presented and discussed in Chap.5.

Chapter 4 - Overarching Safety Management System

4.1. Concept of overarching management system

4.1.1. Background

This chapter outlines considerations that go beyond the engineering aspects of the development of a dam scheme, and into the broader aspects of managing the entire development including the principles for safety management and environmental protection. This expansion of the thinking is required to embed safety firmly within the design philosophy at the early stages of the development in a way that ensures that safety, set in terms of structural safety and operational safety, is secured over the entire life of the dam. The overall objective being that the dam can be constructed safely, operated safely, and decommissioned in a safe manner. Construction safety covers both protection of the public from failure of the dam or temporary works (e.g. cofferdam), and worker safety during construction and during operation. Good performance during construction and commissioning is essential for securing the trust of the public. This includes structural safety, environmental aspects, labour relations and community relations.

All actors involved in the development of a dam have the common objective of a safe, financially viable and environmentally sustainable project in the long term while avoiding losses and accidents during the construction phase. The idea of unifying the management systems of the Owner, the Designer and the Contractor arises because, from the perspective of the public, they are all part of the one development. For example, poor environmental performance during the construction by the Contractor inevitably reflects badly on the Owner/Investor by association. It also reflects badly on safety by creating the impression of a project that is not well controlled with the implication that many things including safety are not well controlled. Just as companies operate in terms of corporate values and principles, the development of a dam scheme will be considered by the public and the licencing authorities to be an entity which as a whole should be guided by an appropriate set of values and principles. Alignment of the values and principles of the actors in the development is a necessary part of establishing a common set of values and principles for the development of the scheme thereby supporting the achievement of the common goals. This is the case no matter how well the actors try to insulate themselves from each other in a contractual sense.

Further, safety in the operational phase of the life-cycle can only be assured if all of the factors that influence operation are understood early in the design phase and appropriate measures established to deal with them under all operating conditions. This includes appropriate consideration in the design of safety in the context of all other functions of the scheme in an integrated way over the whole life-cycle of the project. In this regard, safety refers not just to public safety but to all dimensions of safe functioning including environmental security and workplace safety during construction and in operation.

Ensuring that the dam does not fail during construction, commissioning and within the early years of its service life is the prime objective of safety management in the pre-operational phases. This must be achieved without compromising safety in the operational phase of the life-cycle. Construction flaws, such as segregation in earthfill placement may compromise dam safety in the operational phase. Thus one of the purposes of construction supervision is securing operational safety. Design changes during construction are another area that can compromise safety in the short and long term. Changes in scope during construction, often in the interest of controlling escalating construction costs, represents another potential cause of safety problems later in the life-cycle. Integration of the safety activities and features, the factors that influence safety either directly and indirectly, the operational regime and the operational constraints, with the design and construction provides a more efficient and effective way of ensuring safety in in all phases of the life-cycle.

4.1.2. Management context

In the modern context, companies or other entities such as government departments are managed in terms of some form of management system. The same can be said of projects. While management systems can take different forms, all forms have a common purpose, specifically to provide an organized or systematic way of setting and then achieving objectives. As such, a management system can apply at the top levels of an organization to set policies and objectives, and to provide the enabling structures and resources to achieve these objectives. Within the same company individual projects are managed in terms of a management system designed for project management purposes.

It can be expected that the Owner/Investor, the Designer and the Contractor will have different organizational management objectives and supporting management systems. The Owner/Investor organization can often be expected to be an "operations (production)" focused organization (e.g. a hydropower company or a water agency) that initiates projects on an occasional basis, whereas a Contractor organization can be expected to be a "projects" focused organization. In a "projects" focused organization all work is characterized as a project, with each project as a separate cost centre having its own profit-and-loss statement. In the "operations focused" organization, profit and loss is measured along functional lines and projects exist to support the production process. The Designer organization may also be managed as a "projects" focused organization, but it will need to create a dam scheme that will become part of an "operations" focused organization to be created in terms of a "projects" focused methodology. As such the Designer will need to appreciate and accommodate both types of management approaches in the design. In this context, the design of the safety management system and safety management infrastructure of the dam scheme must be appropriate for an "operations" focused organization.

During construction, the Contractor while working in terms of a "project" focus must adopt an "operation" focus for the purpose of managing the river flows at the dam site. The "operation" focus may take precedence in managing the water and water management requirements might occasionally dictate the project management arrangements for the construction. The modus operandi of the Contractor becomes more operationally focused as the diversion works are closed and the dam approaches the end of construction.

A distinction can be made between "project success", that is the overall success do the dam scheme in the long run even if it was over schedule and over budget during construction, and "project management success" measured in terms of PRojects IN Controlled Environments (PRINCE).

The term "management system" as used in this bulletin refers to such an organized way of setting and then achieving objectives whether it is for the dam development as a whole or a particular activity within the overall dam development process. A management system for a particular activity in the development of a dam will be a subset of the management system of the development as a whole. This activity level "subset" management system can be expected to involve a set of processes that mirror those of the dam development as a whole, but at a different scale and with a different focus. However, the objective of the activity level subset should be identifiable in the overall management system for the dam development. The common elements of a management system are: policy and objectives; planning; implementing; monitoring and evaluation; audit review and reporting, and, continuous improvement (Figure 4.1, from ICOLD Bulletin 154).

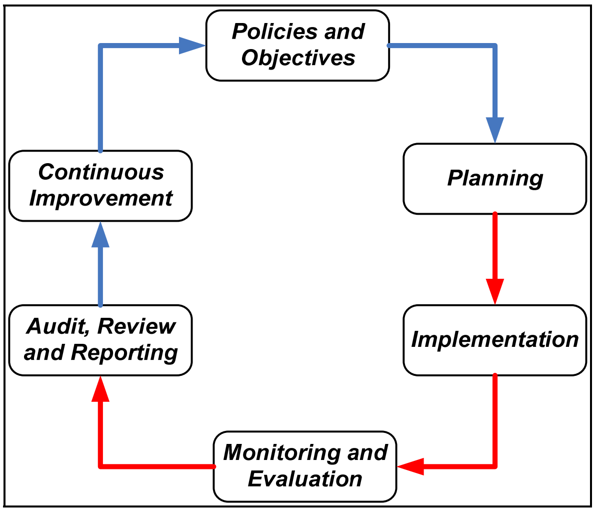

Figure 4.1 General Form of a Management System (from ICOLD Bulletin 154)

Considering the idea of systems and subset systems, or systems of systems, where functions and objectives are organized in a hierarchical way and where there is a particular objective and common focus such as safety. An integrated management system that defines how the different levels of the organization contribute to safety can be illustrated as shown in Figure 4.2. Importantly, these management processes typically contribute to achieving the common safety objectives in different ways.

In the case of a dam development, where there are three principal actors involved in the actual development process the Investor/Owner, the Designer and the Contractor. The roles of the Licensing Authority and prevailing laws and regulations in the dam development are embodied in the design policies and objectives. This management system structure can in principle be applied to the development of a dam where the outer process pertains to the Investor/Owner, the intermediate inner process to the Designer and innermost process to the Contractor. All three have an interest in dam safety for similar and for different reasons. Construction of a dam that can be operated safely over the long term is in the interests of all three actors, albeit in different ways.

The Investor/Owner will want to secure their investment and the objectives that flow from the investment over the long term. They will also want to work towards minimizing the risk of being held responsible for the losses including third party losses and incurring the liabilities that would arise from failure of the dam. However, the Investor/Owner will want to achieve these objectives in an economical way.

The Designer will want to meet the objectives of the Investor/Owner, further enhance their own capabilities while satisfying all interested parties by developing novel and fit for purpose solutions, thereby securing their reputation and the profitability of their company at least over the economic design life of the dam. They will also want to avoid the potentially ruinous outcomes of a dam failure during the economic design life. However, in doing so, the Designer must accommodate the Investor/Owner's objective of securing an operationally safe dam but not at any cost.

The Contractor has associated objectives and constraints especially during the commissioning phase and the early years of the life of the dam. In the case of a dam development, these objectives are all achieved for the various actors through the "implementation" phases.

While the operation of a dam can be modelled in terms of a cyclical process (ICOLD Bulletin 154), the development of a dam is somewhat more linear with iteration between activities as illustrated in Figure 4.3. There are many external and internal influences and constraints that impact the management of a dam development that are not shown in Figure 4.3, the influences and effects of which must be accommodated by the management system, licensing requirements being one of the most prominent. External influences can include constraints imposed by NGO's and other interested parties and the like, whereas internal influences include matters such as organizational culture and human factors.

4.2. Form of management system activities

The principal objectives of the Investor/Owner pertain to securing the products and services provided by the dam in a responsible and economically viable way. The balance between acting responsibly and achieving economic efficiency are a matter of the Owner/Investor's values as typically set out nowadays in a Statement of Corporate Social Responsibility. These values are inputs to and fashion the operation of the management system. However, they significantly influence the context for the rest of the development initiative. The Statement of Corporate Social Responsibility will often embody consideration of how some of the external influences and constraints are accommodate by the corporation.

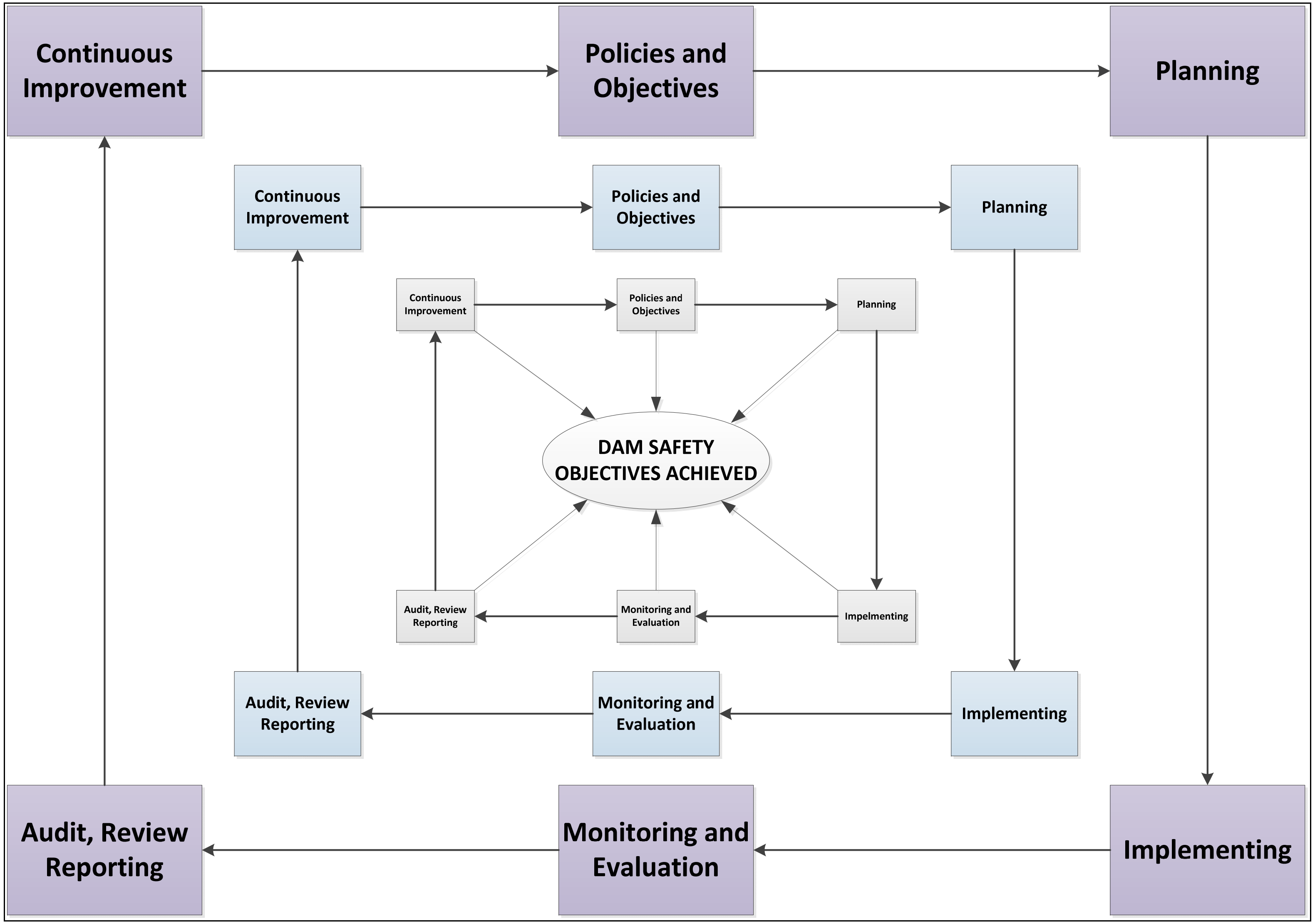

Figure 4.2 Integrated Management System (system of systems) to Achieve Dam Safety

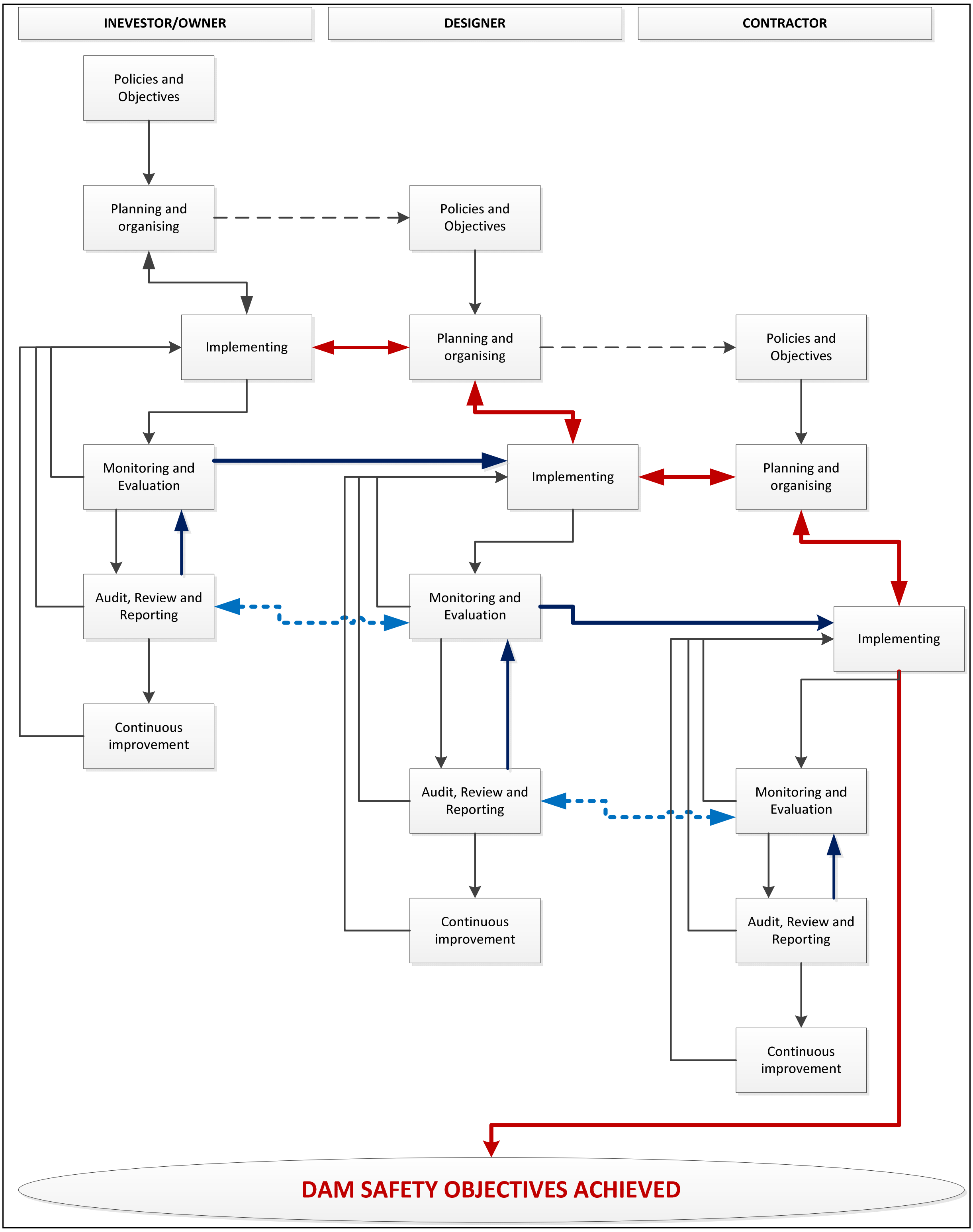

Figure 4.3 Management System Arrangements to Achieve Dam Safety in Implementation

For the purposes of this Bulletin it is assumed that the Investor/Owner, the Designer and the Contractor all have some form of statement of Corporate Social Responsibility.

4.3. Delivering dam safety objectives through an integrated management system

It is clear from Figure 4.3 that the safety objectives are realized (delivered) through the implementation steps of each of the management systems involved. Figure 4.3 applies to the development of new dams and to the upgrading and renewal of existing dams as can be required by the ageing process or by major dam safety improvements.

The contributions to safety can be characterized as follows:

- The Investor/Owner's contribution is "enabling" in that it provides the demands (vision) and the resources to achieve the safety objectives.
- The Designer's contribution is "transformational" in that it transforms qualitative and sometimes quantitative attributes and performance objectives into actionable directions. The Designer's objective is to design a project that satisfies safety requirements and criteria and acceptable industry standards and be conservative to the degree necessary to minimize risks to tolerable and acceptable levels
- The Contractor's contribution is "productive" in that it produces tangible safety performance attributes and features in terms of the Designer's directions which become realized outcomes. The contractor's objective is to achieve the design intent of the Designer and it is the owner/Designer responsibility to maintain an adequate construction quality control and inspection program to make certain that the design intent is satisfied.

4.4. Transformation of project objectives into implementable actions

The Investor/Owner's role in securing dam safety has been described above as "enabling". However, this enabling attribute does not only apply to safety it applies to all aspects of the new development or in the case of a major dam safety improvement project, the renewal process. The safety objectives are built in to the overall objectives of the project. These overall objectives of a dam development are typically varied and rarely are they singular. A dam development may cover several objectives as follows:

- Water management
- Power generation
- Performance during and after severe natural events
- Operational performance, reliability and safety
- Environmental performance
- Community contributions
- Accommodate constraints in the design.

Working with the Designer, these objectives can be expressed in terms of "Key Capability Requirements" (KCR) that play a pivotal role in the success of the dam development and "Capability Requirements" (CR) that support the delivery of the key capability requirements or are stand-alone capabilities that contribute directly to one or more of the objectives.

These "key capability requirements" (KCR) of which there will be several could include for example: Maintain Control During Floods and Maintain Control Post-Earthquake. These key capability requirements and subsidiary capability requirements can be structured as illustrated in Figure 4.4. Clearly, the key capability requirements relevant to "Water Management" and "Extreme Events" have dam safety dimensions.

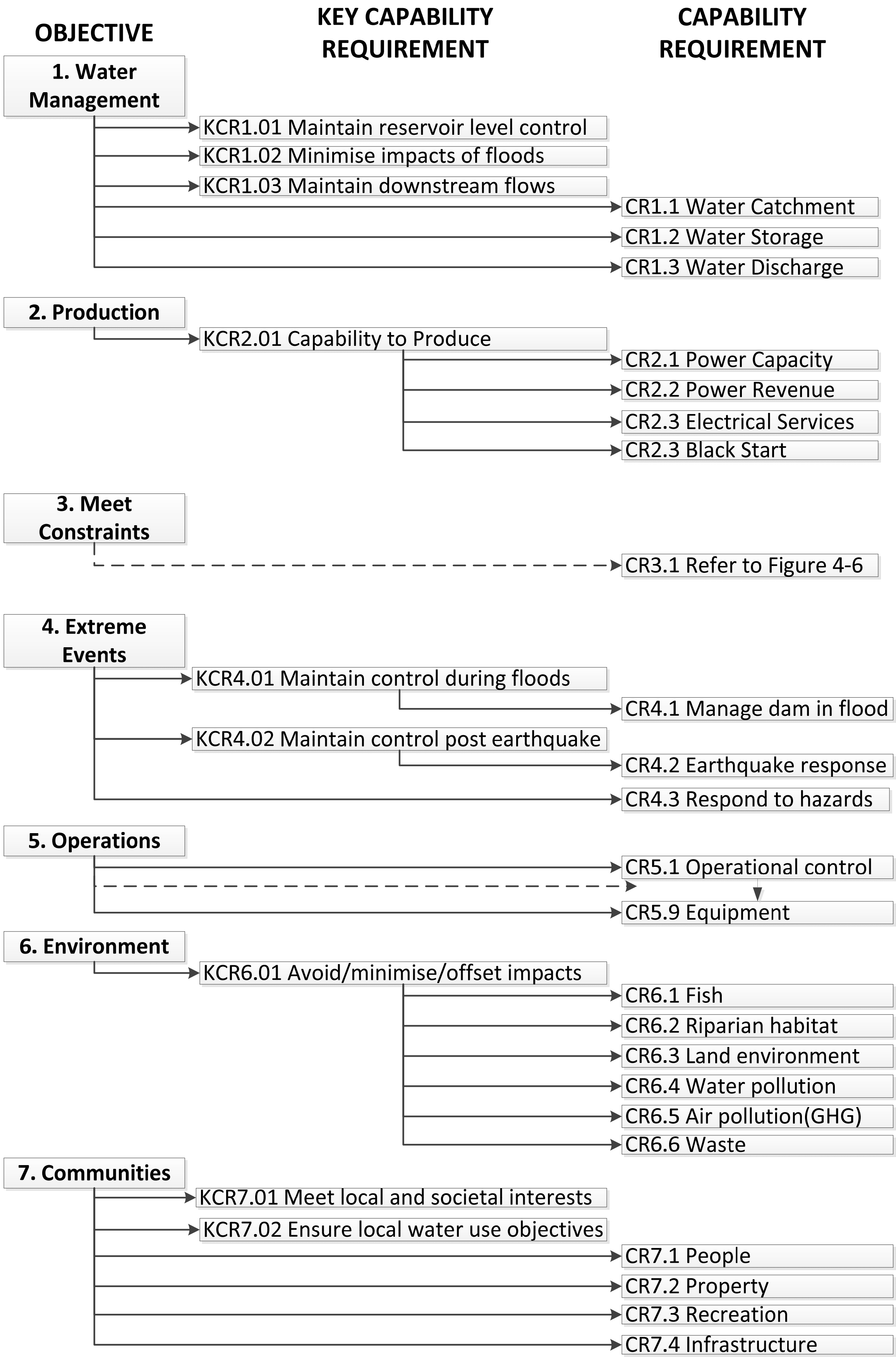

Figure 4.4 Key Capability Requirements and Capability Requirements

The operational characteristics of these requirements can also be described (Figure 4.5).

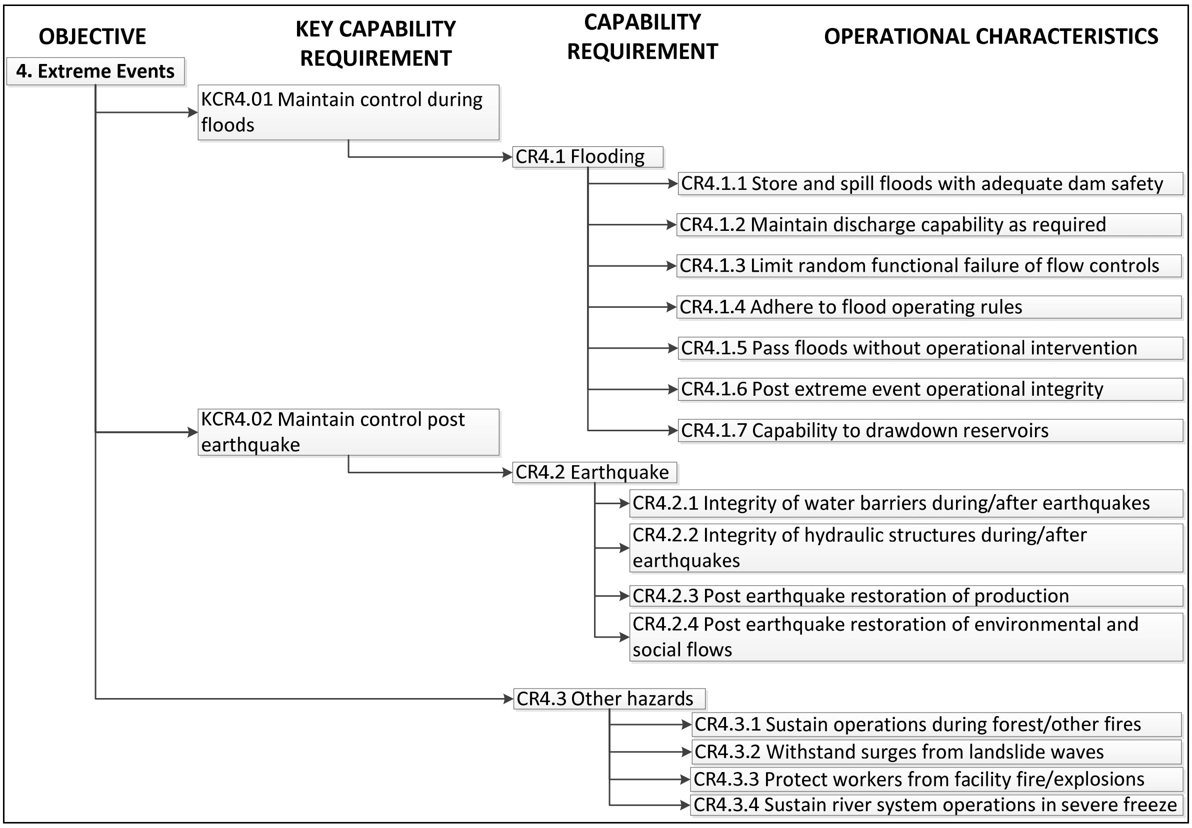

Figure 4.5 Extreme Event Characteristics of Capability Requirements

In addition to the traditional focus on the adequacy of the structural capacity of the dam to withstand extreme events and have adequate stability under common and infrequent loading conditions, the matter of operational safety has gained increased attention in recent years. These matters of operational integrity can be represented in a similar way in "operational" capability requirements (Figure 4.6).
It is clear from Figure 4.6 that there are many safety aspects of the hydraulic operation of dams and reservoirs that must be accommodated in the overall operation process. When viewed in this way, safety cannot be isolated from operations and treated separately.

The systematic process of transforming project development objectives into operational features that are to be embedded in the design and construction of the dam provides a means of establishing a common understanding between Investor/Owner and the Designer as to how all of the objectives of the development including all of the safety objectives can be represented and achieved. These systematically developed Key Capability Requirements, Capability Requirements and Operational Characteristics can then be embedded within the management systems of the Investor/Owner, the Designer and the Contractor. While these operational characteristics are general and qualitative, they provide a basis for the Designer to transform them into engineering objectives including engineering principles and quantitative design criteria.

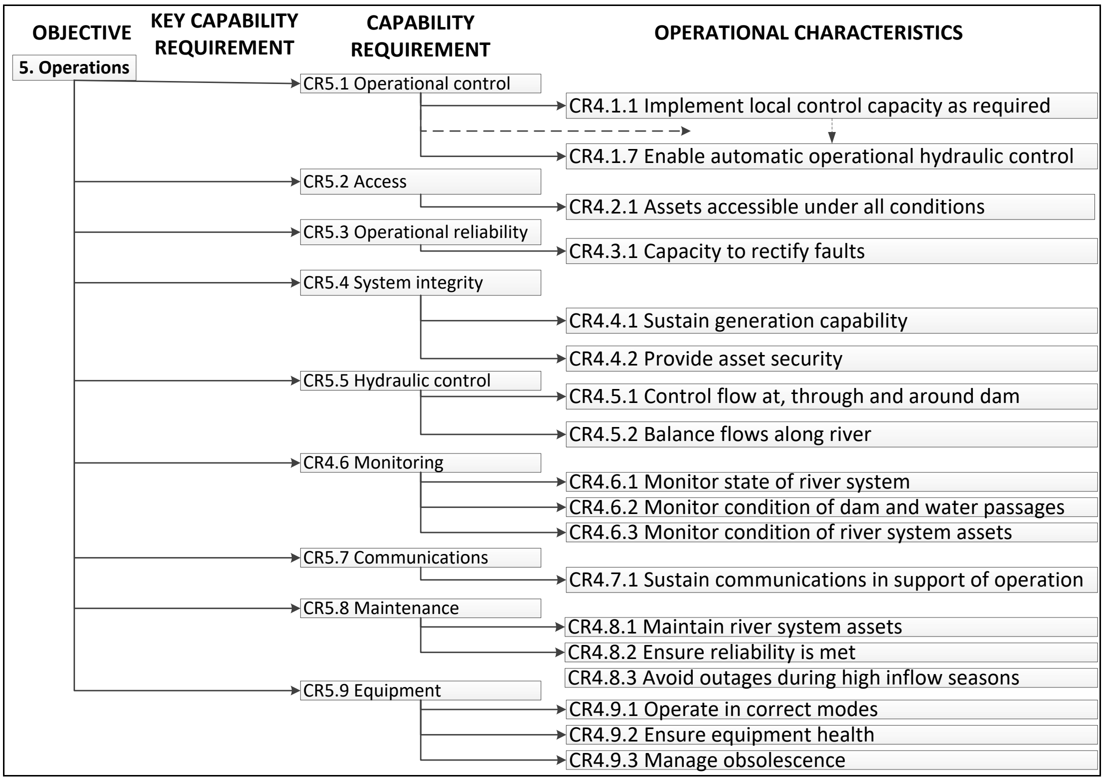

Figure 4.6 Operational Characteristics of the Capability Requirements for Operation

The design of the dam must also accommodate constraints and sometimes these constraints might adversely influence the safety objectives (Figure 4.7).

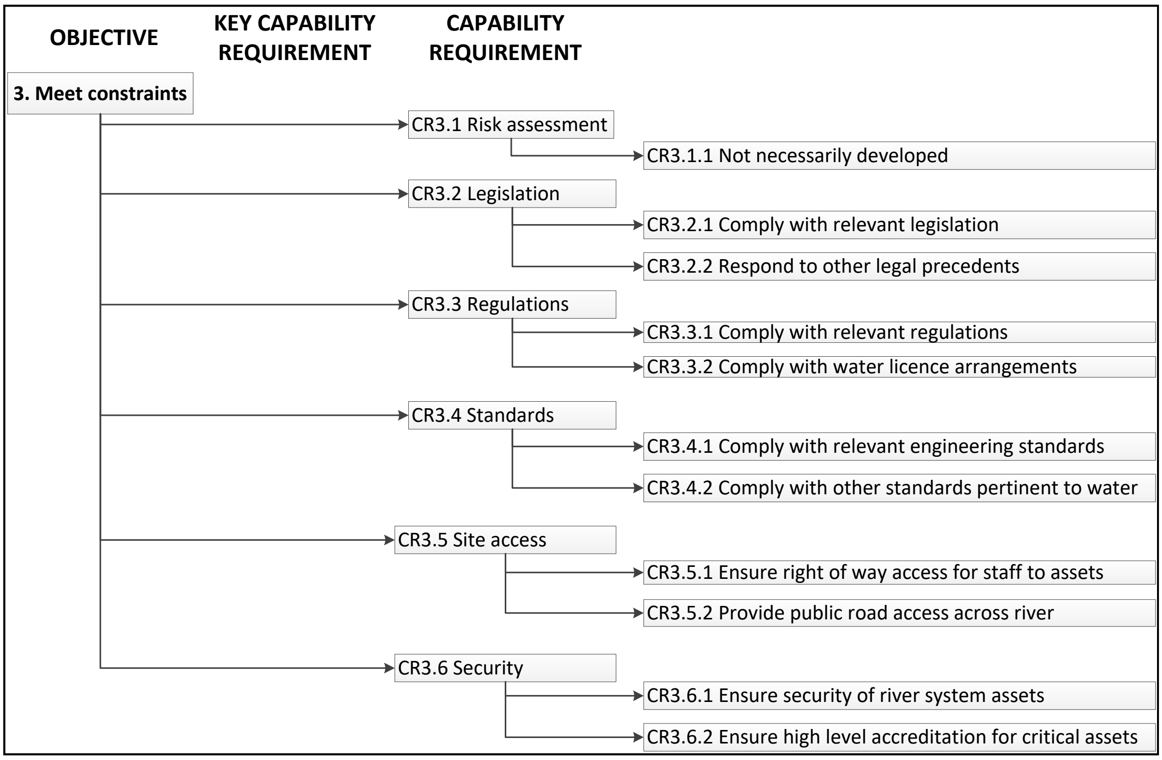

Figure 4.7 Operational Characteristics of Constraints on a Dam Development

Revealing the operational characteristics of the constraints provides a means to identify areas where the constraints compliment safety or contribute to safety, and where they might be at variance with the safety objectives.

4.5. Role of the Owner/Investor in securing the safety objectives

4.5.1. **Overall objectives**

The Investor/Owner will typically identify at least the primary objectives for the dam development at the outset. Initially, the objective with respect to safety could be simply as statement that the dam should be "safe". Other objectives may emerge at the very early stages of the planning process. As discussed above, the Investor/Owner can be expected to have a high level policy or position statement on safety. Unless the Investor/Owner has dam design capability, one of the early decisions by the Investor/Owner in association with the Designer will be whether or not "safety" is a "stand alone" objective, or an attribute of an appropriately designed, constructed and operated dam development. A "safety philosophy" needs to be established at the outset and made known to all from the top level of the Owner's company.

The models described above have a mix of identified safety objectives (extreme events) and safety embedded within other tangible objectives of the development (e.g. operations or regulatory constraints). In reality extreme events, as well as events between normal and extreme, could be embedded within the Operations and may be required under the regulatory regime. Thus, there are no hard and fast rules concerning how these management arrangements to secure safety are established. However the Investor/Owner's commitment to dam safety must be secured regardless of the way the management arrangements are structured to achieve it. This commitment to safety and the capacity to achieve the project objectives must include the capacity to accommodate changes in the costs of the project both as the design evolves and as the construction progresses.

Achievement of the safety objectives is not restricted to establishing objectives and implementation actions as set out above, there are important organizational attributes to consider such as; the Investor/Owner's safety culture; human factors; the financial strength of the organization; the capability to select an appropriately qualified Designer; the approach to managing projects and the management of changes that arise during the pre-operational phases; the approach to quality assurance; the commitment to seamless transition through the pre-operational phases into the operational phases, and records management including securing complete design and construction documentation.

All of these capabilities required to achieve the above must be established in the policies and objectives and the planning and organizing stages of the Investor/Owner's management system. They are transformed into actions or become action supporting attributes in the Implementation stage of the management system.

4.5.2. **General responsibility of the Owner**

The Owner has the ultimate responsibility for ensuring *continuity* and *traceability* in the development of his dam project. He has to make sure that an *independent checking* is also performed, especially at the detail design and construction phases. These requirements (see 3.3) are essential to an optimal and safety conscious development of a project.

Hence the Owner must make it possible that the Designer in charge can follow the project from the very beginning (or at least from the feasibility study on) to the construction phase and to commissioning. It is understood that due to various time and organizational constraints this is often not possible. In this case the Owner must ask that a complete internal documentation, that includes also "hidden" facts or items, be established at the end of each phase to be available in the next project phase.

The Owner must ask for regular independent reviews of the design and at each time when important decisions involving dam safety are to be taken. Independent reviews can be ensured inside the Designer and Contractor organizations, but more preferably by an independent panel of experts. It is the duty of the Owner to make sure that the quality control is effective and not carried out only as a low priority routine task.

The Owner must ensure that continuous liaison is established among the personnel concerned with the various stages of project development so that each concerned discipline and organizational unit knows and understands the activities of the others. This coordination must be given constant attention to be sure that effective action is being taken.

4.5.3. **Responsibility and tasks during design phase**

Usually the Owner contracts a Designer to perform the design studies, establish technical documents for the Contractor, and analyse the dam performance during construction, reservoir first filling and beyond impounding to a point in time where enough instrumentation data has been collected to review the "safety objectives" of the project. Since the first five years are very important in determining the performance of a new dam, the responsibility for monitoring and interpreting the performance data should be clearly defined and the Owner's role in accepting the results should be defined at the outset. Some Owners have in-house design capabilities which are then in charge of these tasks; in this case, the relation between the "Owner" and his internal "Designer" should be formalized in a way that respective responsibilities and duties are clearly identified. The roles and responsibilities of an Owner and of a Designer are different and should not be merged.

Preliminary studies are sometimes carried out by Owners alone, but quite often with the help of a consultant. Safety issues are already important at this stage and the final report of these preliminary studies must include the dam safety aspects. At this stage it is usual (and a good practice) that several options are developed. The role of the Owner is then to select the optimal option for his organization, generally in terms of benefit/cost ratio, construction time, environmental impact and operational economy. Safety aspects are imbedded in the design options but often not clearly displayed. Therefore the Owner must ask the Designer to identify the safety levels of each option so that he can make its decision on a safety informed way. This decision and the reasoning supporting it must be documented.

Feasibility studies and *detailed design* can be performed by a different Designer than the one chosen for the preliminary studies, but it is important that the same Designer is in charge of these two stages, for continuity reasons. The Owner roles during these studies are:

- Set up a general agenda for the project, request periodical reports from the Designer with safety aspects being developed, and some stop and go key points when important decisions have to be taken (general layout, dam and spillway type, tendering and contracting, etc.),
- Appoint an Independent Panel for providing input to work proposed and scheduled. Differences of opinion with the Designer shall be discussed and brought to the Owner which will then determine how to resolve the issues.
- Require compliance with the State/Country regulations, the Owner own regulation (when it does exist), and request the Designer to choose and justify technical standards and criteria which will be used for the design,
- Ensure that dam surveillance is set up at the early stage and that the Designer is in charge of developing surveillance and maintenance procedures to be used during construction, first filling and operational stages,
- Participate to dam site inspections during investigations,
- Plan periodical external audits,
- Develop an Emergency Action Plan to be in place during construction, first filling and operation of the dam.

According to the importance of the projects, other actors are involved in this design phase:

- In countries with a strong regulation the agency in charge requires to be informed of the technical choices and its formal agreement is mandatory.
- Stakeholders (banks, investors, etc.) and/or shareholders and/or public ask for information and sometimes may influence the technical choices of a project, but this should occur without jeopardizing the "safety objectives".

4.5.4. **Responsibility and tasks during construction and commissioning phases**

Construction Phase: At the outset of the construction the Owner shall establish a *site supervision* unit. The Owner can assume this task with its own personal or rely on the Designer to do it, or have a mixed team with personal from both sides. For small project this function can be exerted by one person (the Supervisor), but at large dam sites a team of engineers under the lead of an experienced senior professional (the Chief Supervisor) has to supervise construction activities. This team will be responsible for administering construction and supply contracts, for checking correct execution of the design features and assuring compliance with the specifications. The Chief Supervisor shall have the administrative and technical control of all resources required for accomplishing a safe construction of the dam. It is essential for the site supervision personal to know the conditions (load cases, assumed foundation and material characteristics, etc.) upon which the design is based and the relationship between these conditions and the design features.

The Owner and the Designer together shall set up specific inspection programs including frequent and mandatory inspections during construction to confirm that site conditions are conform to those assumed for design or to determine if design changes may be required to suit the actual conditions. For instance a major requirement consists in the inspection and approval of the dam foundation before placing dam materials. It rather often happens that during construction site conditions are different from those that had been assumed at the design stage: unexpected foundation quality and weather conditions are the most frequent cases, but landslides, material characteristics from quarries or borrow pits area, floods exceeding diversion tunnel capacity etc. can also been encountered. Design personnel must be involved in determining their effects and these can lead to more or less substantial design changes. The Owner shall formally agree to these changes, and must request that the rationales of these changes always take into account their impact on safety. Finally, the design changes and the justification for the decision taken must be carefully documented. At the end of construction the final inspection shall include a complete program for surveillance and testing of operating equipment.

The design function can never be considered finished as long as a dam stands and will be operated; design involvement will thus continue throughout operation of the project. It includes responsibility for planning any dam instrumentation to be installed during construction (and/or later on during operation) to monitor conditions that could potentially threaten dam safety. The design shall identify the purpose of the instrumentation, and include the plans for timely reading, collecting, reducing, and interpreting the data. It shall include an advance determination of critical instrument observations or rates of data change, and a plan of action if observations indicate that a critical condition may occur.

4.5.5. **Project performance vs. dam safety in the development of dam schemes**

That a project such as a dam scheme can be successful even though the project management arrangements did not succeed in controlling say cost or schedule was introduced in 4.1 above and the different dimensions of risk that exists in dam development schemes was introduced in 3.5. These factors mean that what is meant by "project performance" must be clearly set out and agreed between the Owner/Investor, the Designer and the Contractor at the outset and be properly represented in the contractual arrangements for the development of a dam scheme. The dimensions of safety to be considered in the pre-operational and renewal phases of a dam scheme are:

- Worker and workplace safety
- Structural and operational safety of temporary diversion and hydraulic control and works such as cofferdams
- Structural and operational safety of the permanent structure during construction
- Structural and operational safety during first filling and commissioning
- Long term dam safety management requirements

When viewed in this way, the dam safety related activities and requirements fall into both the "project" focused management paradigm and the "operations" management paradigm, and the Designer of the dam scheme must account for all of these considerations. Similarly the designer of the temporary works and especially the designer of the diversion and hydraulic control works, who will normally be employed by the Contractor, should consider any effects that these temporary works might have on the permanent works. This is because it may well be that features of the temporary works becomes absorbed into the permanent works, such as part of a cofferdam forming the upstream toe of the main earth dam.

The type of construction contract will influence the balance between project performance and dam safety, be it dam safety during construction or in the operational phase. Measuring performance relative to the contract is often used an incentive to improve productivity during construction but such incentives, if not carefully formulated, may have an adverse effect on dam safety, particularly over the long term in the Operational Phase of the Life-cycle. Similarly, the balance between responsibility for the design of the temporary works required for construction and the design of the permanent works may influence the safety of the scheme. The financial and schedule objectives for the management of the project should be structured in a way that include proper consideration of the relationship between the during-construction and post-construction dam safety objectives. Therefore there may be tensions between the “project” focused management approach during construction and the “operational” focus of the scheme that emerges as the construction progresses.

Dam safety as it applies to the temporary diversion works and hydraulic controls during the construction phase is best illustrated by consideration of the sizing of the diversion works, typically the cofferdam and the diversion tunnel (or canal). However, the sizing of these temporary works may also affect the construction schedule of the permanent works which in turn may affect the quality of the construction (e.g. rate of placement and compaction of fill materials). The case of the inclusion of a diversion cofferdam in the upstream toe of the permanent earthfill dam is another case where the long term performance of the body of the dam will be influenced by the design and construction of the temporary works. Similarly the design to include a diversion tunnel into the permanent works can be expected to influence the operational safety of the dam scheme.

Beyond the above considerations, there are some aspects of performance of the Contractor during construction and the design that are inherent to the design. Such situations can occur when design assumptions require certain construction targets to be met at different stages of the construction. Thus once the design commits the Contractor to achieving a particular target, there is essentially no turning back.

The weather can result negative impacts to both construction performance and dam safety, as the weather can not only delay the schedule, it can also adversely affect the safety of the works constructed to date by for instance in the case of earth dams introducing a wetter and softer layer within the dam body. Further, in northern regions or at altitude, winter conditions can result freezing effects on the on-going works, which can also adversely affect construction performance and long term dam safety.

The design objectives and the construction project objectives together with the associated risks can be represented in a qualitative risk matrix that identifies the sources of risk on one axis and the stage of the development and operation of the scheme on the other. Alternatively a risk breakdown structure might be developed which might breakdown the risks into say four categories; Technical; External; Organizational; and Project Management with the contributing factors associated with each category listed. However, these “linear” analysis structures are insufficient to deal with the feed-backs that occur and interdependencies between design and construction in a dam development, and also the interdependencies between project performance and dam safety.

The relationship between construction performance and dam safety can be addressed if the management systems and in particular the Safety Management Systems of the Owner/Investor, the Designer and the Contractor are consistent and activities and expectations are linked in a way that develops appropriate synergies between the parties and the activities as illustrated in Figure 4.3.

4.6. Owner Management System

4.6.1. **Policies and general organization**

The Owner is responsible for the development and implementation of policy, resources and procedures for safe design and construction of the dam, and later on for its operation. Whatever the type of Ownership, it is essential to put in place a specific management system for each dam project.

A Dam Project Development Office shall be installed which reports directly to the top management of the Owner or his designated representative. This office shall ensure that the Owner, as a matter of general policy and in actual practice, makes every reasonable and prudent effort to enhance the safety of the dam. Duties of the office shall include surveillance and evaluation of the Owner administrative and technical or regulatory practices related to dam safety concerning design and construction of new dams, and rehabilitation of existing dams.
The functions of the office shall be advisory to the Owner top management. The staffing and detailed duties of the office shall be commensurate with the importance of the dams.

The Owner organization for the design, construction, operation, or regulation of a dam project shall be structured in such a way that a single identifiable, technically qualified manager has the responsibility for assuring that every single administrative and technical safety aspect of dam engineering is adequately considered throughout the development of the project. The position must have continuity of guidance and direction, and the authority and resources for ensuring that these responsibilities can be carried out.

Management shall ensure that organization staffing is sufficient and qualified for the projected workload, and that all programs necessary for the safety of dams are established, continued, and realistically funded. For allocation of manpower and funds high priority shall be given to safety-related functions. Safety-related functions and features must not be sacrificed to reduce costs, improve project justification, or expedite time schedules.

4.6.2. **Role of Monitoring and Evaluation**

Monitoring and evaluation transcend all aspects of the project and as with other features of the overarching management system it differs according to the project activities. The roles and the responsibilities of each of the actors are also different and it is imperative that roles and responsibilities are clearly defined. Monitoring and evaluation may be considered as the quality control process that each individual actor establishes to ensure that their work conforms to the specification of the project. Achieving the right balance between the Monitoring and Evaluation activities and the Implementation activities is as important as achieving the right balance between the Monitoring and Evaluation activities between the different actors. Since evaluation requires information, analysis and judgment, it is important to establish parameters and principles to secure the safety objectives. Properly establishing these arrangements within each of the actor’s management systems and prior to transitioning from one phase of the development to the next are important as these arrangements should not either compromise or be compromised by the contractual and working arrangements of the monitoring and evaluation activities.
More often in major developments such as dams and large civil engineered works, the monitoring and evaluation by one actor’s activities are carried out either in association with or parallel to those of another actor. This latter approach is typically the case in dam development projects, especially in the construction phase.

Monitoring and Evaluation are essential to the Owner in the sense that they are the ultimate means for him to check that his project is on the good track from various aspects (financial, economic, environmental, etc.) and, last but not least, regarding the safety aspects. Monitoring shall consist in a sustained follow-up of the design activities from the preliminary studies to the construction design and implementation.

- At the *detailed design phase* when all features of the dam project become more comprehensive a general check of the design works is recommended. It can be performed with the help of an external Board of Consultants (see below). Evaluation consists usually in recommendations for improving some of the design aspects having in mind an enhanced safety of the dam.
- Monitoring during the *construction phase* shall follow the principles previously enounced (see 4.5.4).

The Owner together with the Designer shall perform from time to time inspections to confirm that site conditions are conform to those assumed for design or to determine if design changes may be required to suit the actual conditions. This process has to be conducted together with the site supervision team and possibly the Board of Consultants. Evaluation will consist in checking whether some design criteria might be relaxed without compromising the safety of the dam or improvement measures have to be taken.

4.6.3. **Role of Audit, Review and Reporting**

The use of an independent Board of Consultants (sometimes termed "Advisory Board") is common in the per-operational phases of a dam development whether it is a new dam or a major dam renewal project (FEMA, 2004). The Board of Consultants will be typically retained by the Investor/Owner to provide a second expert opinion and often to contribute to the design and construction processes by making their knowledge and experience available to the Designer. In particular, the Board of Consultants will have a focus on the safety of the proposed dam over the whole life-cycle of the development as well as the during design and construction phases.

The Board of Consultants can be expected to comprise a small group of highly experienced engineers who together have the breadth and depth of knowledge and expertise to span all of the dimensions of the development. This Board can be expected to meet on a regular basis during the design and construction as dictated by the nature and complexity of the works.

The Designer may engage their own expert advisors to assist those involved with the design to resolve complex analysis and design matters as well as to provide overall oversight for the design process. Similarly the Contractor may engage an independent panel to advise on novel aspects of the design or construction.

Each of the actors would normally be expected to have their own internal audit arrangements or to engage external auditors. Audits can be carried out with respect to financial, managerial and technical performance. Audits are normally set against the management system and sub-management systems of the actors such as the ISO 9100 quality management system that might be utilized by the Designer and the Contractor.

4.7. Role of the other main actors in securing the safety objectives

4.7.1. **Role of the Designer**

As discussed previously, the role of the Designer is "transformational", and as such is central to the whole endeavour of determining how the Investor/Owner objectives can be realized in the Implementation Phase. The Designer will necessarily have the scientific and technical competence to transform the Investor/Owner's objectives into implementable actions. However, scientific and technical competencies are not sufficient in themselves, the Designer must have the organizational capacity to take responsibility for and effectively deliver these large and complex engineering projects. Similar to the Investor/Owner, the Designer and the Designer's organization requires many of the similar organizational attributes as the Investor/Owner. In fact, commonality of these organizational attributes and safety culture synergies between Designer and Investor/Owner contribute to the overall safety culture of the contractual relationship between these two parties.

Notwithstanding the contractual arrangements between the Investor/Owner and the Designer, the Designer is central to the achievement of dam safety because it is the Designer who should know the safety objectives and know how these objectives can be achieved in the design. In many cases it can be expected that the Designer will have to provide guidance to the Investor/Owner concerning the form and nature of the safety objectives and requirements. The Designer will also know which safety design attributes are inherent to the design of the system and its intended operating regime, and also know those safety attributes that can be considered as additional safety defences.

It is preferable that the Designer should also be in a position to ensure that the design intents of the system and safety attributes are achieved in the construction and commissioning processes. This requires that appropriate communication arrangements between the Owner, the Designer and the Contractor are identified in the design process and established in the contractual arrangements between the various parties.

Some good practices for developing a design project organization are as follows:

- The design of a safe dam is under the authority of a highly qualified design manager whose attitudes and actions reflect a safety culture and who ensures that all safety and regulatory requirements are met.
- Separate aspects of design may be served by different sections of a central design group and by other groups subcontracted to specific parts of the project.
- An adequate number of qualified personnel for each activity are essential.
- The engineering manager establishes a clear set of interfaces between the groups engaged in different parts of the design, and between the Owner, Designers, suppliers and contractors.
- The design force is engaged in the preparation of safety analysis reports and operational surveillance and O&M procedures. It communicates with the future operating staff to ensure that requirements from that source are recognized in the design and that there is appropriate input from the Designer to the operating procedures as they are prepared and to the planning and conduct of training.
- Quality assurance is carried out for all design activities important to safety. An essential component of this activity is configuration control, to ensure that the safety design basis is effectively recorded at the start and then kept up to date when design changes occur.

4.7.2. **Role of the Contractor**

The Contractor also has a central role in the achievement of the dam safety objectives as can be assured through the construction techniques, construction monitoring, independent supervision and quality assurance arrangements of the contract. In addition to the role in assuring the safety of the dam as constructed, the Contractor is also responsible for the on-going safety of the dam during the construction, the safety of all temporary works and for ensuring that the long term safety of the dam is not compromised by any temporary works which may become embodied in the overall construction as part of the permanent works (e.g. diversion tunnels becoming bottom outlets).

As with the Investor/Owner and the Designer, the Contractor’s safety culture; the financial strength of the company; the capability to appoint appropriately qualified construction and construction monitoring staff; the approach to construction management; temporary works design, construction and removal; the management of changes; the approach to monitoring and quality assurance; and records management including contributing to delivering complete construction records, all play a role in assuring safety during and after construction.

4.8. Management of risk and uncertainty in a dam development

Management of risk and uncertainty is an inevitable feature of the management of dam development projects. Risk and uncertainty arise together and are inseparable, although they have different features that create the distinction (Hartford and Baecher, 2004). The risks and uncertainties arises from uncertainty and variability in; nature, the properties of the materials used to build the dam, engineering decisions, construction necessities, operational considerations and human factors, with the result that risk and uncertainty are inherent to dams from conception and subsequently through the entire life-cycle. Because risk has its origins in uncertainty, risk, like uncertainty is fundamentally matter of knowledge. As such, the probability of dam failure is not an objectively measurable physical or functional property of the dam. Since the beginning of modern probability theory in the 1600s, there has been a dual meaning: (a) relative frequency in a long or infinite number of trials as in the river flow records over centuries; and (b) objective or subjective degree of belief, as in the anticipated availability of suitable sub-surface conditions prior to an investigation. Acceptance of the above facts by all parties is essential in the development of dams.

The problem of risk and uncertainty presents itself throughout the pre-operational phases of the life-cycle with the risk of flooding during construction overwhelming the diversion works being considered in some detail in considerable detail during the planning of the diversion works. From a functional perspective, the uncertainties and the attendant risks are associated with the containment and the conveyance functions of the dam. While dams are designed in terms of defensive design principles and practices that provide effective means of handling much of the risk and uncertainty that can arise within the design basis, there are limits to the extent to which they can control the risk. These defensive design practices are implemented without the effort of risk quantification.

The emergence of formal consideration of risk and uncertainty in dams engineering and in particular in the assessment of existing dams during the last quarter of the 20th century revealed that conditions can arise that are not adequately characterized in terms of the practices that had evolved over the previous two centuries. This was due to several interrelated factors including but not restricted to; advances in the sciences that underpin dams engineering, changes in design philosophies and practices including the use of materials whose long term performance characteristics were not fully appreciated at the design stage (e.g. the various types of adverse reactions in concrete), the ever increasing complexity of the way dams are operated in the modern context, and human and organizational factors. Nowadays, it is accepted that there are physical limits to the applied loads that a dam can be designed to withstand and it is now recognized that design concepts such as the Probable Maximum Flood, which was originally developed to virtually eliminate the potential for a dam to be overwhelmed by a flood, do not provide the absolute protection originally envisaged. Further there are also economic limits to, and environmental and social constraints on, what can be achieved in the design, construction and operation of a dam. Dam design in the modern context is rather more complex than it was during the major dam building era of the last century and risk and uncertainty analysis methods and risk-informed decision-making provide the designer with additional capabilities to address some of these challenges.

Existing risk analysis and risk assessment techniques can provide valuable information achieved through a formal and transparent process to inform the judgements that are required of all those who are involved in decisions pertaining to the development of a dams. Further and importantly, risk analysis methods continue to evolve and new approaches are emerging to cope with considerations that are not adequately catered for in terms of existing risk analysis methods. Therefore a new and enlarging suite of methods suitable for different applications in dam design can be expected to evolve. Risk assessment is presently not used to perform an economic optimization of the safety of the dam and there are sound political, legal, moral, ethical and scientific reasons that risk assessment should not be used for such optimization. Risk analysis and risk assessment also provide a means of communicating the nature and magnitude of the risk borne by the various stakeholders in the development of the dam. Risk analysis and risk assessment methods are not dealt with in this Bulletin as these methods are provided in other ICOLD Bulletins (ICOLD Bulletins 130 and 154, Hartford et al., ibid.).

The matter of risk and uncertainty for dams considered at the design stage can be divided into four states as follows:

- During construction
- During first filling and during the first five years of operation
- During operation within the hydraulic and structural design limits
- Under extreme limits when the design limits are at the point of being exceeded

The designer must consider all of these matters in the design process and in this regard, dam safety management in the pre-operational phases of the life-cycle includes the design of the management arrangements for risk and uncertainty for all phases of the life-cycle.

Examples of the use of risk analysis and risk assessment of the possibilities to use these methods in the design of a new dam and in the remediation or renewal of an existing dam and subsequently in these operational states include:

i. The replacement of rules of thumb by risk assessment based on stochastic simulation of river flows in the design of diversion works.
ii. The use of probabilistic methods in site investigation and construction materials characterization (Baecher et al, 2003, ISSMGE (draft), 2017),
iii. Analysis and management of the various dimensions of project risk (Jensen, 2014, ICE)
iv. The potential for failure modes and effects analysis, fault tree analysis and event tree analysis (including "bow-tie" analysis) to inform the application of defensive design principles, and in the identification of

opportunities for monitoring for deviations in expected performance and associated early-stage intervention (ICOLD Bulletin 130 and Bulletin 154).

v. Probabilistic analysis and Bayesian inference techniques during first filling and early stage operation.

vi. Systems simulation including stochastic simulation and systems dynamics simulation in both deterministic and probabilistic modes during the operational phase of the lifecycle both within and at the hydraulic and structural limits of the design (Hartford et al., 2016).

vii. The use of event tree analysis in performing what-if type analysis at and above the hydraulic and structural design limits (BC Hydro 1993, ANCOLD 1994).

All of these methods are available to assist in the design of a dam and to better inform the designer's judgments. In particular they provide the designer with the opportunity to better explain and justify the judgments that must be made as the design proceeds.

Examples of the information and capabilities that become available to the designer include but are not limited to the following illustrative examples:

i. Understanding the variation in risk with different combinations of cofferdam height and diversion tunnel/channel volumetric capacity, and the optimization of both the size of the works and the planning of the emergency response in the event of the diversion works being overwhelmed by a flood.

ii. Modification of the emergent design in response the variations and uncertainties that are revealed by the site investigation

iii. Preparation of construction tendering documents and characterization of all of the dimensions of risk and uncertainty in the project.

iv. Informing the selection of and balance across structural, maintenance and operational defences and in the preparation of the operations and maintenance manuals; and informing the design of the monitoring and surveillance regime (see e.g. the *Bow Tie Risk Management Model* in Bulletin 154)

v. Improved understanding of the emergent performance of the dam during first filling and early stage operation.

vi. Ensuring the resilience of the system such that dam safety can be maintained for "system under fault conditions" during operations within the structural and hydraulic design limits.

j) Providing a design that as a whole does not result in a brittle failure in the event of the design limits being exceeded.

Useful as all of these techniques are, they cannot replace the reliance by the designer on intuition and judgement as the design process advances. However, risk analysis techniques, especially when configured with 3-D virtual reality simulations of the functional performance of the design as it emerges, provide the designer with a powerful suite of explanatory capabilities that can be used to demonstrate the appropriateness of the design and in establishing confidence in its safety and resilience.

Presently there is no scope to set the final design parameters of a new dam or dam renewal solely on the basis of a probabilistic risk assessment. However, elements of the temporary works such as the sizing of the diversion works (cofferdam and diversion tunnels) do involve some type of relatively simple risk assessment that is usually economic in character.

4.9. Importance of Management of Changes

Management of changes is an essential element of risk management as it is impossible to know all of the risks and uncertainties involved in a dam development project at the outset. Although changes in the overall dam development objectives may be minor in many instances, changes in how these objectives are achieved during the dam development process are inevitable and may well have a significant impact on safety. This makes management control of changes an essential and common element of the management system arrangements.

The Management of Changes is fundamentally a matter of the management of uncertainty and changed conditions that arise during the course of the project. In addition to not knowing all of the risks and uncertainties, management of changes can cause delays in the construction schedule with attendant contractual implication risks to the project. These changes can have implications for both the safety of the works during construction and for the long term functional and operational safety of the constructed dam. For example, the unexpected exhaustion of a source of fill in a borrow area or aggregate from a quarry might trigger the need for further explorations for suitable materials requiring time that was not necessarily provided for in the construction contract and which leaves the partially constructed works exposed to adverse external effects. In cases where contractual provision has been made, it may be that the slippage of the construction schedule means that part of or even an entire construction season might be lost. Such a loss of schedule may mean that different provisions to address the seasonal constraints on construction other than those originally envisaged might be required.

4.10. Role of Arbitration in Disputes

Management of changes generally involves changes to the details of the work previously defined and agreed in the contract between the Owner and the Contractor or the Owner and the Designer. As such change management can lead to claims which could also result in delays to or cessation of the construction. It is not unusual for such situations to lead to arbitration of the dispute between the parties. To ensure that changes conditions and disputes do not adversely affect safety, the contract should be formulated in a way that ensures that the safety of the construction and the functional safety of the constructed works are not compromised during the dispute.

Making such provisions will obviously involve a cost and the costs of these provisions should be included in the contract and incorporated into the dispute resolution (arbitration) process. Throughout, engineering design, and construction contingencies to deal with the potential for changed conditions should be provided and embedded in the contractual provisions for the management of changes and for dispute resolution.

Chapter 5 - Engineering principles

5.1. General consideration

5.1.1. Design process

Although dams have been built for hundreds of years, dam engineering is not an exact science and is more accurately described as an "art" that requires the designer to balance a diverse range of complex and competing factors that for reasons of nature are inherently uncertainty.

Engineering judgment and experience play a major role in dam design as do architectural style, landform fashioning, environmental appreciation and social empathy. The precise location of a dam, the general layout of the project, the selection of the dam type and shape, the choice of the type of spillway, definition of necessary investigations and their interpretations, monitoring system, etc. are all topics which require experience, and which can only be partly guided by engineering standards. For example, there are practical limitations on the amount of physical data that can be obtained during planning and design. Inferential judgment and extrapolation are necessary to assess the expected foundation conditions and to design an appropriate structure. Experience and intuition are essential in arriving at these judgments.

The experience, knowledge, intuition and creativity of the Designer are therefore of paramount importance, as many input data : hydrology, geology, investigations results, available materials, must be considered at the same time in order to achieve a dam project which will fulfil as well as possible all the objectives of the Owner. The same is true for measures taken during construction, and particularly with river diversion, which may have consequences on dam safety.

Many aspects of a dam project are not calculable or may not be checked through analytical methods; rather they will be attained through experience of the engineer and state of the art (filter width, monitoring system, etc.). Dam design is then rather different to that of standard bridges or buildings design methodologies where the geometry and size of the structures can be entirely optimized by computer once loading is defined. In the domain of dam design, the dam geometry is quite always defined before any calculation is performed. Once the design is substantially established, a great deal of analytical effort is then spent to verify the overall expected performance of the dam as well as to refine and tightly define individual features of the design.

That said, the Designer draws upon mathematical principles and physical laws, while exercising experience-based deductive and inductive judgment in the planning and execution of a dam project. Judgment shall be sustained by experience and knowledge (case studies of incidents) and every design shall incorporate defensive measures where appropriate considering the various load conditions the dam might encounter during operation. Experience-based judgment is equally if perhaps even more important in evaluating and/or improving existing dams. For many of these "older" dams, there is little information available on original site exploration, design, construction and subsequent operation, and much of the desirable information cannot be obtained.

While guidelines or standards exists in many domains and provide useful information; they are based either on experience of many other projects or on theoretical developments. They are also limited in time and may have been overtaken by more recent advances in knowledge. "Guidelines are not a substitute for *good engineering judgment*, nor are the procedures to be applied rigidly in place of other analytical solutions to engineering problems encountered by the Designer. *Designers should keep in mind that the engineering profession is not limited to a specific solution to each problem and that the results are the desired end to problem solving*" (FERC, 2014).

Those charged with designing a dam need to recognize that no dam can ever be completely "failsafe" (refer to Chapter 4.8) because of incomplete understanding of natural forces (earthquakes and floods) naturally occurring and manufactured material variability and human factors (incorrect human actions, design flaws, poor quality in construction, sabotage) and the way these factors combine to result in destructive forces; the behaviour of the materials in response to these forces; and in control of the construction process. The Designer must therefore ensure that uncertainties are properly identified, a competent technical judgment is applied and contingency plans to accommodate adjustments are timely deployed.

The choices made by the Designer are based on several considerations, among which the safety and integrity of the dam should be the most important. But economic aspects are important too, and the final design will often be balanced between these practical constraints while always leaning on the side of safety.

The design must be feasible, in construction and commissioning: the Designer must also understand how the system performs in operation, undergoing maintenance, in repair and decommissioning, in order to properly accommodate these life-cycle phases in the design.

Construction is a critical phase in achieving a safe dam. The construction techniques used for dams are applied in the design of the project in recognition of the critical safety issues involved. As such “constructability” is an essential feature of dam design. The construction aspects and techniques are taken into consideration in the design in order to eliminate as far as possible the need for changes in the design during construction. Mastering geological and geotechnical hazards are particularly important: there are many examples of difficulties encountered during the dam construction due to an insufficient knowledge of these hazards. Thorough investigations and taking into account uncertainty are the best “barriers” to manage this risk.

Any project must be continuously evaluated, and "re-engineered" as required during construction to assure that the final design is compatible with the conditions encountered. Quality of construction is also critical to safety. Deficiencies in materials or in construction practices can occur during all stages of the construction, and constant vigilance is necessary to prevent them. Sampling and testing at a completed project cannot be relied on as an effective substitute for inspection and quality control during construction. Experience in the safety assessment and renewal of existing dams has found that extensive and comprehensive quality control and assurance during construction with clear and comprehensive documentation of the construction records are immensely valuable to the Owner after construction. Modern electronic capture of construction data and 3-D visual modelling enable the development of high quality and detailed construction records that form an essential part of the development of a dam and its entry into service. These records serve as a significant contributor to the risk reduction over the whole life-cycle of the project.

Given the above, the design of a dam should proceed in terms of *alternatives and iterative process*, the best one being finally a kind of a balance between technical and economical optimum that is in harmony with its natural environment and its role in making a net positive contribution to society while ensuring the safety of the structures and their functions.

5.1.2. **Safety engineering principles**

In order to embed safety considerations in the early stages of the design process, a set of “safety engineering principles” shall be shared between the Designer and the Investor/Owner that will ensure that the contributions to safety from design and from investment can be properly secured and embedded in the development from the outset. In this regard, it is important to recognize that engineering principles are not “requirements” rather they represent features to be striven for.

In industrial domains basic or “standard” engineering principles have been developed and documented. They are:

- Redundancy: more than one way to achieve the system output;
- Diversity: different ways to achieve the same function;
- Segregation: output served from different directions;
- Defence in depth: large margins of capacity over demand (in all systems – including redundant systems);

- Fault tolerant (include human fault tolerant): a single fault will not cause loss of system function;
- Fail to a safe condition: If the system does fail, it will be rendered to a harmless condition.

Clearly, a dam/reservoir system as a whole would not be expected to display all of these features, but one or more of the features should be provided for various sub-systems within the dam/reservoir system. In general, the fewer the principles that are achieved the greater the dependence on the quality and robustness of the engineering and system management.

As an example, the redundancy principle implies that “a safety critical system should be designed so that, if possible, the failure of any single component will not prevent the system of performing its function when required. This principle is based on the relatively high probability of a single failure occurring compared to the significantly lower probability of two or more concurrent component failures. While this may be relatively easy to achieve with electronic, electrical and, to some extent, mechanical systems it is more difficult or even impossible to realize with structural features. This difference is mitigated by the respective failure characteristics of the different system types. Electronic and electrical equipment are prone to sudden failure which cannot easily be prevented by condition monitoring or preventive maintenance. Structural and some mechanical systems may be expected to exhibit failure modes which involve progressive degradation mechanisms that, in principle, should be amenable to prevention by monitoring and preventive maintenance. Therefore the single failure criterion is less critical for structural and some mechanical systems than for electronic and electrical systems. When a component does comprise a single failure point for a system then special care has to be applied to the design quality assurance and performance monitoring of that component. The principle of using well proven equipment becomes even more important.” (Ballard and Lewin, 2004).

Therefore the dam body and some mechanical equipment would be expected to meet some specific principles of robustness and failure consequences mitigation in their design and construction, while other features such as the spillway gate control systems embodying most if not all of the above features. These requirements of robustness, surveillance and control of incidents can be named “defence in depth” principles, as used for instance in the nuclear industry, and they can be efficiently adapted for dam design and construction.

In order to address the different dam project components (dam structures, spillway, control system, etc.) in a coherent way, proposed engineering principles for dams are split in three categories: fundamental defence in depth principles, safety design principles and safety assessment principles.

5.1.3. Fundamental “Defence in depth” principles

In the nuclear power industry, “defence in depth” is singled out amongst the fundamental principles. All safety activities, whether organizational, behavioural or equipment related, are subject to layers of overlapping provisions, so that if a failure was to occur it would be compensated for or corrected without causing harm to individuals or the public at large. This idea of multiple levels of protection is the central feature of defence in depth.

The strategy for defence in depth is twofold: first, to prevent incidents and second, if prevention fails, to limit the potential consequences of accidents and to prevent their evolution to more serious conditions. Defence in depth is generally structured in five levels; only four of them have been considered for dams. The objectives of each level of protection and the essential means of achieving them in existing plants are shown in Table 5-1 (which has been adapted from INSAG-12). If one level is to fail, the subsequent level comes into play, and so on. Special attention is paid to hazards that could potentially impair several levels of defence, such as flooding or earthquakes. Precautions are taken to prevent such hazards wherever possible and the plant and its safety systems are designed to cope with them.

The defence in depth principles are more specifically oriented toward operational safety. However they have a direct influence on the design, and it is in this sense that they are treated here.

Levels	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Mitigation of the consequences of significant releases of water	Off-site emergency response

Table 5-1 Levels of defence in depth (adapted from INSAG 12)

Human aspects are specifically addressed in these principles of defence in depth. They include quality assurance, administrative controls, safety reviews, independent regulation, operating limits, personnel qualification and training, and safety culture.
Therefore, applying the defence in depth concept lead to three fundamental principles:

Fundamental principle 1: *Conservative design* and high quality in construction (and operation) (Level 1 of the table)

This is achieved through design practices: dam type selection, spillway type selection, dam siting, design practices and criteria (loading cases, safety factors, etc.), etc. These aspects are addressed in more detail later in this chapter.

Fundamental principle 2: Control of abnormal behaviour and detection of failures, through *surveillance* and monitoring (Level 2 of the table)

This principle implies the identification of *the failure modes* in order to design the surveillance and monitoring system in a way it could detect the preliminary effects of a potential failure. In this respect, types, number, location and measurement frequency of monitoring sensors are directly driven by identified failure modes and their progression rates.

Fundamental principle 3: Control of accidents within the design basis through *engineered safety features* and accident procedures (Level 3 of the table)

In case of abnormal behaviour detection, operational procedures should indicate the different actions to be undertaken, consisting usually of surveillance enhancement, emergency works, etc. The ultimate action will be to drawdown the reservoir through an emergency outlet system, and therefore such a system must be provided in the design. The output flow capacity of this outlet system can be derived from the rate of drawdown considered as relevant to lower the hydrostatic thrust on the dam upstream face in a delay compatible with the failure mode kinetics.
For large reservoirs it is often not practicable to drawdown the reservoir trough an emergency outlet because the necessary discharge value would cause too important downstream damages or the size of the outlet would be impracticable. In these cases the only way to control potential accidents will be emergency works, which should be therefore planned during the design phase. For example, it can have consequences on the size of internal galleries to allow access to drilling equipment, availability of emergency earthfill stocks, etc. Specific procedures, periodically tested, should be developed.
The two last principles are of the highest importance for dam safe design, due to the non-redundancy of the dam structure and some important hydro-mechanical equipment as large gates. It implies a fundamental hypothesis:

A potential dam failure is always preceded by visible or measurable effects,
with a sufficient delay to undertake relevant safety actions

If it would not be the case, dam building could be considered as one of the most dangerous activities in the World. These considerations emphasize the paramount importance

- of surveillance to detect any undesirable phenomenon
- of operational procedures to act rapidly and efficiently in case of detection of failure initiation, and
- of a facility able to relieve the thrust of the reservoir at a rate and a value relevant with the severity of the observed dam behaviour.

The level 4 of Defence in depth principles – off-site emergency response – is addressed in the bulletin 154, but should be implemented at the design stage and be operational from the start of construction.

5.1.4. **Key capability requirements**

The key capability requirements (see §4.4) also referred to as the 'design basis' are a clear statement of the load cases and performance demands to be taken into account in the design. The development of the design basis involves a systematic approach in identifying all credible load cases (or 'events') for which the design must possess adequate withstanding capacity and hydraulic functionality.
This safety design principle urges the proactive consideration at the design stage of all external (e.g. earthquake), internal (e.g. component failure) and interface (e.g. how one device affects another) loading conditions (including operator demands and possible misoperation) to which the design may credibly be subjected.
Identification of these 'loading conditions', in conjunction with a full consideration of the intended functions of the design, helps with the development of a solution which employs appropriate strategies to give the overall structure or system the desired safety characteristics.
Desirable safety characteristics in a design include, for example, a tolerance of faults such that no single points of failure within the design are able, on their own, to give rise to an unsafe condition.
Appropriate strategies to achieve such characteristics may include, for example, the provision of a back-up system to take over from the primary system in the event of failure.
Full consideration should also be given to how operational staff can safely interact with the design under the expected range of normal and abnormal operating conditions.

There are, of course, load cases which, on the grounds of extreme low frequency or negligible impact can be argued to be 'beyond the design basis' and against which the design need not demonstrate any withstand capability. One classical example consists in not considering the simultaneous occurrence of the largest design flood and the largest design earthquake. Depending upon the project there might be other combinations of extreme loads which can be discarded. However sequential occurrences of large or extreme loads should be considered.

In all cases it is appropriate to seek a ductile design at the edge of the design envelope to avoid brittle failure of the dam in the event of the design capacity being exceeded.

5.2. Safety Design Principles

5.2.1. **Siting and Layout**

Principle 1: Facilities and structures shall be sited with due consideration of the hazards posed to them by their environment.

The vulnerability of the proposed new facility itself at its proposed location shall be considered. The all external hazards such as flood, earthquake, forest fire, etc. to which the new facility might be exposed need to be included in the design basis for the facility, unless a lower risk location can be found which eliminates such considerations. These hazards must include risks posed by industrial assets: upstream dams, industrial facilities that could generate obstacles in case of floods events, etc.

Floods and earthquakes are classic external loadings, and the values to be considered are generally defined by regulations of the country or internationally recognized standards. The choice of the dam location cannot generally change the way it will be affected by these loading cases except in the presence of active faults in the foundation.

On the contrary, the best possible knowledge of geotechnical and geological conditions of the selected site is essential for an optimal dam layout. This can often lead to move the dam to find better geotechnical conditions, or even change the type of dam. The importance of thorough investigations, taking into account uncertainties at all levels can never been enough emphasized. Objectives of investigations are to select a relevant location of the dam but also to search for adequate materials for the dam and appurtenant structures. Doing so one must bear in mind the necessary adaptation to geological and/or geotechnical hazards and necessary reactivity in case of unplanned events and/or geological features during the construction phase.

The previous considerations apply also fully to the diversion works location and design: the protection against a flood with a given return period is established considering the risk of flooding of the construction site, and safety aspects depend on the type of dam.

Principle 2: Choice of the dam type and spillway type shall be done with due consideration of their impact on the overall project safety.

The choice of the dam type is certainly the most important for a dam project. Many criteria are explicitly or implicitly taken into account. From a safety point of view, it is obvious that some types of dams are safer at a given location than others. It is mostly the case for earthquakes and flood loading that some dam types withstand better than others. It is therefore important to develop several variants and explicitly take into account the safety aspects in the selection criteria.

The same applies to the choice of spillway type. Several criteria should be considered for this choice: kinetics of the expected floods, debris yield of the catchment, proximity of operators, availability of reliable power supply etc. It is sometimes considered that providing one or two ungated sills in combination with a gated spillway is a good practice. This choice between “passive” and “active” functionality depends therefore on the above criteria and can be considered as one of the second more important decision in a dam design,

5.2.2. Proven engineering practices

Principle 3: Dam design is based on engineering practices that are proven by testing and experience.

If opportunities for advancing or improving the existing design practice are available and seem appropriate, such changes should be applied cautiously and subjected to necessary testing and evaluation in order to develop proper conclusions for the safety of the structures . The design and construction of new types of dams are based as far as possible on experience from earlier projects or on the results of research programs and the operation of prototypes of an adequate size. In case of differential opinions and/or contradictory positions arising between the several actors involved during design and construction the Owner has to settle the debate in a way that the minimal requirements of the Regulatory Agency can be satisfied with the outcome of the dispute.

Systems and components are conservatively designed, constructed and tested to quality standards commensurate with the safety objectives. Approved codes and standards are used whose adequacy and applicability have been assessed and which have been supplemented or modified if necessary. These codes have the simultaneous objectives of reliability and safety. They are based on principles proven by research, past application, testing and dependable analysis (see for example ICOLD Bulletin 123).

Well established methods of manufacturing and construction are used. Dependence on experienced and approved suppliers contributes to confidence in the performance of important components. Deviations from previously successful manufacturing and construction practices are approved only after demonstration that the alternatives meet the requirements. Manufacturing and construction quality is ensured through the use of appropriate standards and by the proper selection, training and qualification of workers. The use of proven engineering continues throughout the dam scheme lifetime. When repairs and modifications are made, an analysis is conducted and a review is made to ensure that the system is returned to a configuration covered in the safety analysis and the technical specifications. Where new safety questions are posed, a new analysis is conducted.

These considerations are an integral part of the approval process by operating organizations and regulatory authorities.

5.2.3. Safe materials and methods

Principle 4: The design of structures, systems and components should adopt materials and methods which ease the works, minimize the risks of harm to workers during construction and operation and which minimize the likelihood of introducing defects.

The successful and safe through-life performance of any asset starts at the design stage. The focus on in-service performance and capability often takes precedence to the consideration of the roles and duties of those who will have to create and assemble the asset. Much can be done at the design stage to make these activities safer. An example would be the incorporation of designated lifting points into item of plant rather than leaving it to the installation team to work out a safe slinging arrangement.

It is also important to maximize the likelihood of the structure, system or component entering service able to fully meet the design intent and as free as possible from defects which might compromise fulfilling of its safety duty. Again, by attentive consideration to materials and methods, the likelihood of such defects can be minimized.

Equipment should be located and practically arranged in a way that they will be easy to inspect, maintain, and repair if necessary. This is obvious and often easy to achieve for hydro mechanical heavy components (gates), but should be assessed for all the electrical and control system equipment. The same recommendations can be done for gauges, monitoring system, etc.

Finally, attention could be paid at the design stage to make decommissioning and disposal activities safer, simply by giving due consideration in advance to how such tasks might be approached and what can be done to ease and assist them.

5.2.4. Preserving asset function through life time

Principle 5: Design for structures, systems and components should give due consideration to the preservation of asset function through-life and to the means by which such functions can be safely preserved and verified.

All industrial assets are developed and employed to fulfil one or more functions. Typical functions might be for a dam to 'retain or safely pass a volume of water' or for a circuit breaker to 'provide electrical insulation on-demand'. The Owner of an asset is concerned, through-life, with the preservation of such functions. Some functions, like the examples given, can be said to be 'safety functions'.

It is important at the design stage to identify functions and consider the means by which they may be preserved and verified through-life. Designs should thus aid, accommodate and support simple and safe processes of testing, inspection and repair with the objectives of making it easy to restore and confirm functional performance

5.2.5. Specific principles for mechanical, electrical and control system equipment

Principle 6: Safety equipment should be designed as functional systems and include reliability requirements.

Only devices fulfilling a safety function are discussed in this bulletin. The safety functions are those that play a role in controlling the reservoir level or the transit flows through the dam. It is important to first define the functions that will be performed by these systems before turning to the equipment that will ensure the required function.

Functional systems meet the needs that must be specified by the Designer of the project. For example one should find in these requirements "standard" expectations about external loads (thrust of the water, operating temperature, corrosion resistance, etc.); but one must add requirements about reliability and time required for a

return to service. To set wisely reliability requirements implies having knowledge of the risks associated with the system malfunction. This means that the risk analysis made for the dam must include dysfunction scenarios of these functional systems to assess their consequences, and to set the required probability of no-dysfunction. This reliability requirement forms part of the broader concept of Safety Integrity Level (SIL).
Designing a functional unit in the field of dams is then not different from what is practiced in the industry. One can note the following important aspects:

- Designing a functional system in the field of dams often requires multidisciplinary skills: mechanical, electrical, electronic transmission, etc.
- The "classical" safe design principles (redundancy, diversity, etc.), as defined in 5.1.2 above, are particularly well adapted and shall be observed for these systems.
- Proven engineering practices shall be applied. Among them methods as FMEA or equivalent should be systematically used to assess the system.
- Proven technologies shall be adopted for the choice of equipment. Typical equipment addressed will be:
    - Backup power: transmission lines, backup generators
    - Gates actuator: electrical motor, gasoline motor acting directly on the hoisting equipment, handle system.
    - Water level gauges and telemetry
    - Gates and moving equipment position gauges
    - Control system
- The use of standard rules of quality assurance is mandatory for all entities: Manufacturer, Supplier and Installer. It is the best way to ensure and to demonstrate the quality of the pieces of equipment.
- Tests and checks during the construction and the commissioning phases should include intrinsic individual controls of each piece of equipment and, above all, global functional tests of the system as a whole.

5.3. Safety Assessment Principles

Safety assessment is the process by which the safety and performance levels of the conceived dam are evaluated. It implies the use of analytical, physical and numerical tools to calculate stresses, displacements, pressures, with the objective of verifying the overall expected performance of the dam as well as to refine and tightly define individual features of the design. Safety assessment includes systematic critical review of the ways in which the dam, structures, systems and components might fail, and identifies the consequences of such failures.

This assessment should be undertaken before construction and operation of a dam scheme begins. The results shall be documented in detail to allow independent auditing of the scope, depth and conclusions of the critical review. It will be subsequently updated in the light of significant new safety information.
The safety analysis report and its review by the regulatory authorities or independent Board of Experts constitute a principal basis for the approval of construction and operation, demonstrating that all safety questions have been adequately resolved or are amenable to resolution.

The safety as assessment process is repeated in whole or in part as needed later in the dam's lifetime if ongoing safety research and operating experience make this possible and advisable.

5.3.1. **General considerations of the required level of safety**

Historically, consideration of the required level of safety of a dam has been a matter for the Designer that became typically introduced at mid-stage of design when design parameters are being formalized.

ICOLD Bulletin 61 on Dam Design Criteria states that the overall objective is to create a *"structural form together with the foundation and environment which, most economically:*

1) *performs satisfactorily its function without appreciable deterioration during the conditions **expected normally** to occur in the life of the structure and,*
2) *will not fail catastrophically during the **most unlikely but possible** conditions which may be imposed."*

Thus, in classical dam design the primary consideration has been for the specification of the "ultimate structural limits of design" for extreme hydraulic and seismic loads, and for the specification of "structural serviceability parameters" under all anticipated operational conditions. These structural serviceability considerations typically involved stability requirements, deformation limits, seepage and hydraulic pressure limits and "internal stability" considerations associated with matters such as material stability (internal erosion, alkali-aggregates reactivity etc.).

From a scientific perspective, it has always been assumed that dam design is a reductionist endeavour, whereby the whole project is subdivided into physical parts, each part is analysed and designed separately, and the parts of the design are assembled into the whole. This reductionist approach of design has for the most part proved to be immensely successful over the years with respect to assurance of the structural safety of dams. However, precisely how successful it has been is limited by experience, as for their most part dams can never be "fully commissioned" for all as-designed conditions. In fact and apart from the most serious weaknesses in serviceability performance that typically manifest themselves within the first years of service it often takes many years to establish the adequacy of the structural serviceability of dams.

In recent years awareness for considering substantially more than the ultimate structural limits and the structural serviceability limits and including a vast array of operational and management considerations has emerged. These operational and management considerations go far beyond "real-time" operational matters and include considerations that are embedded in the Owner's objectives for the entire investment in the dam and the associated management objectives over the whole life cycle. Decisions made during early stages in the dam development process may significantly influence the nature and level of effort required to ensure the operational safety of the dam during the whole life-cycle. Early stage decisions can also significantly influence dam renewal or dam decommissioning opportunities. This is in contrast to the structural limit state and the structural serviceability state that are essentially structural design objectives independent of the development choices of the Owner.

5.3.2. Safety Classification and Standard

Principle 1: The functions of structures, systems and components shall be identified and classified according to their overall significance to safety.

The classification of a dam is usually based on legislation, most countries having defined in their regulations classification criteria. These criteria are mainly based on failure consequences or geometry or both.
The classification of a dam then involves requirements to meet specific safety criteria that are established in a country or jurisdiction. These criteria may be of a general nature in terms of legal duties or the criteria might specify the "Inflow Design Flood" (IDF) or the "Design Basis Earthquake" (DBE). Complete specification of the "safety standards" for dams is generally not done and in many cases general legal duties might apply. Under such circumstances provision for safety in the design could be in terms of:

- compliance with the prevailing laws and regulations, and
- conformance to generally accepted good practices

Where safe operational performance is depending on the integrity and/or reliability of structures, systems and components, then the design basis events shall be identified and the design shall be analysed and assessed to demonstrate that it can withstand these events and the margin by which this is accomplished in each case.
The level of analysis and assessment should be proportionate to the safety classification of each design element. The purpose of classifying the various elements of the design is to allow for some prioritization in the safety assessment with those elements most significant to safety receiving the greatest attention and scrutiny. Inevitably such classification is an iterative process as the design develops and matures.

Examples of dam classifications can be found in the document developed by CODS: "*Regulation of Dam Safety: An overview of current practice world wide*"

5.3.3. Performance assessment

Principle 2: The design basis shall be thoroughly established and recorded, such that all credible loading and performance demands on the design are identified, assessed, and quantified where appropriate and possible.

Verification of a dam project generally includes checking the structural behaviour of the works, and verification of hydraulic operation of the safety appurtenant works (spillway and bottom outlet).

5.3.3.1. Structural performance

Verifying the structural stability comprises the following steps:

- Evaluation of external loading cases (floods, earthquakes, climate conditions): recommendations on methods that can be used for these evaluations are described in ICOLD bulletins.
- Evaluation of material characteristics having a part in the dam stability. The term "material" means here foundations, soils or rock, as well as the materials used to build the dam, concrete, soil and rock extracted from quarries or borrow pits, etc.
- Performance evaluation: many analysis methods can be implemented from the simplest methods of the limit equilibrium types to more complex numerical models using refined material constitutive laws (nonlinearities, coupled water-soil-structure model, temperature effects, etc.) aiming to a more realistic simulation of the dam behaviour. A good practice is to start with simple methods and to refine the methods of analysis with criteria based on the safety classification of the dam and the results obtained from the first analysis.
- Comparison of analysis results with the performance criteria: these performance criteria should be decided a priori between the Owner and the Designer. Guidelines or technical rules from the Regulator (where available) should be also considered. These are generally the permissible limit values for safety factors, displacement, uplift, etc.

The load cases and performance demands constitute the 'design basis'' or "key capability requirements" which have been considered in the development of the design and agreed between the Designer and the Owner.

For the performance evaluation, two complementary methods, deterministic and probabilistic, are currently in use. These methods are used jointly in evaluating and improving the safety of the design.

In the deterministic method, design basis events are chosen to encompass a range of related possible initiating events that could challenge the safety of the dam. Analysis is used to show that the response of the dam and its safety structures to the design basis hypothesis satisfies predetermined specifications both for the performance of the dam itself and for meeting safety targets. It is a "standard-based" approach. The deterministic method uses accepted engineering analysis to predict the course of events and their consequences. It has been until twenty years ago almost the sole method of analysis and most ICOLD Bulletins (see Annex B) treating technical aspects are based on this method. The addition of a Potential Failure Modes Analysis (PFMA) to a standard based program allows the development of a linear chain of events that could lead to a failure. In many cases a PFMA does not address issues outside those already covered by the defined standards.

Probabilistic analysis extends standard-based methodologies by estimating the probability of a component failure and combining that information with the potential consequences in the event the component fails. This evaluation may take into account the effects of mitigation measures inside and outside the plant. Probabilistic analysis is used to estimate risk and especially to identify the importance of any possible weakness in design or operation or during potential accident sequences that contribute to risk. The probabilistic method can be used to help in the selection of events requiring a deterministic analysis and the other way around.

Risk-informed processes also change the metric by which the safety of a dam is measured. Rather than simply comparing the results of an analysis to a defined criterion, risk-informed processes attempt to evaluate the calculated risk against society's risk tolerance. Embedded within society's risk tolerance are the concepts that the risk is being actively managed and has been driven as low as reasonably practicable. However risk-informed approaches, as generally practiced in the dam safety community, are linear and do not consider systemic failure modes.

The AFS (Adjustable Safety Factor) is an example of approach which aims to address stability and strength issues in a full probabilistic way (Kreuzer H. and Léger P., 2013).

5.3.3.2. **Hydraulic performance**

The assessment of safety appurtenant works addresses verification of weirs and sluices discharge capacity as well as the flow conditions. Conventional methods used are those of the fluid mechanics, with tools that can be physical (laboratory models) or numerical. The phenomena to be studied are of widely varying complexity (from a free weir discharge capacity evaluation to two-phase flows with cavitation); the nature of the tools and methods must be adapted accordingly.

5.3.4. Dam as a system

Principle 3: A dam is a system, and dam safety assessment should therefore consider a systemic approach.

The usual practice of safety assessment is an analytic approach: one to check that the dam withstands the different maximum load cases (floods, earthquakes, etc.) independently. In fact a dam is not a single entity onto itself; it is a system of both natural and manmade parts, units and subsystems. A “part” can be thought to be a single piece such as a gate hoist motor. A “unit” is a functionally related group of parts such as the gate hoist mechanism including the motor, gear box, and hoist chain. A “subsystem” is a collection of units such as the spillway including the gates and its complete hoist and control system, the spillway chute and the stilling basin. The dam system would include all the subsystems that we normally associate with a dam but would also include the foundation, abutments, reservoir, and reservoir shore, the operating organization and may also include a powerhouse and all its associated subsystems.
Dams are certainly as complex as other industrial systems; therefore one must take care of possible interactions between the parts of the system. As an example, checking the spillway for the design flood is obviously essential, but does not consider the possible effects of unreliable equipment, energy supply failure, transmission error, human mistakes, etc. This systemic approach has also a time component: ability to restore, during a flood event, the function of out of order equipment is linked to the flood kinetics; ability to discharge a yearly flood several weeks after an earthquake that has affected spillway gates, etc.
On a larger scale, a dam might be a subsystem within a larger system that could be a watershed with projects owned by one or more entities or an entire regional electrical grid.
Generally speaking a systemic approach will make it possible to address “unusual combination of usual events” taking into account all the interdependent factors. Dam failures and incidents are seldom due to a single, easily identifiable cause. Failures are generally the result of multiple causes or actions that combine in unforeseen manner to create the necessary conditions for an uncontrolled release of water.
To effectively manage dam safety risk we must recognize that:

- dams are systems and not a collection of individual components; and
- how individual components and sub-systems interacting greatly affect the risk posed by a given dam.

Analytic approach leads to juxta-positioned discipline education while systemic approach needs multidisciplinary education. Analytical and systemic approaches are complementary and should not be opposite. Risk analysis methodology helps a lot to understand and develop systemic approach.

5.3.5. Risk Analysis

Principle 4: The potential safety risks arising from areas of complexity in the design and/or uncertainty in the design basis should be examined through a proportionate and appropriate use of fault analysis techniques.

Analysis of the design basis, whereby load cases and performance demands are identified and the design ability to meet them is systematically examined, provides a sound foundation for safety assessment.

Design complexity, together with a need (stemming from emergency planning requirements) to understand the design performance a domain beyond the design basis, indicates that the analysis of the design basis on its own is not sufficient.

Risk analysis methodologies are tools which make it possible to cope with this complexity and interactions between parts of the system. Risk analysis is a structured process aimed at estimating both the probability of failure of the dam or dam components and the extents of the consequence of these failures. The risk analysis shall enable to evaluate the performance of the dam under the full range of physical conditions, applied loads and organization response to events. By physical conditions one may understand the condition of the dam itself and its safety equipment (gates, power supply, data transmission…); that includes possible partial or total dysfunctions of these structures and equipment. Applied loads are not only the extreme loads used in the standard based approach but must take into account possible combinations of loads. And finally organizational response of entities involved in design, construction and operation of the plant are an important parameter of the dam safety and should be included in the risk analysis.

ICOLD bulletin 130 provides information about risk analysis methodologies and tools: fault analysis techniques, such as Failure Modes and Effects Analysis (FMEA), Fault-Tree Analysis and Event-Tree Analysis can all be used to explore areas of design complexity and post-fault design performance as the design matures.

5.3.6. Safety assessment for serviceability (Delivery of Design Capability and Performance Capacity)

Principle 5: Potential changes with time of dam subsystem efficiency, evolution of external loadings, and reliability of mechanical, electric and electronic equipment are addressed during the safety assessment process.

Designs must be able to meet the performance levels assumed in the design basis throughout their lives. Operational wear and tear and natural degradation mechanisms all conspire to reduce capability and capacity over time. It is therefore important to fully identify how the design meets each design basis event and performance demand and any limitations and assumptions made during the design development, so that the appropriate actions necessary to maintain the design capability through-life are identified and acted upon.

Indeed, beyond structural resistance assessment, serviceability of the dam and its equipment implies that Designers pay attention to following issues:

- With time efficiency of a drainage and/or a grout curtain can change; hydraulic characteristics of the foundation and/or of an embankment can become modified; obviously these changes are detected by surveillance and maintenance works can then mitigate these changes to a certain extent. Safety assessment should therefore consider these issues taking into account the fact that repairs or maintenance works are not immediate and that the dam must be safe until these repairs or maintenance works are done. Interim measures to maintain safety until the permanent fix is realized should be also included in the safety evaluation.
- Potential changes in performance demand (hydrological, seismic) are likely to occur during the lifetime of the dam. As a result, the spillway discharge capacity, or the structural resistance of the dam may become insufficient. The project can then either incorporate features making it possible to modify the dam in the future to cope with these potential changes, or incorporate at the design stage a provision for these potential changes.
- The reliability of hydro-mechanical equipment and control systems, including human and organizational factors, can also change over time.

Serviceability issues can in turn interfere with resistance assessment and the process between these two aspects of dam safety are therefore to be addressed in an iterative way.

5.3.7. Considering human aspects during operation at the design stage

Principle 6: A systematic approach should be taken to identifying, examining and optimizing at the design stage the expected range of human aspects during operation such that the human influence on risks is minimized.

The range of interactions of people (both operators and the public) with the design over the dam life cycle should be considered as part of the safety assessment. A wide range of interactions will always be possible. They can be assessed thru a variety of human factor assessment techniques to be used by specialists. The level of assessment should be proportionate to the safety classification of the design.
At the concept stage of the design, it is sufficient to give preliminary consideration to aspects such as:

- Which are the interactions required for the design to work (e.g. operator and maintenance personnel actions)? What is the potential for such pre-planned actions to go wrong and how could these hazards be reduced?
- What are the potential risks for incorrect human actions during equipment manoeuvres? These risks should be assessed taking into account several criteria:
    - complexity of the manoeuvres to be performed;
    - intervention of an operator alone or of several operators;
    - ability for the operator(s) to have a direct view on the result of his manoeuvres.
- Which responses are required from the operators to the expected range of external events (e.g. earthquakes, floods) and internal events (e.g. structural, system and component failures)? Can the dependence on operators be reduced in such circumstances? If not, what can be done to protect operators from possible harm as they are performing their duties?
- How might members of the public interact with the design? What might be the implications for safety and security?

Human factors include also ergonomics which is the practice of designing products, systems, or processes to take proper account of the interaction between them and the people which are using them. In essence, the scope is to design equipment and devices that fit the human body and its cognitive abilities. Some examples are the proper labelling of devices, sensors, etc. or taking into account the amount of information an operator can analyse to ensure appropriate decision making, as it is often the case in control rooms where numerous screens provide a lot of data and warning signals.

Chapter 6 - Conclusion

- Dam safety management goes along with the development of a project from the first studies to commissioning of the scheme. It involves a large number of actors ranging from the Owner or Investor to the Designer, the Contractor and the Supplier, etc. usually with a pronounced influence of the regulatory side (state licensing and/or regulatory agency).
- As any dam or dam scheme can be considered as a prototype it can hardly be handled as an industrial product. Dam design cannot be performed according to standards only but it requires a large amount of experience and shall rather follow the state of the art, the state of the practice, and for some features new practices.
- Dam safety concerns essentially structural and operational features. The uncertainty prevailing in design aspects at the onset of the studies shall be progressively reduced by performing investigation work and related studies. This encompasses external loads such as floods or earthquakes as well as geological conditions and material properties.
- Dam safety concerns not only the dam scheme, but also the surroundings, and more specifically the downstream area. Land use restrictions might have to be enforced there in case of significant residual flooding risk.
- Organizational or more generally non-technical aspects leading to a flaw in safety issues can be as important as well. Simple principles of management such as continuity, traceability, independent checking shall allow to avoid pitfalls in the design of a dam, as well as in the whole development of the project.
- The construction phase gives the ultimate possibility of assessing the real site conditions and some design features might have to be modified then under time and cost pressure. Also safety of the structures will ultimately depend upon the quality of the work performed. It is therefore essential to have at this stage efficient communication and decision making provisions between the different actors (Owner, Site Supervisor, Designer and Contractor). The use of the “observational method” is of particular importance in the control of the effects of changes on the design.
- In more general terms one can draw an overarching dam safety management system prevailing for all parties involved. It shall follow the general form described in ICOLD Bulletin 154. An important step consists in developing safety objectives according to the purpose or purposes of the dam scheme and defining the corresponding (key) capability requirements. During the entire process responsibility of the Owner prevails as he has to make sure that all parties involved commit themselves to implement such a system within their own domain of activities and their interaction with other parties.
- Design shall be performed according to a set of engineering principles some of which can be easily derived from another technical domain (e.g. nuclear industry). They are focusing on the fundamental principle of "defence in depth" and call for the use of proven engineering practices as well as of safe materials and methods. Safety assessment involves both structural and hydraulic aspects. But it concerns also serviceability requirements. The importance of the structure within the scheme and the possible effects of its malfunctioning shall be duly considered when assessing the level of safety to be applied.
- In the modern context and recognizing lessons learned in recent decades, the design philosophy should make provision for the multiple influences of ageing effects, reasonably foreseeable future changes in performance expectations and societal expectations, and the effects of advances in science through adoption of an adaptive asset management philosophy.

Safety will follow from a well planned and executed project

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Glossary

As Built Drawings	A set of construction drawings with the indication of any modification made during the construction. As built drawings are especially useful when rehabilitation works or adjunctions have to be made.
Board of Consultants	A panel of highly experienced engineers and specialists in charge of following the development of the project and presenting recommendations to the Owner
Capability requirement	The function a dam scheme should have to guarantee its overall functional performance and safety.
Capacity building	The professional education of new dam operators
Capacity development	The improvement of the professional skills of dam operators
Contractor	An entity in charge of the construction of the dam scheme. Can be bound to the Owner by different forms of contract (unit prices, lump sum, costs plus, EPC, etc.). In case of a General Contractor all construction and supply activities will be concentrated under one entity.
Dam incident	Dam incident refers both to - *Failures* which are catastrophic, i.e. types of incidents typically characterized by the sudden and uncontrolled release of impounded water. - *Accidents* which are lesser catastrophic, e.g. types of incidents which adversely affect the primary function of impounding water.
Dam project	The sum of all activities in the financing, licensing, engineering, construction works, etc. leading to the realization of a dam scheme
Dam scheme	A dam, its reservoir and all facilities (appurtenant structures, headrace, powerhouse, etc.) contributing to the intended purpose(s) of the dam (energy production, water supply, irrigation, flood protection, etc.)
Designer	The person or entity in charge of developing the concept of the scheme and, later on, performing all engineering works (hydraulic and structural analyses, drawings, etc.) required for the realization of the scheme
Developer / Investor	The person or entity funding the development of a dam project. Often identical with the Owner
EAP	**Emergency Action Plan**, sometimes referred to as an Emergency Response Plan, is a set of arrangements developed by the Owner with the purpose of defining the intervention actions that the Owner will implement to respond to incidents and to prevent failures
EPP	**Emergency Preparedness Plan** is an overarching document dealing with the arrangements made by the downstream civil protection authorities to mitigate the consequences of a dam failure and defining the arrangements at the interface between the Owner's responsibilities and those of the civil protection authorities. The EPP may be initiated by the authorities, either on the advice of the Owner or based on their own assessment of the situation.
(Potential) Failure Modes and Effects Analysis (FMEA) and Criticality Analysis (FMECA)	A systems analysis and design technique involving a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service.. FMEA can be extended to include consideration of the criticality of component functionality to system functionality in terms of the FMECA that takes account of the importance of these effects
Hazard	A potential danger in the operation of dams that has to be considered in the design load cases. Main natural hazards encompass floods and earthquakes
Key capability requirement	A main or pivotal function a dam scheme should have to guarantee its safety and deliver the essential features required to ensure that the scheme is of societal benefit.
Licensing Agency	A state agency in charge of granting a construction and/or an operation permit for a new dam scheme. Provides also renewal of time limited operation permits.
OMS manual	A manual containing all necessary information for the operation, maintenance and surveillance of a dam scheme. Is usually split into distinct volumes, especially in case of scheme with a powerhouse.
On Site Operator	The person or group of persons in charge of operating the dam scheme. The experience of on site operators can be very valuable when designing a new dam scheme or planning rehabilitation works at an existing scheme

Owner	The proprietor of a dam scheme from the initiation of the project to the operation of the scheme. The Owner can be also the Operator or he can delegate this function to a third party. The main liability for the safety of a dam scheme rests with the Owner.
Regulatory Agency	A state agency in charge of establishing and enforcing design and operational standards for dams
Residual risk	The risk remaining after having taken all possible measures to mitigate the occurrence of the related hazard(s)
Risk	The product of the probability of occurrence of an hazard multiplied by the cost of the consequences
Safety objectives	Type (structural, operational, reactive against natural hazards) and level of single safety targets to be achieved for a dam scheme.
Site Supervisor	A person or a group of persons in charge of monitoring the construction activities. Site supervision is usually performed by personnel of the Owner or a mixed structure Owner-Designer or can be delegated by the Owner to a third party.
Subcontractor	An entity performing a limited or specialized type of work for a Contractor. Towards the Owner the responsibility rests with the Contractor, but he can have recourse on the Subcontractor in case of constructional error
Supplier	Provider of good supplies in the hydro-mechanical, electrical or control system field. Can have a direct contract with the Owner or be part of larger joint venture under the lead of the Contractor and including other services, such as the design activities.
Surveillance of dam	All supervision activities aiming at insuring the structural and operational safety of a dam. It consists essentially of monitoring of the dam instrumentation, visual observation and regular tests of safety related hydro mechanical components (spillway gates, bottom outlet,..). Proper interpretation of the collected data is an important part of dam surveillance.

Appendix A

Synthesis of Committee Members replies to the Questionnaire issued before drafting the Bulletin

- **Arrangements and practice in your country**

1. How are the respective liabilities of dam Owner, designer and contractor defined in your country?

> - In all countries the safety of the dam is under the responsibility of the Owner which is liable towards the public for all accidents and damages that could occur due to the existence and the operation of the dam.
> - In most cases the responsibility is assigned to the Owner by a general national or federal law on the liability for any industrial undertaking. It is often specified in an Act on Water Storage or Water Use as well as in specific decrees. Also contracts binding contractors, suppliers and consultants include usually clauses that detail the respective liabilities.
> - At the development stage of a project the Owner has to submit the design to the Authority. Approval by the Authority does not mean that it relieves the Owner from his responsibility. This applies also to major repairs or rehabilitation works of dams.
> - The designer has to follow standards, guidelines and professional ethics rules. In case of a design mistake, that has not been previously detected, the designer can be held responsible but within a financial limit set up at the total amount of his fees. Services of the designer are usually covered by a professional liability insurance.
> - Contractors are responsible for the quality of their works. In case of defaults they have to come up with replacing of the defective part of the works at their own costs. They are usually not liable for societal damages resulting from construction errors or, in extreme cases, from a dam failure (see NL).

2. For the phases preceding operation do you have in your country a "dam safety philosophy" or (at a more technical level) principles or standards for dam safety that apply in the design process?
Please indicate here general principles applying, as well as more precise requirements, if any (such as necessity of having a bottom outlet or a well-developed monitoring network, analysis of rates of progression of failure mechanisms, incident response and emergency plans, etc.)
    a. Does "systems engineering" have a role in assuring safe performance within the design process (up to and including the physical limits of the design)? Or is safety incorporated through appropriate factors of safety at the limits of the design on a dam element by dam element basis?
    b. Failure of a dam is rarely due to a single cause. Are combinations of load cases that are individually less severe but more frequent than the limits of design taken into consideration?

> - Almost all countries have a "dam safety philosophy", even if the term is not clearly expressed in their legislation. It is based usually on following aspects:
>   - design according to standards and guidelines (with extreme loads specified by regulations)
>   - safe operating rules, surveillance and monitoring rules
>   - emergency response and emergency preparedness plans, incl. use of facility for lowering the reservoir level
> - Some countries already rely on risk approach methodology (AU, CA, FR, NL, SE, US) to complement dam safety (see Question # 6)
>
>   a. The safety approach at the design stage remains mostly on a dam element by dam element basis with appropriate factors of safety for limit load cases
>
>   b. Combinations of load cases that are individually less severe but more frequent than the limits of design are recognized as being relevant but are seldom considered (US). Techniques such Event Tree Analyses (ETA) for instance could be useful in the future to track down such combinations.

3. Does the safety philosophy <u>in your country</u> mainly, partly or not at all rely on designer skills and state of the art? How important are for you non-standardized design aspects?

   a. Is there a process of "dam safety analysis" that the designer can use to demonstrate that the dam can be operated and maintained in a safe state over the whole life-cycle of the dam?

- In almost all replies it is clearly mentioned that designer skills are of utmost importance, especially for not quantifiable aspects of design (quality of a dam layout, interpretation of investigation results). However it is necessary to rely on standardized and quantified project framework aspects, such as type of operating conditions, loading cases, material strength, safety criteria (FR).
- In many countries one relies essentially on the quality and experience of designers and specialists in charge of reviewing and/or approving dam design (FI, NO, SI, ES, LK, CL, TR).
- Non-standardized design aspects are often difficult to be accepted by the Authority in charge of formally approving the project. In some countries it is practically impossible to propose original non-standard solutions (IT) or consultants prefer to strictly follow official guidelines and have an easier outcome (NO).
   a. A true "dam safety analysis" over the whole life cycle of a dam is not usual. Defensive dam design as advocated in one case (AU) can be considered as an effective approach as it obliges the designer to examine a series of situations where the dam has to respond to external loads and internal conditions with a given safety margin.

4. Which are the provisions legally required <u>in your country</u> for lowering reservoir level and early warning of the downstream population?

- There is only a limited number of countries where the requirement for lowering the reservoir level is explicitly mentioned in the legislation, either in a law on natural hazards or in an Act on Water Storage or Water Use.
- In several countries this requirement derives from a more general statement on the liability of Owners towards the public in case of inappropriate handling of a risk.
- Provisions for early warning of the downstream population is limited in some countries to Class 1 dams. It can be either by systems directly triggered by the Owner or by an alarm sent first to the Authority that will be then in charge of warning the population and implementing the evacuation measures.
- There is only a limited number of countries where the requirement for lowering the reservoir level is explicitly mentioned in the legislation, either in a law on natural hazards or in an Act on Water Storage or Water Use. In some cases (see CL) this requirement applies only to flood control dams.
- In several countries this requirement derives from a more general statement on the liability of Owners towards the public in case of inappropriate handling of a risk.
- Provisions for early warning of the downstream population are limited in some countries to Class 1 dams. It can be either by systems directly triggered by the Owner or by an alarm sent first to the Authority that will be then in charge of warning the population and implementing the evacuation measures.

5. Are any requirements <u>in your country</u> for dam safety during construction and/or modification works?

- Practice dictates that the risk posed by a dam during construction shall not exceed existing risk levels of the dam during operation (AU, FI), but specific requirements for dam safety during construction are not explicitly contained in the legislation of most countries.
- Main hazard during the construction phase is the river diversion. Selection of the diversion flood is usually made according to local past experience and some state of the art considerations. In most countries it has to be approved by the Authority as part of the construction permit.
- Major repairs or modification works can be assimilated to construction. In such cases the availability of a sufficient discharge capacity through a bottom outlet or spillway openings or both is determining.

6 Are risk analyses used <u>in your country</u>? If yes, are there some specific requirements or standards? What is your feedback?

Whatever your response, in which domain do you think Risk Analysis could better help you at the design stage?

- Risk analysis techniques are used in an increasing number of countries for dam safety evaluation (AU, CA, FR, NL, CLL, SE, US), but usually in the framework of safety assessment of existing dams. The main goal of risk assessment is the description of the dam failure modes, the evaluation of their occurrence and the related consequences (FR). Risk assessment can be driven by internal requirements of the Owners with focus on societal, environmental and financial aspects (CL) and/or by governmental requirements where a corresponding legislation has been established.
- Feedback from the experience gained varies with the length of the period over which risk assessment has been used. For one country that have been instrumental in promoting quantitative risk analysis (Australia) this technique has proved to be very useful and instrumental in prioritization of investment across dam portfolio, extent of upgrades, internal communication of upgrade needs and cross comparison between Owners.
- As pointed out by the French Committee risk assessment in the design phase allows to identify the causes of selected failures scenarios taking into account all possible aspects, such as hydrological and seismic hazards, sensitivity of structures and components, component dysfunctions (i.e. not opening or accidentally closing of gates and valves) and human factors. Combination of all aspects contributing to an accident scenario is highly complementary to the classical design approach. It allows for the development of a criticality matrix containing all selected scenarios which can be used for categorization and comparison (FR).
- Unlike the Australian concept that uses a quantitative approach to risk analysis the French concept applies a qualitative judgment and the Authority does not approve the risk analysis but produces only a judgment.
- Risk assessment would be most useful to be applied already at conceptual and pre-feasibility stages when the project is being defined (CL). The risk matrix and risk log ideally would flow and grow from stage to stage et be updated as the design advances to the next stage.

7. What in your country is the importance of environmental constraints on design and construction of dams?

- In all countries environmental constraints appear to be important and have to be considered at the design and the construction stage. Environmental Impact Assessment (EIA) reports are nowadays standard requirements almost everywhere not only for major dams, but also for smaller structures. Constraints concern basically the reservoir area, the dam site, the reservoir (and powerhouse) operation modes, as well as the dam downstream area.
- Constraints need to be evaluated and analysed consequently with good dam safety practices: modifying the operation mode of a reservoir or incorporating a fish ladder, as examples, need to be assessed to make sure that they do not affect the dam nor the safe operation of the scheme (US).

8. In your country are the dam designers usually involved in the preparation of an operation/ maintenance manual?

- Practice differs from country to country. In some countries O&M are not compulsory (FI, SI) or replaced by a maintenance program (IT), but in all countries a monitoring program is required, that is usually set up by the designer.
- Designers are mostly involved in the preparation of O&M manuals, whereas the technical specifications regarding operation and maintenance of electrical and hydro-mechanical equipment are prepared by the suppliers.
- It is important to have the "risk thinking" present in the O&M manuals and the dam safety engineer, at least, participating in the preparation of the manuals (US)

9. In your country, is the life cycle of a dam from concept to decommissioning considered at the design stage?

- Decommissioning of hydro dams is usually not considered at the design stage. Dams are thought in most cases to "last forever" or, at least, for the duration of the concession of the scheme (50 to 80 years).
- Only in case of tailing dams the decommissioning process has to be established at the design stage and forms part of the mining concession, that has usually a much shorter duration than concessions for hydro dams.

- **Arrangements and practice in your company**

10. Do you conduct peer review of design for your dam projects?
    a. Is the peer review a completely independent check of all design assumptions and calculations, or
    b. Is peer review based on an independent opinion as to the adequacy of the design based on comparison with design standards?

- Practice differs from country to country.
- New designs are usually checked by an internal committee of experienced engineers within the consulting firm and then submitted to the regulatory authority for (external) approval. The authority usually gather expert(s) to examine the project and check its conformity to standards and guidelines and appreciate the adequacy of non-standardized solutions, if necessary (DE, NL, CH)
- In France the review is performed by a national technical committee representing the Authority and whose recommendations are mandatory.
- In Australia and the USA the Owner has the duty to charge a board of (officially agreed) consultants to perform the review. This applies also to major rehabilitation of dams.
- True peer reviews (according to a), where all design assumptions and calculations are checked, are not common in most countries. They are in any case not compulsory and left over to the appreciation of the Owner and/or of the authority.
- Safety reviews of dams are foreseen in most countries at regular time interval (5 to 10 years usually). They encompass not only analysis of the monitoring data and of the overall condition of the dam, but also review of the hydrological and seismic data (need to update?).

11. Are arrangements for transferring design principles (design records, technology transfer and training, development of permanent institutional knowledge) incorporated into the organization of your company?

- Owners/operators and consulting firms usually have an own system of keeping standards, technical documentation, design and performance records as well as as-built drawings These systems are more or less developed from company to company, but with the increasing importance and versatility of the information technology they can be easily consulted and referenced to.
- Updating of protocols is not always done on a consistent way (CL) and after switching to operation different data bases might develop at the Owner head office and at the operating office.
- In some countries (FR, NO) there is a legal obligation for Owners to keep well documented records regarding maintenance and monitoring procedures and data from the construction phase. The documentation shall be supported by the operators and the designers.
- It is recognized that workshops and seminars contribute greatly to transfer of knowledge, but they do not replace "on the job" training activities.

12. How do you take into account the influence of “organizational, management and procedural” factors over the life-cycle of the dam in dam design?

- Although these factors become increasingly important in large organizations owning and/or operating dams several replies did not correctly address the question

- Non-technical factors regarding organization, management and procedural aspects are usually not taken into account at the design stage
- In several countries Owners have to develop for the operation phase their own safety management system (SMS) that defines the organization, the role and responsibility of each actor, etc. (FR)
- In planning the operation phase some principles, such as good ergonomics of control rooms, computer assistance for flood routing, presence of two operators for spillway operations, installation of intrinsically safe systems when the response time of the operator is incompatible with the kinetics of feared events, etc. will allow to reduce or eliminate the impact of deficient human behaviour in the operation of a dam (FR).
- In complex system such as the Dutch water defence structures full machine interference did not prove to be satisfactory, the main concern being the closing operation of the structure. Thus human interference has been introduced as correcting influence of the main control mechanism. Regular training of the operational staff is an important issue, which is accounted for in the fault tree analysis (NL)

13. Are physical uncertainties taken into account in the design? If yes, how?

- Structural design: physical uncertainties can intrinsically be considered by adopting higher safety factors or lower strength values. Where safety factors are prescribed by the law or referenced by guidelines there is a trend towards performance of a comprehensive and detailed investigation in order to minimize the uncertainty affecting the material and foundation parameters. The analysis is then conducted to reach the required safety factor (JP).
- Where there are little or no investigation results, parametric studies can help weighing the influence of varying parameters on the safety factors. The associated risk has to be evaluated.
- Another procedure consists in using parametric studies for the material characteristics coupled with a semi-probabilistic approach for stability analyses (FR)
- A different approach can consist in adopting a priori a "defensive" design or a design with some redundancies, such as prescribing wider or multiple filters in an embankment dam (CL)
- Hazards:

  a) The hydrological parameters are determined on a probabilistic way. The return periods for design and maximum floods are usually set up in national guidelines. The higher are the consequences of a dam failure the longer shall be the selected return period. Diversion floods are often determined on a case by case basis as their size depends upon the duration of the river diversion. In some countries they are defined a priori by the Authority.

  b) Seismicity: the international standard calls for the use of deterministic and probabilistic methods in almost all countries.

14. How do you take into account or try to minimize the influence of human factors in dam design?

- Influence of human factors in design can be avoided or at least minimize by having rigorous review processes. This applies also to dam surveillance and monitoring programs. Working in design teams with regular meetings, and participation of the technical review panel and dam safety regulator in the more relevant meetings will also contribute to reduce the effects of human errors (AU).
- Detailed description of the tasks to be achieved by the consultants in charge of design and requirement for them to present and explain their designs to the Owner and the authority are also an efficient way of reducing the influence of human factors (DE).
- Redundancy in monitoring equipment allows to detect early enough errors of reading and thus is also a way of limiting the influence of human factors (IT).

15. How is functional performance taken into account compared to structural performance?

- Almost all repliers believe that both aspects are important and shall be considered at the design stage.
- Nevertheless whereas structural performance relies on a standard based design, there is nothing similar for the functional performance (FR). It is therefore important to have the operational staff invited at the early stage of project development to bring in their input/needs in the design (AU).
- Functional performance is usually considered at the detail design stage, exceptionally at earlier stages. The attention of the designer goes rather to structural performance as this aspect is directly linked to structural safety (CH).
- Functional performance of complex systems can be evaluated by fault tree analysis (FTA) and integrated structural performance (NL).
- Functional performance, if not appropriately considered, can affect structural performance. This is, for instance the case, when a proposed reservoir operation is changed for various reasons including environmental reasons. This change might affect the functional performance and in turn have also a detrimental effect on the structural performance of the dam (US).

k)

Abbreviations: AU = Australia
CA = Canada
CH = Switzerland
CL = Chile
DE = Germany
ES = Spain
FI = Finland
FR = France
IT = Italy
JP = Japan
LK = Sri Lanka
NL = Netherlands
NO = Norway
SE = Sweden
SI = Slovenia
TR = Turkey
US = United States of America

Appendix B

ICOLD Bulletins dealing with dam safety aspects

Subject	Bulletin N°	Title	S	F	O
a) on risk and safety	B 29	Risks to third parties from large dams	X	X	X
	B 59	Dam safety - Guidelines	X		X
	B 130	Risk assessment in dam safety management		X	X
	B 154	Dam safety management - Operational phase of dam life cycle		X	X
	B 156	Integrated flood risk management		X	X
b) on design and analysis	B 53	Static analysis of embankment dams	X		
	B 52	Earthquake analysis for dams	X		
	B 61	Dam design criteria - Philosophy of choice	X	X	
	B 122	Computational procedures for dam engineering	X		
c) on river diversion	B 48a	River control during dam construction		X	
d) on hydraulic structures	B 49a	Operation of hydraulic structures of dams		X	X
	B 142	Report on safe passage of extreme floods		X	X
e) on dam break analysis	B 111	Dam break flood analysis - Review and recommendations			X
f) on quality control	B 47	Quality control of concrete	X		
	B 56	Quality control for fill dams	X		
	B 136	The specification and quality control of concrete dams	X		
g) on small dams	B 109	Dams less than 30m high - cost savings and safety improvements	X	X	
	B 157	Small dams - Design, surveillance and rehabilitation	X	X	
h) on contracting	B 85	Owners, consultants and contractors		X	

S = structural safety F = functional safety O = operational safety