Dam safety

Handbook
Risk assessment and risk management for dams

Svartevatn Dam (Photo: Sira Kvina)

Statkraft

2022

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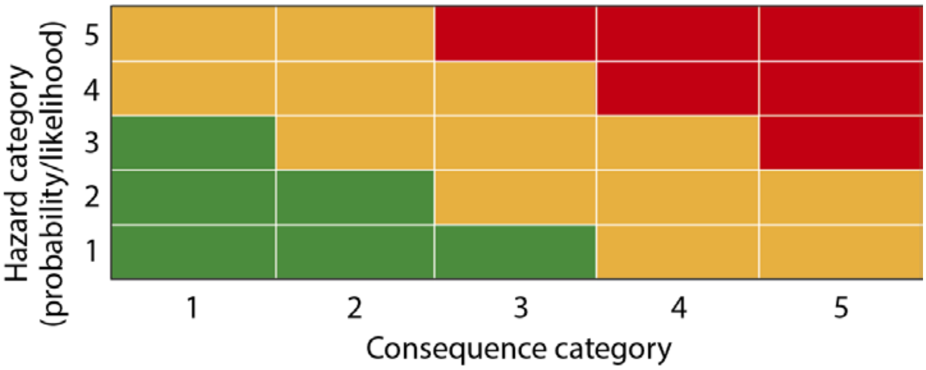
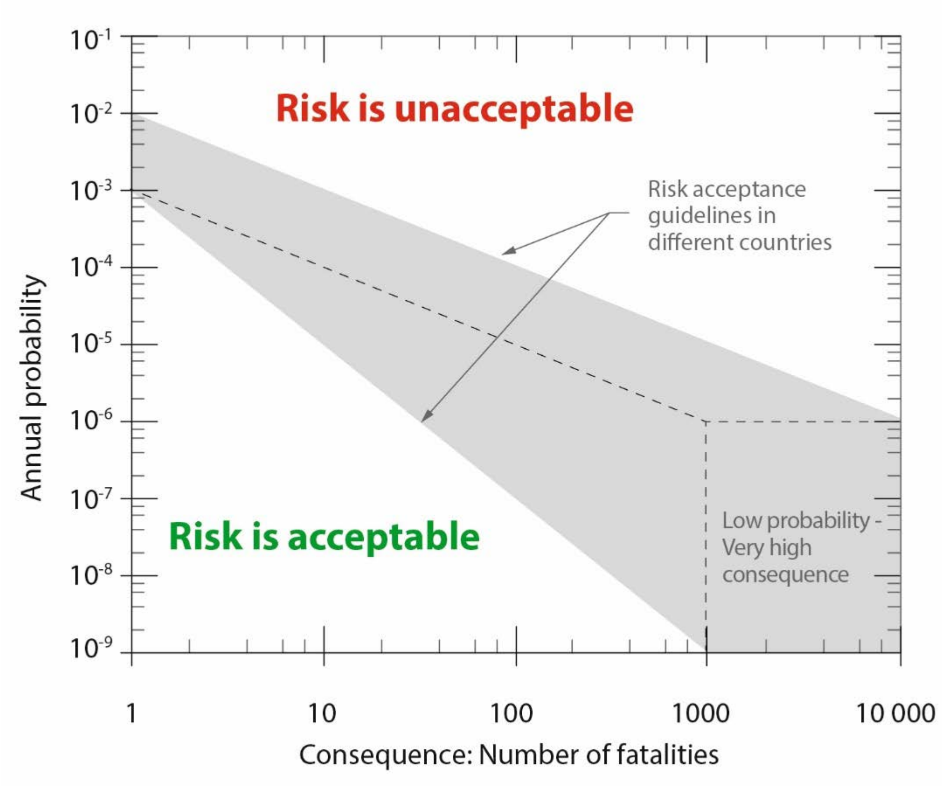
Qualitative risk matrix



Quantitative risk diagram



PREFACE

This handbook provides practical guidance for carrying out risk analyses of a dam (or series of dams). The target groups for this handbook are Dam Safety officers (DS) and their managers in the Statkraft organisation. Some of the information is also relevant for the local Dam Safety Team on site. In addition, the Statkraft processes “Dam safety preparedness planning” and “Emergency Response planning” should benefit from the risk concepts, approaches and methods presented.

The objective of the handbook is to assist personnel in Statkraft to carry out risk analyses and to evaluate the risk in a systematic manner. The handbook is a supplement to existing rules, standards and guidelines.

Risk assessment of dams is not new. Risk analyses of dams has been carried out since the early 1990s. The methods and perception of the usefulness of the approach have, however, evolved over the years. The handbook is based on the 2021 international practice within risk assessment and risk management of dams.

The handbook explains risk concepts and describes risk analyses for both embankment dams and concrete dams, as well as risk acceptance criteria from around the world. Several examples illustrate the different analysis methods available today.

This handbook is prepared exclusively for Statkraft Energy AS. A first handbook was prepared in Norwegian, primarily for Norwegian dams, under the Project "*Damsikkerhet i et helhetlig perspektiv*" for Energi Norge[1], under the leadership of 30 energy companies in Norway. The present English version is adapted for international users and brings in additional material from international practice. It leaves out aspects that were strictly related to Norwegian practice.

The handbook was prepared by NGI. The handbook can also be found as an "NGI report" (no distribution), with documentation of NGI's internal control in the NGI project files.

Oslo, Norway
2022-03-31

[1] "Dam safety from a holistic perspective" for Energy Norway, a non-profit organization representing 30 energy production, distribution and trading companies in Norway.

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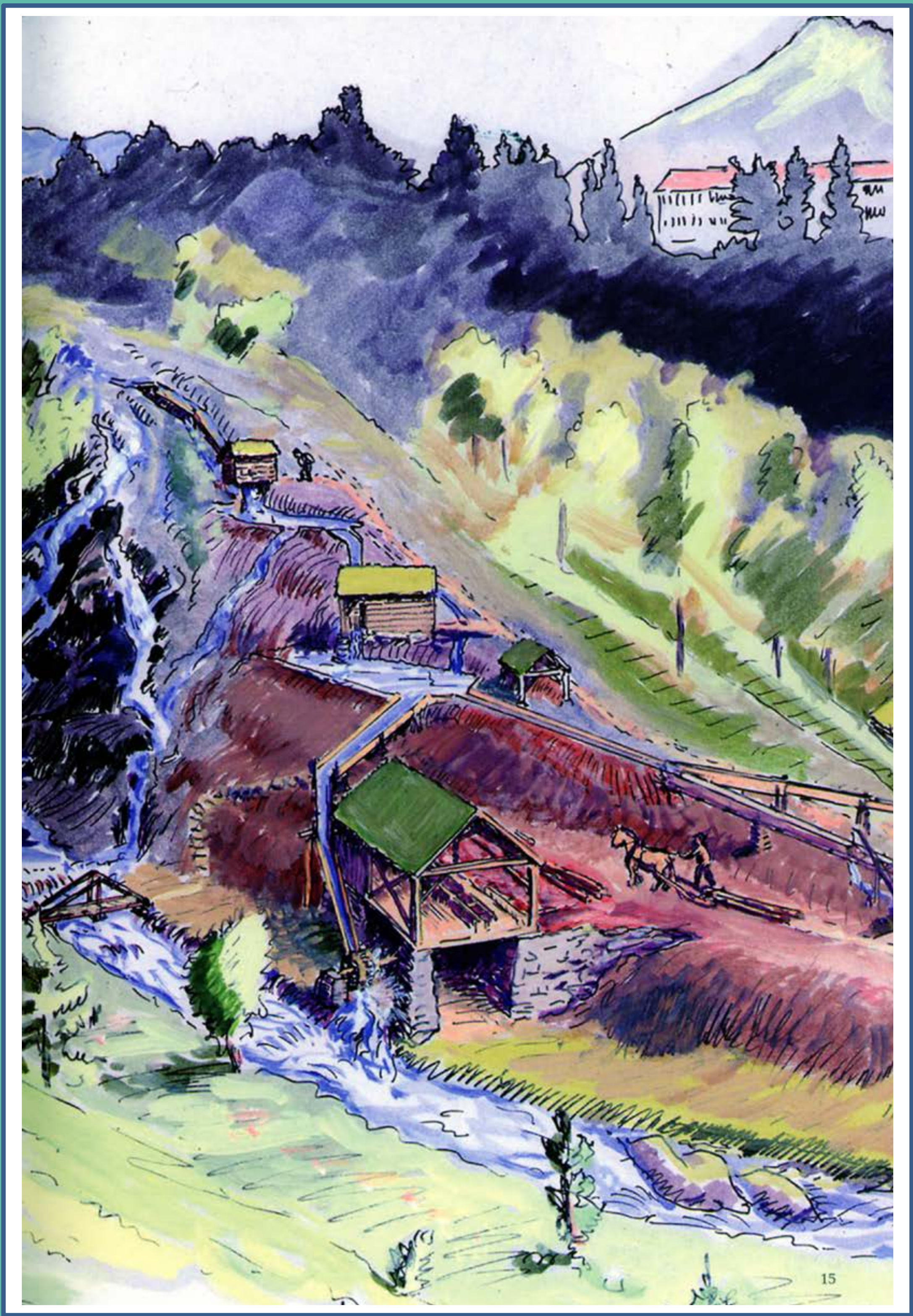
Risk assessment



Source: NVE brochure

Objective of handbook

This handbook on risk assessment for dams provides guidance on risk assessment and management and its implementation in practice.

The handbook describes the risk assessment methods in use today (2021) to assess dam safety and how the results of the assessment can serve as a tool for making risk-informed decisions. The risk assessment aims to help, for example, decide on the need for dam rehabilitation or other safety measures. The handbook provides examples of both qualitative and quantitative analyses, including examples of failures modes that can result in an unsatisfactory behaviour of embankment and concrete dams.

The handbook describes the construction of risk diagrams and how they can be used to compare either different dams or different rehabilitation options. Risk acceptance criteria in different countries are also presented. The risk framework and analysis methods in this handbook deal with dam safety only. It does not deal with aspects such as information safety or facility security.

The handbook has the following target groups: Dam Safety officers (DS) and their managers in the Statkraft organisation. Some of the information will be relevant for the local Dam Safety Team on site as well. In addition, the Statkraft processes "Dam safety preparedness planning" and "Emergency Response planning" will benefit from the approaches and methods presented.

Structure of handbook

The handbook has four main sections:

Risk assessment, including:
- Risk assessment
- Standard-based requirements and risk-based assessments
- When should one do a risk assessment of a dam?
- Experience with recent risk assessments of dams
- Advantages and drawbacks of the risk-based approach for dams

Risk assessment and risk management approach for dams

Three examples of risk assessments for dams (the annexes contain additional examples)

Risk communication and preparedness

Eleven annexes, organised in three parts, present more detailed information:
- Part I Tools for risk assessment
- Part II Additional information, useful for risk assessment
- Part III Reference material.

In the handbook, important text is outlined in coloured boxes:

Red text:
Important safety aspects

Blue text
Complementary information

Risk assessment

Risk assessment

A risk assessment estimates the risk associated with a facility, for example, a dam. As part of the assessment, the uncertainties are evaluated, as well as how these uncertainties influence the dam functionality and safety. The objective of a risk assessment for a dam is to demonstrate that the risk is acceptable and/or comparable to the risk level for other dams or other constructions, or to compare, for example, the effect of different rehabilitation measures.

A risk analysis will provide a qualitative or quantitative[1] estimate of the hazard (likelihood or annual probability of an undesirable event occurring) and the consequence(s) of the undesirable event. Risk is often expressed with an annual reliability index or an annual failure probability[2].

The conventional approach to estimate the safety of a dam is to use a 'deterministic' analysis, for example, where one calculates a safety factor. In this handbook the terms 'deterministic' analysis and 'probabilistic' analysis are used:

- A deterministic analysis aims at demonstrating that a facility can sustain an identified load within a 'design basis'. The deterministic analysis evaluates a 'nominal' performance. No randomness is involved in the development of future states of the facility. The approach does not consider the full range of possible outcomes and does not quantify the likelihood of each of these outcomes. Deterministic scenarios may actually underestimate the potential of a failure.
- A probabilistic analysis aims at providing an estimate of the risk associated with a facility, and an estimate of the uncertainties involved. While a deterministic analysis considers the impact of a single scenario with a single set of input data, a probabilistic analysis attempts to include all possible scenarios, their likelihood and impact. A probabilistic analysis is comparable to large series of sensitivity analyses (many thousands, even millions), and includes the randomness of the parameters in the analysis. Probabilistic risk assessments help understand and account for the uncertainties. Discussing the uncertainties will bring on a debate that always leads to added insight and more robust decisions.

The handbook recommends that the risk assessment is done **in addition to** conventional (deterministic) analyses because the two approaches are complementary. Most of the quantitative risk assessments today include a deterministic calculation as the first step of the probabilistic calculation.

A risk assessment provides the opportunity to combine in a systematic manner the results of engineering analyses, experience, expert opinions and engineering judgment. It also can combine any other available information to form a basis in a decision-making and risk management process. A risk assessment considers the risk due to both normal and extreme events throughout the life cycle of a dam, and can be adjusted in light of new observations or events.

Risk assessment encourages a proactive mindset for the identification of potential problem areas, and requires a justified reasoning for the choices made in the analysis. 'Risk-Informed Decision-Making' (RIDM) is a requirement in ISO (2394:2015)[3] standards. This requirement is now also incorporated in ICOLD Bulletins.

Use of risk assessment in industry:
There is an increasing use of risk assessment in the building and construction, energy (petroleum, wind, nuclear), mining and environment sectors.

[1] Depending on the method of analysis used.
[2] Annual reliability index and annual failure probability are mathematically related (Annex F).
[3] Acronyms can be found in annex I and references in Annex K

It has become expected that risk assessment and management be adopted for dams. Society requires, more than before, that the risk associated with facilities or infrastructure be evaluated.

There are several different methods to do risk assessment, from simple qualitative risk matrices to advanced quantitative methods. The method to use and level of detail in the analysis depend on the objective of the risk assessment, the available information, the consequences of an undesirable event or a failure and the uncertainties involved.

Risk assessment of dams in other countries:

Risk assessment and risk management are increasingly used in the hydropower and tailings dam sectors, e.g., in Australia, Canada, the UK and the USA (Annex H). Risk-informed decision making (RIDM) has long tradition in process industries and has recently been implemented in the offshore and dam sectors.

Annex J provides a list of the ICOLD Bulletins that set main focus on dam safety.

For the risk assessment of a dam , it is of primary importance to know the facility well, and to have reviewed the information available, such as the geology, site conditions, prior investigations and the behaviour of the dams during its history.

Standard-based requirements and risk-based assessments

There are two approaches to assess the safety of a dam:

(1) Standard-based approach, using deterministic analyses (the conventional approach);

(2) Risk-based approach to provide the basis for risk-informed decision making (RIDM).

In the conventional deterministic approach, safety is assessed by following established rules for loads, resistance and design. The conventional approach has evolved over many years, based on recognized good practice gained from theoretical considerations and experience. The recognized good practice has served the goal of dam safety well, and is a necessary component of dam safety management. However, the approach is not well suited to safety issues such as internal erosion, spillway functionality, reliability of calculations, human factors, operational problems and uncertainties.

There are always uncertainties in the analysis of a dam: if there are uncertainties, then the failure probability is not zero. In several countries (Annex H), dam safety can be documented with risk assessments demonstrating low risk, using a minimum reliability index or maximum annual failure probability requirement, while also ensuring that the dam satisfies deterministic safety requirements.

Risk assessment implicitly accounts for the uncertainties in the analysis and in the condition of the dam. In a conventional analysis, the uncertainties are covered by a safety factor, and sometimes by sensitivity analyses. Sensitivity analyses consider a variation in input parameters in a mathematical model, but are difficult to apply when the formulation of a sequence of events cannot be described with equations (for example, internal erosion, ageing of concrete, and so on). In addition, the uncertainty in the calculation method is not considered.

Complementarity of conventional analyses and risk assessment:

Conventional deterministic analyses and risk assessments are usually done together. For dam safety, the two approaches should be used together to provide improved insight in a dam's safety.

Risk assessment brings new and complementary insight to conventional analyses. Risk assessment does not replace conventional analyses. Risk assessment provides additional information about the dam's safety and helps the dam owner to make robust decisions in a risk-informed process.

Risk assessments are thus a useful tool in assessing dam safety in addition to the conventional deterministic dam safety regulations.

Citation - limitations of standard-based safety factors:

"The prescription of the Factor of Safety (FS) is attractive to regulators, but experience with case histories, such as Samarco, reveal that over-reliance on prescribed values is not adequate to eliminate failure. In my experience, we have been using FS = 1.3 during operations on very challenging sites in the oil sands industry for many years. At the other end of the spectrum, I have encountered cases where FS = 1.5 may not be adequate due to either enhanced ductility or enhanced brittleness. The prescription of FS in regulation, if necessary, requires thoughtful input from experienced designers and recognition of the characteristics of regional practice.

This leads to a wide choice in regulatory perspectives from that adopted in Chile where upstream construction [*for a tailings dam*] is banned regardless of calculated FS, to that currently being adopted in the revised Alberta Dam Safety Guidelines where no specification of minimum FS is made. In this instance, existing industry guidelines are referenced, but the selection of the FS must consider influencing factors such as:

– Consequence of failure
– Uncertainty of material properties and subsurface conditions
– Variable construction and operating conditions
– Comprehensive site investigation and geotechnical monitoring
– Soil response (contractive/dilative) and its variation with confining stress and shear stress laws
– Time-dependent, deformation-dependent and stress path-dependent processes
– Strain incompatibility of different materials
– Seismic loading as appropriate
– Implementation of an effective risk management system (e.g., the observational method)."

Morgenstern (2018)

When should one do a risk assessment for a dam?

Risk assessment is useful in the following situations (the list is not exhaustive):

– Dams with high consequences, e.g. where there is a risk of live loss or large societal costs, and where stakeholders need to demonstrate that a dam has an acceptable risk level.
– Dams with cascading effects in the case of a dam breach, during both design and the lifetime of the dam.
– Dams where there are large uncertainties. Uncertainties always increase the failure probability and reduce the reliability of a dam. Two dams with same factor of safety from a conventional (deterministic) analysis but with different uncertainties, will have very different margins of safety and failure probability. This is further illustrated in the next section and in Annex F.
– Dams where (1) sudden or continued behaviour changes occur; and (2) external loads, such as climate change, are expected to change significantly.
– Dams where decisions under uncertainty need to be made.

What does one get out of a risk assessment?

Risk assessment for dams is most often used to identify failure (or breach) causes and failure mechanisms, evaluate the risk (qualitatively or quantitatively) in a risk diagram, and compare the risk level with international dam failure statistics or statistics for other constructions and facilities.

Risk assessment is very useful for identifying the most vulnerable component or components in a dam system. The assessment is also used to establish and compare the effect of various measures in a design or rehabilitation phase.

The risk diagram provides insight and an increased understanding of the threats, consequences and risks associated with dam breach.

- Dams where (1) rehabilitation measures need to be compared for an optimum selection; (2) the effects of rehabilitation need to be compared; (3) the cost-effectiveness of either rehabilitation or maintenance measures needs to be compared.
- Dams in a dam portfolio to compare their safety margins and rank the rehabilitation operations.
- To establish emergency preparedness and emergency response plans.

Risk assessment is suitable for the following situations:

- Consider all plausible scenarios that can lead to undesirable behaviour or failure of a dam;
- Compare the risk for one dam with the risk for other dams or other constructions and facilities;
- Ensure the same safety margin for dams with comparable consequences;
- Rank the dams in a portfolio of dams;
- Improve the insight in risk factors in a dam.

Risk analyses can be easily adjusted during the entire life cycle of a dam, as significant changes occur.

Risk assessment techniques are also used to analyse the reliability of components in a dam system, for example, load and load combinations that may be more critical than the ones used in design, gate failure (and their consequences for operation), flood calculations, operational safety etc.

Experience with recent risk assessments of dams

The five examples summarized below illustrate the varied learnings from recent risk assessments. In each case, the analysis contributed to an increased understanding of the dam safety. They also established how the dam safety compared with international practice.

A few examples of the results of risk assessment for five dams

Dravladalen Dam for Statkraft Energy AS: The failure mode screening and reliability considerations led to the identification of a so far unidentified, but critical, failure mode. Rehabilitation was required. The analyses documented the significant risk reduction through the rehabilitation. After rehabilitation, failure probability was shown to be lower than the international failure frequency of other dams worldwide.

Nyhellervatn Dam for E-CO Energi: The continuous leakage monitoring provided enough information to confirm no progression of internal erosion. The dam was perceived as solid, robust and well-behaved over 50 years. Consideration of the failure probability of the downstream slope documented that there was no need for rehabilitation, even if the traditional deterministic analysis suggested the need for rehabilitation of the downstream slope.

Nesjen dam system for Sira Kvina energy company: The risk assessment of the Nesjen Main Dam suggested a safe and robust dam. Internal erosion was the critical failure mechanism. The risk assessment showed that an optimal rehabilitation would be achieved if one planned for controlled overtopping of Saddle Dam 4 under an extreme flood event. Overtopping of Saddle Dam 4 had significantly smaller consequences than the Main dam, and water discharge at the saddle dam would reduce considerably the risk of a breach at the Main Dam.

Strandfossen Dam for Eidsiva Vannkraft AS: The risk assessment identified the most critical mechanisms and causes of a breach and examined the effect of risk reduction measures. The analyses showed a high annual failure probability compared to other dams. Based on the comparison of several risk reduction measures, efficient rehabilitation was quickly implemented.

Viddalsvatn Dam for E-CO Energi: The now 50-year old dam had had leakage and internal erosion issues during its first 20 years. The risk assessment looked into the failure probability associated with further internal erosion and possible overtopping due to a massive rock slide into the dam reservoir, thus creating a large flood wave. The analyses quantified the risk reduction potential of five rehabilitation schemes and documented that the most extensive measure was not necessarily the most risk-reducing one.

The analyses are described in Lacasse and Höeg (2019) and in more detail in Energy Norway reports (on website (in Norwegian).

Advantages and drawbacks of the risk-based approach for dams

In accord with international practice, this handbook recommends that risk assessment be done **together with** conventional (deterministic) analyses. The two approaches are in all ways complementary. The conventional analyses are already well-established and are an integrated part of most of the risk assessment tools used in practice (Lacasse and Höeg, 2019).

Risk assessment brings in more information and therefore provides a more complete (holistic) picture of the risk associated with a dam than the deterministic analyses alone. Since the risk-based approach is done **in addition to** the deterministic analyses and provides additional insight on the safety of a dam, there are no technical drawbacks per se in doing a risk assessment. It is, however, possible to discuss advantages and drawbacks of the risk-based approach on a general basis.

Advantages:

Independently of the analysis method used, risk assessment has the following advantages:

- Risk assessment does a systematic review of all uncertainties, elements of the facility and their interrelationship and potential failure modes.
- The process of a risk assessment requires a debate on the uncertainties which provide additional insight and understanding of the factors and sequence of events that may lead to unsatisfactory performance of a dam. This insight is an indispensable element of robust decision-making. Even a coarse analysis with risk matrices will identify the uncertainties and add real insight.
- The results from risk assessment provide a snapshot of the risk associated with a dam where the hazard (likelihood of a failure) is shown as a function of the consequences:
  - A risk diagram gives a more complete understanding of the safety of the dam than the conventional analyses alone.
  - The risk diagram can be used to compare the safety on one dam with that of several dams and with international risk acceptance guidelines (Annex A). There exists a large body of international experience on risk assessment and risk acceptance, dam failures and other incidents that can be used for comparisons (Annexes D and H).
- Risk assessment can, in a single analysis, look into the potential of a dam failure resulting from both extreme events, normal events and any unusual combination of "normal" events.
- The risk assessment can easily be adjusted over the entire lifetime of a dam.
- The approach can assess the risk for one dam, a series of dams, or separate dam components.
- Many of the analysis methods are simple to use: e.g., risk matrix, event tree analysis, fault tree analysis, bowtie analysis, to name a few (Annex A). Each provide an overview of the potential causes and mechanisms for a dam failure and an understanding of how a dam or a system of dams may fail.
- The simpler qualitative analyses can be used to indicate whether or not a more advanced quantitative analysis is needed.
- Once one is familiar with risk concepts and risk terminology, they are an excellent communication tool across different areas of expertise.

Drawbacks:

Risk assessment has the following drawbacks:

- A robust risk assessment, with quantitative estimate and a risk diagram, requires more work, time and resources than a conventional analysis alone. A qualitative analysis will be less demanding, usually.
- Some of the uncertainties and probabilities needed for a quantitative analysis can be difficult to evaluate. The assessment by experts, often subjective, can be required, together with

engineering judgment. It is however important to point out that the same uncertainties are found in the conventional analyses. The systematisation of the uncertainties and expert advice is simply more visible in the risk-based analyses than in the conventional analyses.

- The uncertainties and judgment required mean that the quantitative risk results are not exact, but give an approximate estimate of risk level.
- In risk assessments, attention is often given primarily to the technical aspects and what can go wrong. Human error and organisational aspects can be overseen (refer for example to the ICOLD dam failure statistics in Annex D). At the same time , such probabilities are difficult to quantify.
- There is unfortunately, today, much confusion in newspapers and in everyday speech with the use of the words 'hazard' and 'risk'. Hazard and risk are distinct and well defined in the risk engineering world, but in common speech the words are often interchanged. In everyday speech, the word risk is often used to describe both hazard and risk[1].

False drawbacks:

Three aspects are often suggested as drawbacks weakening the risk-based approach, but they are not drawbacks as they are also omnipresent in conventional (deterministic) analyses:

- The use of engineering judgment in risk-based analyses: This is an erroneous perception. Yes, risk-based analysis mentions the use of experience and engineering judgment more often than conventional analyses do. However, it is important to realise that the deterministic analysis cannot be completed without the use of engineering judgment and experience either. The same amount of engineering judgment and experience is required for conventional analyses. Annex F includes additional remarks on the use of engineering judgment.
- Need for more knowledge on the dam than for deterministic analysis: The same knowledge is required for both conventional and risk-based analyses.
- Need to update the risk assessment with time: Risk, just like a deterministic factor of safety, do not remain the same throughout the lifetime of a dam, as both hazard and consequence will change with time from construction to decommissioning, and under climate, demography, urbanisation and environmental changes. Acknowledgement of these changes and their effect on the safety assessment needs to be done, both for conventional and risk-based assessments.

Avoiding complacency

Independently of the methods used to do risk assessment, it is important to avoid complacency. Iterations should be considered in the case of large uncertainties.

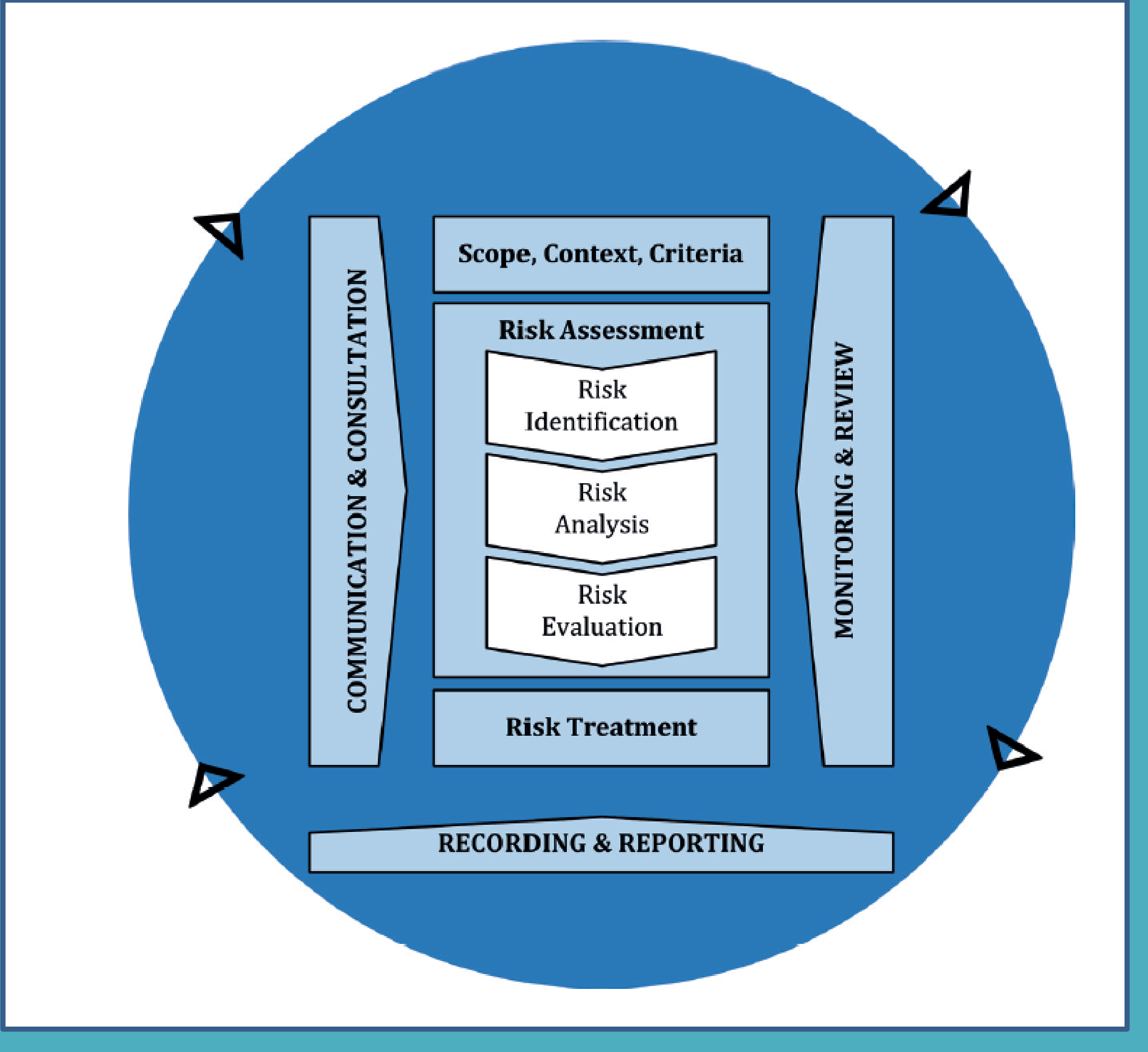
To have completed a risk assessment does not mean that the risk is satisfactorily managed, or that the risk will not change. It is as equally important to invest in an effective and sustainable management of the dam safety and involved risks.

Risk management should be implemented and integrated throughout operation, maintenance, monitoring, and communication. One should also remember that risk is evaluated at one time, and that changes of conditions will change the risk level.

Risk analysis, risk assessment and risk management should be reviewed and updated regularly throughout the dam's life, e.g., in light of extension of operation time, unexpected observations, experiences during serious incidents, and process and technology changes.

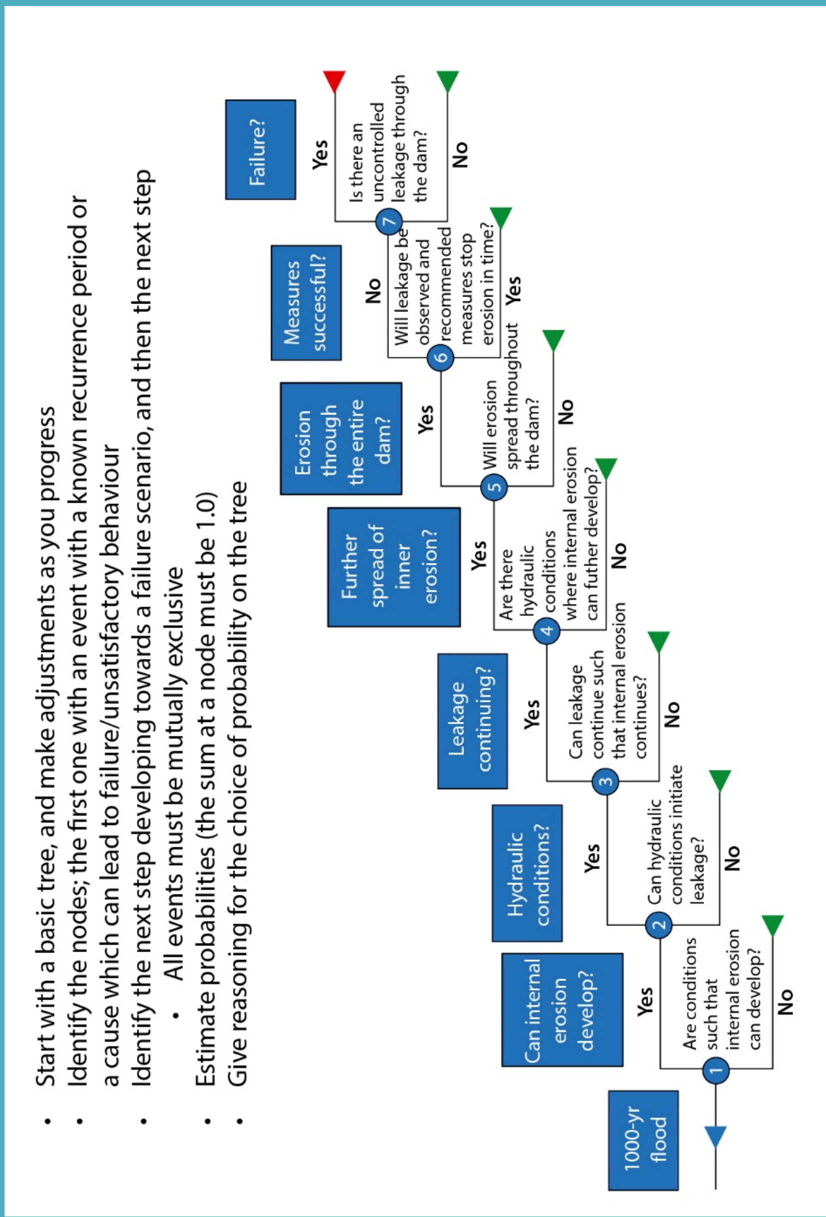
[1] Definitions can be found in Annex I and risk concepts are briefly described in Annex F. Risk is the product of 'Hazard' times 'Consequence' where hazard is the likelihood or probability for an event to occur in a defined period of time, and consequence is for example, loss of life, economical losses, environmental damage. This is also described in more detail in the next section.

Risk assessment and risk management approach



ISO's framework for risk management (after ISO-31000:2018)

Event tree analysis

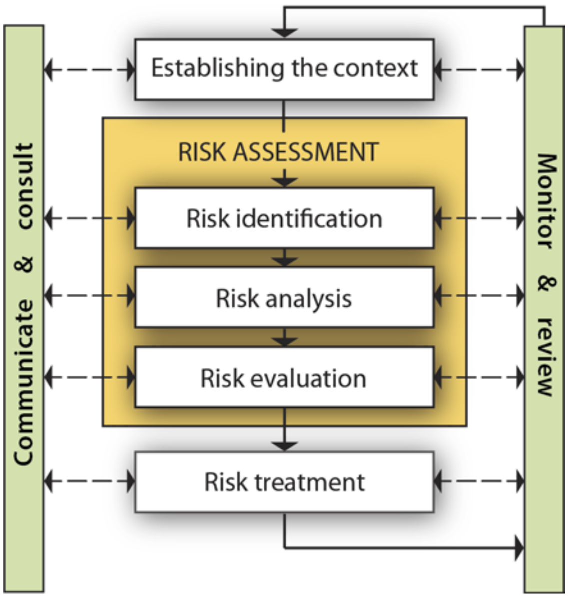


Risk assessment approach

Framework for risk assessment and risk management

Risk management has been formalised into a framework by ISO 31000:2018 (figure on cover page of this section and simplified in the figure below[1]), with an integrated process of risk assessment and risk treatment (new wording for risk mitigation) that includes communication and consultation on the one hand, and monitoring and review on the other hand. The process systemizes the knowledge and uncertainties, to evaluate the risk and its significance. In 2018, ISO added a "recording and reporting" requirement, and the entire process was assimilated to a revolving circle.

Risk management is the process of identifying, analysing and assessing risks to enable informed decisions on accepting or controlling risks by minimizing them. Risk management integrates the recognition and assessment of risks with the development of appropriate risk mitigation strategies. It comprises six main tasks: (a) Danger or hazard identification; (b) Causal analysis of the dangers or hazards; (c) Consequence analysis, including vulnerability analysis; (d) Risk assessment combining hazard, consequence and uncertainty assessments; (e) Risk evaluation of whether the risk is acceptable or not; and (f) Risk treatment.



ISO's framework for risk management in 2009

The risk management process for a dam uses four steps: risk identification, risk analysis, risk evaluation and risk treatment (or mitigation):

1. Risk identification, where threats and failure modes are identified. Step 1 answers the question: 'What can happen'?
2. Risk analysis, where likelihood, consequences and uncertainties are considered (and quantified in quantitative analyses). Step 2 answers the questions: 'What is the likelihood for an event? If the event occurs, what is(are) the consequence(s)?'
3. Risk evaluation, where the risk is compared to risk acceptance criteria or other statistics. Step 3 answers the question: 'Is the risk acceptable?'
4. Risk treatment, where risk reduction options are considered and implemented. Step 4 answers the question: 'What can be done to reduce the risk down to an acceptable level?'

[1] The figure was used ot illustrate the ISO 3000:2009 framework earlier.

Risk assessment for dams:

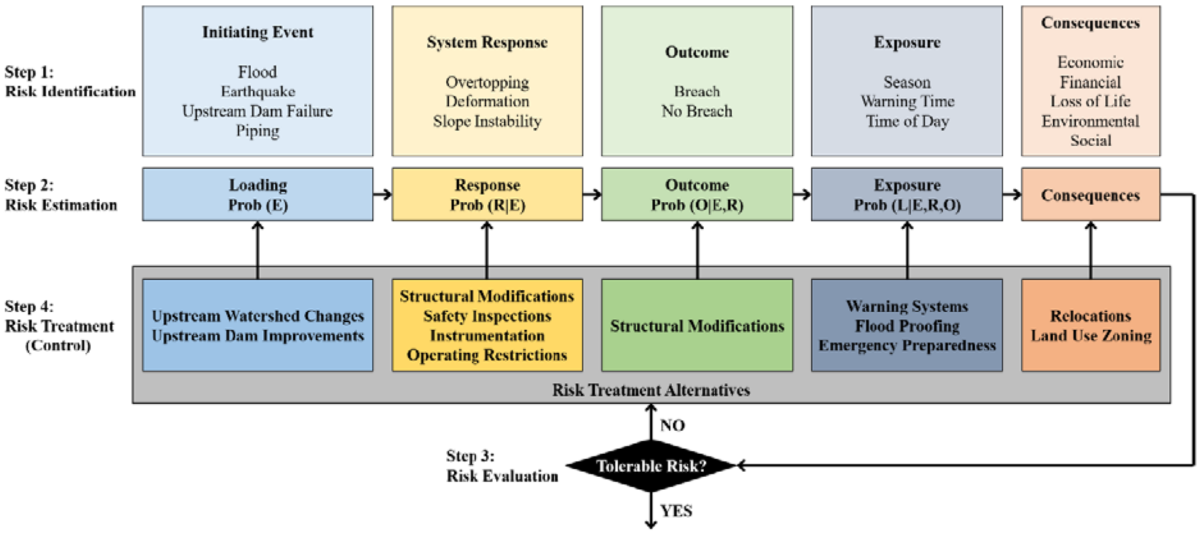
Risk identification: Select the level of detail/complexity for the analysis; screen potential failure modes by examining all potential triggers and mechanisms; list the consequences of a breach, including loss of life, property damage, environmental or social damage and ant other losses.

Risk analysis: Estimate the risk level qualitatively or quantitatively by evaluating the hazard (probability of events) and consequences with some metric for each and all plausible failure modes; present the result in a risk diagram (risk matrix or quantitative diagram of hazard vs consequence).

Risk evaluation: Compare the estimated risk with risk acceptance guidelines from different countries; consider computed risk for other dams, other facilities and dam failure statistics (e.g., Annex D).

Risk treatment: Do a cost-effectiveness analysis of risk mitigation measures, also considering the risk reduction potential of each rehabilitation measure.

All risk assessments use a form of the following practical framework, usually with a focus on one or several of the aspects listed. The four steps (Steps 1 to 4) on the left and at the bottom correspond to ISO's (2018) steps for risk assessment and risk management. In Step 3, if the risk is tolerable or acceptable, the analysis is completed. If the risk is not tolerable or acceptable, the dam owner should consider risk treatment alternatives and then redoing the risk estimation.



Typical framework for risk assessment (modified from Bowles & Schaeffer, 2014; DeNeale et al, 2019)

Note for Step 2 (where Prob = Probability):
Prob (R|E) = Probability of Response given the Loading (often a probabilistic model)
Prob (O|E,R) = Probability of Outcome given the Loading and Response (often a probabilistic model)
Prob (L|E,R,O) = Probability of Exposure given the Loading, Response and Outcome (often a probabilistic model)

Risk = Hazard · Consequence

Risk is the product of hazard times consequence. The risk is estimated or calculated by risk analyses that account for the uncertainties in the hazards and consequences. A risk analysis can be qualitative, semi-quantitative (where either hazards or consequences or risks are ranked) or quantitative (where the hazard, consequences and risk are quantified).

Hazard is usually expressed as the probability of an event occurring over a period of time. Hazard is identified by answering the following questions:

- Which conditions can lead to undesirable conditions or undesirable behaviour?
- Which aspects in geology, design, foundation or construction can cause a breach?
- Which investigations (laboratory, field, numerical) document the conditions?
- Which data can document the properties of the dam and foundation?
- Are the available data consistent and can they be validated?
- Given this information, which failure modes are plausible?

Risk, *R = Hazard · Consequence:*
R = H · C
H =Hazard = likelihood or probability for an event to occur in a defined period of time
C = Consequence due to the hazard (loss of life, economical losses, environmental damage, …)

The potential failure modes that could lead to an uncontrolled release of water from the dam reservoir are screened to ensure that all plausible scenarios are included. This is probably one of the most important step in the risk assessment. The identification of the potential failure modes requires a detailed review of the dam's function and resistance characteristics. Expertise from persons with first-hand experience with the dam construction, operation and behaviour is essential in the analysis. Other significant factors are, for example, the age of the dam. For an embankment dam , the first five years are the most critical, as illustrated in the statistics in Annex D.

The objectives of an analysis of potential failure modes are to:

- identify all triggers and mechanisms that can lead to a breach;
- describe each failure mechanism from its initiation, progressive development and continuation to an uncontrolled water release;
- describe the extent of the breach, including factors that can reduce or exacerbate the probability of a breach occurring.

Probabilities:

- Hazard: probability of an event occurring, e.g., a 1000-year flood has an annual probability of occurrence of 0.001 or 10^{-3} per year.
- Failure probability: probability of a failure caused by a sequence of event one.
- Total failure probability: sum of the probabilities due to all scenarios leading to failure.

The severity of the consequences can be identified in the same manner.

Risk diagrams

In a qualitative analysis, risk is usually divided in three zones described as simply 'low', 'medium' and 'high' risk. The division in three (or more) risk zones is flexible and decided by the user (Annex A).

Quantitatively, the risk is illustrated in a risk diagram showing the annual failure probability (the hazard) and the consequences. These curves are called *F-N* curves, where *F* is the cumulative frequency of events expressed as an annual probability and *N* describes the consequences (Annex A). The figure below shows examples of two risk matrices and one quantitative risk diagram where both scales are logarithmic. The consequence axis can be fatalities, costs, environmental damage, number of closed roads, interruption of infrastructure etc. Such risk diagrams are widely used internationally.

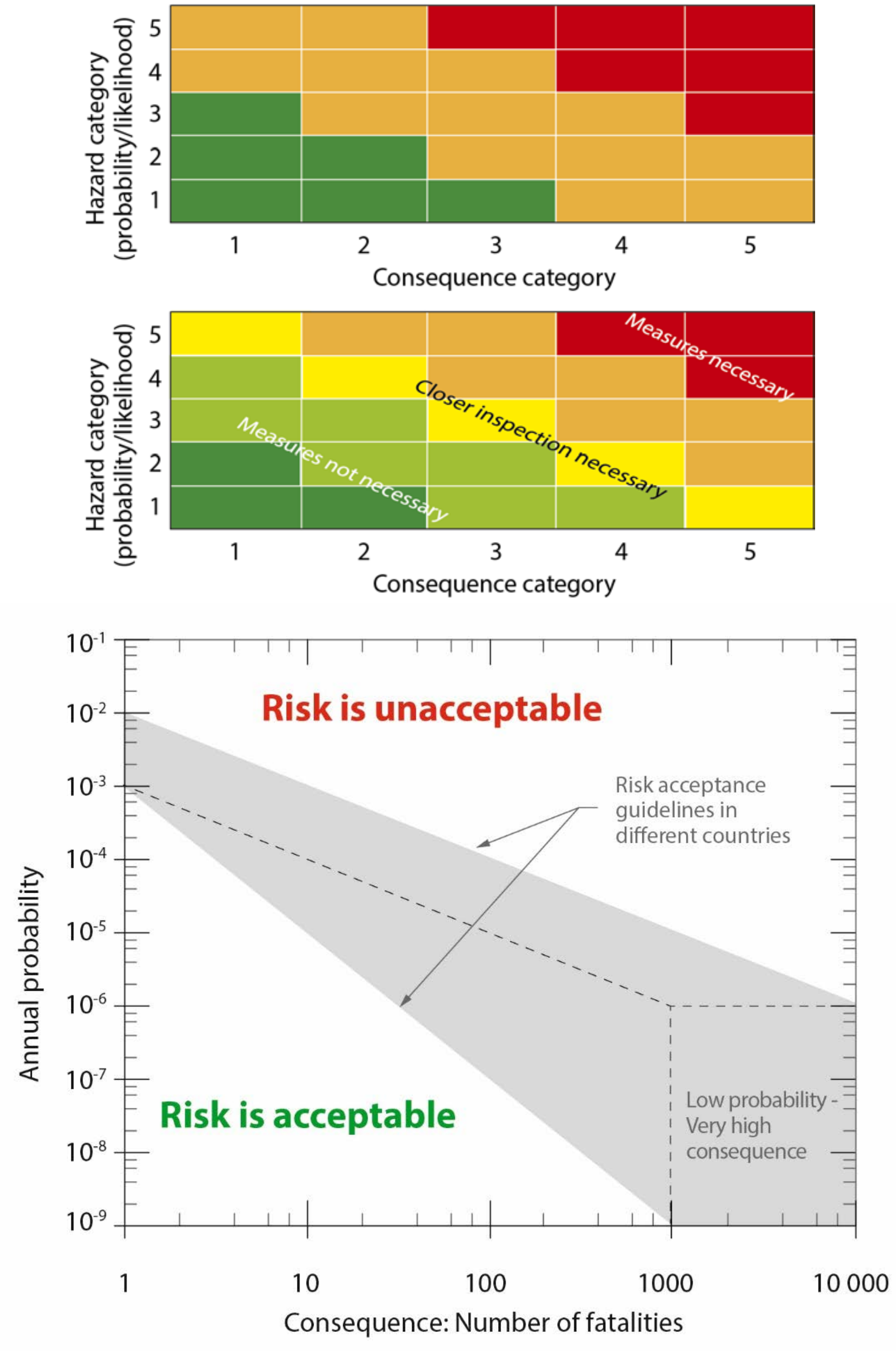
At least two risk zones are identified in a quantitative risk diagram: 'acceptable risk' and 'unacceptable risk'. In between, one can add a 'Tolerable risk' zone, where the risk needs to be managed with analyses, follow-ups and risk reduction measures. Often the ALARP-principle, "***A**s **L**ow **A**s **R**easonably **P**racticable*" (Annex F), is used.

Acceptable and unacceptable risk:

– Acceptable risk ("*Broadly acceptable risk*", UK guideline)

– Unacceptable risk

In between, there can be a Tolerable risk zone, where the ALARP principle should be followed (Annex F).



<u>Top diagram</u>: 3x3 and 5x5 qualitative risk matrices with low (green), medium (yellow and orange) and high (red) risk zones, and with indication of required mitigation measures. <u>Bottom diagram</u>: International guidelines in risk diagram where grey area is the envelope of guidelines in different countries (modified from Lacasse and Höeg, 2019).

In the above quantitative risk diagram, the grey area represents the envelope of the boundaries of acceptable and unacceptable risk recommended in international guidelines. The dashed line is the most commonly used guideline to separate acceptable and unacceptable risk. In the zone of very low probability and very high consequences events, further studies of the risks involved and how to reduce the risk are required.

Even if there are differences in the guidelines from different countries (grey area in figure), the limit for acceptable risk is quite comparable for one and 10 fatalities(note that the vertical and horizontal scales are logarithmic):

- For one fatality, the acceptable annual failure probability is between 0.01 and 0.001 (10^{-2} and 10^{-3}).
- For 10 fatalities, the acceptable annual failure probability is an average of 0.0001 (10^{-4}).
- For 100 fatalities, the acceptable annual failure probability is between 0.0001 and 0.0000001 (10^{-4} to 10^{-7}).

The dashed line is used in the guidelines for dams in the USA, Canada and Australia and for man-made slopes in Hong Kong.

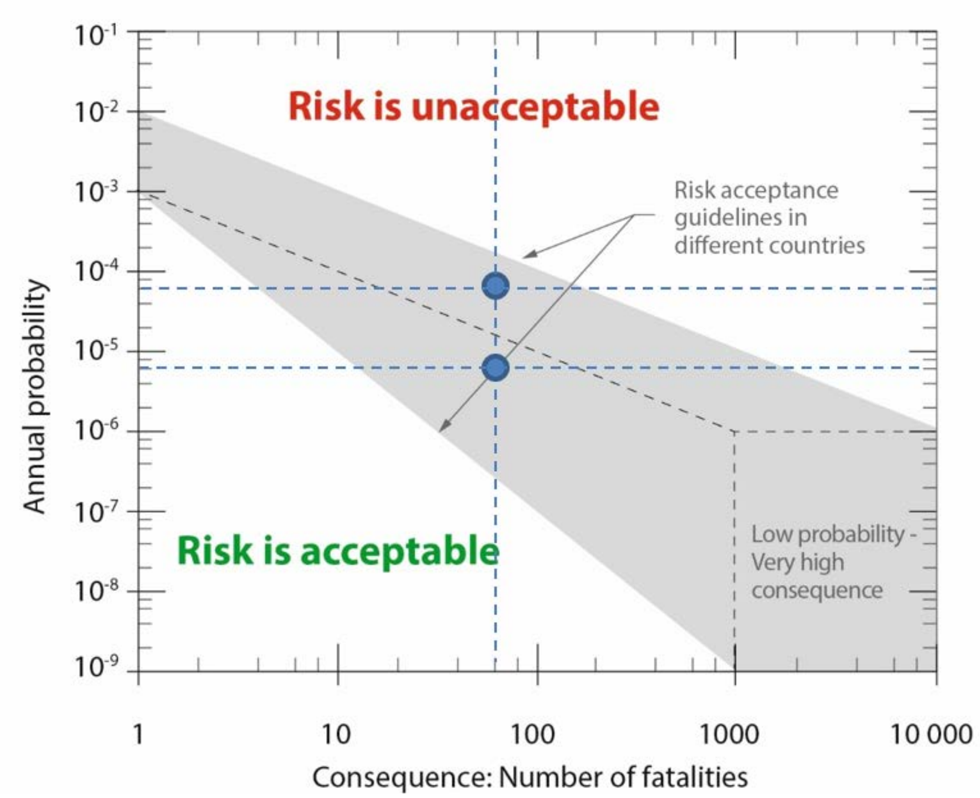
Risk acceptance criteria usually do not operate with a sharp division between the zone of acceptable and unacceptable risk. Examples of the different national guidance are given in Annex A, Section A4.

Usefulness of the risk diagram

The risk diagram enables one to consider both the hazard and the consequences, so the risk, associated with an (undesirable) outcome. Many regulations today use only the severity of the consequences to classify dams and the need for rehabilitation. The drawback of this approach is that it gives an incomplete picture of the actual risk. The figure below illustrates how two dams with the same consequences can have very different failure probability, and therefore very different levels of risk.

Two different dams having the same consequences do not have the same level of risk:

The two dams with the same consequences plot in the risk diagram along the same blue vertical dashed line. The two dams can have very different annual failure probabilities. In the figure, the risk and failure probabilities for the two dams are shown with the two blue circles (annual failure probabilities of 10^{-4} and 10^{-6}). One dam falls in the acceptable risk zone, while the other falls in the unacceptable risk zone. The difference in the annual failure probability is due to the difference in the characteristics and the uncertainties in the two dams. The example shows clearly that, despite the two dams being in the same consequence class, there can be a very large difference in the failure probability, and thereby in the risk associated with the dam, its safety of the dam and the need for rehabilitation. Consequence alone is not a sufficient measure of risk.



Significance of annual probabilities

Hazard expressed as an annual failure probability refers to the frequency of the occurrence of the event in one year. An annual failure probability of 10^{-4} (=$1 \cdot 10^{-4}$ or 0.00001 per year) means that the event can occur once in 10,000 years. For a dam with a life of 100 year, this probability means that the event may occur is 0.01 times (or $1 \cdot 10^{-2}$ or 1%) during the life of the dam.

> **Significance of a probability of 10^{-4} /year:**
> Annex D explains exponential numbers and shows how an annual probability of 10^{-4} relates to real life risks.

Analysis of dam failure probability

There are several methods to do risk assessment, from simple qualitative risk matrices to more advanced numerical tools. Lacasse & Nadim (2007) summarized many of the methods, and the details of the methods are only briefly mentioned in this handbook. Annex A lists most of the methods in use today. The methods are divided into two categories: (1) qualitative and semi-quantitative methods, and (2) quantitative methods. Table A2 in Annex A gives a subjective perception of the suitability and difficulty of implementation for each of the methods. One can select the analysis that is most suitable for a situation to analyse, given the data available. Often, one will combine two or more methods in a risk assessment.

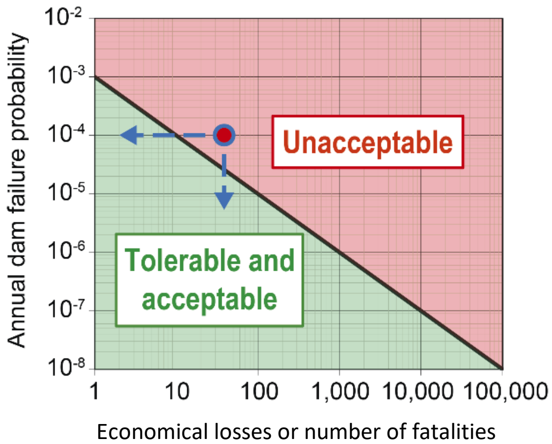
Risk evaluation

Risk matrices and risk diagrams provide a snapshot of the risk associated with a dam. The quantitative risk assessment quantifies:

- the probability of a dam failure (or other undesirable event) as an annual probability;
- the exposed population, potential number of fatalities or other losses as a consequence of a dam breach (e.g., losses downstream, rehabilitation costs, loss of income, environmental damage, loss of reputation etc).

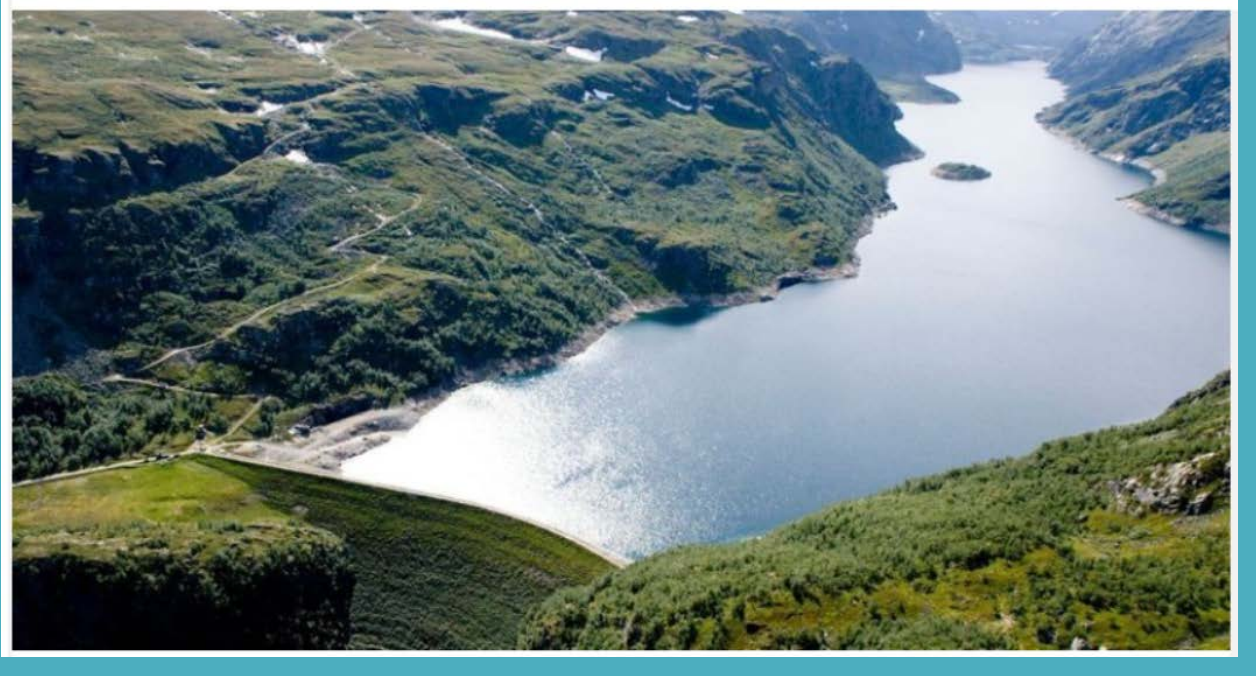
Risk, as the product of a likelihood and consequences has the unit of 'life loss per year' or 'MUSD or M€ per year'.

After comparison of the risk with a diagram of acceptable and non-acceptable risk, risk reduction measures are considered. The figure below exemplifies the calculated risk for a dam (red circle). The dam is found to lie in the unacceptable risk zone. To reduce risk, one can either reduce the likelihood of a failure by strengthening the dam or reduce the consequences with, for example, early warning system, evacuation etc.



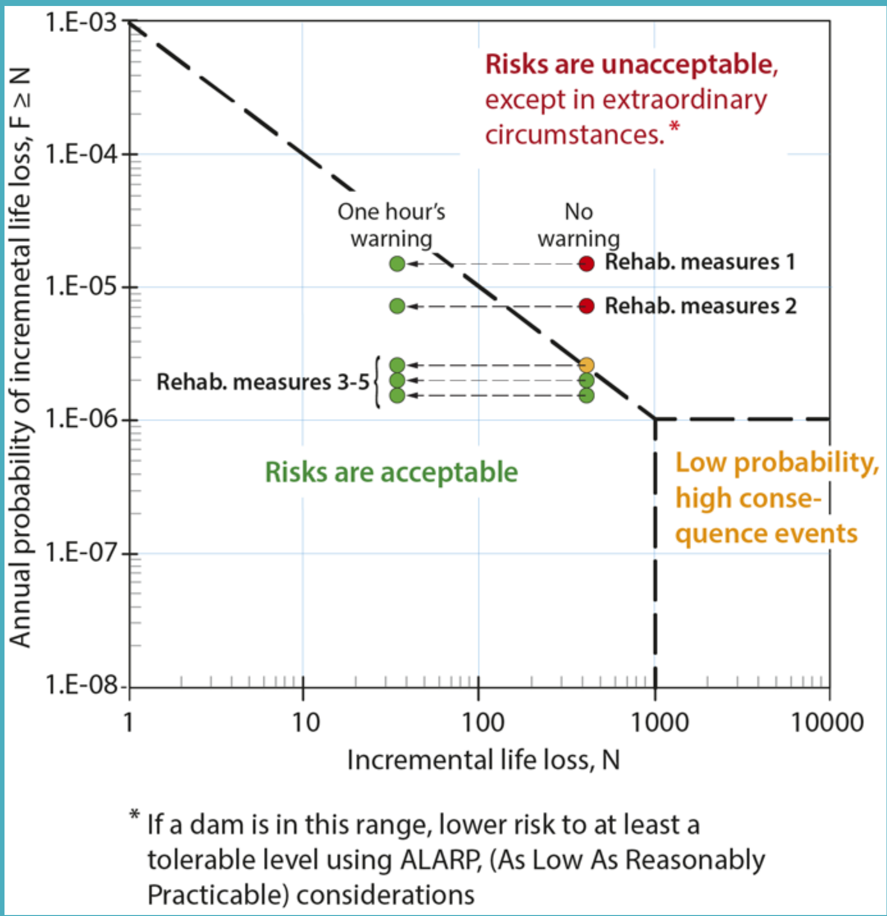
Risk mitigation by reducing the likelihood of an event or reducing the consequences

Examples of risk assessment for dams



Viddalsvatn Dam in Aurland County (Photo Hafslund Eco)

Example of change in risk with different rehabilitation measures and warning times



Risk diagram showing effect of different rehabilitation measures and warning on risk level

Examples of risk assessment for dams

Three examples are given:

1) Analysis of dam failure probability, with event tree analysis;
2) Analysis of fault in machine cooling, pump system or gate operation with fault tree analysis;
3) Analysis of stability of embankment dam slope with Monte Carlo simulations.

The analysis methods are briefly described and a quantitative example illustrates the use and results of each of the three methods. Annex A presents an overview table of the different tools available to do a risk assessment of a dam. The following methods are discussed in Annex A.

QUALITATIVE AND SEMI-QUANTITATIVE METHODS

Risk matrix
Bowtie analysis
Risk register
Maturity matrix
Failure mode analysis, FMEA, FMECA and PFMA

QUANTITATIVE METHODS

Event tree analysis, ETA
Fault tree analysis, FTA
Monte Carlo simulations, MCS
Bayesian Network, BN
Response Surface Method, RSM
First and Second Order Reliability Methods, FORM and SORM
Stress testing

Additional examples with most of the methods listed in Annex A can be found in the annex, together with a short description of each method. The Table below gives an overview of the examples in this handbook.

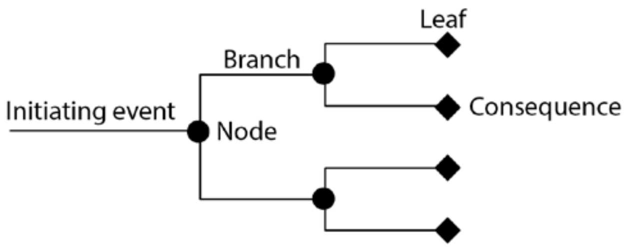
Overview of methods descriptions and examples in handbook (in the present section or in Annex A)

Risk assessment method	**Paragraph in main text or Annex A**	
	Method description	**Example**
QUALITATIVE AND SEMI-QUANTITATIVE METHODS		
Risk matrix	Section A2.1	Section A2.1
Bowtie-analysis	Section A2.2	Section A2.2
Dam Safety Maturity Matrix (DSMM)	Section A2.3	---
Risk Register	Section A2.4	
The Observational Method	Annex G	---
FMEA, FMECA and PFMA	Section A2.5	Section A2.5
QUANTITATIVE METHODS		
Event tree analysis (ETA)	In main text & Section A2.6	Ex. 1 in main text
Fault tree analysis (FTA)	In main text	Ex. 2 in main text
Bayesian updating	---	-
First order second moment (FOSM)	---	---
Monte Carlo simulations (MC)	In main text	Ex. 3 in main text
Bayesian Network (BN)	Section A2.7	Section A2.7
Response Surface Method (RSM)	Section A2.8	---
First and Second Order Reliability Methods	Section A2.9	Section A2.9
Stress testing	Section A2.10	---

Example 1: Event tree analysis to obtain dam failure probability

Description of event tree method

The objective of an event tree analysis (ETA) is to evaluate the probability of failure resulting from an initiating event. The event tree analysis describes the sequence of events that can lead to a failure. An initiating event, and the following events make a sequence that can lead to damage or dam failure. The event tree presents the sequence of events in a visual manner. The graphical representation is assimilated to the branches of a tree.



Elements in an event tree analysis

The analysis usually starts with a triggering event or a mechanism that influences the system. The analysis then maps all possible following events. Each step of the analysis answers: "What happens if the previous events on the breach of the tree have occurs?" A probability is assigned to the branches of the tree in each node. The analysis works using a "for-over logical thinking" process.

The event tree analysis is a powerful tool[1] that helps identify all hazards (and ensuing consequences) in a system that can happen after an initiating event.

The event tree analysis uses a nine-step procedure (expanded from Høeg 1996; Vick 2002):

1) Site visit and inspection of the dam including geology, siting and site conditions.
2) Overview of observations, earlier events and other relevant behaviour of the dam.
3) Brainstorming on all triggers and failure modes, and screening of the plausible failure modes or triggers. This step is called 'failure mode screening'.
4) Discussion and agreement on scales to describe uncertainties and probability estimates in the event tree.
5) Gradual construction of event trees and estimate of probabilities at each node.
6) Continuation of each sequence of events until failure (or non-failure).
7) Calculation of probabilities for each branch leading to a failure and total failure probability.
8) Evaluation of probabilities obtained.
9) Iteration, if necessary.

The process is best carried out through a workshop format, regrouping persons with diverse, but relevant, expertise on the dam and risk and a facilitator. Step 3, 'failure mode screening', is the most important step of the analysis. Failure modes that are not plausible or events with very low probability of occurrence are eliminated, for example, meteorite downfall or high earthquake occurring at the same time as a 1000-year flood.

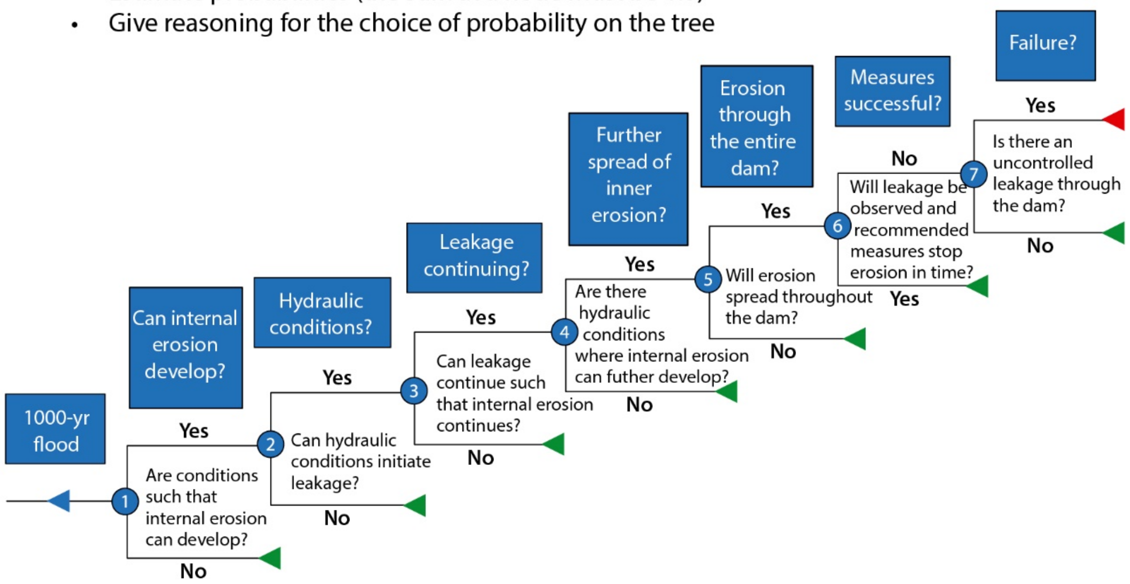
> **Expert opinion:**
> "*The collective judgment of experts, structured within a process of debate, can yield as good an assessment of probabilities as mathematical analyses*" (Vick, 2002).

[1] Event tree analysis is widely used, for example, in the nuclear power, hydropower, mining, space and chemistry industries.

Construction of event trees

The figure below presents a schematic illustration of the steps for the construction of an event tree. Annex A (Section A2.6) presents and even simpler version of an event tree.

- Start with a basic tree, and make adjustments as you progress
- Identify the nodes; the first one with an event with a known recurrence period or a cause which can lead to failure/unsatisfactory behaviour
- Identify the next step developing towards a failure scenario, and then the next step
    - All events must be mutually exclusive
- Estimate probabilities (the sum at a node must be 1.0)
- Give reasoning for the choice of probability on the tree



Schematic event tree analysis: procedure and sequence of events

The event tree is constructed gradually with nodes and branches. The initiating event is usually a trigger or an event with a known return period. The next event is a logical development after the first event has occurred. Probabilities are assigned at each node. In one node, the events need to be mutually exclusive and collectively exhaustive, such that the probabilities in one node sum up to unity[1]. This is easily achieved with a Yes/No, as illustrated above. The selection of the probability values shall be documented, with a chain of reasoning, usually in an explanation table accompanying the event tree.

In the figure above, the failure probability due to a 1,000-year flood is evaluated. In this schematic example, one looks at the geology, topography, hydraulic conditions, initiation and continuation of leakage, implementation of remediation measures and success of the measures, and further development of a dam failure (marked with a red triangle). All other branches do not lead to failure.

There is no unique way to construct an event tree. The workshop participants select the sequence of events. Often the sequence is changed as part of the discussions. Trees can have many branches and become very large. It is also important to not add too many events, as this will artificially reduce the computed probabilities on one branch. It is also found convenient to set the most critical outcome at the top leaf on the branch.

---

[1] For example, ramifications at a node in a 'Yes' or 'No' branches, or in three temperature T branches, either $T \geq$ 100 °C, 0°<T<100° or $T \leq$ 0°C.

The probabilities at the nodes of the event tree are given as either single values or a range of values[1] which reflect the uncertainty in the probability estimates. The range of probabilities give a lower and upper estimate. The values most commonly used in event tree analysis are given in the table below[2].

Estimate of probabilities (single values and range of values) in ETA and verbal description of probabilities.

Probability	Verbal description
0.001 (≈0.0 – 0.005)	**Virtually impossible,** *known physical conditions or process that can be described and specified with almost complete confidence*
0.01 (0.005 – 0.02)	**Very unlikely,** *although the possibility cannot be ruled out on the basis of physical or other reasons*
0.10 (0.02 – 0.33)	**Unlikely,** *but it could happen*
0.50 (0.33 – 0.66)	**As likely as not,** *with no reason to believe that one possibility is more or less likely than the other*
0.90 (0.66 – 0.98)	**Likely,** *but it may not happen*
0.99 (0.98 – 0.995)	**Very likely,** *but not completely certain*
0.999 (0.995 – ≈1.0)	**Virtually certain,** *known physical conditions or process that can be described and specified with almost complete confidence*

Estimate of probabilities, each event, each failure mode and total failure probability

At each node of the event tree, the probabilities should be based on:

- Statistics from observations, model tests, laboratory or *in situ* tests, analysis of data etc.
- Calculations of physical mechanisms, e.g., stability, seepage or deformation analyses.
- Earlier experience with similar constructions, processes (like internal erosion) etc.
- Discussion at the workshop and consensus reached after discussions.
- Engineering judgment and expert opinion.

The assigned probabilities need to be justified:
The probability estimates shall be based on a demonstrable chain of reasoning and not on speculation. Consensus is reached through discussion using standard descriptors (table above).

The failure probability along one branch of the event tree is calculated from the product of the probabilities at each node. The failure probability for one failure mode is the sum of the probabilities on all the branches leading to a dam failure in one event tree.

The total failure probability for a dam is the sum of the failure probability for all failure modes, considering all event trees. It is therefore important that the probabilities in the different event trees are comparable and addable, for example an annual failure probability. Other units can be used (probability per 10 years, or 100 years.

[1] IPCC (2012) recommended, in its report on extreme events, that a range of values be used instead of a single probability value to include an uncertainty in the estimated probabilities. These range of values can also be used to establish the distribution of the failure probabilities with, e.g., Monte Carlo simulations.

[2] Each country has its own methods to describe probabilities; decision on the descriptors of probability is made by the participants in the workshop. Section A2.6 (Annex A) presents two tables of verbal descriptors, the one used by the nuclear energy industry, the other used in China.

Quantitative examples from practice

The figure and explanation table on the next page provide an example of an event tree for a 29-m high embankment dam. The event tree analysis looked at the probability of leakage and erosion through the core and the rock foundation of an embankment dam. At each event node, a probability was estimated. In the figure, the boxes on top of the event tree show the sequence of events in the analysis:

- Is there leakage and erosion in the fractured rock?
- Does self-healing occur?
- Is there leaching from core to bedrock?
- Do the fissures heal?
- Does failure occur?

The probabilities at each node are based on the chain of reasoning in the table beneath the tree. The figure also shows the product of the probabilities (red lines) along each sequence of events leading to failure. Failure is marked with a black triangle. Event sequences not leading to failure are terminated with an open circle with the word 'STOP'.

The first table below gives an overview of the different failure modes and the computed failure probabilities for each. The values shown are for the best estimate of the probabilities at each node of the event tree (and not for a range of values in this case). Two failure modes have the highest annual failure probability (about $5 \cdot 10^{-6}$): the modes 'summer flood with glacier melting in reservoir' and 'internal erosion'.

The second table gives the total annual failure probability for the 29-m embankment dam. The total probability due to geotechnical or natural causes (the sum of all annual probabilities except the sabotage and terror case) was estimated as 10^{-5} or once in 100,000 years.

Overview of event tree analyses and annual failure probabilities for each scenario for 29-m embankment dam

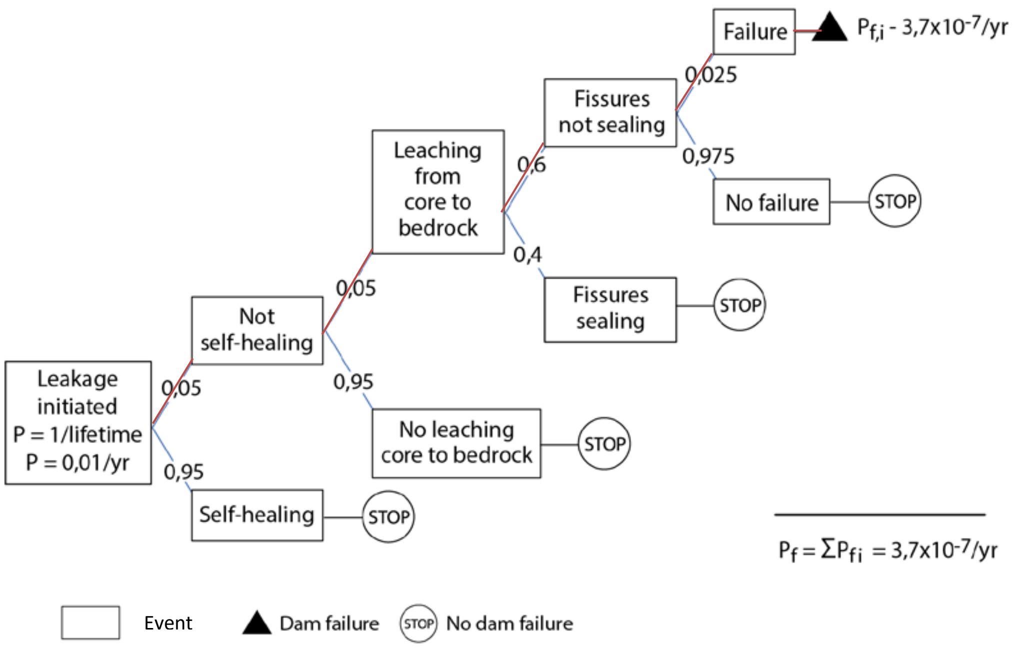
Failure mode or external trigger		**Annual failure probability, $P_{f\ annual}$**
Internal erosion		$4.7 \cdot 10^{-6}$
Flood	Winter season: Ice and hard-packed snow blocking spillway	$2.4 \cdot 10^{-7}$
	Summer season: Glacier melting into reservoir	*For $Q > Q_{10,000}$:* $5.4 \cdot 10^{-6}$ * *For $Q \leq Q_{10,000}$:* $3.7 \cdot 10^{-7}$
Earthquake		$9 \cdot 10^{-8}$
Sabotage/terror		$2 \cdot 10^{-7}$

* Q is the flood intensity, $Q_{10,000}$ is the extreme flood, with 10,000 year return period

Total failure probability due to geotechnical and natural causes for 29-m embankment dam

Failure mode or external trigger		**Annual failure probability, $P_{f\ annual}$**
Internal erosion		$4.7 \cdot 10^{-6}$
Flood	Winter season Ice and hard-packed snow blocking spillway	$2.4 \cdot 10^{-7}$
	Summer season Glacier melting into reservoir	$5.4 \cdot 10^{-6}$
Earthquake		$9.0 \cdot 10^{-8}$
Total failure probability, geotechnical and natural causes		$\mathbf{1.0 \cdot 10^{-5}}$

Leakage and erosion in fractured rock	Self-healing	Leaching	Sealing of fissures	Dam failure
A	B	C	D	E



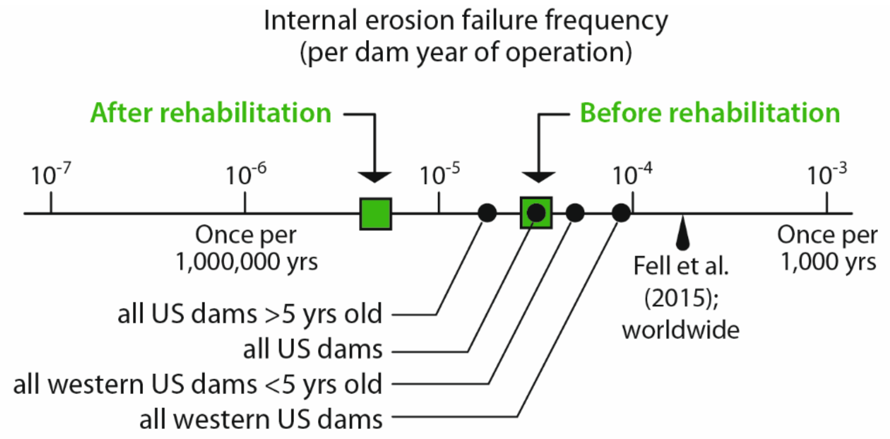
Event	Explanation	Probability
A **Leakage through the rock foundation**	Leakage that could cause erosion of the core initiates in the rock foundation: this has not happened in the first 40 dam-years; unlikely that this will get worse or better with time; life of dam is 100-150 years.	P = 1% during the dam life
B **Self-healing**	During construction, injection work was done carefully (injection reports and inspection reports); rock of bad quality was removed (top 10–15m). But the geology information is incomplete.	P[0.05; 0.95]
C - Leaching core to bedrock	Large volumes need to be washed out to damage the core: unlikely to very unlikely that this may happen with this type of rock.	P[0.05; 0.95]
D - Sealing of the fissures/faults	After discussion, it was concluded that it was somewhat more probable that the fissures and faults will not seal themselves than seal themselves.	P[0.6;0.4]
E **Damage large enough to initiate failure**	Development of sinkhole takes time: it would be seen on leakage measurements and remediation can be started; it is more critical if piping develops upstream. Damage on the dam does not mean breach (ex.: dam in Sweden was damaged by sinkhole, but no failure occurred). 1st estimate: probability (failure) = 0.01: some said this was too low, others too high. Consensus in between.	P[0.025; 0.975]
E - Dam failure	One branch leads to failure; P_f is product of probabilities along the branch.	P_f = 3.7 x 10^{-7}/yr

Example of an event tree analysis and explanation table with the discussions and selected probabilities: case of leakage and erosion in the dam core and rock foundation, rockfill embankment dam

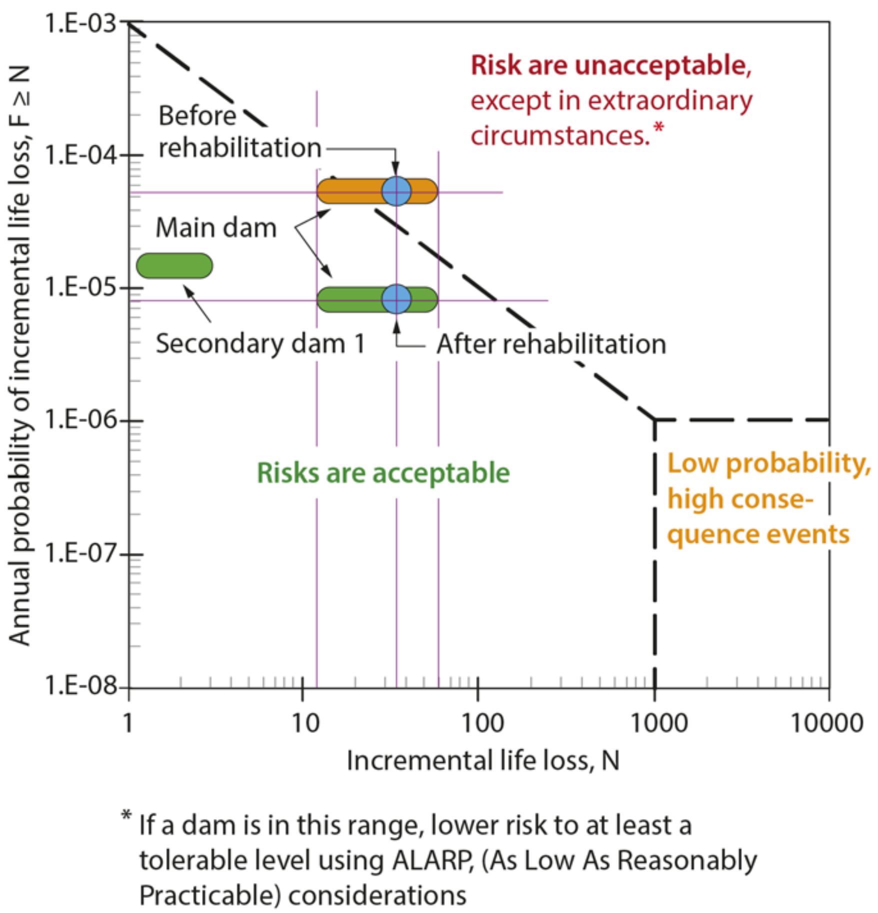
Risk diagram for a dam

The results from the event tree analyses are generally used to compare the failure probability with that of other dams. Three examples are given: (1) comparison with the frequency of dam failure due to internal erosion with the ICOLD and Fell *et al*. (2015) statistics; (2) risk diagram comparing the risk associated with two dams and showing the effect of rehabilitation on the risk; (3) – on the cover page of this section: risk diagram comparing the effect of five different rehabilitation measures (to reduce the failure probability) and the effect of warning time for the population (to reduce the consequences).

The risk can also be compared to other international statistics, such as those summarized in Annex D.



Comparison of failure probability due to internal erosion before and after rehabilitation and with ICOLD's statistics



Risk diagram for two dams before and after rehabilitation (orange and green ellipses). Blue circles give best estimates.

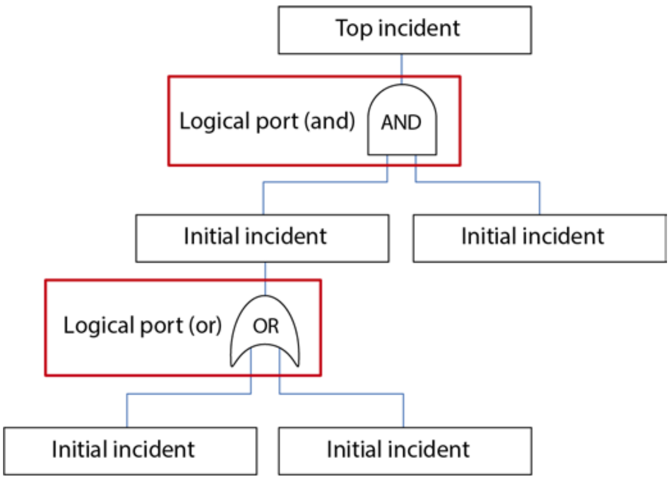
Example 2: Fault tree analysis of a dam component

Description of fault tree method

Fault tree analysis (FTA) is a simple and versatile method that is used in reliability assessment, most often to find the potential of the failure of a component. Fault tree analysis can help find the cause and the probability for an undesirable situation to occur, and estimate the reliability of different safety barriers that are considered. The analysis can be qualitative, semi-quantitative or quantitative. The analysis shows the relationship between an undesirable event and the causes for this event. It gives the answer to the following questions:

- Which combinations of faults and events may be linked to the undesirable situation?
- How often will this undesirable event or combination of events occur?
- Which faults/defects or combination of causes have the strongest influence on the occurrence or non-occurrence of the event.

A fault tree is composed of a top incident or top event (the undesirable event) and is decomposed into the initiating events that can cause the top event to occur. Whereas the event tree analysis (ETA) is a bottom-up sequence analysis, the fault tree analysis (FTA) is a top-down process. The events in the fault tree analysis are interrelated with logical gates, the '**AND**'-gates and the '**OR**'-gates, each with its characteristic symbol, a straight (AND) or concave (OR) entrance gate:



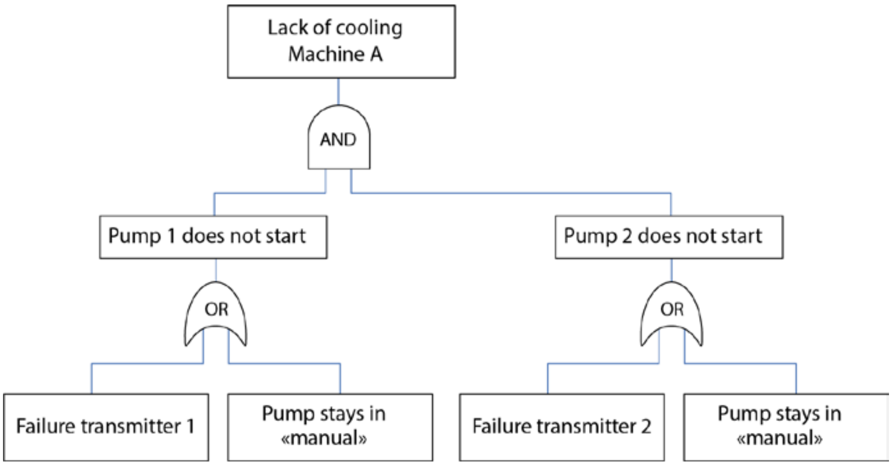
Principle for fault tree analysis ('incident' is the synonym of 'event')

Construction of fault tree

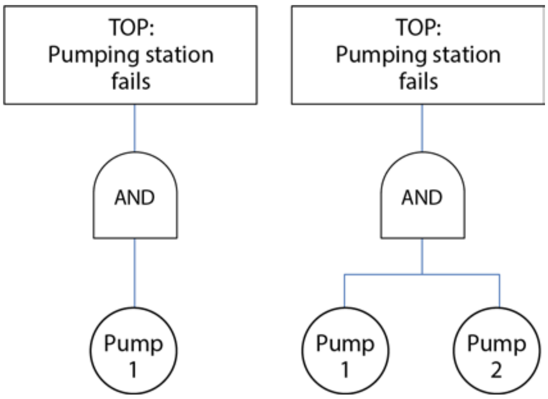
The first step consists of defining the top event (or incident), or the situation one wishes to avoid. In the example below, 'Lack of cooling of Machine A' is the top event, judged to be a major fault in a system.

The next step consists of adding the causal events that make the top event possible (or plausible). In the 'Lack of cooling of Machine A' example, Machine A is equipped with two pumps, and one (only one) needs to be operative to provide the required cooling. The initiating events are then 'Cooling pump No. 1 does not start', AND 'Cooling pump No. 2 does not start'. The two events need to happen simultaneously, so the logical gate is an AND-gate. The logical port OR would not work since one pump is still starting with the OR gate. Then 'Cooling pump No. 1 does not start' and 'Cooling pump No. 2 does not start' can also have initiating events, for example, "a transmitter failure' or 'the pump not starting automatically (stays in manual mode)'. Here the logical gate is an OR because only one of the events is sufficient for the pump to not start. In this manner the tree is "built down" to cover all relevant causes that can lead to the top event.

A fault tree gives a visual, simple overview of the causes leading to the top event. The structured approach aims at including all the fault factors in a system. The focus of FTA is usually on system and equipment, so experienced operative personnel are important for the analysis. Human error, faulty maintenance, power failure etc are examples of causal events. A quantitative example is given below.



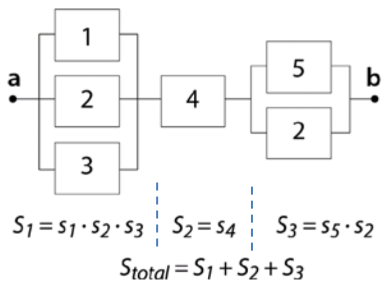
Example of a fault tree analysis of lack of cooling for Machine A



Fault tree analysis for one and to pumps, each with fail rate Q = 0.005/yr or (5/1 000)/yr.
<u>Left</u>: One pump: availability is (1-0.005)/yr = 0.995/yr, so down time is 43.8 hrs/yr;
<u>Right:</u> Two pumps: fail rate of the two pumps together is 0.005 · 0.005 = 0.000025/yr;
availability is (1 – 0.000025) = 0.999975, so down time is 0.2 hrs/yr.

Calculation of probabilities

The calculations are similar to parallel and series in electricity circuits. The probabilities of events in parallel (**AND** gates) are multiplied, the probabilities of events in series (**OR** gates) are summed:



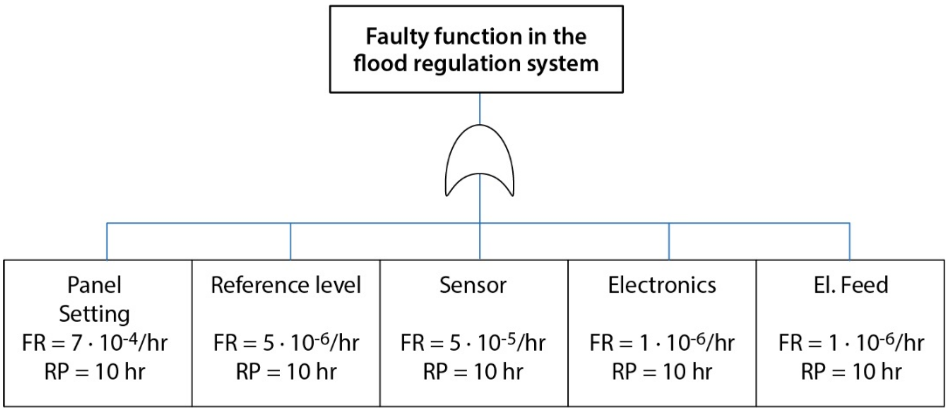
*Principle for the calculation of the probabilities between **a** and **b** in FTA (S and s are probabilities)*

Examples of analysis of fault in flood regulation

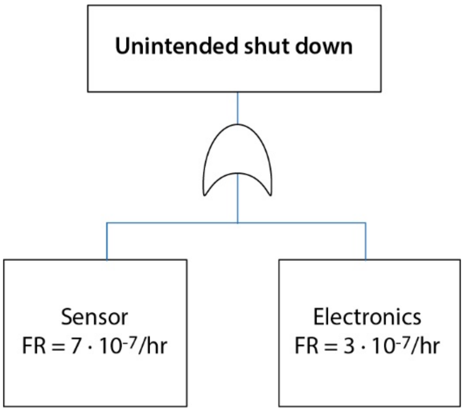
The system consists of the panel settings, reference water level, sensor, electronics of electrical feed (on batteries). Three fault mechanisms are plausible for the flood gate system:

- Faulty function at the time of the rising water level.
- Unexpected closing of the flood gates.
- Unexpected opening of the flood gates.

For the three conditions, the top event is increased water flow and a 'Faulty function of the flood regulation system'. The fault tree for the faulty function of the flood regulation system is given below, together with probabilities for fault rate and the time required for finding the fault and reparation. Such numbers are obtained from earlier experience at the dam site, and perhaps from event tree analyses. The fault tree for unexpected closing of the flood gates is also shown.



Fault tree for faulty function in the flood regulation system (FR=fault rate; RT=reparation time)
All gates are OR gates: Total probability is $7.57 \cdot 10^{-4}$ */hr or 0.0008/hr*



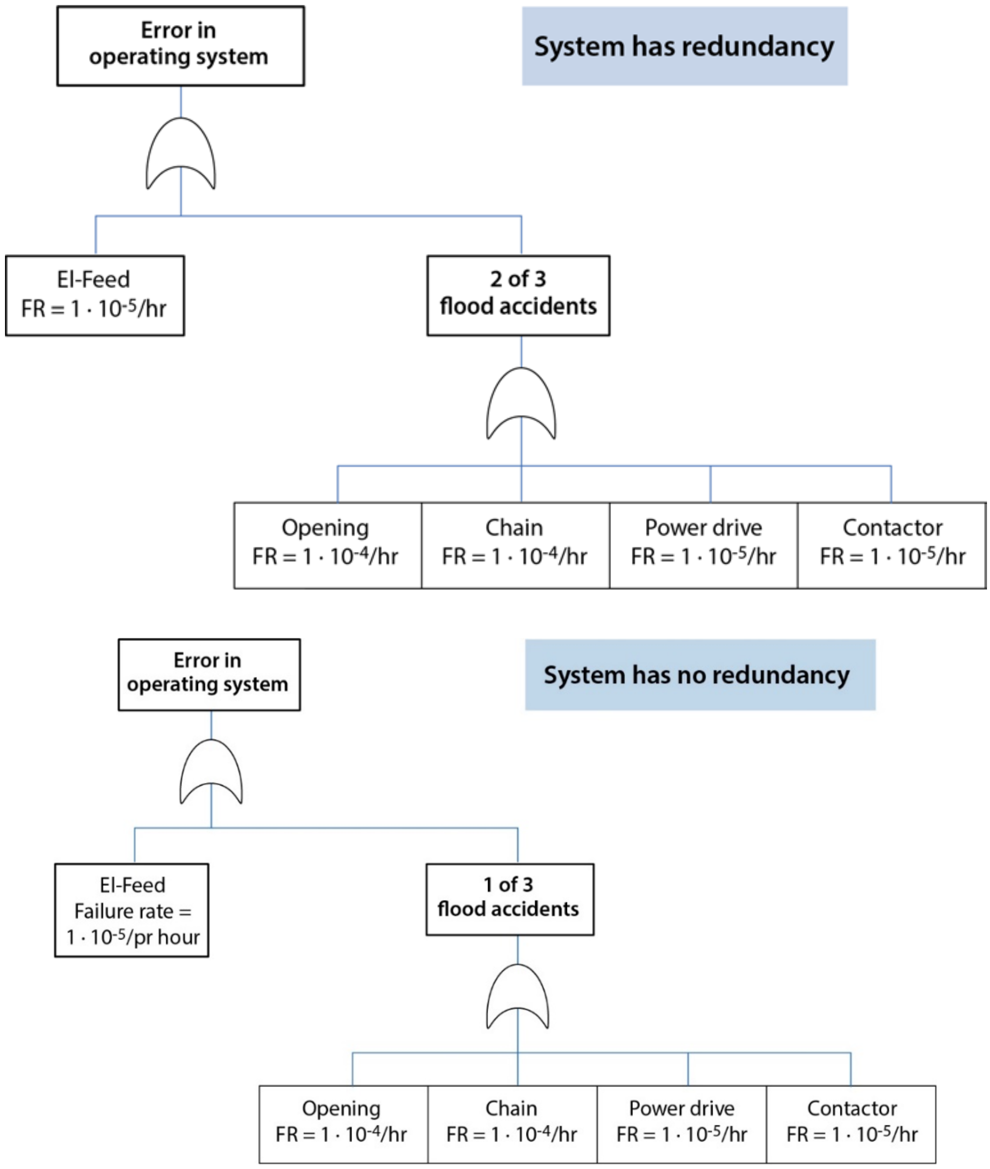
Fault tree for unexpected closing of the flood gates (FR=fault rate)
$7 \cdot 10^{-7}$ */hr = ca. 0.6% /yr for fault in sensors; about 0.3%/yr for electronic fault)*
Total probability is $1 \cdot 10^{-6}$ */hr or 0.9%/yr or close to 1%/yr*

The next example shows the fault tree for an error in the operation of the flood gate system, first for a system with redundancy[1], second for a system without redundancy:

1) System with redundancy, where it is possible to have a successful gate operation even if one of the three flood gates cannot be opened. The top event 'Error in operating system' will occur only

[1] Redundancy: duplication of critical components or functions of a system with the intention of increasing the reliability of the system

if 2 of the 3 flood gates cannot be opened at the same time. The fault probabilities for each of the causes leading to the top event 'Error in the flood gate operation' are given in the figure. The opening of one gate depends on four factors: Opening, Chain, Power Drive and Contactor. The probability of one gate malfunctioning is the sum of the four probabilities, which equals a failure probability of $P_f = 2.2 \cdot 10^{-4}$.



Fault tree for flood gate operations with (upper) and without (lower) redundancy (FR=fault rate)

For the case of a system with redundancy, three cases are considered:

a) If the causal events are independent for each of the three flood gates, the fault probability for 2 of the 3 flood gates is $3P_f^{\,2}\,(1 - P_f)$ or $\approx 1.5 \cdot 10^{-7}$. P_f is an OR-gate with four conditions, and is the sum of the probabilities, $2.2 \cdot 10^{-4}$. The three flood gates have the same failure probability, P_f. The probability of two gates failing at the same time (AND-gate) is the product P_f^2. Since there are three independent gates, the probability of the event is then close to $3\,P_f^2$. This is approximated to $1.5\,P_f^2$. The exact solution is $3P_f^{\,2}\,(1 - P_f)$, but the value $(1 - P_f)$ is very close to 1.0 (0.99999973). Combined with the electrical feed event (OR-gate), the probability of the top event is $1 \cdot 10^{-5}$ (sum of probabilities).

b) If the three gates fail at the same time due to the same cause, then the failure probability is the initial probability , or $P_f = 2.2 \cdot 10^{-4}$.

c) If the failure causes are not independent, and one assumes a geometrical mean value to represent the dependent probability, the probability of two faulty gates becomes, with the probability of one gate only failing still $P_f = 2.2 \cdot 10^{-4}$, the square root of the product of the a) and b) probabilities, or $(1.5 \cdot 10^{-7} * 2.2 \cdot 10^{-4})^{1/2} = 5.7 \cdot 10^{-6}$. Combined with the electrical feed event (OR-gate), the probability of the top event is $1.6 \cdot 10^{-5}$ (sum of probabilities).

2) System has no redundancy: the top event occurs if only one of the three flood gates cannot be opened. The functioning of the two other flood gates has no influence on the top event. The fault probability can be calculated, assuming that the three flood gates are independent: the fault probability is therefore 3 times P_f (for each of the three gates) or $6.6 \cdot 10^{-4}$. Combined with the electrical feed event, the probability of the top event is $6.7 \cdot 10^{-4}$ (or close to 10^{-3}).

One could have also analysed the three gates separately, if they each have different failure statistics

Example of analysis of dam breach with FTA

A fault tree analysis for a dam breach by overtopping is illustrated below:

The top event is the dam breach (failure) due to overtopping. The causes for the overtopping can be 'water level too high', 'erosion of the crest', 'settlement of the crest'.

The 'water level too high' can be due to exceedance of the design flood or failure of the spillway. 'Erosion of the crest' can be due the occurrence of the erosion and the lack of repair (no action). The 'settlement of the crest' can be due to no action taken after the settlement occurred.

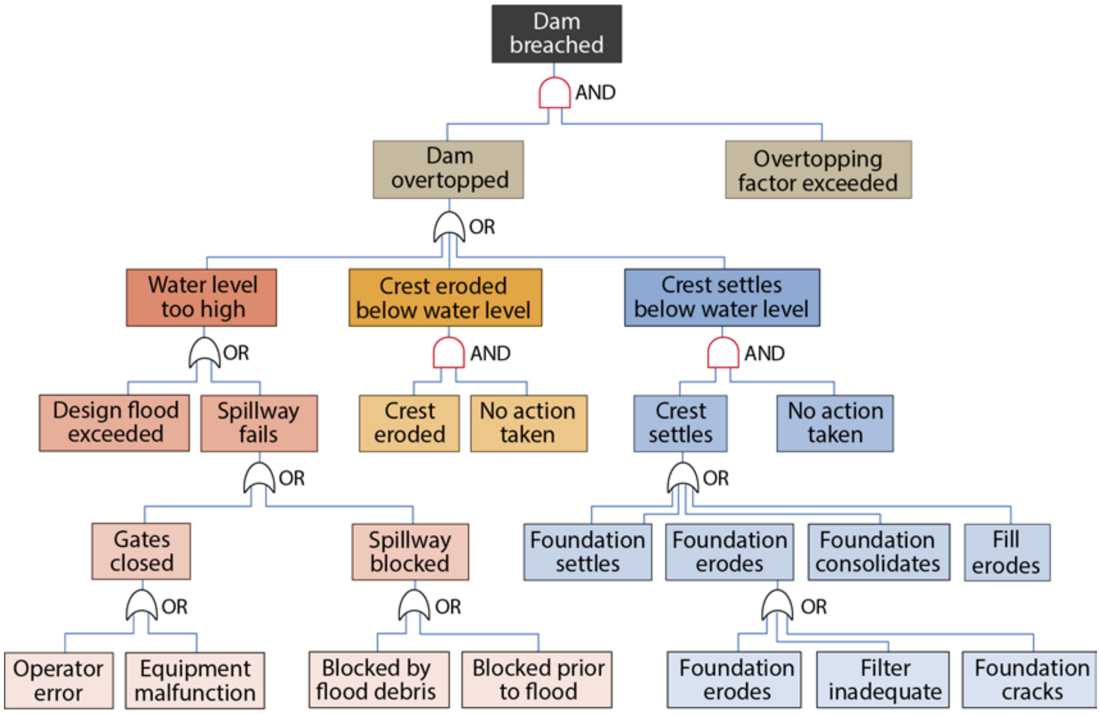
In turn:

- the 'spillway failure' can be due to the gates being closed or the spillway being blocked.
- The 'crest settlement' can be due to settlement of the foundation, erosion of the foundation, consolidation of the foundation, or erosion of the fill (a side analysis would also have to look of an earthquake causing settlement of the crest).

  Then

  - Gates closed: due to operator error or equipment malfunction.
  - Blocked spillway: due to flood debris, due to inadequate maintenance (blocked prior to the flood).
  - Erosion of the foundation: due to the foundation eroding, inadequate filter(s) or cracks in the foundation.

Probabilities need to be assigned to each of the steps and the probability of the top event is then calculated.



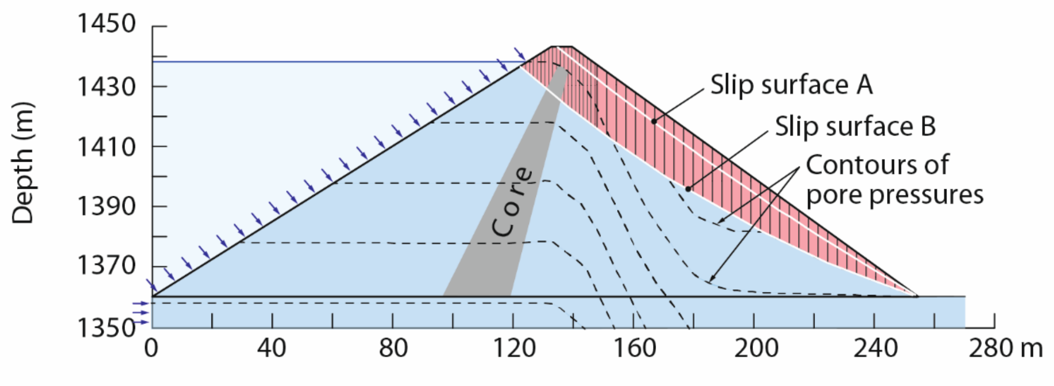
Fault tree analysis of a dam breach under a flood event

Example 3 Monte Carlo analysis of downstream slope stability

The Monte Carlo simulation technique is a well-known approach, readily available in Excel and other mathematical or statistical software packages. The method can simulate physical and mathematical systems, and requires that the event to be simulated can be expressed explicitly with a mathematical formulation. For dams, the approach is often used for simulating the stability of a slope and evaluate the probability of a sliding failure. At times many simulations may be needed, if the failure probability is very low. The approach, however, gives a very good approximation of the mean and one standard deviation of a probability distribution, without the need of many simulations (for example, less than 1000 simulations).

Example of the analysis of the slope stability of a downstream rockfill embankment dam

The results of a deterministic analysis of a slope stability are shown in the figure below. Two critical slip surfaces were considered ("Slip surface A" and "Slip surface B"). The lowest deterministic safety factor was calculated as 1.32 for Slip surface B (the safety factor was 1.58 for Slip Surface A).

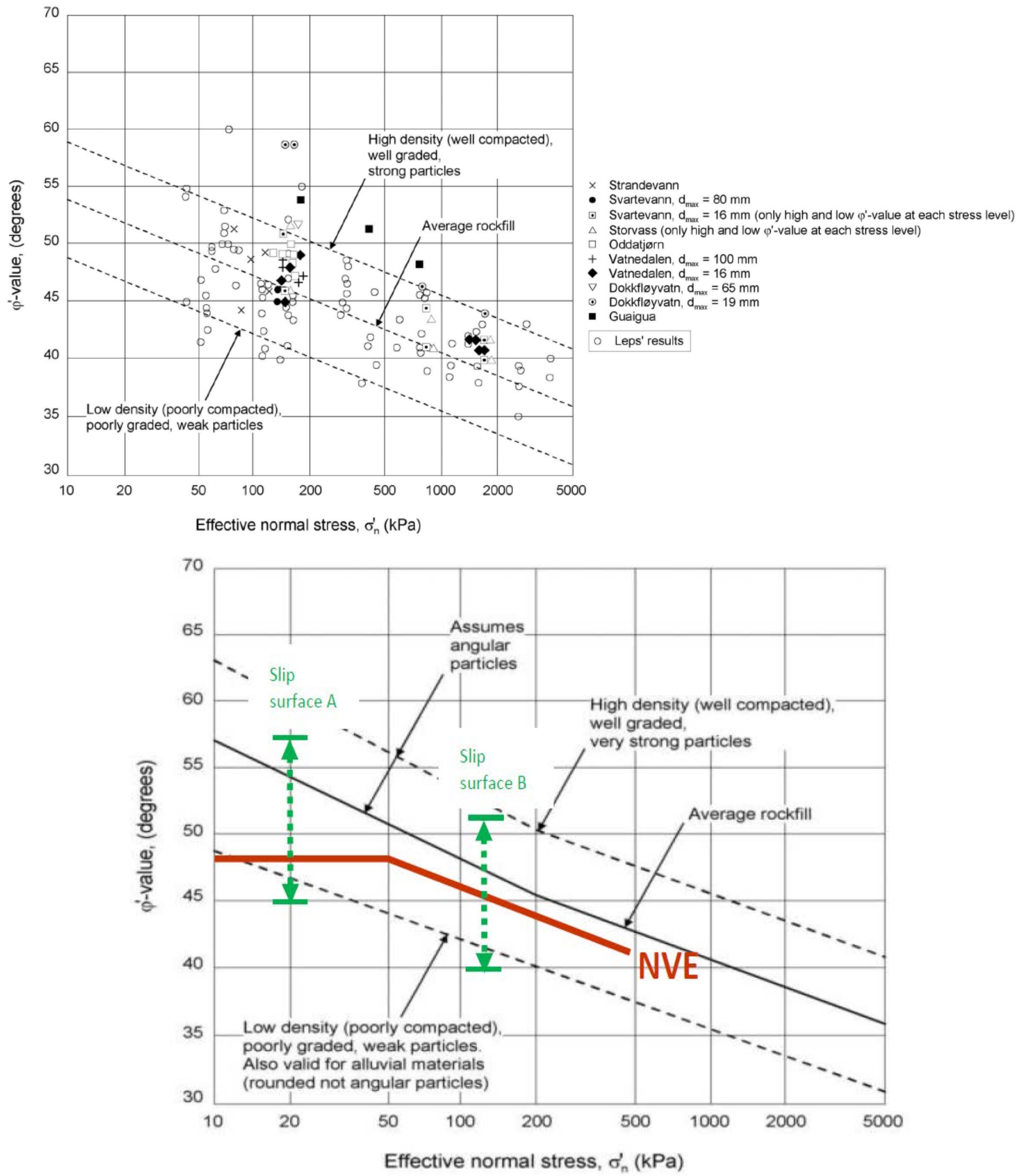


Slope modelled in the Monte Carly analyses, with deterministic slip surfaces

Monte Carlo analyses were run for the two slip surfaces to compare the failure probabilities computed for the two slip surfaces. Each uncertain parameter was included in the analysis. The parameters were described as random variables, with values covering the entire range of range of values measured in the laboratory. For some parameters, values from the literature, with the variability, were used.

In the stability analysis, the most significant uncertain parameter was the friction angle for the downstream rockfill. The figure below illustrates the variation of the friction angle with rockfill quality, compaction quality and effective vertical stress. The range of values is wide and is based on the results of multiple laboratory tests in the laboratory over a period of more than 30 years (Leps, 1970; Lacasse & Höeg, 2019). The ranges in green illustrate the values used in the Monte Carlo analysis for the rockfill effective friction angle. The ranges were chosen as conservative values compared to the ranges of values measured in the laboratory. The friction angle was given a normal distribution. The line in red show the prescriptive maximum values used in deterministic analysis.

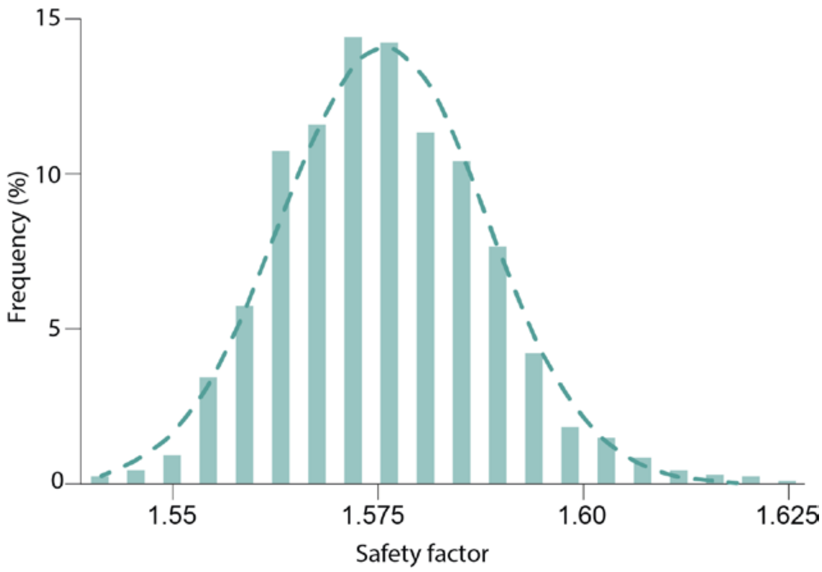
The results of the Monte-Carlo analyses of the downstream slope stability under stationary w groundwater conditions are shown in a table together with results of the deterministic (conventional) stability analyses. Even with a safety factor under 1.4, the downstream slope had a very low failure probability, denote P_f. A safety factor of about 1.4 can therefore represent a very stable situation, even if it is less than the prescribed values of 1.5. The probabilistic analysis also provides, in addition of the failure probability and the most significant uncertain variable, the minimum and maximum values of the safety factor, based on the simulations with all the uncertain variables in the stability analysis. The probability distribution of the safety factor for the shallower Slip Surface A from the Monte Carlo analysis is shown on the figure below the table of results.



Shear strength data underlying recommendation in lower figure (EBL 2003/NGI 2002 (upper diagram)) and secant friction angle (ϕ')-values for rockfill in prescriptive analyses (red) and for risk assessment (green, width shows extent of normal probability distributions) (Lacasse & Höeg, 2019) (lower diagram).

Results of the Monte Carlo analysis of the downstream slope, compared with the deterministic factor of safety

Slip surface	Deterministic SF	Probabilistic analysis		
	Safety factor, SF	Minimum SF	Maximum SF	Failure probability P_f
Shallower A	1.58	1.44	2.05	$P_f < 10^{-10}$
Deeper B	1.32	1.21	1.71	$P_f = 7 \cdot 10^{-7}$



Probabilistic distribution function of the safety factor for slip surface A in the stability analysis.

Comment to the three example analyses

It is important to note that the analyses prove a "snapshot" of the risk, at one point in time, for the conditions and circumstances analysed. Risk can change with time as changes occur (construction on and around the dam, rehabilitation work, climate change, change in the number of exposed persons or exposed dwellings, changes in exposure or infrastructure around the dam, etc). The risk assessment should be updated. The second round of analysis is always easier and more rapid than the first round.

Often there is a need for only simpler (qualitative or semi-quantitative analysis methods). One can start with simpler analyses like a risk matrix, and determine whether or not there is a need to examine certain situations with more advanced analyses. If the risk matrix shows medium-high to high risk, and this will influence the decisions to be made, then one should perhaps also do event tree analyses of Monte Carlo or SORM analyses. Annex A describes all the methods mentioned.

In the event tree or fault tree analyses, one can argue that the experts may have subjective opinions or that some may try to dominate a discussion. It is therefore important to have an experienced facilitator when the probabilities are discussed in a workshop. Group discussion and consensus are important. The need to include the uncertainties in the probability assessments that are arrived at by consensus is also important. As far as possible, the probabilistic assessments should be based on relevant experience and data (measurements or calculations). These are important elements to weigh in the discussions and reaching consensus.

Combining several risk analysis methods is often very useful, for example, failure of component scan be analysed with fault tree analyses, while the dam breach itself with event tree analyses. In an event tree analyses, one can evaluate the stability of the embankment slopes with Monte Carlo or First Order Reliability Analysis. Often event tree analysis (and Bayesian Networks analyses) are also combined (Annex A).

Risk communication and emergency preparedness

La Grande rockfill dam built on clay, James Bay, Northern Québec, Canada

Risk communication and emergency preparedness

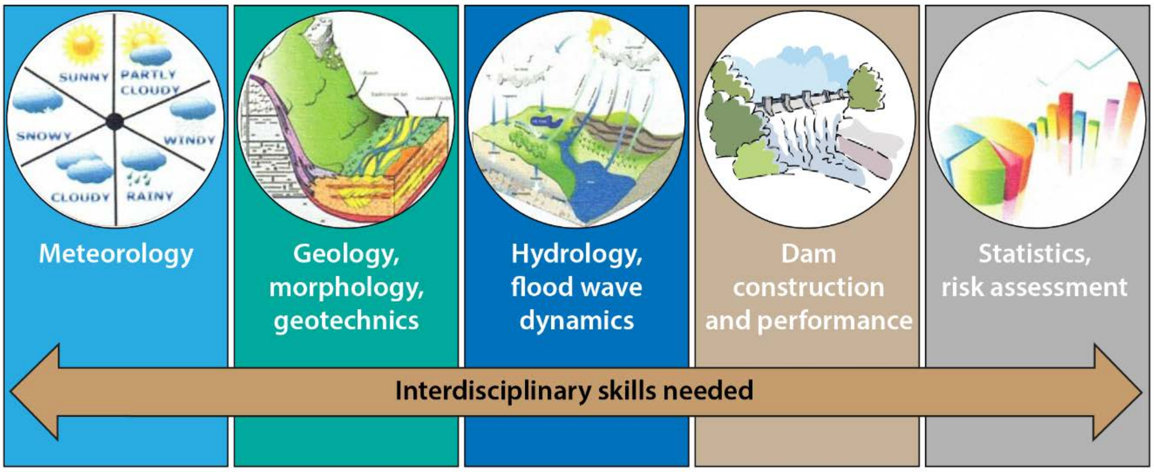
Example of a not necessarily effective risk warning

Risk communication and preparedness

Risk communication

Communication during risk assessment

To do the risk assessment of a dam, there is a need for multi-disciplinary expertise, especially if the analysis is in a workshop or discussion format. The figure below gives an example of such inter-disciplinarity that can be needed for a risk assessment. The most important is the knowledge and experience with the dam itself, the site geology and the dam construction and behaviour over its period of operation. The dam owner and its personnel have therefore an important role in the risk assessment exercise.



Example of required interdisciplinary expertise for an effective risk assessment

Communication with decision-makers, stakeholders and the public

A communication strategy needs to be carefully planned. Good communication with decision-makers and non-technical stakeholders should include:

- Understanding the position of each concerned party and the type of information each party needs. Delivery of data alone, for example, will not stimulate discussion or collaboration.
- Showing that one has to always deal with uncertainty in daily life (e.g., financially, technologically, climate effects, health and future)- Uncertainties are normal (see also Annex D).
- Avoiding complex and/or confusing (technical) formulation. If numbers are used, the numbers and their meaning need to be explained.

An example of a possible key to good communication strategy is the Progressive Disclosure of Information (PDI) approach (Kloprogge et al., 2007). The technique uses several layers of information, from non-technical to gradually more specific and specialised concepts, each tailor-made for the audience. For example, technical reports about uncertainties are for the specialists (called the "inner layer") whereas press releases and public notices are for the public ("outer layer").

The concept is further exemplified with the information to be given on uncertainties in the table below: the communication strategy on contents, style and level of detail from a dam owner to the inner and outer layer is described, with the level of detail increasing in the downward direction.

Explaining uncertainties: advice on contents, style and level of detail from a dam owner

Increasing detail level ↓

Inner layer (e.g., reports, technical notes)	Outer layer (e.g., press releases)
The uncertainties are listed and explicitly described.	The uncertainties are implicit in the wording used (e.g. with the word 'can')
The uncertainties are part of the scientific approach used for the analysis.	The uncertainties are mentioned where they are necessary to explain the results.
An explanation for each uncertainty is given from a scientific point of view.	The uncertainties are set in a socio-political context.
A balanced account of all uncertainties that may influence the risk assessment is set up.	The uncertainties are given significance relative to the socio-political agenda.
The type, size (e.g., standard deviation) and sources of the uncertainties are described.	The implications of the uncertainties are weighted against socio-political benefits and drawbacks.
The implications of the uncertainties (how they influence risk and mitigation) are listed.	The implications of the uncertainties are presented with the socio-political results that are achieved.
Complete description of the uncertainties, with technical terms and equations, is made.	Details are given, if they are considered relevant for drawing a 'policy' (but not in technical terms).

Preparedness

There is a range of emergencies that may occur in connection with a dam facility. It is important that the dam owner be prepared to react effectively if an emergency situation should arise. Two components are essential: emergency preparedness plan and emergency response plan. Contingency plans should be developed for all facilities, taking into account the risk profile, risk management and critical controls for the facility. Examples of emergencies are structural failure in a plant, rising water level, sudden leakage, development of a sinkhole etc. Other emergencies that can affect the operation and safety of a dam are, for example, loss of power, earthquakes and other extreme conditions such as forest fires, landslides in reservoir, avalanches, and so on.

Emergency response plan (ERP)

An emergency response plan describes the measures the dam owner and other affected parties initiate to prepare for an emergency situation, and to react if an emergency situation arises. Elements of the emergency response plan to be implemented should be developed in collaboration with the parties concerned. For example, the emergency response plan needs to be adapted if there are few people and little equipment available locally to ensure that equipment, fuel and personnel can be rapidly transported to the site. Specific response plans are required for on-site power generation and infrastructure. Suggested contents for an emergency response plan are given in the table below.

Emergency preparedness plan (EPP)

For emergencies that may have a downstream impact on safety, the environment, and/or the infrastructure, an emergency preparedness plan needs to be developed for both internal and external use. The emergency preparedness plan should be elaborated with input from local communities, including local, municipal and national authorities, if relevant. Copies of the plan need to be delivered to all potentially affected stakeholders, including first responders and parties responsible for emergency preparedness. Information in the emergency preparedness plan can be used by exposed communities, to assist in the development of their own emergency plan(s). Suggested contents for an emergency preparedness plan are given in the table below.

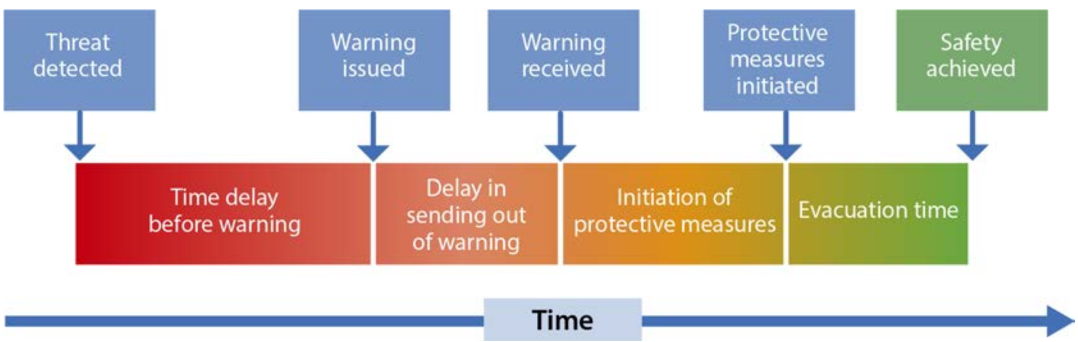
In an emergency situation, it is essential to account for the potential time delays in the process of an emergency situation, from the detection of a threat, issuance of warning, receipt of warning, initiation of mitigation or protective measures and evacuation time. The figure below illustrates schematically the time delays that may occur.

Emergency response plans (ERP):

- Potential emergency situations and conditions that will require the implementation of the ERP.
- Resources (people, equipment, material) needed to respond to emergency situations, including resources that need to be permanently on-site.
- Roles and responsibility for (1) dam owner, employees, contractors and consultants, and other agencies involved; (2) the command structure in case of an emergency situation; and (3) the contracts and agreements for reciprocal assistance.
- Access to the website (include different purposes).
- Communication: system, equipment and material.
- Procedures to activate plan (internal and external warning, and communication plans for emergency situations; updated contact information, both internal and external).
- Requirements and plans for training of personnel, both internal and external).
- Procedures and measures to be implemented to:
  - Prevent an unclear situation from becoming an emergency situation.
  - Limit consequences for life and health, environment and dams.
  - Reduce consequences (evacuation and rescue plans).
- Mechnanisms to warn potentially exposed parties of an unclear situation or a situation in progress (e.g., alarms downstream for emergency warning).
- Requirements for monitoring.
- Procedures and frequency for (1) testing the ERP with simulations, and (2) update the ERP.

Emergency preparedness plans (EPP):

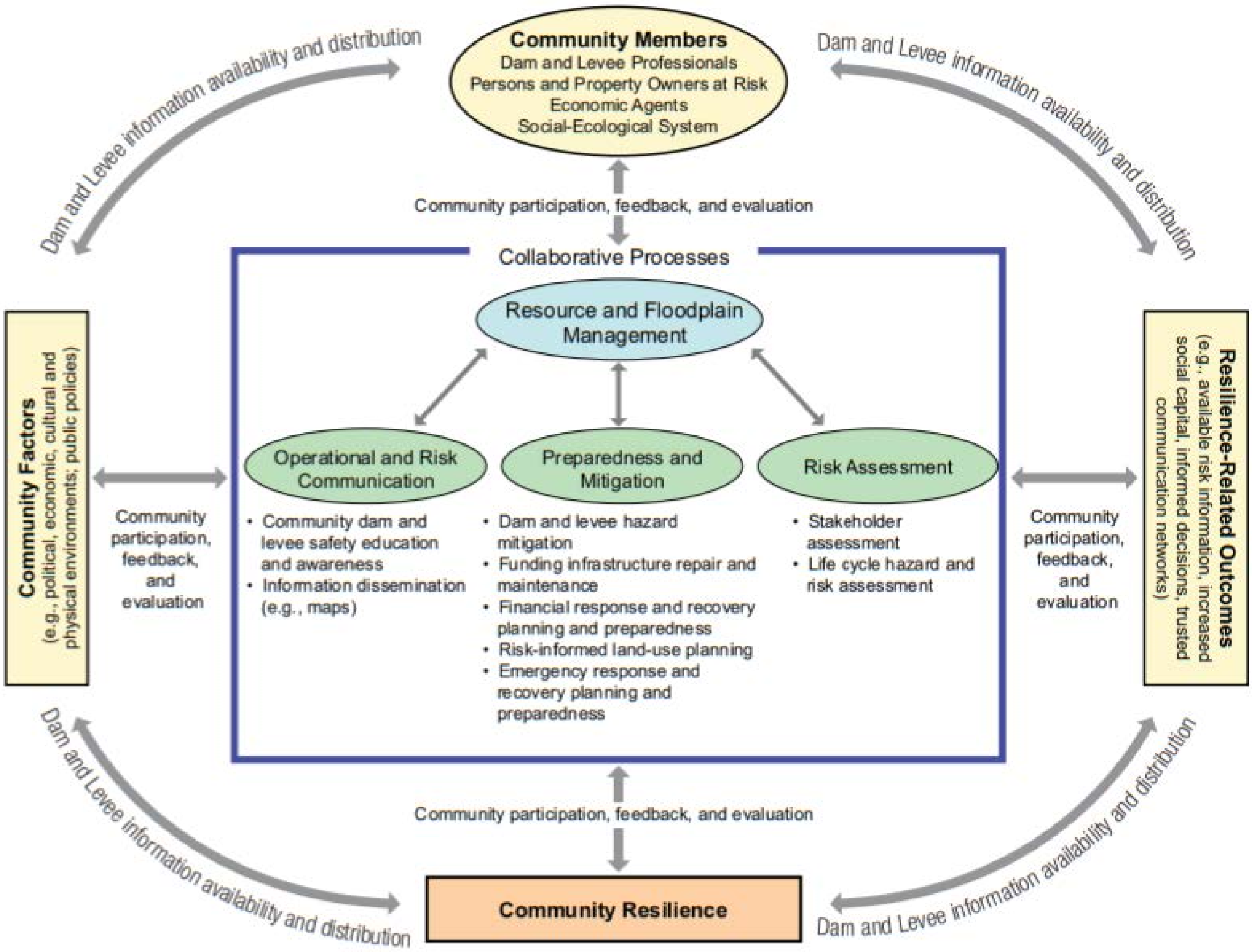
- Description of dam and dam system and its functions, potential emergency situation(s) and potential sequels of emergency situation(s).
- Dam owner's role and responsibility and command stucture in the case of an emergency situation.
- Warning procedures to follow under an emergency situation and when an emergency situation is expected, including updated contact information.
- Mechanisms to warn potentially exposed parties on an imminent or developing danger and emergency situation (e.g., alarms downstream).
- Procedures and frequency for testing and updating EPP.



Example of the time delays in warning of a threat and in evacuation (adapted from USACE and FERC, and using cellular phones for warning).

Community-focused resilience

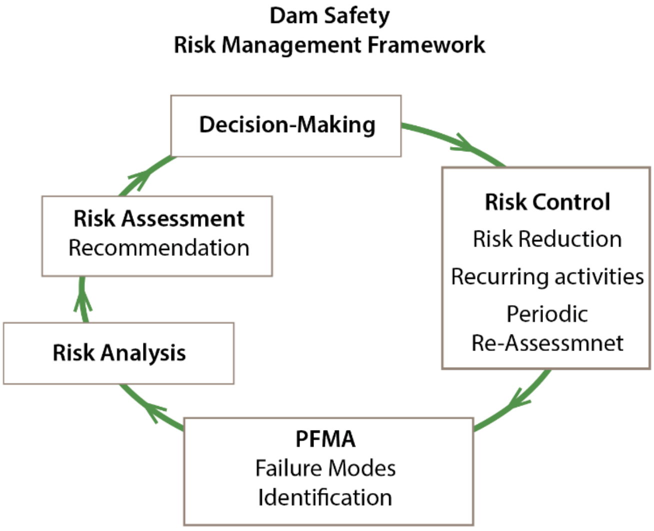
There is a growing trend in dam practice to develop plans for safety governance and community resilience. When possible, efforts should be made to progressively move towards increased focus on resilience and community. This would enable information access and collaborative risk management and gradually bring a cultural shift. Benchmarking of the progress with safety and engagement should be included. The figure below gives an example of a community resilience framework prepared for dams and levees in the USA.

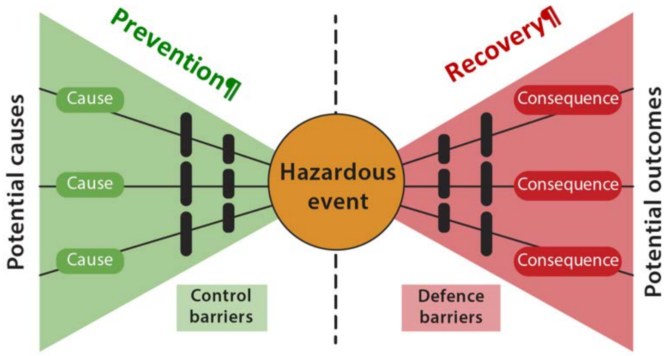


Conceptual framework for community-focused resilience collaboration for dam and levee safety (NRC, 2012).

Annexes

Annexes





Failure mode analysis, FMEA- and PFMA integrated in risk management framework (top) and Bowtie analysis (bottom)

Annex A Analysis methods and examples

Contents

Annex A Analysis methods and examples

A1 Overview of analysis methods

Annex A gives a brief description of most of the current methods available today together with examples. The annex includes a description of how to do the analyses, the required input and output and the results obtained.

The long table on the next page (Table A1) lists essentially all of the methods available today and suggests, for each method, a range of application and an estimate of the difficulty of use. The difficulty of use is categorised with five indices:

1 Simple
2 A few calculations or macro-operated Excel-spreadsheet(s)
3 Needs functions in Excel or MATLAB, may need a consultant
4 Commercial software, requires usually a consultant
5 Complex approach, used in special cases, and mostly with a consultant

For several of the methods (marked with* in Table A1), the risk assessment is best done in a workshop format, to identify triggers and failure modes, consider consequences and assess probabilities. It is practical to have an experienced facilitator to leas the workshop. For methods in Category 3 or higher, a consultant would help run the risk assessment together with the dam owner. There is today good software for the more advanced methods , such as the FORM og SORM methods. The four last methods in Table A1 are usually done by personnel with background in statistics and risk analysis.

The table below gives an overview of the contents of Annex A, with respect to the methods and examples described. Three of the methods have already been described in the main text.

Overview of methods descriptions and examples in Annex A

Risk assessment method	Paragraph in main text or Annex A	
	Method description	**Example**
QUALITATIVE AND SEMI-QUANTITATIVE METHODS		
Risk matrix	Section A2.1	Section A2.1
Bowtie-analysis	Section A2.2	Section A2.2
Dam Safety Maturity Matrix (DSMM)	Section A2.3	---
Risk Register	Section A2.4	
The Observational Method	Annex G	---
FMEA, FMECA and PFMA	Section A2.5	Section A2.5
QUANTITATIVE METHODS		
Event tree analysis (ETA)	In main text & Section A2.6	Ex. 1 in main text
Fault tree analysis (FTA)	In main text	Ex. 2 in main text
Bayesian updating	---	-
First order second moment (FOSM)	---	---
Monte Carlo simulations (MC)	In main text	Ex. 3 in main text
Bayesian Network (BN)	Section A2.7	Section A2.7
Response Surface Method (RSM)	Section A2.8	---
First and Second Order Reliability Methods	Section A2.9	Section A2.9
Stress testing	Section A2.10	---

Table A1 Overview of current risk assessment methods, suitability and level of difficulty.

Method (level of difficulty)	Short description and suitability
QUALITATIVE AND SEMI-QUANTITATIVE METHODS	
Risk matrix* **(1)**	Assesses hazard (likelihood) and consequence categories. ***Suitable for:*** Doing a preliminary estimates; get an idea of the level of risk to expect; decide whether or not there is a need for more detailed risk assessment.
LCI (Life Cycle) analysis ō **(1)**	Lists hazards and consequences over the entire lifetime of a dam. ***Suitable for:*** Showing potential threats; used to estimate financial/environmental losses.
Bowtie analysis* **(2)**	Identifies threats and the barriers to reduce threats and consequences. ***Suitable for:*** Risk management; to decide whether or not there is a need for more detailed risk assessment.
DSMM Dam Safety Maturity matrix* **(2)**	Checklist to evaluate the status of a dam safety program/process. ***Suitable for:*** Valuating the risk management system in a company; follow its evolution.
OM The Observational Method **(1)**	Analyse worse thinkable conditions; prepare in advance mitigation measures. ***Suitable for:*** All situations; requires monitoring.
FMEA, FMECA, PFMA *◊ Potential failure mode analysis (3 alternatives) **(2)**	Identify 'all' failure modes and if there is a need for more advanced analyses. ***Suitable for:*** All types of dams and safety problems.
QUANTITATIVE METHODS (ALL METHODS INCLUDE THE UNCERTAINTIES IN THE ANALYSIS)	
ETA Event tree analysis* ◊ **(2)**	'What if' analysis: initiation → progression → undesirable event or failure, quantifies the probabilities (hazards) and consequences.
FTA Fault tree analysis* ◊ **(2)**	***Suitable for:*** All types of dams and safety problems, gives failure probability.
Bayesian updating ō **(2-3)**	Updates an estimate, once more information becomes available. ***Suitable for:*** Instrumented dam: if unexpected event occurs and risk level may change.
FOSM First-Order Second-Moment ō **(3)**	Simple calculation of the effects of uncertainty on failure. ***Suitable for:*** Stability analyses; need explicit expression; method has limitations.
MC Monte Carlo simulations ◊ **(3)**	Repetition of analysis with random values for each uncertain parameter. ***Suitable for:*** All types of dams, needs many simulations if failure probability is low.
BN Bayesian Network*◊ **(3-4)**	An alternative to ETA, with graphical representation. ***Suitable for:*** All types of dams and safety problems.
RSM Response Surface Method **(4)**	Models response obtained from a complex calculation with polynomial. ***Suitable for:*** Calculating probabilities for a complex system, uses, e.g., FORM/SORM.
FORM/SORM ◊ 1st Order Reliability Method 2nd Order Reliability Method **(4)**	Taylor series expansion of a limit state; advanced MC type of analysis. ***Suitable for:*** Problems with an explicit formulation; somewhat improved estimate with 2nd order SORM; more efficient and more complete than MC.
Stress testing* **(5)**	Tool for global analysis of extreme events. ***Suitable for:*** Complete analysis of the dam and surrounding system(s); events with very low probability and very high consequences.

◊ An example is given in either the main text or in Annex A.
ō The method is not further explained in the handbook.

A2 Hazard analysis

A2.1 Risk matrix

About the method

Risk matrices give an estimate of risk by placing the hazards and consequences into different cells in a matrix. The cells are usually colour-coded and divided into a low, medium and high risk zone. Risk matrices can be of different sizes and with different risk zone definitions. Figure A1 shows an example of a 3 x 3 and a 5 x 5 risk matrix. Independently of the number of cells in a matrix (from 3 x 3 to 7 x 7) risk matrices have usually three risk zones:

High/Unacceptable risk (red): requires risk reduction measures.
Medium risk (orange): required considering putting in place risk reduction measures.
Low/Acceptable risk (green): no measures required.

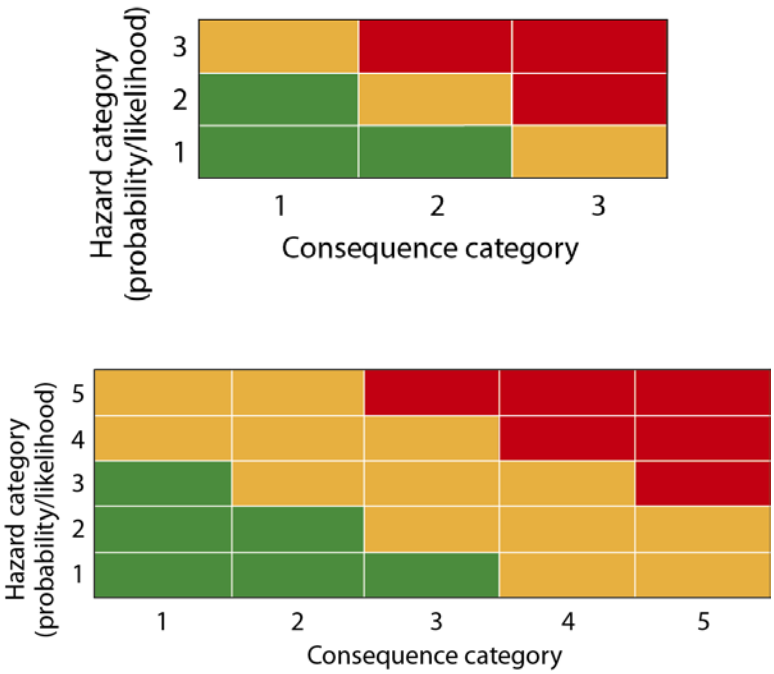


Figure A1. Risk matrix with low (green), medium (orange) and high (red) risk zones.

In a 3 x 3 matrix, the likelihood (probability) is divided into three categories: 1-Low, 2-Medum and 3-High. The consequences are also divided into three categories: 1-Low, 2-Medum and 3-High.

In a 5 x 5 matrix, five categories are used: for likelihood, the categories are selected as a function of 'how often can one event occur' or simply time. For consequence, the severity of the consequences is considered. Consequences need to include loss of life or health, material losses, work delays, and damage to environment, property, surroundings, etc, and third-party damage.

The tables below give examples of definitions of five categories for likelihood (probabilities) and consequences as part of the risk matrix construction. The user can select his/her own set of category definitions. There are no set rules, as long as the categories are defined. Figure A2 gives four examples of risk matrices. A risk matrix can be divided in different risk zones, and the risk zones do not need to be symmetrical. The selection of the high-risk zone depends on 'what is acceptable', and 'what is not acceptable'. One of the matrices shows possible mitigation measures assigned to each of the zones of low, medium and high risk.

Table A2 Examples of category definitions for likelihood and consequences in a 5 x 5 risk matrix.

Likelihood category	Probability of an undesirable event	Frequency
1	Very low probability	Less than once per 10 years
2	Low probability	Once per 5-10 years
3	Uncertain (do not know, 50% probability)	Once per 1.5 years
4	Probable	1-10 times per year
5	Nearly certain that the event will occur	More than 10 times in one year

Consequence category	Degree of severity	Economical losses L_e (€) (example)
1	No consequence	$L_e \leq 10{,}000$
2	Small consequence	$10{,}000 \leq L_e < 30{,}000$
3	Important consequence (dangerous)	$30{,}000 \leq L_e < 100{,}000$
4	Critical consequence	$100{,}000 \leq L_e < 1{,}000{,}000$
5	Catastrophic consequence	>1,000,000

Consequence category	Life and health	Material or environmental damage
1	No or very light personal injury	Insignificant material or environmental damage
2	Few and small personal injuries	Smaller material damage, some small environmental damage
3	Few, but serious, personal injuries or illness	Significant material or environmental damage
4	Potential fatality, several serious personal injuries, serious illness or permanent injury	Serious material damage, serious and long term environmental damage
5	One fatality or many serious personal injuries	Extensive material damage or very serious and lasting environment al damage

Running the analysis

The probabilities and consequences are usually discussed in a workshop-format. The workshop participants are personnel with relevant experience, competence and interest in the problem analysed. During the workshop, a list of the hazards and consequences is first drawn up. The risk is evaluated by placing each of the hazards and ensuing consequences in one of the cells in the risk matrix. It is important to assess all the plausible scenarios. The discussions in the workshop aim at obtaining agreement on the probability (likelihood) and consequence of each scenario studied. In addition, the workshop participants need to agree on the zones in the risk matrix that will represent Low, Medium and High risk. They depend on the definitions adopted for the likelihood and consequence categories.

Input, output and results

Usually the estimates are done in the workshop. The consensus categories reached during the workshop are placed in the matrix.

The results include the risk matrix and the list of the risk elements that need risk reduction measures.

Tool for the implementation of risk matrices in practice

Today, most of the risk matrices constructed in plenum (at a workshop) are compiled in an Excel spreadsheet. It is quite rapid to prepare such a spreadsheet, with macros to update the matrix as the evaluation for each event, scenario and potential consequence are made. Standard macro-activated spreadsheets already exist for risk assessment of effects of vibrations on foundation (Langford *et al.* 2019), stability of excavations (Kalsnes et al, 2016), damage due to groundworks (Piciullo et al. 2021; 2020; Langford *et al*. 2020) and the analysis of tunnel safety.

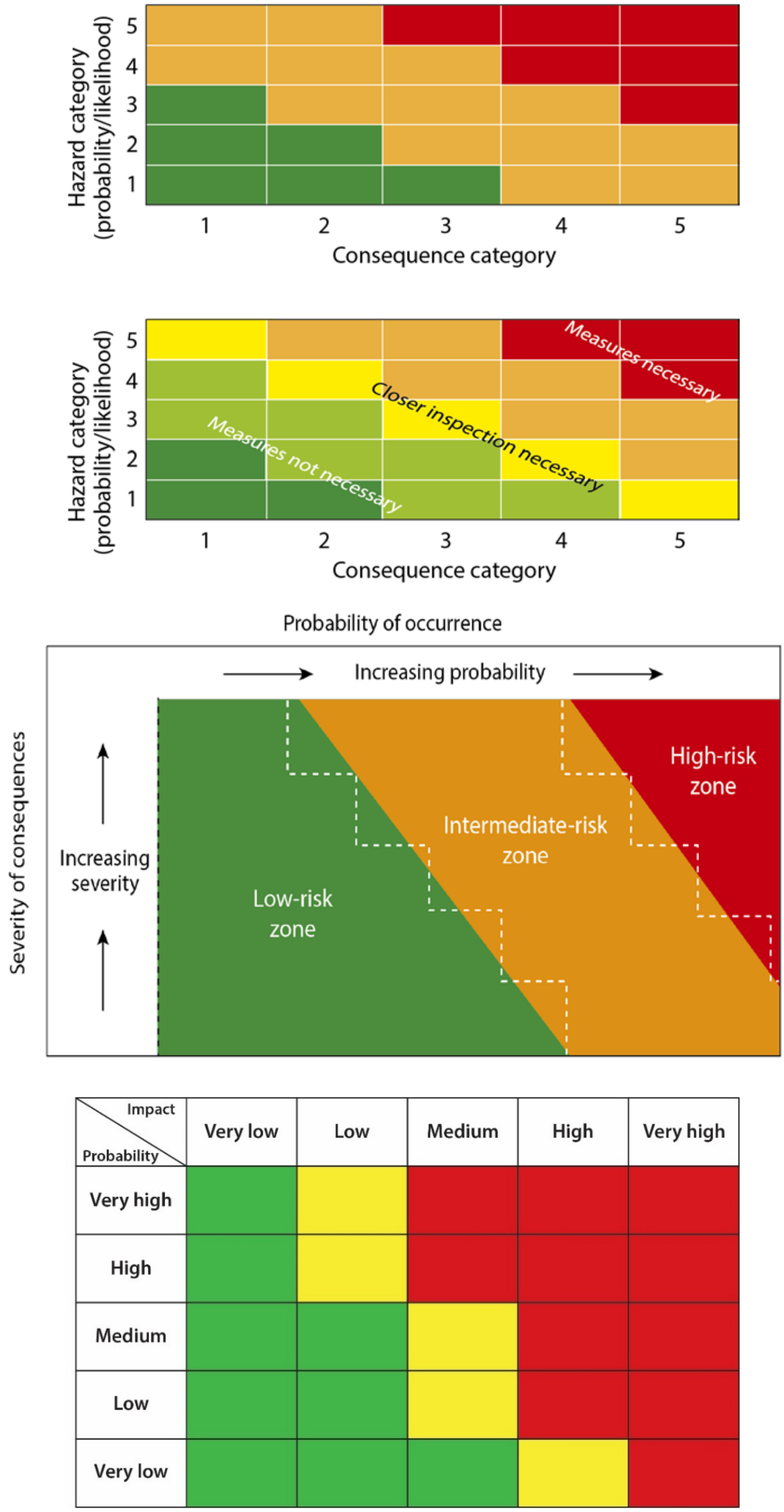


Figure A2. Examples of risk matrices, mitigation measures and division in three risk zones.

A2.2 Bowtie analyse

About the method

Bowtie analysis is a simple visual tool that can evaluate qualitatively the reliability of an entire system. The model is mostly used for risk management, especially for the development, implementation and review of risk management plans, but also involves risk assessment. Because the approach is visual, the Bowtie analysis is a good communication tool. It illustrates (1) the relationship between potential hazards and failure or failure mechanisms and how the hazards can lead to adverse events; (2) the consequences of an incident should it occur, and (3) the controls that may be developed to reduce the risk either the likelihood of an incident or the consequences (Fig. A3).

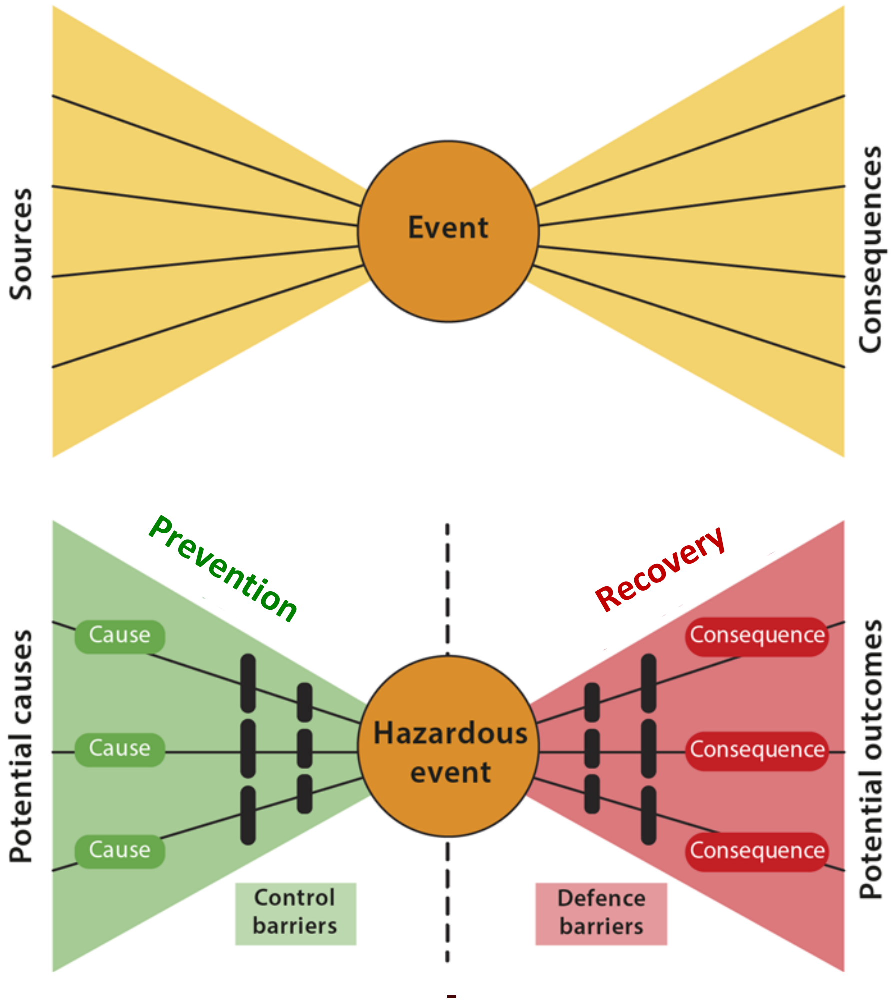


Figure A3. Illustration of Bowtie approach

The Bowtie method visualizes the relationship between an adverse event, the cause(s), unintended and unexpected scenarios and preventive and mitigating measures that are available to limit the consequences. At the heart of the Bowtie chart is the risk event, e.g. a dam break. On the left side are the causes for the event, e.g., an earthquake or flood. On the right side are the potential consequences, e.g. loss of life, damage to property, financial loss. The Bowtie analysis can assess several events from cause to consequence. The left and right sides are larger than the centre because there are many sources that can lead to a single risk event and many consequences that can follow one event. Choosing an 'Event' in the centre of the Bowtie provides a focus for the analysis.

The bowtie expresses probability and consequence via the left and right sides of the arrangement using "the **Swiss cheese model** (Fig. A4). The analysis tries to find the causes and conditions (holes in the Swiss cheese) that may align and lead to a failure. The same can be done for the outcomes (consequences), although this "Swiss cheese" approach is less used for the outcomes. The approach can "demonstrate" the effectiveness of existing or intended control measures.

The bowtie approach is a versatile, structured analysis when quantification is not possible. The method has been used successfully in many different technological industries. The approach requires the participation of an interdisciplinary team.

Running the analysis

The Bowtie analysis involves three qualitative aspects of risk: risk analysis, risk assessment and risk management. The method goes through the following steps:

1) Define the incident in the centre of the bowtie ("What happens when this event occurs")?
2) Identify the threats that are causing the event (what is the cause and how is control lost?)
3) Identify existing protection barriers for each threat:
    - barrier to prevent the occurrence of the event;
    - can the controls fail, or can their effectiveness be compromised?
4) Identify for each barrier escalation factors and factors that cause the barrier to fail:
    - how to prevent the danger from being released?
    - how can control be maintained?
5) Identify, for each barrier, controls for the escalation factors:
    - factors that prevent the barrier and / or recovery measure from becoming ineffective;
    - how to ensure that the controls do not fail?
6) Identify the consequences (there may be several consequences)

Swiss cheese model (Fig. A4):

The Swiss cheese model illustrates a system's defense against failure. The model has a series of barriers, represented as slices of Swiss cheese. The holes in each slice represent weaknesses in some parts of the system and vary continuously in size and position over the slices. The system produces failure when a hole in each barrier becomes aligned, and allows "a path for accident".

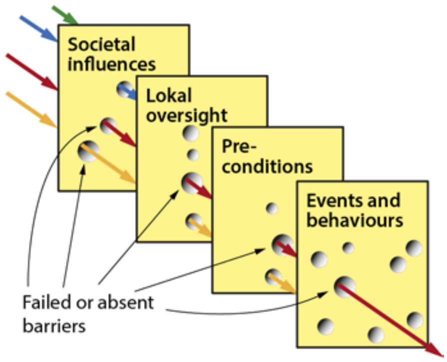


Figure A5 illustrates the Bowtie method with the Swiss cheese assimilation. The method leads to the listing of preventive and emergency measures. A separate list of controls is usually created because many controls are associated with more than one escalation factor or barrier.

Example for a tailings dam

Figure A6 gives an example of the Bowtie analysis for a tailings dam published by the Mining Association of Canada (MAC, 2019).

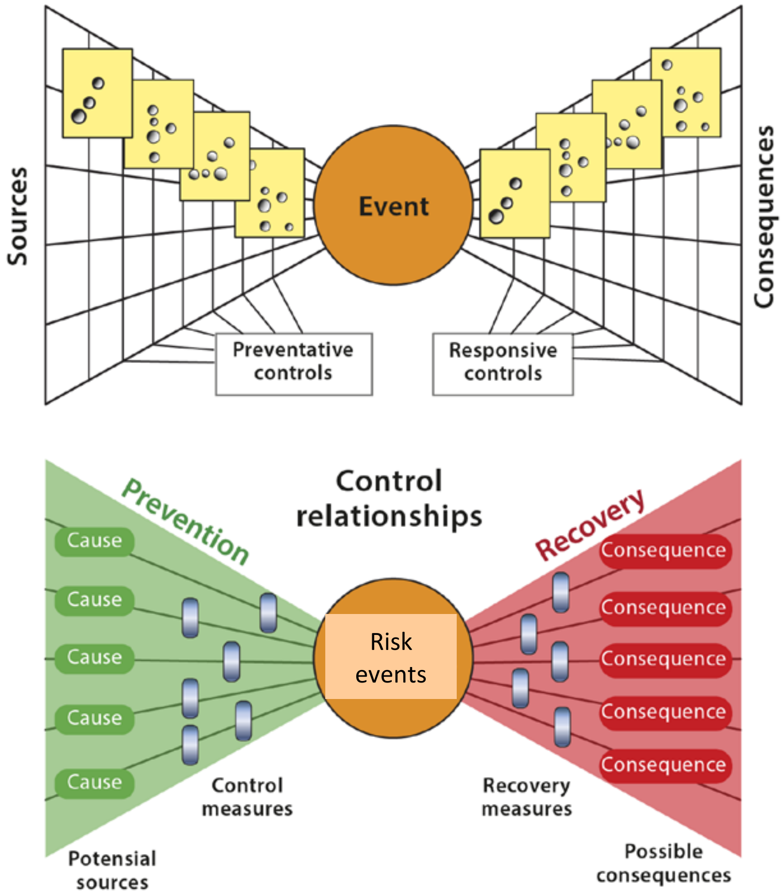


Figure A5. Bowtie-analysis, control measures and prevention and recovery measures

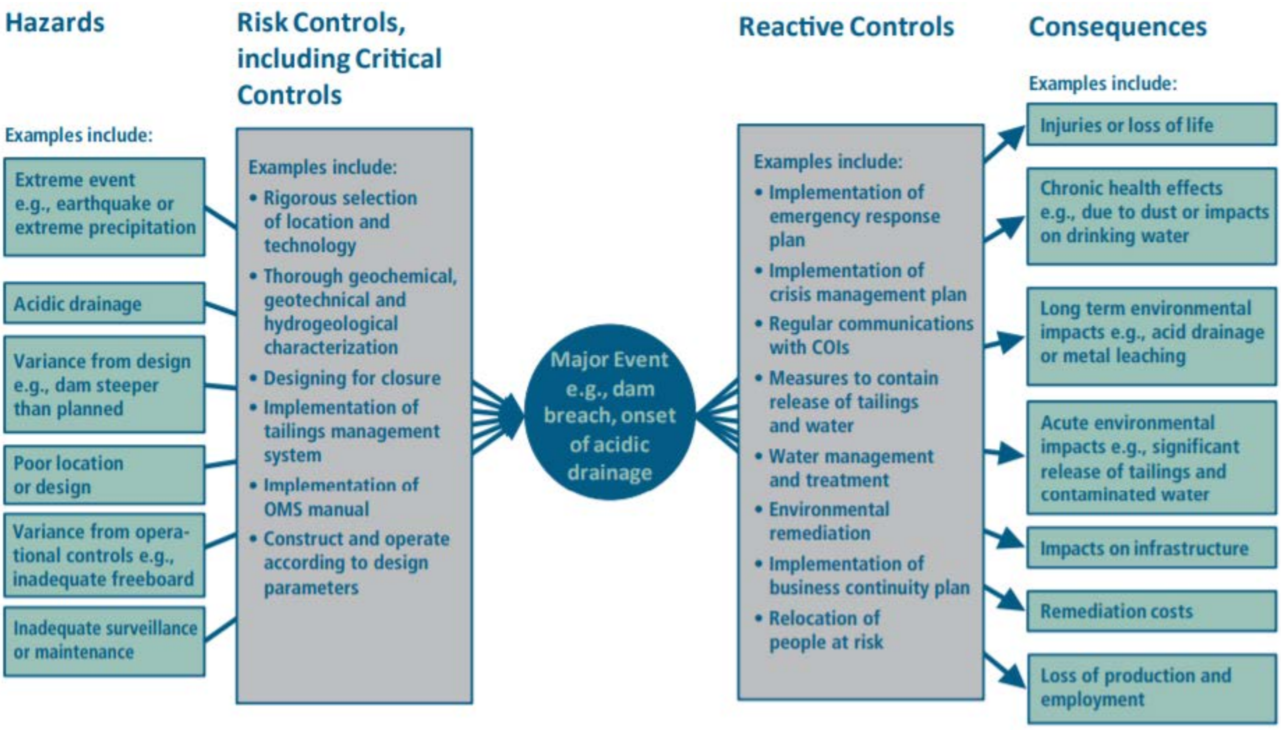


Figure A6. Example of a Bowtie analysis with hazards, risk controls, reactive controls and consequences (MAC, 2019)

A2.3 Dam Safety Maturity Matrix, DSMM

<u>About the method</u>

A maturity matrix is a tool to evaluate the status and effectiveness of a dam safety risk management system. The matrices were developed in CEATI's Dam Safety Interest Group (DSIG) to assess the effectiveness of their own dam safety program compared to industry practice, and to help identify improvement measures (Foster & Smith 2019). Dam owners need to manage many complex activities to maintain and operate their dams safely. Identifying and continuously improving the key elements of the dam safety program and associated practice is challenging, yet crucial. The use of Dam Safety Maturity Matrices (DSMM) is one way to do this.

The maturity matrix is usually a simple paper-based system with checklists, often in Excel format. In a maturity matrix, the development of risk management is assessed at different times and the progress evaluated. For example, a maturity matrix looks at all aspects of the operation of a dam (Fig. A7): personnel, documentation, systems and processes. The maturity matrix (Fig. A8) qualifies the status of an activity or process, from 'Needs development', 'Medium', 'Good practice', 'Best practice', to 'Leading'. By running assessments periodically, progress can be measured over time, gaps can be identified and actions prioritised. The discussions are also used to adjust the goals, if necessary, and re-oriented towards new priorities.

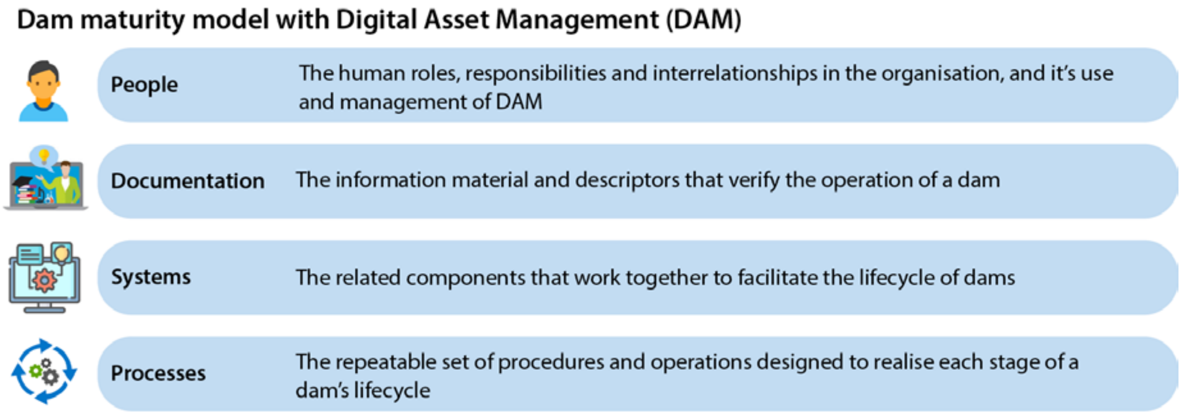


Figure A7. Dam Safety Maturity Matrix developed by CEATI

Matrix on: Monitoring - part: Monitoring program

Maturity category	Description of maturity				
	Needs development	Medium	Good practice	Best practice	Leading
Program developed for realistic failure modes					
Documentation, including inspections					
QA/QC completed					
Are objectives met?					
Any problem uncovered?					

Figure A8. Example of Dam Safety Maturity Matrix with description of maturity (Foster & Smith , 2019)

<u>Running the analysis</u>

A maturity matrix analysis is usually run in a workshop format and reported with an Excel matrix. A questionnaire is often sent to all stakeholders in advance of the workshop with questions about the current status and desired progress of the dam safety system in the company.

The implementation is very simple. In the workshop, the participants' answers are captured "live". Ease of use (with e.g. Excel) is absolutely critical, as the facilitator may need to capture and revise entries quickly. Goals, priority and action details are entered in the spreadsheet. For each topic, the current state and where one wants to be are ranked (with or without priority, action, a person in charge, and the time scale for completion). The workshop is used to discuss and adjust the answers. The most important objective is to identify the weaknesses (aspects that are less mature) and agree on measures to improve these aspects. The whole analysis consists of several matrices.

Table A3 shows a 'master matrix' that summarizes the moments that were assessed with each maturity matrix, and Table A4 provides am example of maturity matrix for monitoring. The maturity is estimated by five descriptors on the level of "expertise" or maturity for each aspect of the dam: "Needs development", "Medium", "Good practice", "Best practice" and "Leading expertise". Other categories or descriptors can also be used.

An even higher level of detail in monitoring is found in Figure A8. Note that in the tables blow, some aspects may not apply, for example to be the leading expertise on the "understanding the dam".

Table A3. 'Master'-maturity matrix where 12 main matrices will be constructed, and with hypothetical results shown.

DSMM analysis Main elements in matrix	Description of maturity				
	Needs development	Medium	Good practice	Best practice	Leading expertise
1. Understanding the dam					---
2. Monitoring					
3. Equipment water control					
4. Water reservoir operation					
5. Personal security					
6. Emergency response plan					
7. Dam maintenance					
8. Safety and risk management					
9. Revisions, observations					
10. Competence, lessons learnt					
11. Information security					
12. Management					

Table A4. Maturity matrix for monitoring for Element 2 'Monitoring' (Table A3), and with hypothetical results shown.

DSMM analyse Element2. Monitoring	Description of maturity				
	Needs development	Medium	Good practice	Best practice	Leading expertise
a. Monitoring program					
b. Inspections					
c. Instrumentation					
d. Data storage and management					
e. Interpretation of observations					
f. Follow-up of observations					

A2.4 Risk Register

About the method

A Risk Register is a record of all risks a community may face. It is the output of a risk assessment process, usually using qualitative estimates. The Register contains all information processed on risk identification and risk estimates, and describes which risk requires the more urgent attention. The Risk Register, when completed, contains the following information:

- Risk statements linking the risk source, hazard, impact area and consequences
- Present status
- Description of existing controls
- Consequence level
- Likelihood level for each hazard
- Risk level
- Confidence level
- Risk priority
- Additional comments, if needed

The approach is not very different from the Bowtie analysis.

Running the analysis

The objective of the analysis is to develop a systematic and comprehensive table of existing and potential risks. The analysis is usually run in a workshop format, often over several days, depending on the level of detail. It should involve all or most of the stakeholders and a pool of expertise in order to share ideas and understanding of risk(s). The steps in the analysis are:

1) Identify and describe the hazard(s) and its source(s).
2) Develop hazard scenarios.
3) Write risk statements for each hazard and impact area (where consequences occur).
4) Estimate the annual probability of the event(s) (AEP in Tables A6 and A7).
5) Determine the confidence level in the estimate.
6) Identify hazards controls.
7) Identify existing controls.
8) Identify where controls are needed and/or treatment (mitigation) options.

The identification of risks must be in real time, comprehensive and systematic to ensure that all risks are considered. The outputs of the analysis are:

- A comprehensive list of all potential risks to the community including key details of the risk(s).
- Credible worse case hazard scenario for relevant hazard(s).
- Risk statements concerning each plausible hazard.
- The Risk Register with the risk sources, hazards, impact areas, risk statements and controls.
- List of actions.

The results of the risk assessment are used to determine further action. Before decisions are made, the team needs an indication of the robustness of the risk assessment. To consider this, the level of confidence in the risk assessment process is used to identify and communicate uncertainty. Table A5 suggests a procedure to determine the confidence level in an estimate based on a discussion among many participants in a workshop.

Table A6 presents a template for a Risk Register.

Example of a Risk Register

Table A7 presents an example of a risk register for a flood scenario.

Table A5. Example of confidence level description

Confidence Level	Description	Supporting evidence	Team expertise	Consensus
Highest	Likelihood, consequence and risk are easily assessed, with almost no uncertainty.	Recent or historical event of similar magnitude at location of interest or quantitative modelling and/or analysis of highest quality and large quantity of relevant data.	Has relevant expertise and has demonstrated technical expertise.	Full agreement among participants.
High	Likelihood, consequence and risk are agreed to, but with some uncertainty in the assessment.	Recent or historical event of similar magnitude at a comparable location or quantitative modelling and/or analysis of sufficient quality and sufficient quantity of relevant data.	Has relevant technical expertise.	Disagreement on minor aspects only, which have little effect on the assessment of likelihood and consequence.
Moderate	Likelihood, consequence and risk could be placed in two categories; there is significant uncertainty.	Historical event of similar magnitude at a comparable location; or extrapolation of relevant quantitative modelling, analysis and/or data is required to derive results of direct relevance.	Has good and relevant technical expertise.	Disagreement on significant issues, which leads to an assessment of different categories of likelihood and/or consequence-
Low	Likelihood, consequence and or risk could be placed in three or more categories; there is major uncertainty.	Some comparable historical events through anecdotal information; or extensive extrapolation of quantitative modelling, analysis and/or data is required to derive results of direct relevance.	Has good general technical expertise,	Disagreements on fundamental issues related to the assessment of likelihood and/or consequence, which lead to a range of rating categories.
Lowest	Likelihood, consequence and risk could be placed in four or more categories; there is major, fundamental uncertainty-	No historical events or quantitative modelling or analysis or data to support the assessment of likelihood or consequence.	Has no relevant technical expertise for this assessment.	Fundamental disagreement on categories of likelihood, consequence and/or risk; and little hope of reaching an agreement.

Table A6. Example of a template for a Risk Register

Risk no.	Risk Statement	Risk source	Hazard	Impact Area	Existing prevention/ preparedness controls	Existing Recovery/ Response Controls	AEP	Consequence Level	Likelihood Level	Risk Level	Confidence level	Risk Priority	Treatment Options

Table A7. Example of risk register for a flood event

Risk no.	Risk Statement	Risk Source	Hazard	Impact Area	Existing Prevention/ Preparedness Controls	Existing Recovery/ Response Controls	AEP	Consequence Level	Likelihood Level	Risk Level	Confidence Level	Risk Priority	Treatment Options
1	A significant rainfall event in <location> causing flooding will impact the health of persons and cause death(s).	Severe Rainfall	Flood	People	• Early warning system • Flood forecasting • Flood information brochures pre-season • Flood awareness kits	• SES rescue boats available but limited • Evacuation plan including shelters	0.05	Major	Likely	Extreme	Moderate	1	• Further develop and implement early warning systems • Pre-season advisory/awareness campaign on risk mitigation activity and options • Development of a specific flood response plan including a detailed evacuation plan • Establish arrangements with medical services cooperated response
2	A significant rainfall event in <location> causing flooding will impact crops and consequently harvest, resulting in financial losses.	Severe Rainfall	Flood	Economy	• Early warning system • Flood forecasting • Drainage system maintenance • Farm dams	• Some business continuity plans in place • Land use zoning	0.05	Moderate	Unlikely	Medium	Moderate	3	• Encourage business continuity plans, e.g. use harvest for stock feed • Land use planning • Culvert maintenance • Improvement in farming dams
3	There is a risk that a flood will cause substantial damage to infrastructure services that may result in shutdown and inconvenience to residents for periods 24 hours or more.	Severe rainfall	Flood	Social setting	• Early warning system • Flood awareness kits • Radio announcements	• Evacuation plan including shelters • SES rescue boats available but limited • Evacuation signs	0.05	Moderate	Likely	High	High	3	• Identify access routes for safe self-evacuation • Increase SES resources, e.g. rescue boats • Develop further a detailed evacuation plan including roles and responsibilities and resourcing • Pre-season advisory/awareness campaign on risk mitigation activity and options

A2.5 Failure mode Analysis, FMEA

About the method

Failure Modes and Effects Analysis (FMEA) is a structured, logical framework that enables dam owners to use available knowledge and information in a systematic way to understand the sources of risk for a dam or a dam system. The analysis 'qualifies' (describes) the effect of a potential failure development on a dam (or dam system). The FMEA can evaluate the effect of a failure of each element in a system (and in the sub-systems) along several possible paths until the effect on the dam or dam system function is known. The severity of each failure is then classified and the probability is estimated. The framework includes risk analysis, risk assessment and risk management. The method is similar to a qualitative event tree analysis (described in the main text). One could also choose to quantify instead of qualifying the probabilities, and one can add an uncertainty factor to the analyses, but this rarely done, one turns to event tree analysis rather. Figure A8 illustrates the FMEA method integrated in a risk management framework, as recommended by FERC (2016).

There are two variations of the FMEA method: (1) "Failure Modes, Effects and Criticality Analysis" (FMECA), where 'criticality' expresses the importance of the components on the good functioning of a dam or a dam system; and (2) "Potential Failure Mode Analysis" (PFMA) focusing on identified, targeted areas within a dam or a dam system with potentially serious and plausible shortcomings, so that limited financial resources can be used more efficiently to ensure dam safety.

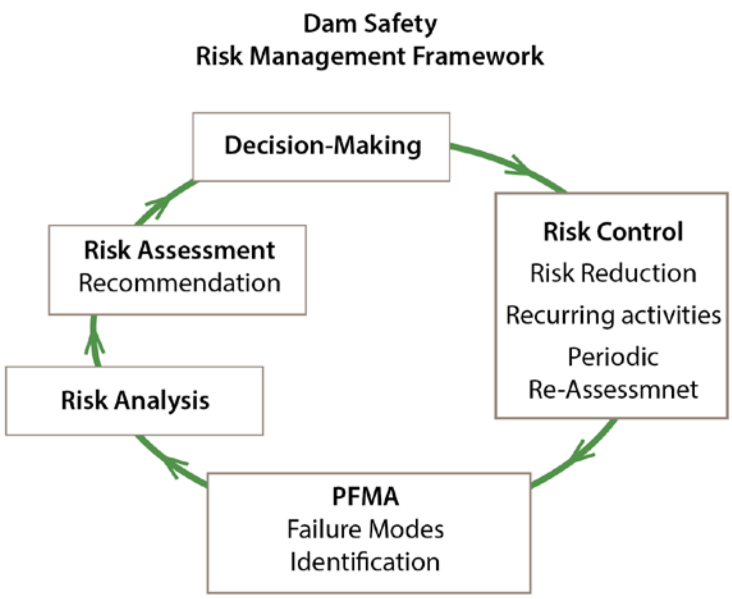


Figure A8. FMEA og PFMA method integrated in a risk management framework

Running the FMEA analysis

The analysis consists of the following steps:

- Describe the dam and its function(s); make sure everyone understands the way the dam works.
- Create a block diagram, with the most important components and/or processes and the logical relationship among them; establish a structure for the block diagram.
- Use the block diagram to list elements and their functions.
- Identify all the causes and mechanisms of failure, in which way a component or process does not satisfy the design intention (e.g., failure mechanisms due to spillway, overtopping, uplift, overturning, cavitation, etc.).

– Describe the effect of each failure mechanism and trigger.
– Identify probable causes, existing controls, detection methods, etc.
– Enter a qualitative probability factor (or category).
– Evaluate risk (probability x consequence), again qualitatively.
– Determine or recommend mitigation measures
– Assign responsibilities and deadlines.
– Follow up and update as needed, measure progress on completion of mitigation measures.

The analysis is usually done in a workshop format with brainstorming about chains of events that can lead to failure, evaluation of relevance and rapid elimination of less relevant chains of events. Figure A9 gives an example of a block diagram and Table A8 summarizes the steps in the analysis. To evaluate confidence in the probability and consequence estimates, one can use the categories in Table A5.

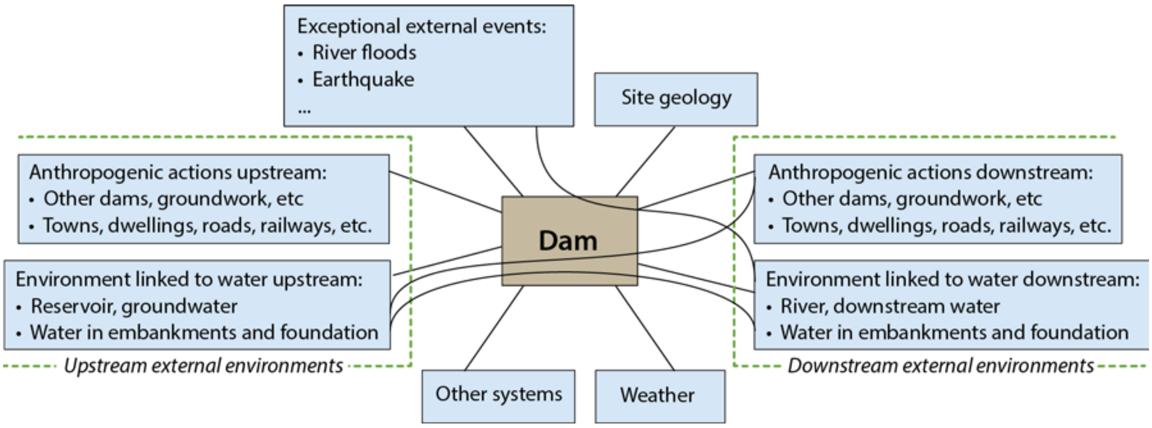


Figure A9. Example of a block diagram in a PFMA analysis for a dam

Table A8. Steps in the PFMA-analysis

1. Identify failure modes (mechanisms and triggers)
2. Assess failure probability
3. Estimate consequences
4. Assess degree of confidence in probability and consequence assessments.
5. Categorise and prioritise risks
6. Plan risk reducing measures and mitigation
7. Prepare a summary report

Potential failure modes and triggers

Identifying and characterizing all the potential failure causes and mechanisms is the key to the analysis. The analysis includes a number of events or threats such as: (1) Natural hazards (e.g., earthquakes, landslides, extreme weather events, floods); (2) Incidents related to a structural part (e.g., water pipes, gates, hatches, slopes); (3) Operating events (e.g., failure of a pump). For each potential failure mechanism, the probability of the event occurring is estimated together with the potential magnitude of the event (e.g., maximum credible earthquake, likely largest flood). There can be a large number of potential failure mechanisms. The most important risks should be prioritized in the analysis. An FMEA analysis also assesses the potential for chain reactions or combinations of mechanisms that may have greater effects than each failure mechanism taken separately.

Effects and consequences

Once the potential failure mechanisms have been identified, the potential effects on the dam/dam system are identified to understand the potential effects that may be caused by a failure mechanism (e.g., collapse of a slope, release of water through the spillway, overtopping). For each identified effect, potential consequences of that effect are also identified. Consequences can occur in a number of areas, including legal implications as well as:

- Loss of life.
- Health and safety for personnel and the public.
- Damage to the environment.
- Damage to private or public property.
- Damage or delays in the operation and production of the dam.
- Damage to infrastructure on site or outside the site.
- The dam owner's finances and reputation.

FMECA-analysis (Failure Mode-Effects-Criticality Analysis)

The FMECA analysis expands the FMEA analysis so that each identified breach mechanism and cause are ranked by importance and "criticality". The criticality analysis is usually qualitative or semi-quantitative, but can be quantified using observed failure frequencies. In risk analysis, the FMCEA methodology can be used for parts of the system or for individual events in a chain of events. USACE (2012) issued guidelines for conducting risk analyses for dams with the method.

FMECA-analysis:

The FMECA analysis maps the ways in which an equipment, process etc can fail, what effect it has locally and globally as well as the criticality of the Failure. Criticality is defined as a combination of consequence and probability.

PFMA-analysis (Potential Failure Mode Analysis)

With the PFMA, the identification and investigation of potential failure modes is done in a more cost-effective way than with the FMEA analysis because only the most relevant/plausible chains of events are considered.

Comment

The FMEA / FMECA analysis methods are tools that are adaptable to many different purposes. They can contribute to improved design, higher reliability, better quality, increased safety and reduced costs. The methods can also be used to establish and optimize maintenance plans and/or contribute to controls, inspections and other quality assurance and risk management procedures. The methods also provide a knowledge base on failure modes, mechanisms and causes and delivers additional information for corrective measures that can be used as a resource in future troubleshooting work and as a training tool.

Both US and UK standards recommend that the FMEA be supplemented with other methods, especially where multiple failure mechanisms and sequential effects must be considered. The FMEA turns out to be "essential, but not sufficient" method, according to many publications on the risk assessment method. The analysis can also end up with very large spreadsheets. The method is good for supplementing the Fault Tree Analysis method (presented in the main text). The most useful aspect of the FMEA method is the thorough description of the dam and its function, and the block diagram that shows the important components of the dam and their interrelationships.

Example

Figure A10 (in two parts, on two pages) gives an example of an FMEA analysis of a dam.

Comp. ID	Description	Functions and operability requirements
I.1.1	Reservoir slopes	Retention of pounded water and tailings
I.1.2	Reservoir bottom valley	Water-tightness at the reservoir basin
I.2	Remaining catchment basin	Catchment of the rainfall water
III.1.1	Upstream protection layer	Protection of the upstream shell from the waves' action
III.1.2	Upstream shell	To guarantee the mechanical stability of the dam
III.1.3	Downstream shell	To guarantee the mechanical stability of the dam
III.1.4	Clayey core	Positive control of the phreatic surface and seepage flow
III.1.5	Geomembrane	Watertightness of the zones above the core
III.1.6	Chimney drain	To prevent core internal erosion and drain seeping water
III.1.7	Drainage blanket	To drain and filter the water from the chimney drain and from the foundation
III.1.8	Downstream toe drain	To drain and filter the water from the drainage blanket
III.2.1	Rock foundation (below 244 m elevation)	To support the capacity of the embankment and provide some water-tightness at the core base
III.2.2	Rock foundation (above 244 m elevation)	To support capacity of the embankment and provide some water-tightness at the plinth base
VII.1	Spillway structure	To ensure a controlled discharge under exceptional inflow conditions
VIII.1	Drainage wells	To collect all the seepage water (through the embankment and foundation)
VIII.2	Pumping system	To pump the water collected in the wells back into the reservoir

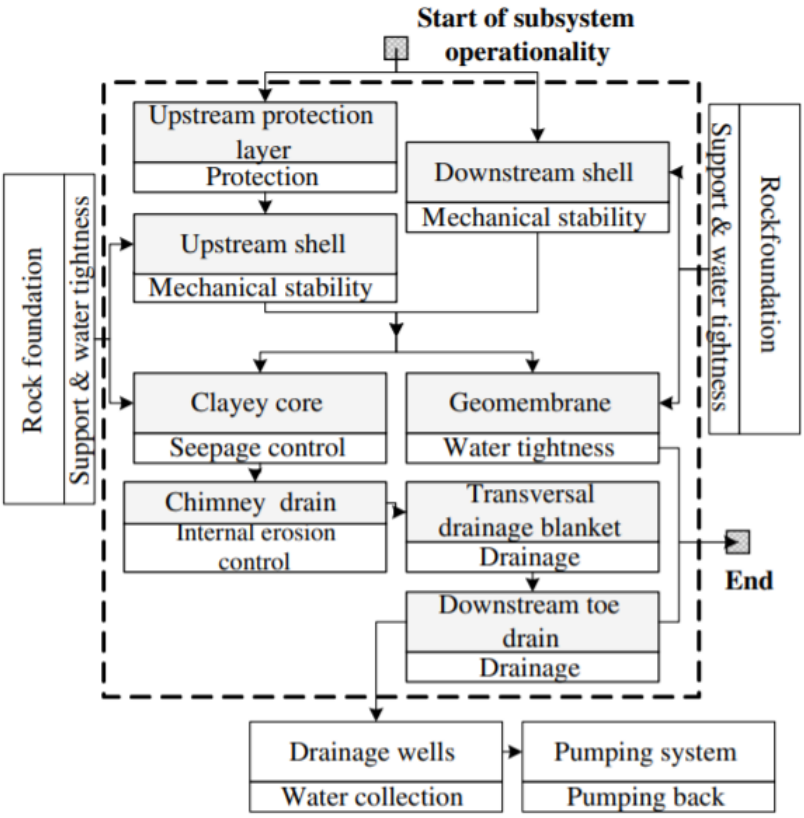


Figure A10 continues on the next page

Comp.	ID	Failure mode	Root causes
Upstream protection layer	III.1.1.(1)	Erosion	Waving under wind action, chemical alterability, wetting – drying cycles and thermal variations (fracture and weathering) of rockfill material
Upstream shell	III.1.2.(1)	Instability	Seismic action, chemical alterability, insufficient interface resistance (soil/geomembrane)
	III.1.2.(2)	Excessive deformability	Chemical alterability, collapse, creep, inadequate compaction
Downstream shell	III.1.3.(1)	Instability	Seismic action, insufficient shear strength in the contact between materials applied in different phases
	III.1.3.(2)	Excessive deformability	Third heightening loading, creep, inadequate compaction of third phase materials
	III.1.3.(3)	External erosion	Overtopping due to exceptional inflow conditions
Clayey core	III.1.4.(1)	Excessive seepage (without cracking)	Chemical alterability, material dissolution, excessive hydraulic head and gradients
	III.1.4.(2)	Excessive seepage (with cracking)	Hydraulic fracturing
Geomembrane	III.1.5.(1)	Cracking	Stress cracking, chemical attack, perforation, incorrect installation (core and foundation connections, overlapping, sunlight exposure and punching)
Chimney drain	III.1.6.(1)	Internal and external instability	Inappropriate materials, incorrect construction, chemical alterability
	III.1.6.(2)	Insufficient drainage	Insufficient thickness
Drainage blanket	III.1.7.(1)	Internal and external instability	Inappropriate materials, incorrect construction, chemical alterability
	III.1.7.(2)	Insufficient drainage	Inappropriate grain-size distribution, insufficient dimensions given the water level increase
Downstream toe drain	III.1.8.(1)	Internal and external instability	Inappropriate materials, incorrect construction, chemical alterability
	III.1.8.(2)	Insufficient drainage	Inappropriate grain-size distribution, insufficient dimensions given the water-level increase, external obstruction
Rock foundation (below 244)	III.2.1.(1)	Excessive seepage	Rock discontinuities, schist chemical alterability, deficient clearing, grubbing and stripping
Rock foundation (above 244)	III.2.2.(1)	Excessive seepage	Rock discontinuities, schist chemical alterability, deficient clearing, grubbing and stripping, deficient connection to the concrete plinth

Figure A10. Example of a FMEA-analysis (Santos et al., 2012):
Top figure (previous page): Components in analysis
Mid figure (previous page): Block diagram
Bottom figure (this page): Failure modes (mechanisms and causes)

A2.6 Event Tree Analysis (ETA)

Schematic of event tree analysis

Figure A11 illustrates schematically an event tree for internal erosion in an embankment dam. The nodes (red circles) are where the probabilities are assigned. At each node, a question is asked, given that the previous event a have occurred. The outcomes are given as triangles. A green outcome indicates no failure (or breach), the one red outcome (red triangle) indicates failure. There can be several outcomes resulting in a failure in one event tree.

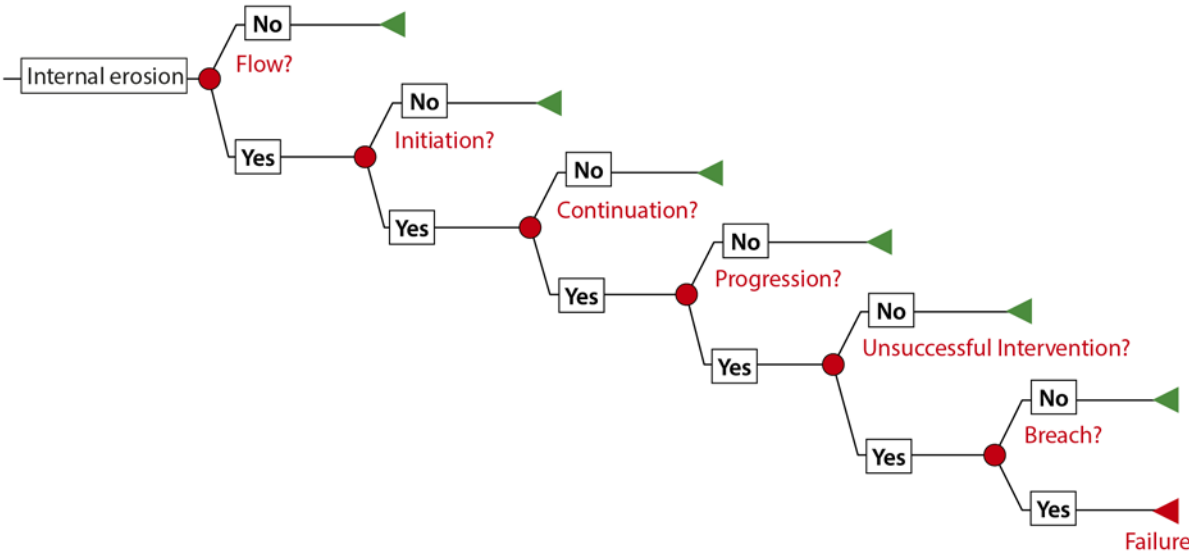


Figure A11. Schematic illustration of an event tree analysis and example of notation used.

Estimate of probabilities in an event tree analysis

There are many different tables for the description of uncertainty and probabilities. As far as possible, one should link the subjective assessment of probabilities to experiences under comparable circumstances. This forces the expert team to weigh in the probability estimate the relevant precedent events. Different countries have different tables and numerical values. The tables in the main text are among those most often used in risk assessments for a dam. Barneich *et al.* (1996) developed for the nuclear power industry a "Subjective Probability Estimate Guide" (Table A9). These guidelines reflect the probability as perceived for the nuclear industry and should be compared to ensure that consistent probability values are used throughout an event tree analysis.

In China , the probability estimates in Table A10 are used (Zhang *et al*., 2016; Li *et al*., 2006).

Table A9. Guidelines for subjective probability estimates for the nuclear energy industry (after Barneich et al., 1996)

Verbal description	Probability
Event is virtually certain.	1
Event had been observed in the available database.	0.1 (10^{-1})
Event has not been observed earlier or only once in the available database; several potential failure scenarios can be identified.	0.01 (10^{-2})
Event has not been observed earlier in the available database; it is difficult to imagine any plausible failure scenario, perhaps one scenario can be identified.	0.001 (10^{-3})
Event has not been observed earlier, and no plausible scenario can be identified, even after detailed discussions.	0.0001 (10^{-4})

Table A10. Subjective probability estimates for risk assessment of dams in China (Zhang *et al.*, 2016; Li *et al.*, 2006).

Verbal description	Probability	Probability
Event is virtually unlikely	0.000001 – 0.0001	$10^{-6} – 10^{-4}$
Event is very unlikely	0.0001 – 0.01	$10^{-4} – 10^{-2}$
Event is likely	0.01 – 0.1	$10^{-2} – 10^{-1}$
Event is very likely	0.1 – 0.5	$10^{-1} – 5·10^{-1}$
Event is virtually certain	0.5 – 1.0	$5·10^{-1} – 1$

A2.7 Bayesian network (BN)

About the method

A Bayesian network (BN) is a tool for modelling uncertain event sequences. The Bayesian network was developed in the area of artificial intelligence and is an expanded and more powerful form of event tree analysis[1]. A Bayesian network creates a graphical and numerical probabilistic model that describes relationships among events. The network can be expressed as follows:

$$B = G(Z, E)$$

where B is the network and G a function with nodes (Z) and arcs (E). Z is a vector with the uncertain parameters ($z_1, z_2, \ldots z_n$), E represents the probabilistic relationships among the uncertain parameters. Figure A12 illustrates three types of relationships among the events: (1) linearly series-connected, (2) converging and (2) diverging. A network relationship cannot be a closed circle.

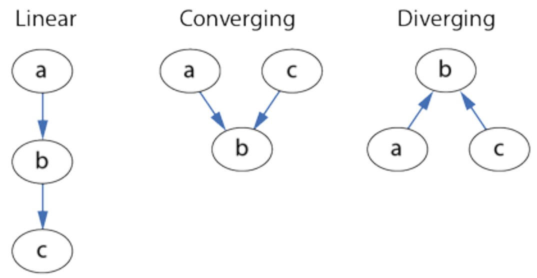


Figure A12. The three relationships between events a, b og c in a Bayesian network

Running the analysis

The selection of input parameters for a Bayesian network analysis is best done using a workshop format, as for event tree analyses, where the probabilities and the relationship between the events are discussed. The same method as for event tree analysis (ETA) is used to discuss and determine probabilities for each event. The actual calculations and graphics are prepared with the Matlab software package. Probability values and the uncertainty in the probability values for each event need to be determined, as well as the relationships between the events. The analysis gives the probability of failure for each scenario and the total probability of failure for all the scenarios combined. In addition, the analysis, combined with Monte-Carlo simulations, can provide the distribution (PDF) of failure probabilities for the dam, with an average and minimum and maximum value for failure probability.

Example

A Bayesian network analysis of an embankment dam for the failure scenario 'ice and hard-packed snow blocking the spillway' is presented in Figure A13. These analyses supplemented the results from event tree analyses. A Monte Carlo simulation was also done, using a range of probabilities for each event to describe the uncertainty in the probability estimates. The top figure illustrates the network with the relationships among the events for the case 'Ice and hard-packed snow blocking the spillway'. The probabilities in the lower figure (best estimate is shown) were established through a consensus in the same way as for event tree analyses.

.[1] Bayesian network hac been applied to dams only for the past 4-5 years.

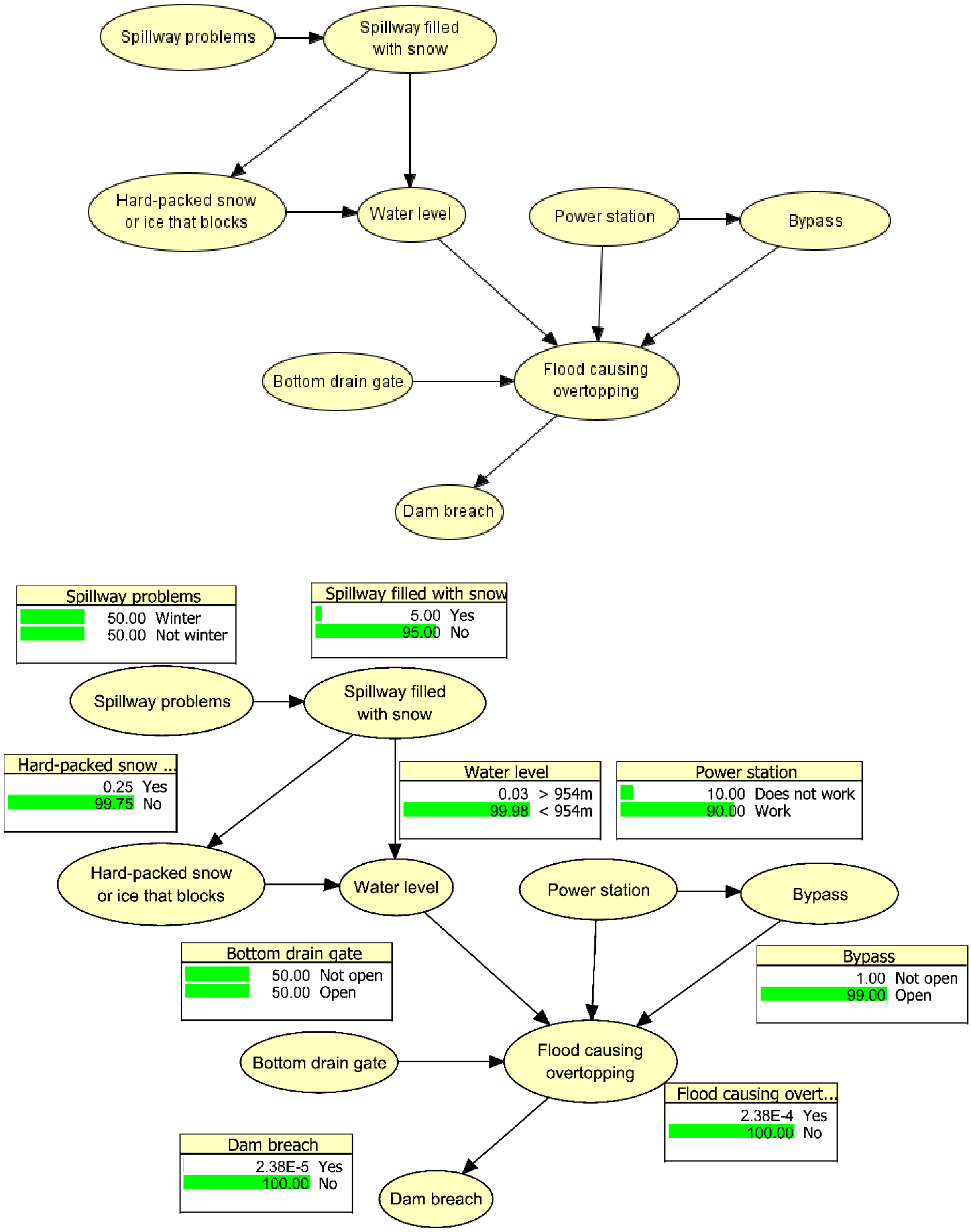


Figure A13. Bayesian network for dam failure due to 'ice and hard-packed snow blocking the spillway': network structure (top) and probabilities (lower) (in % points (i.e., 99 = 0.99)*; green bars show relative magnitude).*

The Monte Carlo analyses were run to delimit the effect of lower and upper estimates on the calculated failure probability and quantify the average failure probability. The Monte Carlo simulations used the "Bayesian Network Toolbox" in MATLAB. Figure A14 shows the distribution of the failure probabilities for the analysis in Figure A12. The Monte Carlo results are given as a histogram of failure probability. A lognormal function was used as the "best fit" of the histogram. The mini-table in Figure A13 summarizes the statistical probability of failure obtained after 512 simulation. The probability of failure caused by 'ice and hard-packed snow blocking the overflow' had the following values:

Mean ($P_{f\,annual}$) = $2.3 \cdot 10^{-7}$/year
Minimum ($P_{f\,annual}$) = $4.0 \cdot 10^{-8}$/year
Maximum ($P_{f\,annual}$) = $7.7 \cdot 10^{-7}$/year

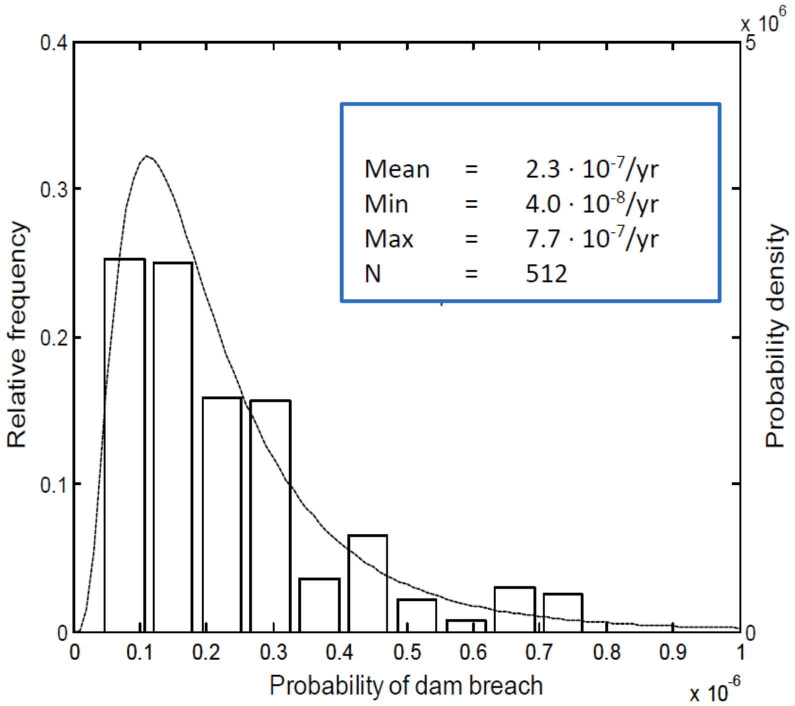


Figure A14 Probability distribution function of the failure probability for the dam under the 'ice and hard-packed snow blocking the spillway' scenario.

A2.8 Response surface method (RSM)

About the method

The Response surface method can model probabilistically complex problems that are usually modelled with finite elements (FEM) or other advanced models. Ordinarily, the approach has two stages: in a first step, deterministic FEM analyses are repeated by varying each uncertain input parameters in function of its statistical distribution. In the second stage, the results of the deterministic analyses are approximated by a second-order polynomial, which is then to analyse, for example the stability of the dam embankment. Figure A15 illustrates the approach (this is today a "standardized" approach for this type of analysis, and can be run relatively easily by an experienced consultant).

Running the analysis

The probability estimates are obtained by combining the deterministic 2D or 3D FEM analyses with a "response surface" and a reliability-based calculation of failure state such as FORM and SORM (see A2.9). Once a response surface has been found to fit the deterministic results, the following steps are performed to calculate failure probability: (1) quantify uncertainty in input parameters and the analysis method; (2) express the limit state function (expressing failure); (3) do the FORM analysis; and (4) calculate failure probability (P_f) and reliability index (β).

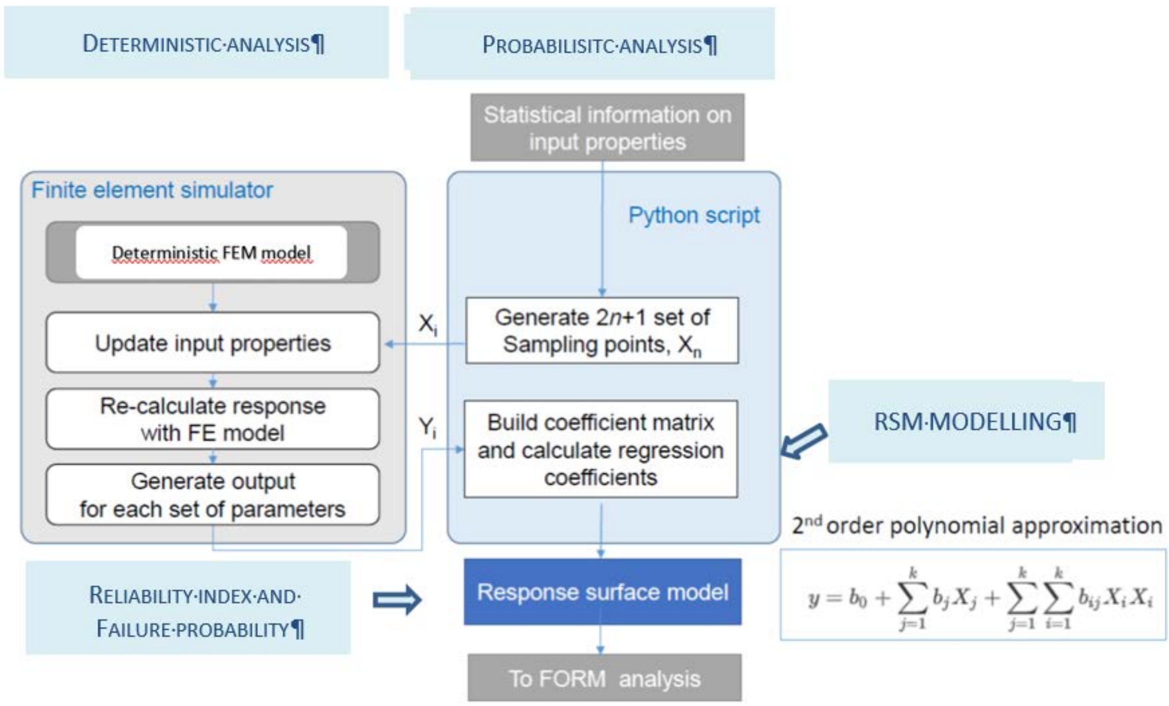


Figure A15. Response surface method (RSM) for analysis of failure probability.

Each input parameter in the analysis are first examined statistically and is expressed in terms of a mean, standard deviation and probability distribution. For each scenario, the FEM analyses were run 2*n*+1 times (where *n* is the number of uncertain variables (i.e. non-deterministic) in the analysis) to establish the second order RSM polynomial approximation (right bottom on Fig. A15). The polynomial approximation was then used in the first-order reliability method (FORM to obtain reliability index and failure probability).

A2.9 FORM/SORM, First and Second Order Reliability Method

About the method

The First Order Reliability Method (FORM) and the Second Order Reliability method (SORM) (Hasofer and Lind, 1974) calculate the reliability index and failure probability, and give a ranking of the significance of the input parameters on the failure probability. Hasofer & Lind (1974) proposed an invariant definition for the reliability index, which is directly related to the failure probability. The starting point for FORM is the definition of a limit state function *G(X)* describing failure, where *X* is the vector for the uncertain parameters in the analysis. The function is defined so that *G(X)* > 0 means satisfactory behaviour and *G(X)* ≤ 0 means failure. If the probability density function for all random variables $F_x(X)$ is known, the probability of failure P_f is given by:

$$P_f = \int_L F_x(X)\ \mathrm{d}X$$

where *L* is the domain of *X* where *G(X)* ≤ 0. In general, the above integration cannot be solved analytically. In the FORM approach, the vector of random variables *X* is transformed into the standard normal range *U*, where *U* is a vector of independent Gaussian variables with zero mean and standard deviations of 1, and where *G(U)* is a linear function.

The failure probability P_f is then (where *P* means "the probability that ..."):

$$P_{\mathrm{f}} = P[G(U) < 0] \approx P[\sum_{i=1}^{n} \alpha_i U_i - \beta < 0] = \Phi(-\beta)$$

where α_i is the direction cosine of the random variable U_i, β is the distance between the origin and the hyperplane *G(U)* = 0, n is the number of random variables *X*, and Φ is the standard normal distribution function. The vector of the direction cosines of the random variables (α_i) is called the vector of sensitivity factors, and the distance β from the origin to the "design point" is the reliability index.

Figure A16 illustrates how FORM works. The boundary state function $g(X_n)$ is key to the definition of the safe and unsafe conditions. The analysis has the following steps:

- Quantify the uncertainty in the parameters and analysis method.
- Express the limit mode function.
- Run the FORM analysis (comparable to millions of Monte Carlo simulations).
- Calculate the failure probability (P_f), the reliability index (β) and the sensitivity of P_f to each random variable.
- Check the "design point" (where failure occurs) to ensure that the coordinates correspond to the modelled situation.

In Figure A16, deterministic analyses would have been carried out with the limiting equilibrium method (LEM) or the finite element method (FEM). The failure probability is the number of cases where failure occurs (with the random parameters) divided by the total number of cases analysed. Applications of FORM to problems for offshore structures are given in Lacasse & Nadim (2007). SORM has a second order (non-linear) approximation and usually gives answers that are close to the answers from FORM.

Example

During an event tree workshop for a dam, the safety of a concrete saddle dam against sliding and overturning under winter ice loads needed to be assessed (Fig. A17). The dam had 15 pillars. For a well-defined problem such as sliding and overturning of concrete pillars, FORM and SORM are more suitable than. e.g., an event tree analysis. The COMREL software was used.

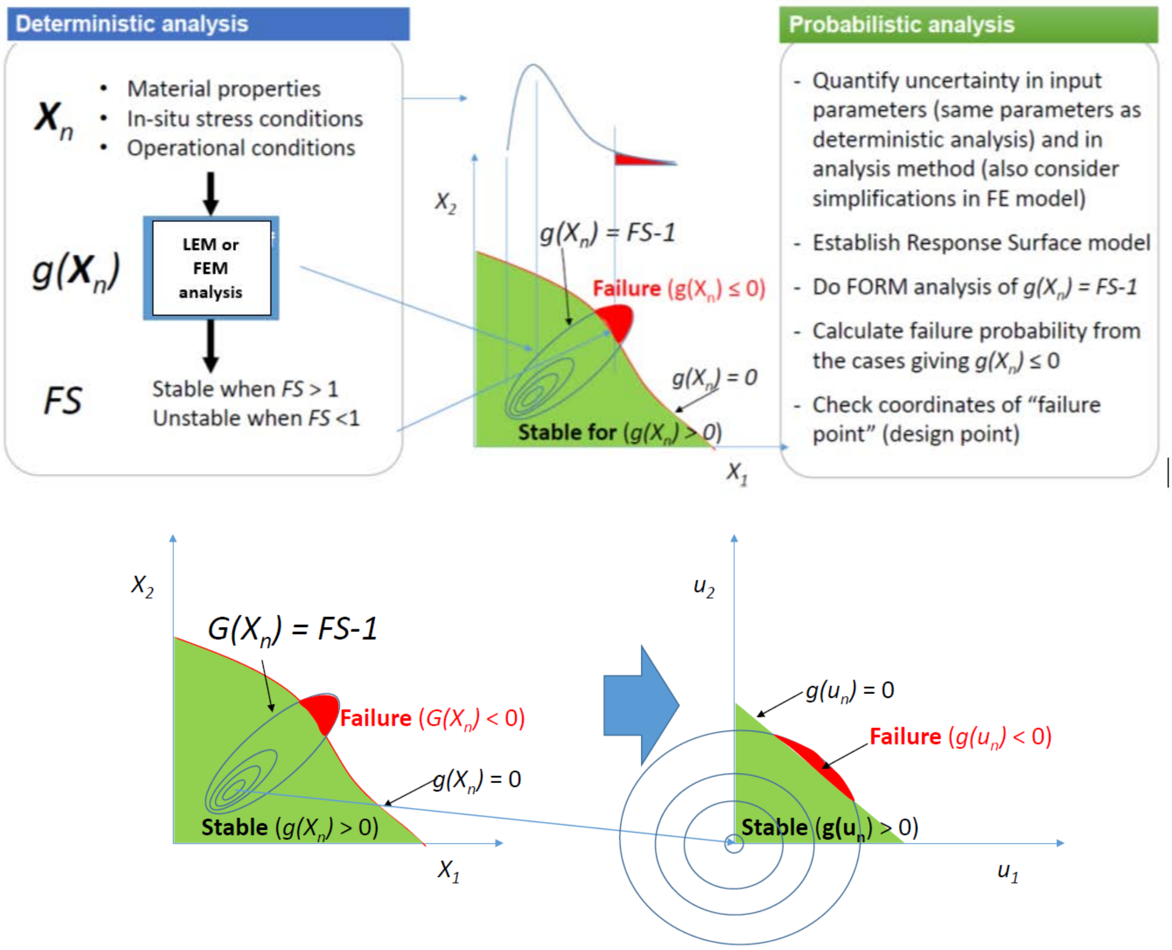


Figure A16. Illustration of FORM analysis

Figure A17. Analysis with FORM and SORM of concrete dam with 15 pillars. Pillar 2 and 5 from the left (west abutment) were the most critical

Pillars 2 and 5 were the two most critical pillars. The ice load was 500 kN, i.e. 100 kN/m over a width of 5 m. In the probabilistic calculations to assess the failure probability, the ice load was assumed to be representative of a 500-year ice load as a "base case". In the SORM analyses of stability, the entire probability distribution of the ice load, i.e. all return periods, was included in the analysis. The effect of the uncertainty in the ice load return period was also assessed with a return period of 10 years for the 100 kN/m ice load. The results of deterministic load analyses were used in the FORM and SORM analyses as average values, except for the friction angle between concrete and rock. An average of 45° was used as the best estimate for friction angle, with a standard deviation of 3°. Table A11 summarizes the annual failure probabilities under the ice load calculated with the SORM analyses.

Table A11. Annual failure probability for Pillars 2 and 5 under an ice load of 100 kN/m, return period 500 years.

Pillar	Annual failure probability (SORM), $P_{f\,annual}$	Annual reliability index (SORM), $\beta_{f\,annual}$
2	$1{,}0 \cdot 10^{-5}$	4.3
5	$1{,}3 \cdot 10^{-5}$	4.3

The estimated failure probability for Pillar 2 and Pillar 5 was 10^{-5}/year. The one and most significant parameter was the ice load (Fig. A18). On the one hand, the maximum ice load behaves like a short-term impact load: when the ice load is at its highest, the ice breaks down and the load immediately becomes much smaller. On the other hand, if the return period of 100 kN/m is shorter than 500 years, the failure probability increases. For a 100 kN/m ice load with a 10-year return period, the calculated failure probability increased to $3 \cdot 10^{-3}$/year and $2 \cdot 10^{-4}$/year for Pillars 2 and 5 respectively. The uncertainty in both size and return period in the ice load thus has a very large impact on the calculated failure probability. With a failure probability of $3 \cdot 10^{-3}$/year, risk reduction measures need to be considered.

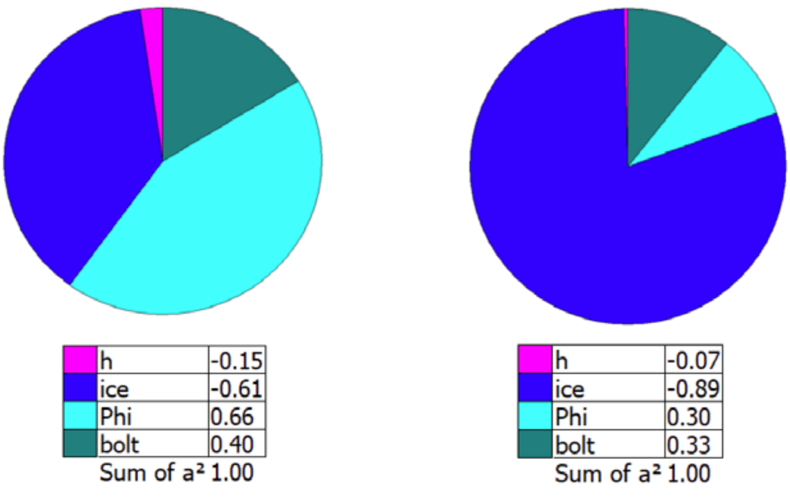


Figure A18. Sensitivity factors for uncertain parameters in SORM analysis, Pillar 2: Left: Base Case; right: 10-yr return period.

For an even more complete probabilistic analysis, one can perform a system analysis (all 15 pillars, with the software SYSREL) and calculate the failure probability for all 15 pillars (separately or together). The estimated annual failure probabilities for Pillar 2 and Pillar 5 were 10^{-5}/year. The safety factor for the other pillars was much higher than that for Pillars 2 and 5. The other pillars will not contribute much to increasing the total failure probability. The system failure probability for all 15 pillars increased to $2 \cdot 10^{-5}$/year with an ice load of 100 kN/m with a return period of 500 years, and to $3.5 \cdot 10^{-3}$/year with an ice load of 100 kN/m with a return period of 10 years.

A2.10 Stress Testing (for extreme events)

About the method

For an event with 'very low probability' and 'very high consequences', such as an expected maximum flood (PMF), tsunami or earthquake with a long return period and over 1000 fatalities, it is difficult to use probabilistic methods alone because there is little experience that can contribute to quantify probabilities. Extreme events can cause dramatic and serious consequences and cascading events (e.g., collapse of transport and power supply, extensive evacuation, etc.) before a dam will breach. Most social security preparedness measures will then have already been triggered. A possible dam break will then only cause an increase in risk (incremental risk) (Annex D).

A system analysis for extreme events can be done with the stress testing method combined with several of the probabilistic methods described earlier. Stress testing is used today in the nuclear, aviation and banking industries, to test safety and vulnerability. In geotechnics, stress testing has recently been used in Hong Kong to predict landslide scenarios and the vulnerability of existing emergency preparedness during extreme rainfall. The method is also suitable for assessing a system of several dams that affect each other under extreme conditions.

Stress Testing:

Stress testing is one of the newest tools in risk assessment. Following the Tōhoku earthquake that caused a tsunami and the Fukushima Dai-ichi nuclear accident, WENRA (Western European Nuclear Regulation Association) imposed in 2011 and 2012 stress testing on all nuclear power plants in western Europe.

A3 Consequence analysis

Important steps in a consequence analysis include:

- Selection of scenarios to analyse.
- Selection of consequence categories.
- The intensity of the water discharge spatially.
- Identification of potentially flooded areas, based on flood calculations (wave velocity, water depth and outreach).
- Population exposed and potential material damage.
- Objects exposed downstream, both in space and time.
- Mapping of warning opportunities and emergency preparedness.

Exposure:

Spatial exposure: flood calculations, depending on the failure scenario, flow parameters and downstream conditions, delimit the exposed area and population, as well as time to reach the exposed elements at risk.

Temporal exposure: it may be relevant to look at the people's residence pattern with time and season. It also depends on whether the dam breach has been warned, the time for the warning to reach the population, the quality and clarity of the warning, the instructions to follow and whether people are prepared for the emergency.

Potential loss of life and property damage can be calculated through relationships for fatalities and injuries as a function of the intensity of the dam wave. The range of the dam breach wave extend as far as needed downstream that it no longer involves any danger to life or material damage.

Figure A19 gives an overview of possible consequences of a dam break (Hartford and Baecher, 2004). The consequences fall in three categories: life and health, economics (material values only) and environmental damage. Losses not included in Figure A19 are the socio-economic losses that are due to loss of life and health, compensation costs for the dam owner in the event of loss of life and health, and the dam owner's loss of reputation and loss of trust as energy supplier to society.

A3.1 Loss of life

Both the UK and the US have models for calculating fatality rate, the number of fatalities divided by the number of persons exposed.

Factors influencing the number of fatalities due to a dam failrue:

- Trigger and type of dam failure.
- Number of exposed persons.
- Water depths and flow velocites downstream.
- Possibility to see or hear the water discharge as wave is approaching.
- Time of day, weekday and time of the year.
- Weather conditions, and air and water temperatures.
- Activities of the exposed persons at the time of the dam failulre.
- State of health of the exposed persons.
- Type and quality of building where persons are residing/working.
- Existence of warning system and required warning time.
- How succesful the evacuation is, and evaluation time.

USBoR published Table A12 where fatality rate figures are given as a function of the available warning time and the perception of the danger by the population (USBoR, 1999). It is important to check the definitions used in such tables (there are several). For example, USBoR defines fatality rate as the proportion of the non-evacuated population that lose their lives.

Figure A20 shows the British (Brown & Gosden, 2004) and American (USBoR, 1999) recommendations for calculating the fatality rate of the exposed population as a function of the warning time and the intensity of the flood wave. To determine the fatality rate, the value of the water discharge intensity (horizontal axis) is entered and one of the red, green or black lines is selected. There are also other methods for calculating consequences.

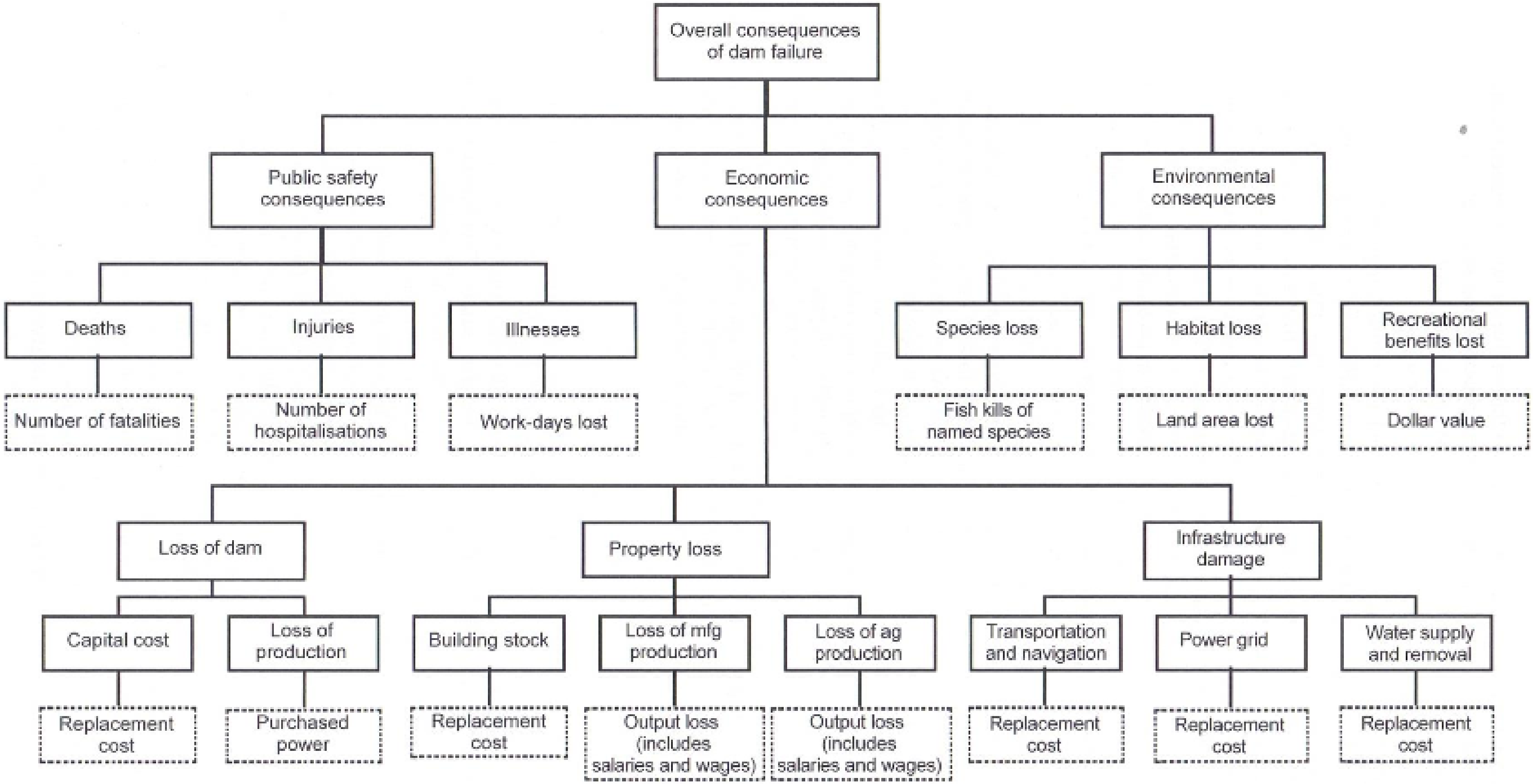
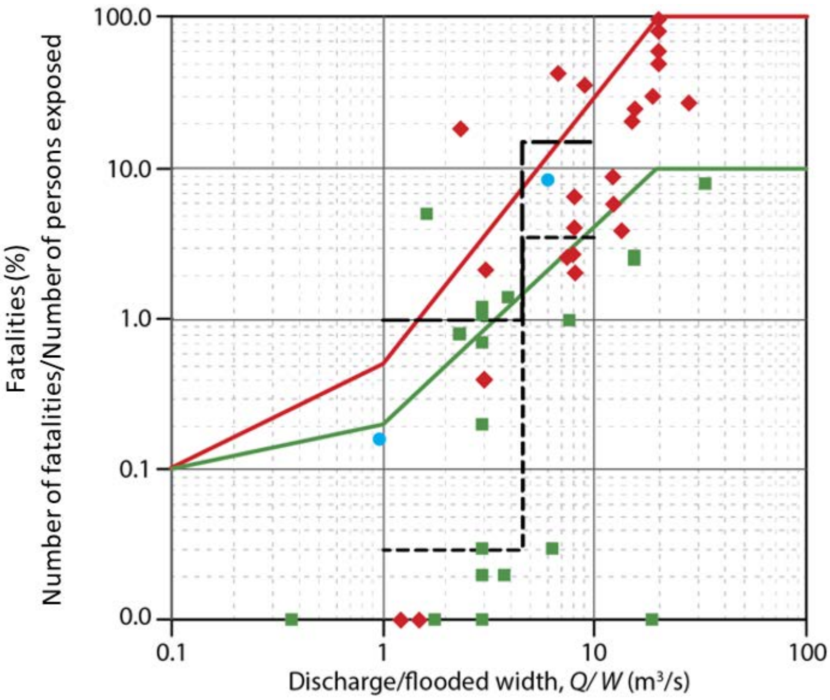


Figure A19. Overview of potential consequences of a dam failure (life and health, economic and environmental losses (Hartford & Baecher, 2004)

Table A12. Expected fatality rate (number of fatalities divided by the number of persons exposed) due to dam failure (USBoR, 1999)

Discharge intensity	Warning time (min)	Perception of danger	Fatality rate
High	0 (none)	---	0,75 (0,3-1,0)
	15-60	Unclear Goods	Use above numbers with the number of persons exposed those who are estimated exposed after the warning is given.
	>60	Unclear Goods	
Medium	0 (none)	---	0,15 (0,03-0,35)
	15-60	Unclear Goods	0,04 (0,01-0,08) 0,02 (0,005-0,04)
	>60	Unclear Goods	0,03 (0,005-0,06) 0,01 (0,002-0,02)
Low	0 (none)	---	0,01 (0-0,02)
	15-60	Unclear Goods	0,007 (0-0,015) 0,002 (0-0,004)
	>60	Unclear Goods	0,0003 (0-0,0006) 0,0002 (0-0.0004)



Notation	Warning conditions	Reference
◆	No warning (USBoR, 1999)	USBoR (1999)
■	Some warning (USBoR, 1999)	USBoR (1999)
———	Recommended, no warning	Brown & Gosden (2004)
———	Recommended, > 1h warning	Brown & Gosden (2004)
– – –	Recommended, no warning	USBoR (1999)
●	Fatalities in the UK, fluvial floods	Brown & Gosden (2004)

Figure A20. Estimate of number of fatalities as a function of discharge intensity and warning time (after Brown & Gosden 2004; and USBoR 1999) (intensity of discharge is ratio of discharge velocity to width (m^3/s)).

A3.2 Material losses

The material losses caused by the dam flood wave depend on the velocity and depth of the water discharge. For example, the damage can be obtained according to either the British (Brown & Gosden, 2004) or the American recommendations (USACE, 2012) in Tables A13 and A14.

Table A13. Damage on buildings due velocity and depth of breaching wave in the UK (Brown & Gosden 2004).

Seriousness of damage on buildings	***Discharge intensity*** **- *V* = average velocity, *D* = water depth**
No damage	Flood wave keeps within the existing flow canals/corridors
Flooding only	$V< 2m/s$ **or** $D \times V < 3m^2/s$
Structural damage	$V> 2m/s$ **or** $3m^2/s < D \times V < 7m^2/s$
Destruction	$V> 2m/s$ **and** $D \times V > 7m^2/s$

Table A14. Criteria for building damage in the USA (after USACE 2012).

Type building	Partial damage	Completely destroyed
Wood building		
Not well-anchored	$D \times V \geq 2m^2/s$	$D \times V \geq 3m^2/s$
Well-anchored, good foundation	$D \times V \geq 3m^2/s$	$D \times V \geq 7m^2/s$
Concrete building, brick construction	$D \times V \geq 3m^2/s$ **and** $V \geq 2m/s$	$D \times V \geq 7m^2/s$ **and** $V \geq 2m/s$

V is average velocity and *D* is water depth

Example

Figures A21 to A23 show an example of an impact assessment of a dam failure caused by an extreme flood or earthquake, for loss of life, environmental damage and economical losses, respectively. For the three cases, the calculated total breach probability from the event tree analysis of $4.6 \cdot 10^{-5}$ /year (as calculated form event tree analyses) was used as the input probability in the event tree for consequences. It is also possible to continue the calculation to establish the risk of loss of life (number of deaths per year, and the costs of one life lost) and calculate socio-economic losses.

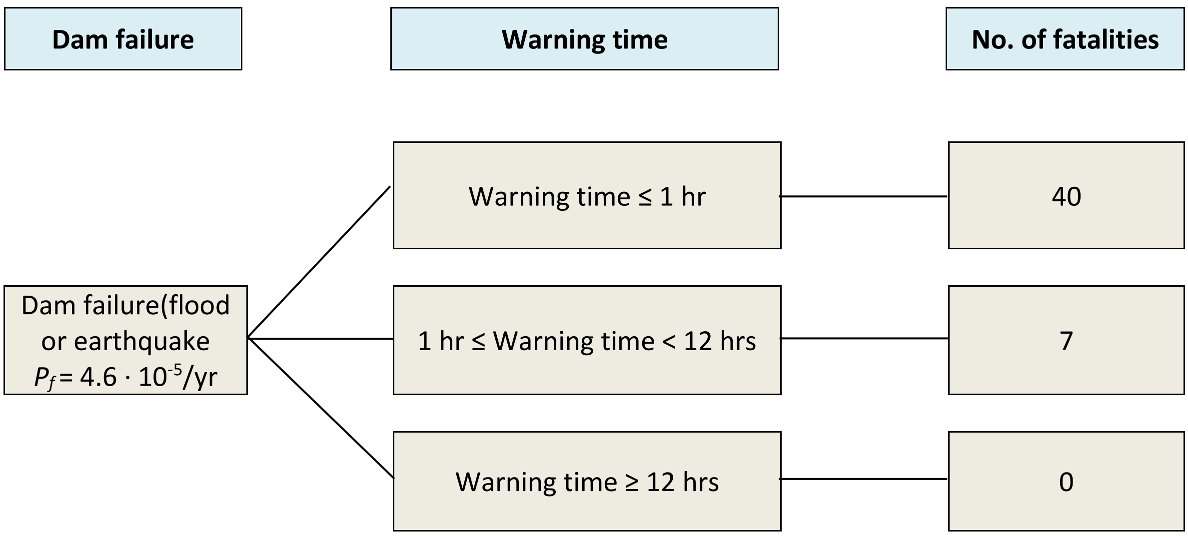


Figure A21. Example of consequence analysis in terms of fatalities, assuming that an emergency preparedness plan is in place and warning routines (text messages to all mobile phones in area) have been followed.

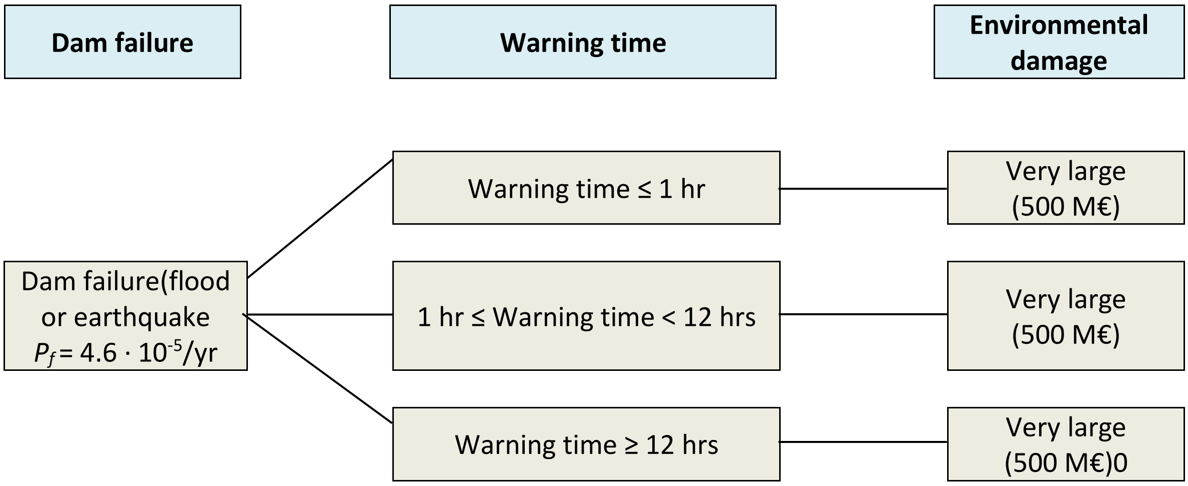


Figure A22. Example of consequence analysis in terms of environmental damage (numbers are examples only).

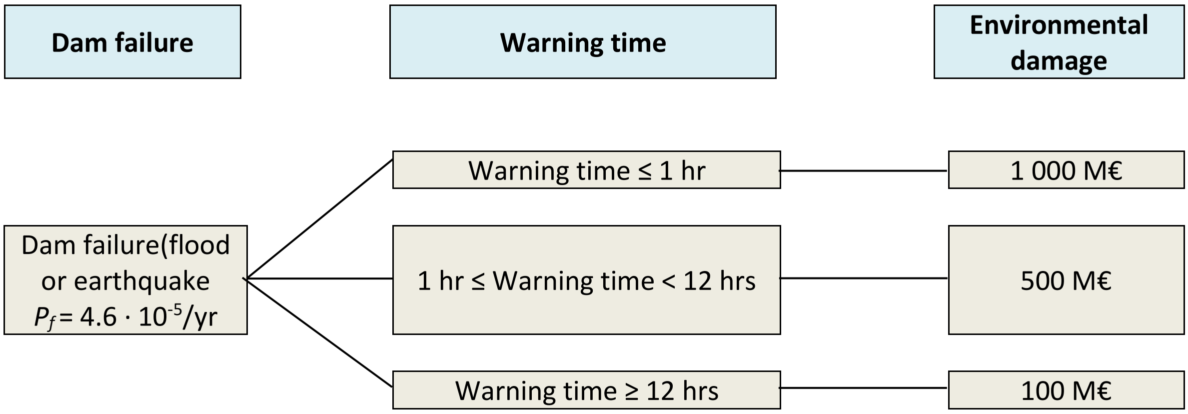


Figure A23. Example of consequence analysis in terms of economic losses, assuming that an emergency preparedness plan is in place and warning routines have been followed (numbers are examples only).

A4 Risk acceptance criteria

A4.1 Risk acceptance criteria from different countries

Figures A24 to A31 present risk acceptance criteria from several countries. These recommendations are the basis for the recommended risk acceptance for Norwegian dams in the main text. Figure A24, which assembles the most complete set of guidelines, are mostly recommendations for dams, or for general civil engineering constructions. The Hong Kong guideline is for man-made slopes. The most commonly used risk acceptance criterion today is the USACE/ Canada/ Hong Kong recommendation. Annex E describes what the probability number mean in terms of everyday activities.

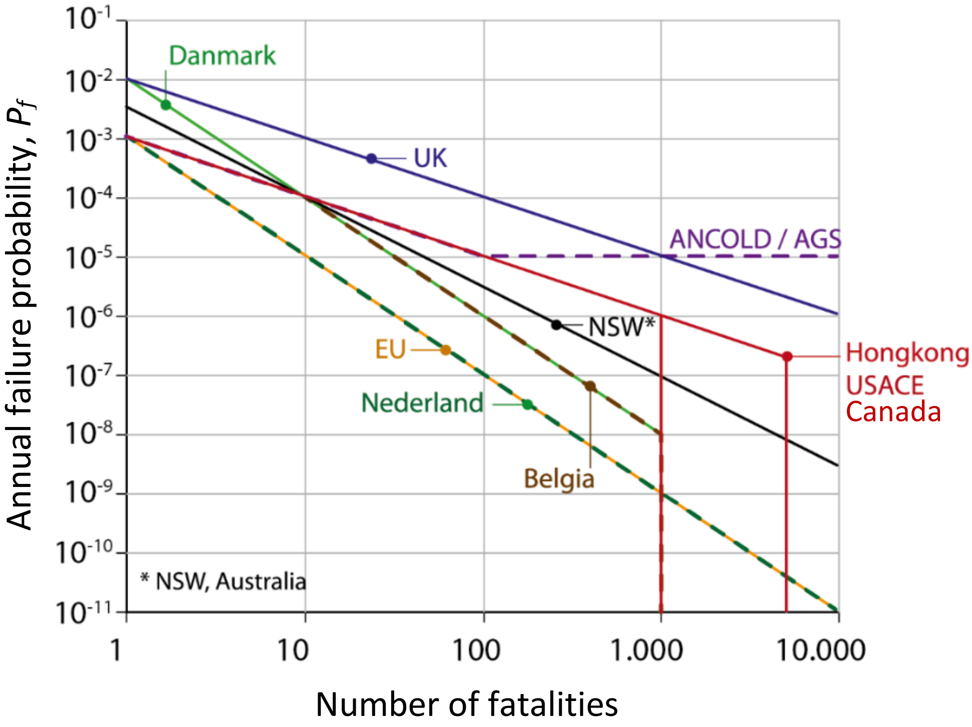


Figure A24. Risk acceptance criteria in several countries

The first practical risk diagram in Figure A25 was proposed by Whitman (1984). Whitman's (1984) recommendation was based on the perception of several civil engineers at MIT of how often different types of constructions fail. The Whitman chart suggests, for one fatality, that a failure probability of 10^{-2} to 10^{-3} per year or a loss of USD$1 million (in 1984 USD$) is acceptable. The green line is the acceptable risk, the red line is the limit of the marginally acceptable risk. The area in between the red and green lines corresponds to the ALARP zone. Dams are found in the area circles in blue , below the green line.

Figure A26 presents the recommendation from USACE (1997) for infrastructure on land in the USA. USACE (1997) is an old publication. At that time, one was not concerned about a reference time, or stating probabilities that are comparable (e.g. annual probability). The probabilities were probably meant to be annual probabilities, because the publication mentions in the text that the probability would be higher if one considered the probability over the entire lifetime of the construction.

The recommendations of the US Bureau of Reclamation (USBoR) are shown in Figures A27 and A26. The graphics are slightly different , but the numbers are comparable. On the left diagram in Figure 28, the area under the red line and above the grey line at 10^{-4}/year is a bit problematic: the user is not sure what to use in the USBoR diagram.

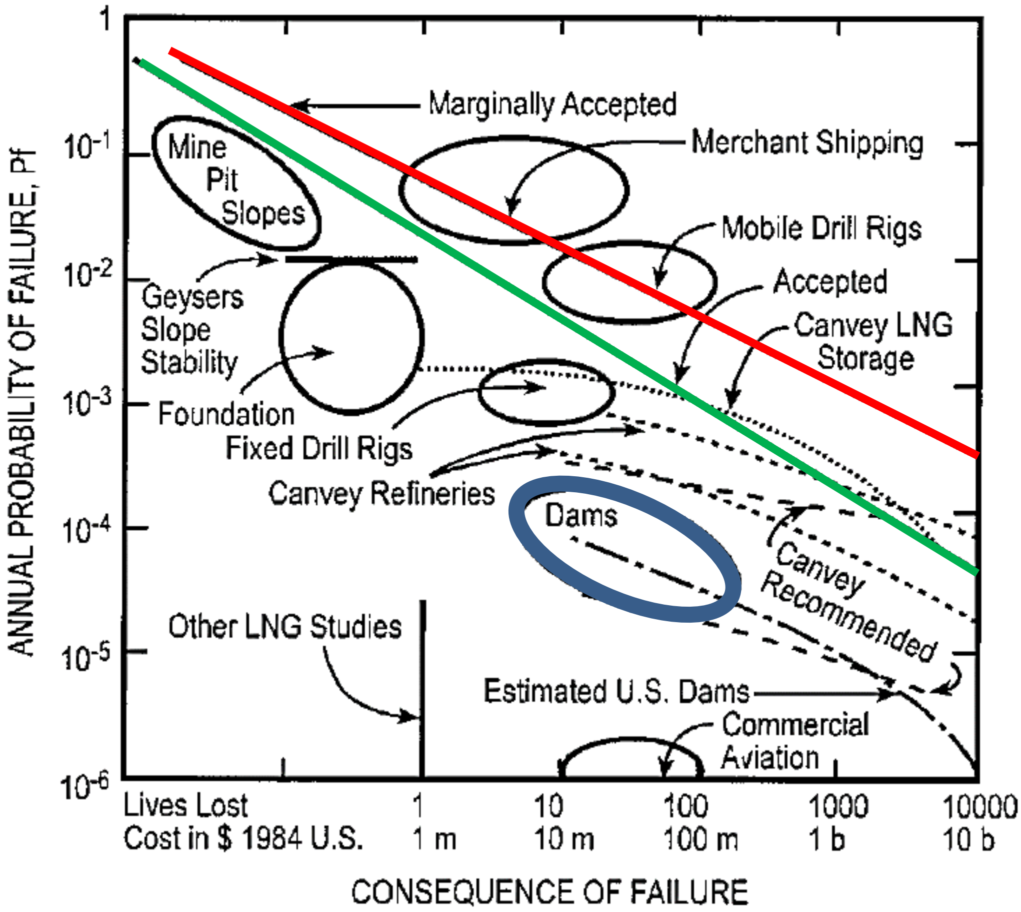


Figure A25. Acceptable (green) and tolerable ("marginally acceptable" - red) risk for civil engineering constructions (Whitman 1984; Baecher & Christian 2003) (economical losses in 1984 USD$)

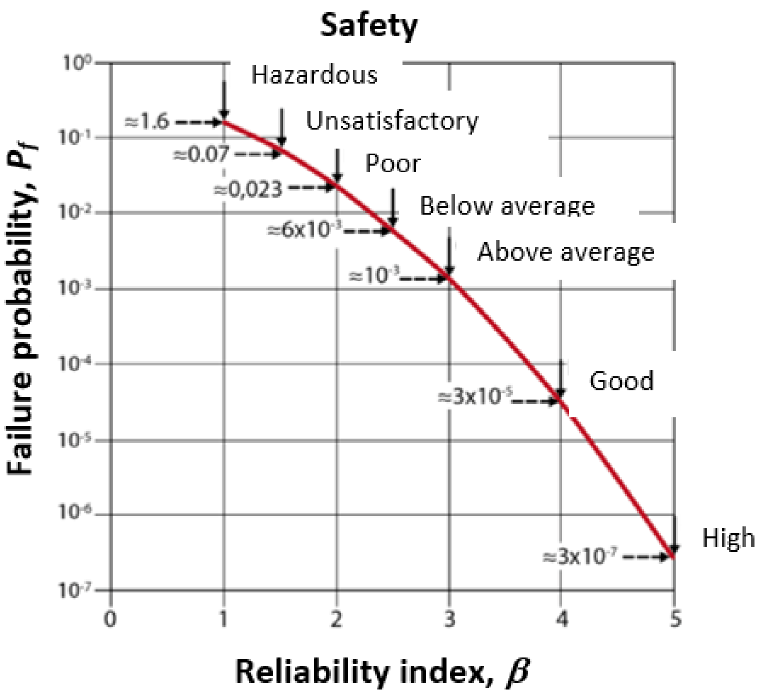


Figure A26. Reliability index, failure probability and safety assessment for infrastructure on land (USACE, 1997) *(the curve is for a normally distributed safety margin, see Annex F).*

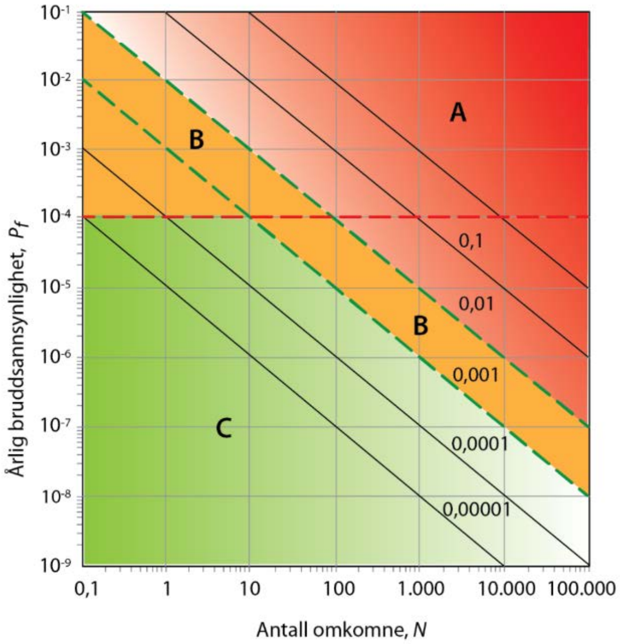


Figure A27. USBoR (2003) acceptable (green), tolerable (orange) and unacceptable risk (red)

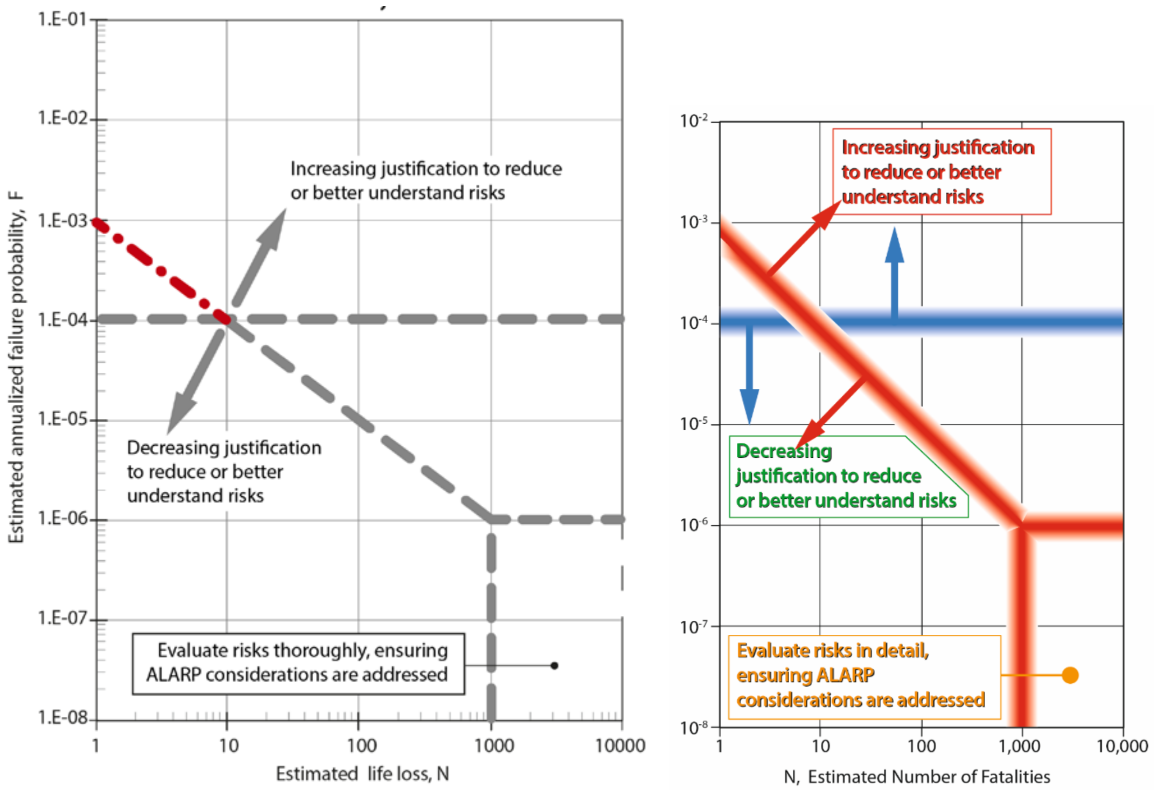


Figure A28. Risk diagram and need for risk reduction measures (after USBoR, 2011)

In practice, one uses the red line, corresponding to the iso-lines in Figure A27. On the right diagram of Figure A28, the delineations between the zones of acceptable and unacceptable risk are not strict, but can be interpreted as a gradual change.

In addition to the guidelines shown in Figure A24, the UK made and excellent qualitative illustration of acceptable, tolerable and unacceptable risk (Fig. A29), without quantified probabilities. In Figure A29, the individual risk is the one governing the recommendation. In Figure A24, an annual failure probability of 10^{-2} is considered acceptable for one person, and 10^{-3} is the limit between unacceptable and acceptable risk for 10 fatalities.

In Norway, the annual event occurrence probability of 10^{-2} is used as upper limit for buildings such as garages exposed to landslides and avalanches. For inhabited homes exposed to the same hazards, the annual occurrence probability limit is set to 10^{-3} (PBL 2008, corrected 2010). These rules are illustrated in Figure A30.

For offshore installations, NORSOK (2012) recommended that the total reliability (all failure modes, all systems, including structure and foundation) should have an annual failure probability less than or equal to 10^{-4} (or annual reliability index $\beta \geq$ than 3.7, Annex F).

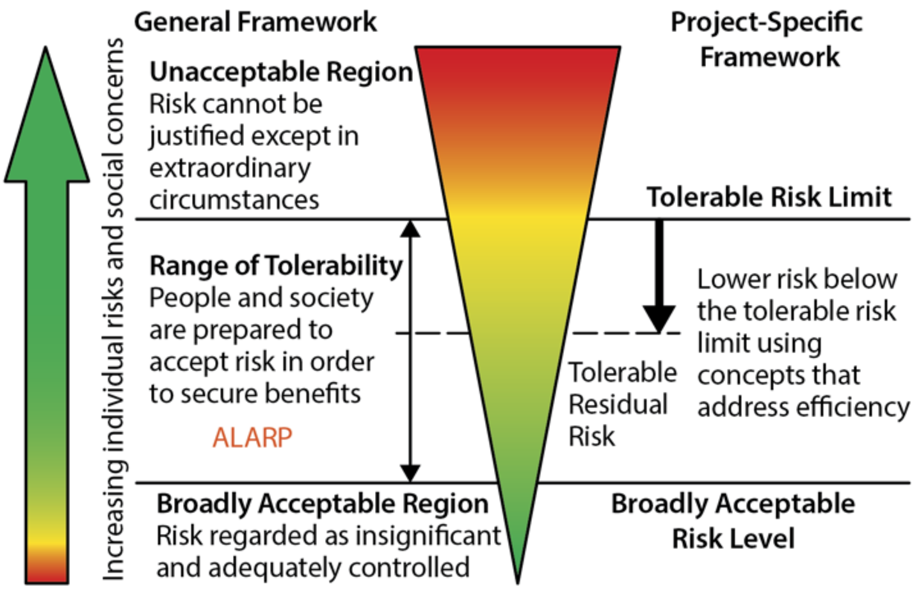


Figure A29. Acceptable, tolerable (ALARP) and unacceptable risk in the UK (HSE, 2001)

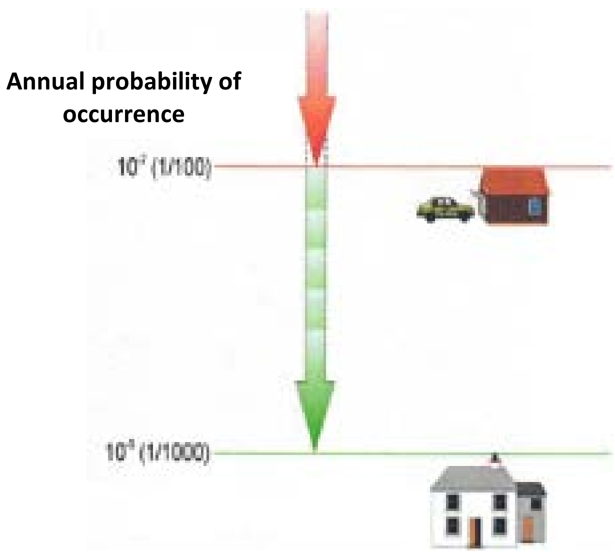


Figure A30. Limits on probability of occurrence in Norway for landslides and avalanches.

A4.2 Individual and societal risk

Risk is commonly presented in one of two graphical forms as an estimate of the entire probability distribution of potential life loss:

- *f-N* diagram: A discrete (non-cumulative) probability distribution in which each pair "probability-consequence" (*f, N*) is plotted (as e.g., in the forthcoming Fig. A32).
- *F-N* diagram: A cumulative probability distribution in which the probability-consequence (*f, N*) pairs are ordered in descending order of magnitude of *N*, and *f* is cumulated from largest to smallest to calculate the annual exceedance frequency. The mean of *N* is the area under the cumulative *F-N* curve.

USACE (2014) developed the interim risk guidelines shown in Figure A31. Two types of incremental risk are considered: individual risk (in green on the left side of Figure A31), and societal risk (in blue to the right). Societal risk is represented by the distribution of the estimated annual probability of potential life loss die to dam failure for all loading types and conditions, all failure modes, and all population exposure scenarios This plot is the *F–N* diagram, of the annual probability of exceedance of potential life loss (*F*) versus incremental life loss (*N*).

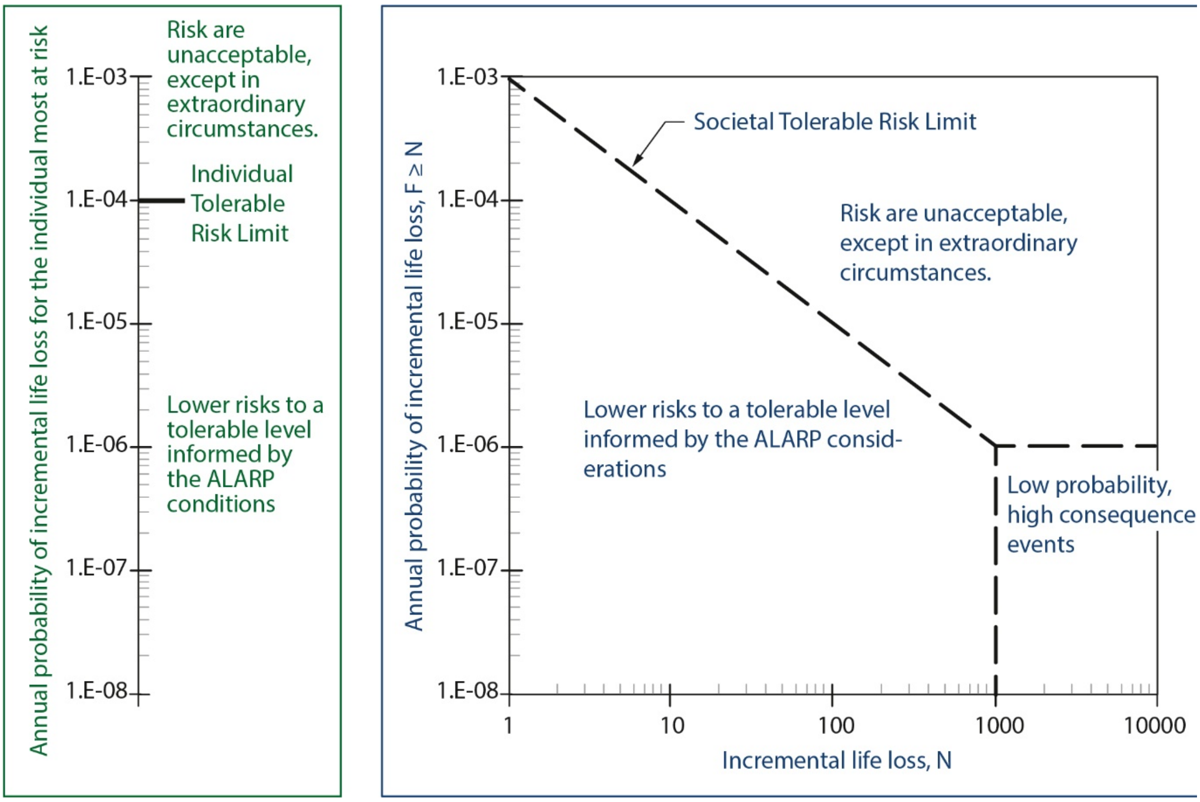


Figure A31. Guideline for incremental risk: left: Individual risk: Right: Societal risk (USACE, 2014).-

Several countries require or have guidelines for safety for people who could potentially be affected by a dam breach, in the form of explicit and quantified risk acceptance criteria. For risks that express human loss, a distinction is made between 'individual risk' and 'societal risk'. Table A15 summarizes guidelines for the upper limit of individual risk in Australia, the USA and the UK.

Table A15. Criteria in three countries for acceptable individual risk related to dam failure or other facilities[1].

[1] Upper limit for the most exposed person (Annex F).

Country/Organisation	Upper limit, individual risk	Reference
Australia (ANCOLD)	10^{-4}/year (existing dams) 10^{-5}/year (new dams)	ANCOLD (2003)
Australia - New South Wales	10^{-4}/year (existing dams) 10^{-5}/year (new dams)	Eddleston (2015)
USA (U.S. Army Corps of Engineers)	10^{-4}/year	USACE (2014)
Canada	10^{-4}/year (existing facility) 10^{-5}/year (new facility)=	CDA (2007; 2013); Morgenstern (2018)
United Kingdom (UK)	10^{-4}/year	Eddleston (2015)

Where individual risk is only a simple probability, societal risk is an annual (usually) probability distribution over the number of consequences (for example fatalities or financial losses). Regulation related to food, drugs and the environment is based on individual risk. Construction, offshore energy industry, natural hazards and transport are usually managed based on societal risk. Societal risk is expressed by an annual probability distribution and shall include the events from all load cases, all boundary conditions, all failure mechanisms and all types of vulnerability.

A4.3 Discussion of risk acceptance criteria

In 1997, USACE proposed target reliability levels as a function of the desired behaviour of a construction (Fig. A26). The curve relating failure probability and reliability index is explained in Annex F). In its guidance for "geotechnical and infrastructure projects". USACE (1997) considered that a reliability index of at least 4 (or $P_f \approx 3 \cdot 10^{-5}$) is necessary to ensure good performance in a system, and that a reliability index of 3 ($P_f \approx 10^{-3}$) will represent a performance 'above average'.

If one compares Figures A24 and A25, the F–N diagram for the different country guidelines is more stringent than Whitman's original recommendation. The comparison shows an evolution in the thought process about risk and exposed population.

The area to the right in most risk diagrams, where fatalities are greater than 1000, and the failure probability is very low, requires detailed assessment of the type stress testing described in section A2.10. This special consideration also reflects risk aversion in cases of very high number of fatalities.

As shown in Figure A28, the boundaries between acceptable and unacceptable risk are not a sharp distinction but an area that is assessed from one pond to another along with the uncertainties and available documentation.

The UK qualitative risk diagram (Fig. A30) is often used to communicate about risk and assess whether risk should be reduced. HSE (the authority in the UK) has a "Tolerability of Risk" framework based on how risk is managed in an individual's life. Individual and societal risk belong to one of three categories.

- "Broadly acceptable": risks that people often live with in their normal lives (e.g., health risks associated with lifestyle diseases, use of mobile phones and so on- see also Annex E).
- "Unacceptable" / "Unacceptable": risk to individuals and society is not worth taking regardless of the benefits (e.g., building residential areas on toxic landfills)
- "Range of tolerability" or "area of tolerance": individuals and societies are willing to live with the risk of securing certain benefits, provided they are sure that the risk is properly managed, reviewed and further reduced if and when practicable (e.g., vehicles and airlines), following the ALARP principle. With few exceptions, risk that is unacceptable should be reduced to a "tolerable" level, regardless of the cost. In the ALARP interval between acceptable and unacceptable risk, the risk should be reduced as much as practically reasonable. As a rule, it will be a cost-benefit assessment that determines what is perceived as 'practically reasonable' where risk-reducing measures are to be implemented.

The risk diagram in the different country guidelines can also be compared with the frequency of other events in everyday life. Figure A32 gives an example with the historical fatalities in the USA due to natural hazards and due to anthropogenic (man-made) hazards.[1]

Figure A33 presents data for a number of natural and anthropogenic hazards in other countries.

A4.4 Extension of Whitman's risk diagram

ASCE (2020) published an updated version of Whitman's risk diagram. This is reproduced in Figure A34. In the update, human daily life individual risks are added, e.g. death due to heart disease and cancer, the risk of a car accident and the estimated risk associated with the New Orleans dikes prior to Hurricane Katrina in 2005. Financial losses are shown in 1984 US dollars.

In Figure A34, the green line is the same as Hong Kong's criterion in the risk chart in Figure A24. The log-log diagram shows straight risk lines. These can be expressed as:

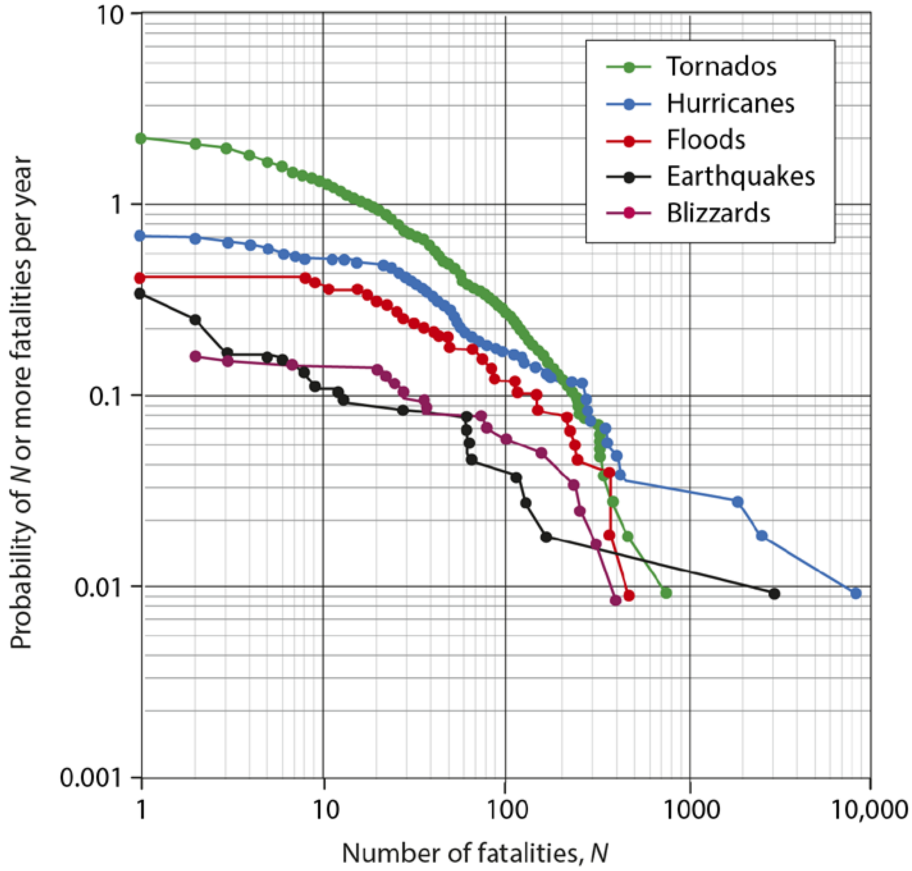
$$F \cdot N\alpha = k$$

where F is the probability of failure, N is consequences such as financial loss or number of fatalities, k is the intersection of the probability axis (N = 1).

For the Hong Kong risk criterion in Figure A24 (green line in Figure A34), k = 0.001 and α = -1. The *F-N* curves (on a log-log scale) with a slope α = -1 are curves describing the same risk (equi-risk lines). Each of the straight lines are "equi-risk lines", where the risk is the same along the entire line. A line with slope steeper than α equal to -1, so leading to lower consequences, reflects 'societal risk aversion'. Risk aversion means society reacting more negatively with a larger number of fatalities and/or larger economical or environmental losses.

In the lower part of Figure A34, two additional equi-risk lines are shown, along with the human daily life risks. For the case where there is no loss of life (to the left of 10^0 on the upper fatality scale), other consequences, such as economical losses, loss of trust from clients or society, etc. will be determinant for the decision on acceptable or tolerable risk. Usually such decisions are based on a cost-benefit assessment (where costs are not necessarily only direct economic costs). Equi-risk lines can help provide a wider perspective on acceptable risk level when there are no life losses at stake.

[1] These curves are for the USA and not site-specific or facility-specific. For example, there are 86,359 dams in the USA (USACE National Inventory of Dams – *nid.usace.armi.mil*). Thus, the curves for "Facilities caused by dam failure" should be factored by 86,359 and by the weighted average age of the dams in the dam population to approximate the average fatality risk per dam per year (Baecher *et al.*, 2015).



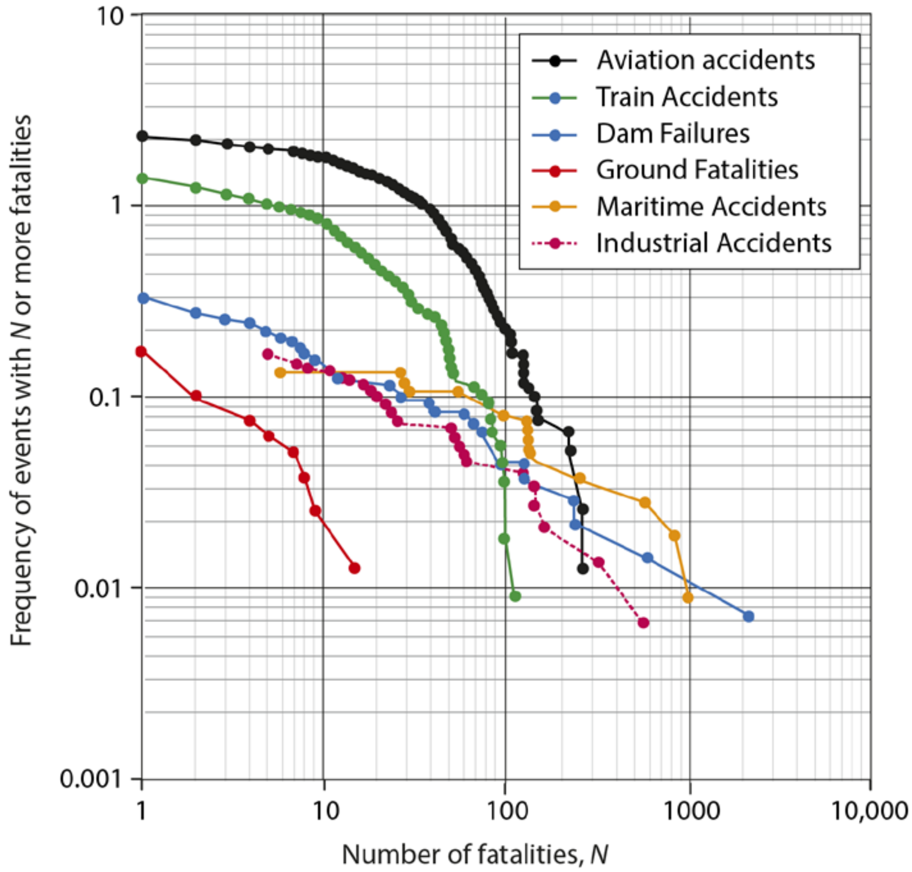


Figure A32. Frequency curve for accidents and disaster fatalities in the USA (1900–2010): top: natural hazards; bottom; man-made accidents (Abedinisohi, 2014; Baecher et al., 0915).

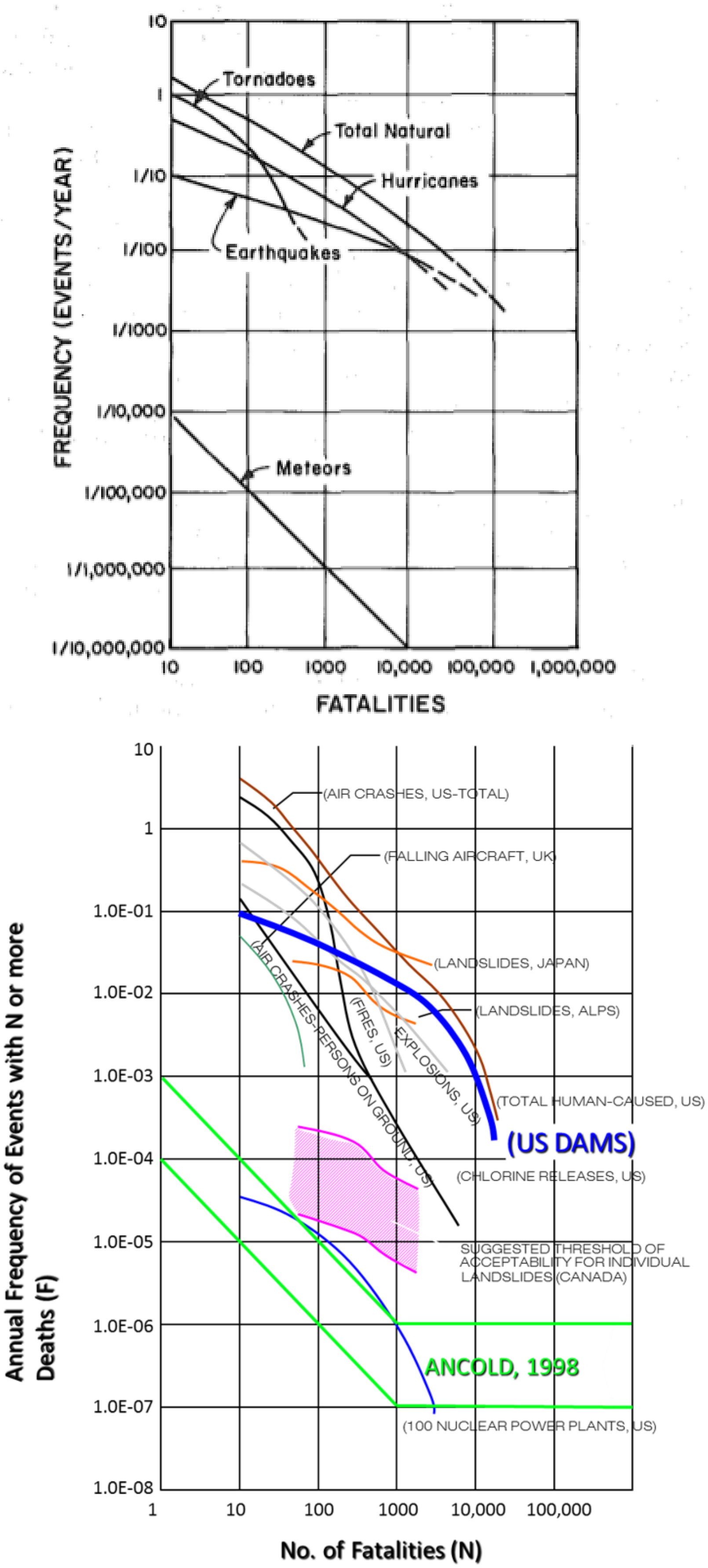


Figure A33. Risk curves for different natural hazards and anthropogenic hazards(after USNRC,1975).

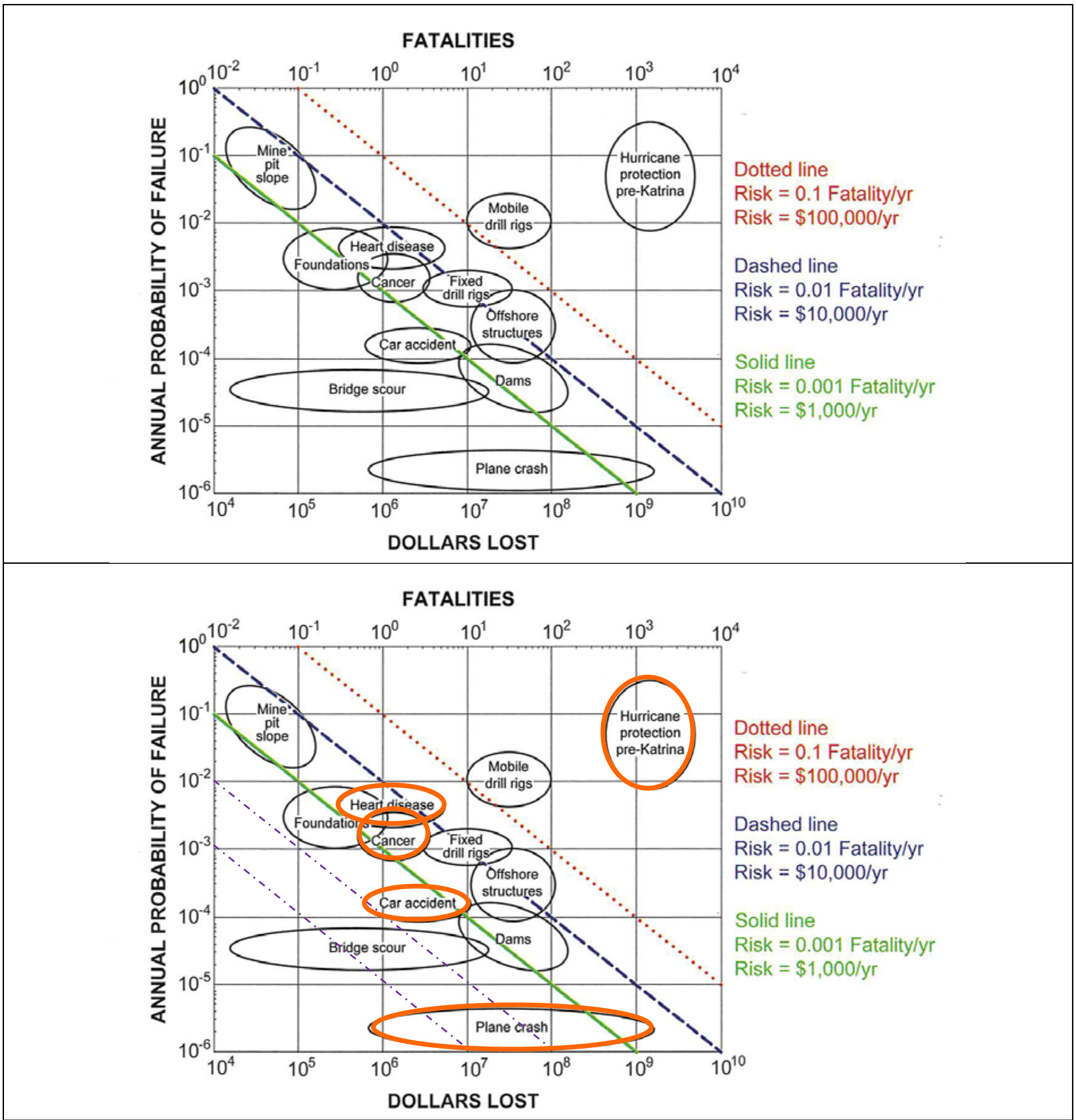
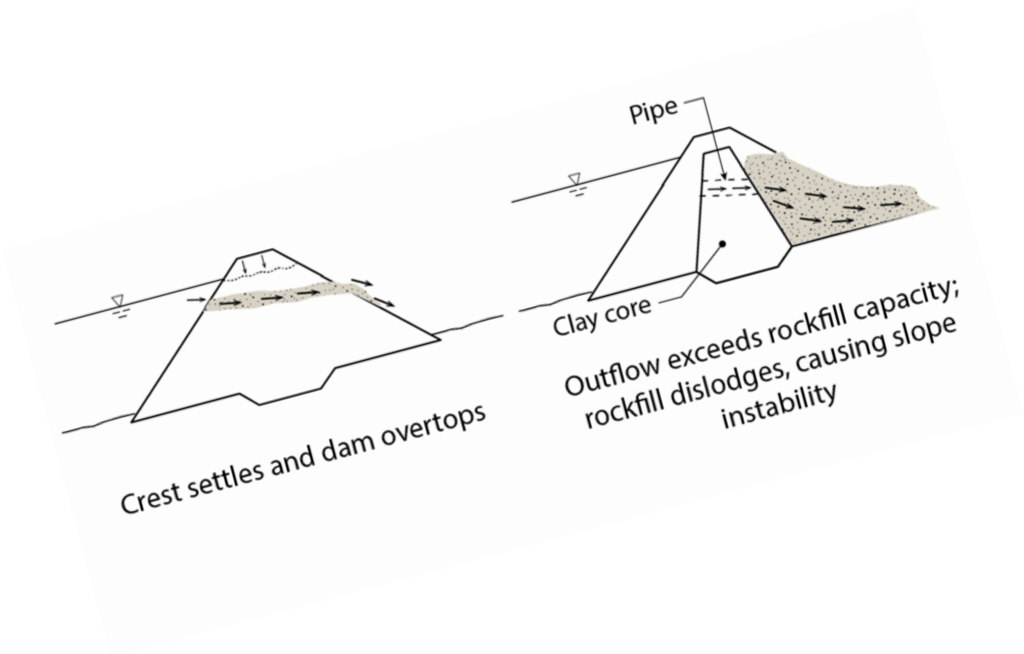


Figure A34. Extended Whitman risk diagram with lines of equi-risk, daily human life risks and risk from dikes in New Orleans prior to Hurricane Katrina in 2005 (ASCE, 2020)(economical losses in 1984 USD).

Annex B Failure modes for embankment dams

Contents



Failure by internal erosion in dam core followed by unravelling of downstream embankment.

Flood in Kvam in Norway in 2013 (Photo: Håkon Mosvold Larsen / NTB Scanpix)

Annex B Failure modes for embankment dams

B1 Failure mechanisms and triggers for embankment dams

Failure and damage mechanisms need to be reviewed systematically for each dam to be assessed. This annex lists general failure mechanism categories for earth and rockfill embankment dams. The analysis and prioritization of the plausible failure mechanisms and triggers is the essential and most important step of a risk analysis. A failure can be linked to four main categories of events: hydraulic events, seismic events, internal and external erosion, and war/terror/sabotage.

In a risk analysis, an overview is made of the failure modes, both with respect to weaknesses in and around the dam and external trigger factors. For embankment dams, new statistics [(ICOLD (2020, Bull. 99); Appendix D] suggest that over 98% of the known failure cases are attributed to one of three modes: (i) internal erosion (39%), (ii) overtopping (40%) and (iii) structural failure (29%).There is a marked reduction in embankment dam failures built after 1950. Most failures occur in the first five (5) years of the dam. Internal erosion failures occur mainly under normal operating conditions.

Most common potential events:

Internal erosion: Internal erosion that can occur under normal operation and under extreme conditions, e.g. toe erosion, pipe formation in the dam's fill or core, a "sinkhole", leaching of the fines in cracks in a rock foundation.

Hydraulic events: Events that are triggered by intense precipitation, extreme snowmelt and floods, a rock or soil avalanche in the dam reservoir, blockage or overflow of the spillway, errors in reservoir operation, wave or ice loads.

Seismic events: Events triggered by earthquakes or other tremors that can cause settlements, cracks, landslides into the dam reservoir or "liquefaction" and large deformations.

War/terror/sabotage events: The threat of intentional actions or complots, such as terror or sabotage should be considered.

ICOLD (2005, Bull. 130) divides **failure mechanisms for concrete and embankment dams into seven main categories**: (1) hydraulic (overtopping from natural forces, (2) floods exceeding the reservoir capacity), (3) internal erosion and / or pipe formation through or next to the dam, (4) mass movement and slope instability, (5) structural failure in the dam material, (6) movement and/or failure in the foundation, and (7) settlements and crack formation.

Annex D summarizes dam failure and incident statistics for embankment dams.

The most common failure mechanisms and causes to consider in a risk assessment for soil or rockfill dams are as follows:

Weakness in and around the dam:

- Internal erosion.
- Stability of embankments, sliding of upstream or downstream embankments.
- Landslides in the reservoir causing a flood wave and overtopping.
- Weakness or erosion in the soil or rock foundation.
- Blocking of spillway.
- Operative measure leading to failure.
- Ageing of concrete, if there is concrete in parts of the dam.

External triggers:

- Floods caused by intense or extreme precipitation, snow or glacier melting.
- Ice or hard-packed snow or debris blocking the spillway.
- A combination of these factors, occurring seasonally or simultaneously.
- Climate change impacting the conditions of the dam.
- Wave and ice loading leading to instabilities on the upstream side.
- Earthquake loading.
- External events such as meteorites, airplane crashes (if plausible).

B2 UK guide for quantitative risk assessment - failure modes

Brown & Gosden (2004) systematically reviewed factors that should be analysed in dam failure and incident analysis. The factors are stated in table for different initiating events. The most important triggers for overtopping of the dam in the UK are extreme rainfall and landslides in upstream reservoirs. Other initiating events such as wind and waves are usually also reviewed. Brown & Gosden (2004) presented list of contributing factors for:

- Failure due to extreme rainfall (Table B1).
- Failure due to failure in upstream dam (Table B2).
- Failure due to internal instability (embankment dams) (Table B3).
- Failure due to instability of appurtenant works (Table B4).
- Failure due to other threats, including aircraft strike, human error, seismic loads, snow/ice loads. terrorism, vandalism and wind.

Table B1. Contributory factors to events initiated by extreme precipitation (Brown & Gosden, 2004).

Condition	Contributory factor to be considered in risk assessment	
	Likelihood of deterioration mechanism to occur	**Likelihood of dam failing given deterioration mechanism initiates**
Intrinsic conditions	Spillway capacity Obstructions in spillway Reservoir surface Freeboard for floods Vegetation/trees around reservoir rim Geometry and detailing of abutments (drains?) Steep slopes in reservoir (previous landslides?)	Level and width of crest Erosion resistance of crest and downstream face Material type (vegetation and underlying material) Erodibility of shoulders and toe Slope stability of shoulders and toe
Other	Level of reservoir prior to storm (reservoir often empty?) Quantity/quality of earnings and time to operate gates Duration of inflow	

Table B2. Contributory factors to events initiated by failure in upstream dam (Brown & Gosden, 2004).

Condition	Contributory factor to be considered in risk assessment	
	Likelihood of deterioration mechanism to occur	**Likelihood of dam failing given deterioration mechanism initiates**
Intrinsic conditions	As for Table B1	As for Table B1
Other	Level of reservoir prior to storm (reservoir often empty?) Quantity/quality of earnings and time to operate gates Condition of upstream dam Rate of development of breach in upstream dam Attenuation between reservoirs Volume of water in upstream reservoir	

Table B3. Contributory factors to events initiated by internal instability (embankment dams) (Brown & Gosden, 2004).

Condition	Contributory factor to be considered in risk assessment	
	Likelihood of deterioration mechanism to occur	**Likelihood of dam failing given deterioration mechanism initiates**
Intrinsic conditions	Narrow core Profile of foundation (differential settlements) Internal geometry and construction of embankment Relative stiffness of zones of embankment Defect in original construction Foundation excavation depth and foundation treatment Material forming foundation	Erodibility of clay core (compaction, water content) Properties downstream fill (filter, limits leakage?) Properties of upstream shoulder (limits leakage?) Velocity of flow/hydraulic gradient Vulnerability of downstream face to erosion
Other	Rapid changes in reservoir level Chemistry of reservoir water, and local groundwater	Tortuosity of path Reservoir level/dam height

Table B4. Contributory factors to events initiated by internal instability (appurtenant work) (Brown & Gosden, 2004).

Condition	Contributory factor to be considered in risk assessment	
	Likelihood of deterioration mechanism to occur	**Likelihood of dam failing given deterioration mechanism initiates**
Intrinsic conditions	Defects/poor quality material in original construction Properties of backfill to culverts/pipes Geometry of foundation External geometry of pile/culverts Ageing material No operating instructions for electro-mechanical equip. Lack of maintenance Joints in pipe/culverts	Velocity of flow Backup power Height of dam/level of appurtenant works relative to reservoir level Lack of upstream control No other means of reservoir drawdown
Other	Rapid changes in reservoir level Chemistry of local groundwater	Reservoir level

B3 Threats to dams

Derfra (2011) listed a majority of threats against dams (Table B5), based on experience in the UK and a literature study. Each of these threats, can lead to a dam failure, according to Derfra.

Table B5. Overview of threats to dams, all types of dams (after Derfra, 2011)

Earthquake	**Human activities**
Extreme precipitation or flood form snow/glacier	Change in infrastructure nearby
Ice, frost, frost heave, freeze-thaw, ice loads	Ageing of dam or dam material
Geology	Mining or other activity in area
Change in groundwater regime or quality	Faulty design
Failure, faults, movement, changes in upstream reservoir	Faulty dam operation
Animal borrows	Sabotage or other malevolent actions
Strong sun, strong winds	Aircraft crash or other accident
Water (from unknown source) increasing load on dam	Terror

B4 Checklist for embankment dams

Table B6 gives an example of a checklist used by the US Army Corps of Engineers when doing safety assessment of embankment dams.

Table B6. USACE's checklist for safety assessment of embankment dams (modified after Bowles et al., 2003)

Embankment dams: Factors initiating undesirable events		
Flood	**Earthquake**	**Normal operation**
Internal erosion	Liquefaction (dam or foundation)	Leakage and internal erosion
Embankment slope instability (upstream and downstream)	Instability and large deformations (vertical or horizontal)	Slope instability
Erosion and unravelling of dam toe	Erosion and unravelling of dam toe	Erosion and unravelling of dam toe
Surface erosion	---	Surface erosion
Wave action	---	Wave action
Erosion in foundation	---	Erosion in foundation
Foundation instability	Foundation instability/deformations	Foundation instability/deformations
Embankment instability	Embankment instability	Construction work near the dam
Overtopping (freeboard)	Overtopping due to liquefaction or large settlements/deformations	

B5 Overtopping

Overtopping of dams can be caused by floods as a result of extreme rainfall, settlements of the crest due to seismicity or landslide of the downstream embankment, flood wave in the dam reservoir due to landslide in the reservoir. Overtopping can also further develop into embankment failure. In a joint report, USBoR (2012) and USACE (2012) listed the following key factors influencing the risk of overtopping for an embankment dam:

- Dam type (the material the bam is built of).
- Type of overtopping (continuous flow or waves).
- Factors influencing the erosion process through the downstream embankment.
- Flood frequency.
- Spillway capacity.
- Configuration of spillway(s) and hatches/gates.
- Blocking of the spillway by landslide debris, driftwood etc.
- Depth and duration of the overtopping.
- Shape of the dam crown, especially the height at its lowest point.

B6 Internal erosion

The sequence of events that occur after the initiation of internal leakage or intern al erosion cannot be analysed completely quantitatively or with modelling (Bowles *et al.,* 2013; Fell *et al.,* 2015; USBoR, 2012; USACE, 2012). Bowles *et al*. (2013) recommended using historical data for the quantification of internal leakage and internal erosion initiating events. Although numbers are important, the following aspects are even more important for the risk assessment:

- Developing an understanding of the dam's strengths, weaknesses and vulnerabilities in relation to the different internal erosion and leakage damage mechanisms, and
- Showing the structure of the chain of events that could lead to a failure and study or recommend measures that could stop the internal erosion.

The internal erosion process can be divided into four phases: 1) initiation of erosion; 2) continuation; 3) progression of erosion to a continuous process throughout the dam and 4) initiation of failure. Examples of the process for erosion in embankment dams are illustrated in Figures B1 and B2, and the erosion in the dam foundation in Figures B3 and B4, and the initiation of failure in Figures B5 and B6. These figures are based on Fell *et al.* (2015). Fell *et al*. has also excellent chapters on:

- "Internal erosion and piping of embankment dams and in dam foundation" (Ch. 8).
- "Design, specification and construction of filters" (Ch. 9).
- "Embankment dams, zoning and design for control of seepage and internal erosion and piping" (Ch. 10).
- "Methods for estimating the probability of failure by internal erosion and piping" (Appendix A).

Figure D9 (Annex D) shows international statistics of dam failure due to internal erosion and lists the factors that increase and reduce the internal erosion and failure probability, based on Ac ICOLD study.

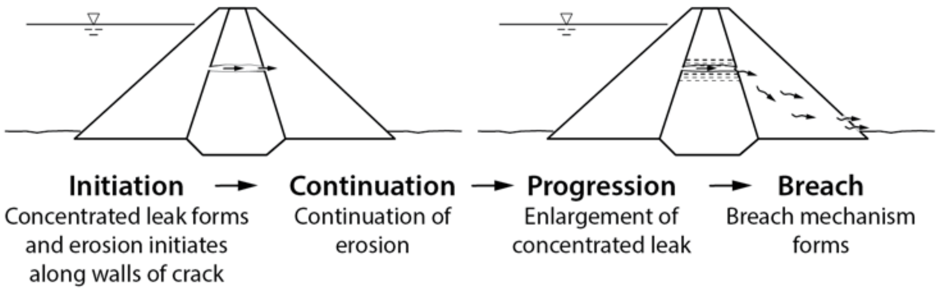


Figure B1. Internal erosion in the embankment initiated by erosion in a concentrated leak.

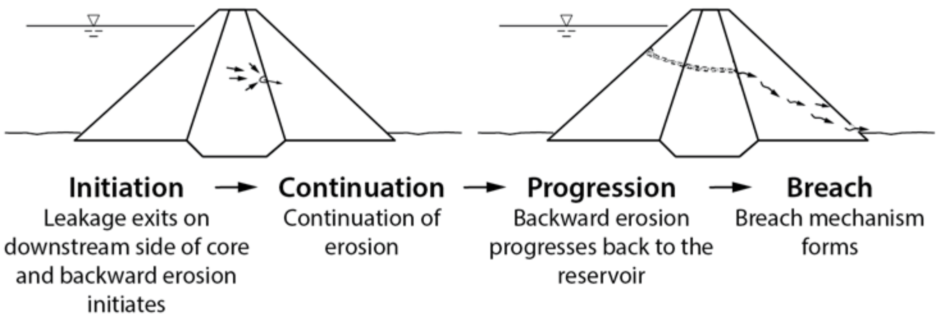


Figure B2. Internal erosion in the embankment initiated by leak and backward erosion.

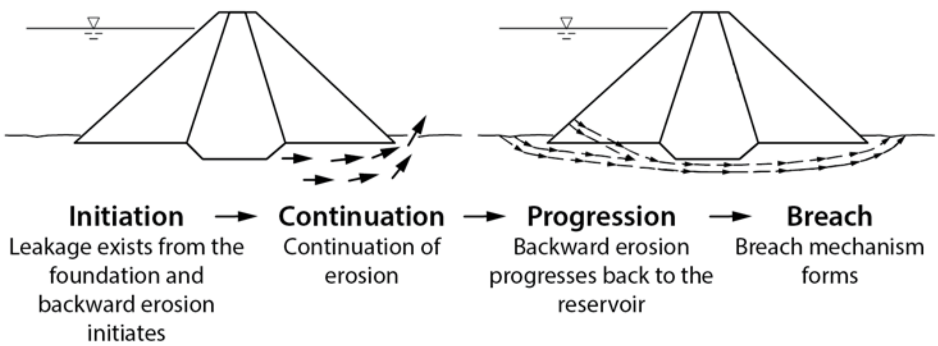


Figure B3. Internal erosion in the foundation initiated by backward erosion piping.

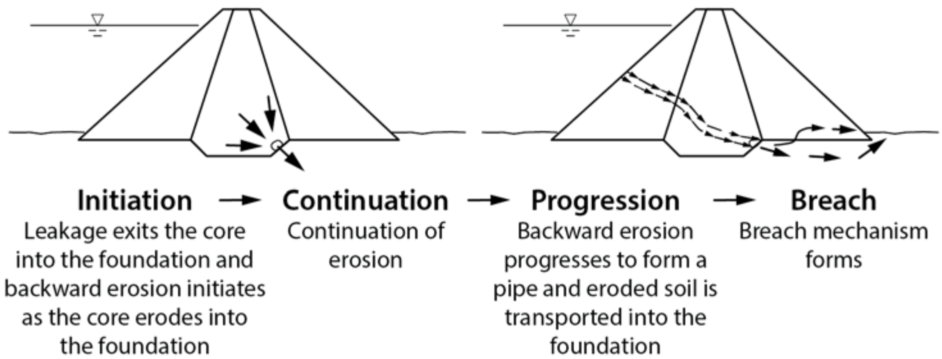


Figure B4. Internal erosion from embankment to foundation initiated by backward erosion.

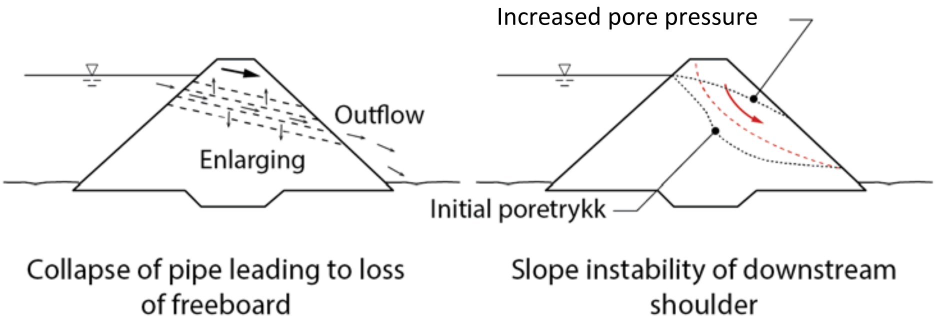


Figure B5. Potential breach due to pipe enlargement and slope instability.

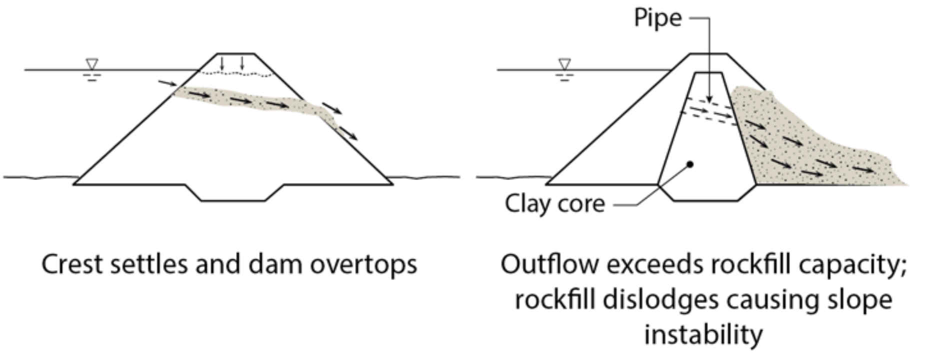
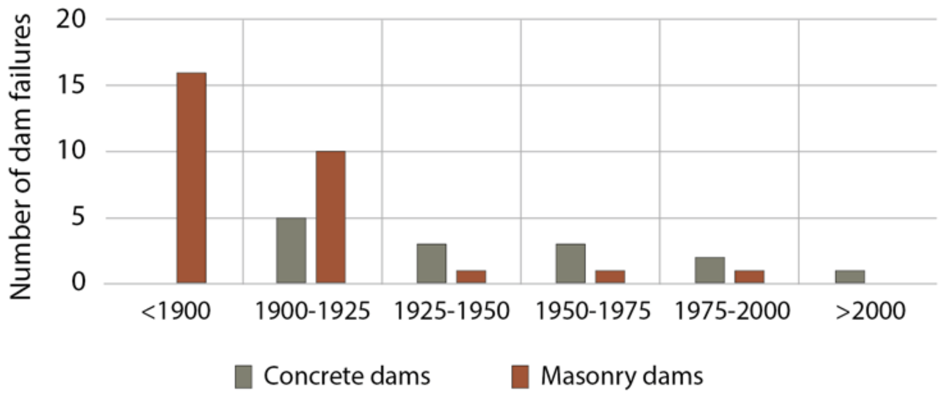


Figure B6. Potential breach due to overtopping by settlement and unravelling of the downstream face.

Annex C Failure modes for concrete dams

Contents



Number of dam failure for concrete and masonry dams (1900-2020) (ICOLD Bull. 99, 2020)

Concrete dam for Fitvannet in Norddal County in Møre og Romsdal (Norway).

Annex C Failure modes for concrete dams

Many of the paragraphs and tables in Annex B on failure mechanisms for embankment dams apply to also concrete dams. The reader should also consult Annex B, especially sections B2 and B3.

Concrete gravity dams consist of solid concrete. They are often constructed along a straight line or may be slightly curved or angled, depending on site-specific considerations. Gravity dams are well-suited for sites with sound rock foundation and offer suitable performance as overflow spillways. Construction of a concrete gravity dam is typically completed using either conventionally placed mass concrete techniques or using roller-compacted concrete (RCC).

The loading conditions acting on a concrete gravity dam are maintained through the structure's geometric shape and mass and through material properties of the dam and foundation (USACE 1995). Figure C1 illustrates common loading conditions that impact a concrete dam and foundation.

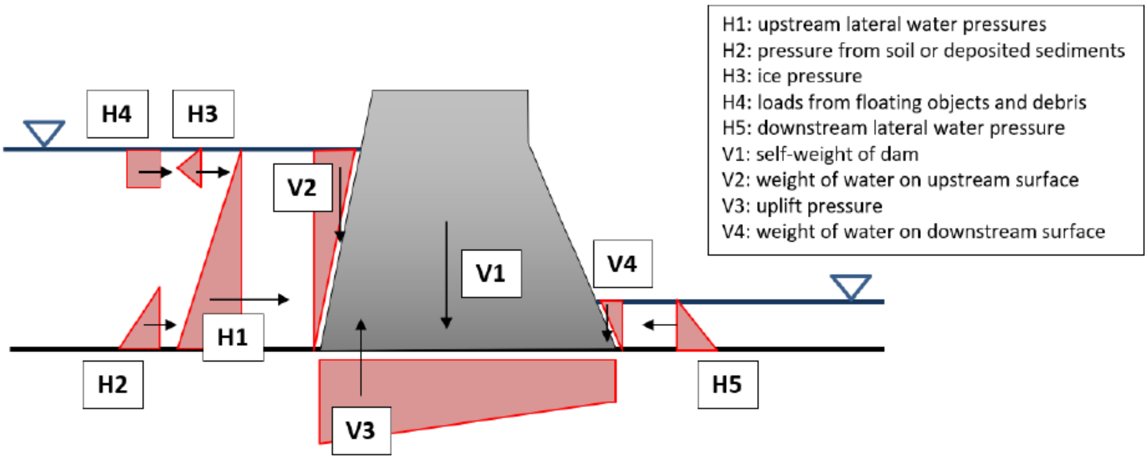


Figure C1. Common vertical and horizontal loads on a concrete gravity dam and foundation, with red diagrams representing vertical and horizontal load distributions on the dam (after Smith et al, 2017).

C1 Failure mechanisms and triggers for concrete dams

Failure and damage mechanisms need to be reviewed systematically for each dam to be assessed. This annex lists general failure mechanism categories for concrete dams. The analysis and prioritization of the plausible failure mechanisms and triggers is the essential and most important step of a risk analysis. A failure can be linked to four main categories of events: hydraulic events, seismic events, internal and external erosion, and war/terror/sabotage, as described in Annex B.

For concrete dams, new statistics [(ICOLD (2020, Bull. 99); Appendix D] suggests that the dominant failure mode is structural failure. Overtopping was more important for concrete dams built before 1975. Most failures occur in the first five (5) years of the dam.

Annex D summarizes dam failure and incident statistics for concrete and masonry dams.

The most common failure mechanisms and causes to consider in a risk assessment for concrete dams are as follows:

Weakness in and around the dam:

- Sliding and overturning of the concrete dam.
- Damage to the concrete, chemical (alkali- or sulphide) reactions.

- Landslides in the reservoir causing a flood wave and overtopping.
- Weakness or erosion in the soil or rock foundation.
- Quality of spillway of culverts
- Blocking of spillway.
- Operative measures leading to failure.

External triggers:
- Floods caused by intense or extreme precipitation, snow or glacier melting.
- Ice or hard-packed snow or debris blocking the spillway.
- A combination of these factors, occurring seasonally or simultaneously.
- Climate change impacting the conditions of the dam.
- Wave and ice loading leading to instabilities on the upstream side.
- Earthquake loading.
- External events such as meteorites, airplane crashes, (if plausible).

C2 Checklist for concrete dams

Table C1 gives an example of a checklist used by the US Army Corps of Engineers when doing safety assessment of concrete dams, under floods, seismic loading and normal operation.

C2.1 Forces on as concrete dam (Fig. C1)

The basic forces on a concrete dam forces on the concrete and the gates from the reservoir, water pressure during construction ("uplift forces") and the weight of concrete. There are also many other forces that can act on the concrete dams:

- water pressure on the downstream side of the dam;
- internal water pressure: in pores, cracks, joints, possibly internal chambers;
- temperature variations;
- chemical reactions;
- creep: deformation of the concrete under constant load over a long period of time;
- silty sedimentation building up on the upstream side over time;
- ice load on the upstream side;
- wave load on the upstream side;
- earthquake load;
- settlement of the foundation or connecting appurtenances;
- other constructions on the dam crest.

C3 Threats to concrete dams

Derfra (2011) listed a majority of threats against dams (Annex B), based on experience in the UK and a literature study. Each of these threats, can lead to a dam failure, according to Derfra.

C4 Stability

Important failure mechanisms to consider are stability of the concrete structure, reinforcement and foundation. The stability analyses include:

- Load cases from country design requirements (dam construction, water reservoir (up and down), hydrostatic pressure, internal hydrostatic load (uplift water pressure, "Uplift"), earth pressure, dead weight, external stresses (floods, earthquakes, ice loads) and temperature.

- Concrete quality: compressive and tensile strength of concrete, effect of aging, temperature and cracks and fissures in the concrete, as well as aggregate reactivity (e.g., alkali reactions).
- Foundation: Rock quality, shear strength in rock, cracks, fault planes, weakness in concrete-foundation interface.
- Construction quality: contraction and construction joints and water stops, spillway and its construction, foundation grouting and drainage, and adit-system, rock bolts and rock anchors.

When re-evaluating a concrete dam, observations and indications of unexpected or undesirable behaviour, changes in loads or from natural events should be included in the stability assessment.

Table C1. USACE's checklist for safety assessment of embankment dams (modified after Bowles et al., 2003)

Factors that can initiate undesirable events in concrete dams		
Flood	**Earthquake**	**Normal operation**
Internal stability		
Outer stability		
Piping in foundation	Internal stability	
Stability of embankments	Outer stability	
Flood capacity	Piping in foundation	Sliding in foundation
Extreme flood/precipitation	Stability of embankments	Piping in foundation
Overtopping	Flood capacity	Overturning of dam
Spillway and pond system	Overtopping	High stresses in concrete
Gates/hatches: stability, capacity	Spillway and pond system	Overtopping
Structural stability	Gates/hatches: stability, capacity	Reservoir capacity
Hydraulic stability	Structural stability	Appurtenances
Overtopping of walls	Hydraulic stability	Silt sedimentation in reservoir
Mechanical or electrical systems	Overtopping of walls	Construction work near the dam
Obstruction (debris, landslide)	Mechanical or electrical systems	
Silt sedimentation in reservoir	Appurtenances	
Stability of intake	Ageing of concrete	
Stability of tunnel		
Ageing of concrete		

C5 Failure modes

The following failure modes should be considered:

- Sliding on a horizontal (and near-horizontal) plane;
- Sliding on an existing sliding surface in the foundation
- Overturning;
- Water pressure under foundation
- Stresses exceeding shear strength in concrete or in foundations;
- Overstressing or buckling;
- Erosion (internal and external)

A combination of two or more of the mechanisms, for example, overturning and sliding, erosion leading to slipping over the foundation and buckling leading to overload must also be considered.

Failure modes can occur in parallel or in series. In parallel, e.g. when the shear strength of the foundation varies along a sliding surface or by fragile behaviour of the foundation material. In series, for example, if a reinforcement is undersized, the overload (possibly the fracture) can propagate from one gate to the other, or through the development of a crack. Another example, cracks that start as a result of heavy shaking due to an earthquake during a period of high water in the reservoir. The cracks may start at the change in the slope on the downstream surface of a gravitational dam. Due to cyclic "rocking" of the structure under an earthquake, the dam may crack into monoliths, and instability sets in. The dam can fail when several monoliths suddenly slide down below the water level.

ICOLD statistics (Annex D) show that, for massive concrete dams, the number of dam fractures is greatly reduced for dams built after 1940. In terms of foundations, slippage, leakage and internal erosion seem to be the predominant cause of failures in concrete dams, while overtopping seems to be the most common cause of failure in masonry dams. Important factors to consider include:

- Nature and condition of the rock,
- Observations of abnormal conditions (leakage, erosion, deformations).
- Static water pressure on the dam and in the foundation.

C5.1 Assessment of the foundation

Evaluation of the foundation is important since the foundation is often the cause of dam rupture on concrete dams. The following conditions should be considered: (1) local and global stability of the foundation in terms of potential slippage and build-up of pore pressure; (2) resistance to weathering and degradation as well as any potential for erosion and damage as an extreme flood develops; and (2) fixity of rock bolts in rock.

In the cases where slipping in the foundation has occurred, shale rocks with zones of weakness seem to be dominant. Shales with limestone also seems to have a greater probability of failure. There have been no failures of dams with basalt (igneous rock) foundations.

It is especially important to assess the risk of build-up of porewater pressure and potential zones with sliding planes. Layering with horizontal potential sliding surfaces where the faults are oriented parallel to the dam axis can be critical, especially in combination with high porewater pressure. At the same time, poor rock conditions with a lot of fracturing can lead to increased drainage of the water in the rock, so that there is no danger of pore pressure building up in the foundation under the dam.

C5.3 Kinematically feasible failure modes

It is absolutely essential that there be a proper assessment of the geological structure in the dam foundation and, based on this, the kinematically feasible failure modes should be identified. Examples of typical failure modes are given in Figure C2. Fell *et al.* (2015) mentioned that there may be different failure modes in different parts of the dam foundation.

It is not sufficient to consider only the mode of failure involving shear along the concrete-foundation contact. In most dams, there may be more critical conditions involving shear along discontinuities in the rock foundation if these have a lower strength than the concrete-foundation interface.

The analysis should also consider failure within the concrete in the dam, usually controlled by the most likely weaknesses within the concrete, probably the construction lift joints. In some dams, there will be identifiable weak planes due to deterioration on lift joints and cracking due to thermal expansion and contraction on major discontinuities in the geometry of the dam.

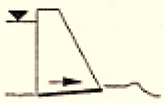
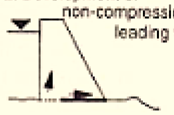
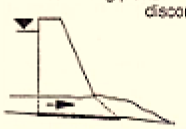
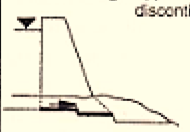
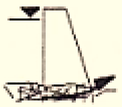
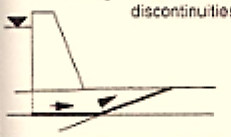
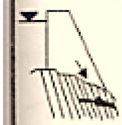
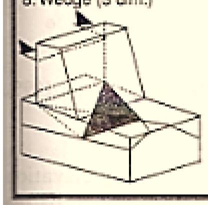
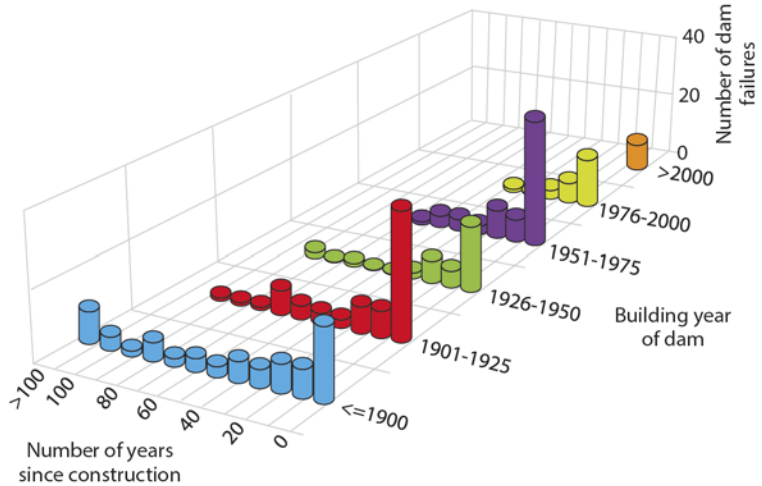
Mode	Condition	Comments
1. Shear along concrete rock contact 	- Shear along weak discontinuity at or near concrete-rock contact.	- Possible if weak foundation or poor excavation and/or foundation treatment. - Infrequent mode. Check for condition, particularly in old dams.
2. Development of non-compression zone leading to shear 	- Development of non-compression zone (a computed crack) leading to shear along the concrete-rock contact.	- Can occur even in good foundations.
3. Shear along planar discontinuity 	- Shear along planar or near planar discontinuity in rock foundation.	- Frequent mode.
4. Shear along stepped discontinuities 	- Shear along stepped discontinuities or along surfaces stepping down between parallel discontinuities in rock foundations.	- If step(s) not large then failure surface may be approximated by an inclined plane. - Large steps may require higher level of analysis.
5. Shear through jointed rock mass 	- Shear through highly jointed rock mass (both natural or blast induced) or through weak rock mass.	- Infrequent mode - May be used in moderately jointed rock masses (with an adjustment to assigned Hoek-Brown rock mass strength) - Failure surface usually approximated as being planar.
6. Shear along combined discontinuities 	- Shear along a combination of two or more discontinuities.	- Occasional; usually assume planar mode (3) during initial assessment. - Limit equilibrium analysis can be used for more detailed analysis.
7. Toppling 	- Loads at toe of dam causing toppling of bedded rock formation.	- Infrequent but should be evaluated in bedded or highly jointed (parallel) rocks - If dam heel lifts block may continue movement by shearing through toe (mode 2.).
8. Wedge (3 dim.) 	- Wedge formed beneath block by combinations of major faults, shears and/or joint sets.	- Infrequent but should be evaluated where major features such as faults/shears cross foundation and combine with jointing. - Rigid body, 3-dimensional analysis.

Figure C2. Kinematically feasible failure modes (BC Hydro, 1995; reproduced by Fell et al., 2015).

Annex D Dam failure statistics

Contents



Number of dam failures as a function of year of construction and age of dam, all dam types (ICOLD Bull. 99, 2020)

D1 Introduction

Appendix D summarizes statistics on incidents and dam failures. The majority of the statistics are from ICOLD, and a number of additional other results from the literature have also been summarized. To compare the statistics in the different figures with a dam under study, it is important to also compare in terms of year of construction, age of the dam, dam type and dam height.

D2 ICOLD dam failure statistics

D2.1 Statistics for all dam types: embankment, concrete and masonry dams

ICOLD Bulletin 99 (rev. 2020) presented the latest statistics for dam failures, using a database of 59,071 dams, of which 322 failed. The graphs look at number of dam failures, cause of failure, year of construction (1900 to 2020), type of dam and age of the dams. A tabular overview is made of the statistics included. Table D1 lists the statistics for all types of dams. Table D2 lists the statistics for embankment dams and Table D3 the statistics for concrete and masonry dams. Table D4 provides an overview of statistics on the cause of dam failures for all dam types. The ICOLD dam failure statistics selected for this handbook can be found in Figures D1 to D29.

D2.2 Conclusions from the ICOLD statistics

D2.2.1 Embankment dams

For embankment dams, the ICOLD statistics show that:

- The two most common failure modes are overtopping or internal erosion.
- There have been many fewer embankment dam failures since 1950.
- Most dam failures occur in the first years of the dam during and shortly after first filling).
- There are almost no failures of embankment dams older than 30 years
- 98% of the known failure cases are attributed to one of three failure modes: (i) internal erosion (39%), (ii) overtopping (40%) and (iii) structural failure (29%).
    - Overtopping most often occurs under large flood conditions.
    - Internal erosion occurs most often occurs under normal conditions.
- For earth fill embankment dams, geotechnical aspects (66%) and insufficient spillway capacity (28%) are the most frequent causes. For rockfill dams, geotechnical aspects (32%) and insufficient spillway capacity (64%) are also the most frequent causes.

D2.2.2 Concrete and masonry dams

For concrete and masonry dams, the ICOLD statistics show that:

- For 79% of the dam failures, the dams were built before 1930.
- A quarter of the dam failures occurred during first filling, while about 50% of the dam failures occurring within 10 years after first filling. Dam failures very rarely occur in old concrete dams.
- 42% of the dam failures are related to the foundation, in the form of erosion or as a shear failure (slippage) in the foundation. Overtopping is almost always due to exceptional floods.

D2.2.3 All dam types

The ICOLD statistics suggest that:

- Most failures occur for dams with height between 15 and 75 m. Dam failure occurs rarely for higher dams, and has never occurred for a dam higher than 100m.
- Since 2000, 70% of dam failures have occurred under exceptional flood conditions.
- Inadequate design and inadequate construction are the most frequent organizational causes of dam failure for concrete dams. For embankment dams, inadequate operation during floods caused about 10% of the dam failures.

D2.3 ICOLD's dam failure statistics

Table D1. ICOLD statistics on number of dam failures, all dam types (Figs D1 – D5) and per dam type (Figs D6 – D8).

Fig.	Statistics
D1	Total number of dams and number of failures in % of total dams (1900 – 2020), all dam types
D2	Total number of dams and frequency of dam failure per dam type (1900 – 2020)
D3	Number of dam failures in the first 10 years of the dam's life, all dam types (1900 – 2020)
D4	Number of dam failures as a function of construction year and age of dam, all dam types (1900 – 2020)
D5	Number of dam failures versus dam height, all dam types (1900 – 2020)
D6	Number of dam failures (in %) as a function of the age of the dam at failure, per dam type (1900 – 2020)
D7	Number of dam failures per dam type and per causes of failure (1900 – 2020)
D8	Number of dam failure as a function of the time of construction, per dam type (1900 – 2020)

Statistics, embankment dams

Table D2. ICOLD statistics for embankment dams (Figs D9 – D14).

Fig.	Statistics
D9	Annual failure probability of embankment dams due to internal erosion
D10	Technical causes of failure in embankment dams (1900 – 2020)
D11	Number of dam failures in % and technical causes of failures in embankment dams (1900 – 2020)
D12	Causes of internal erosion in embankment dams (1900 – 2020)
D13	Age of dam at failure, embankment dams (1900 – 2020)
D14	Number of failures, causes of failures and age of dam, embankment dams (1900 – 2020)

Statistics, concrete and masonry dams

Table D3. ICOLD statistics for concrete and masonry dams (Figs D15 – D21)

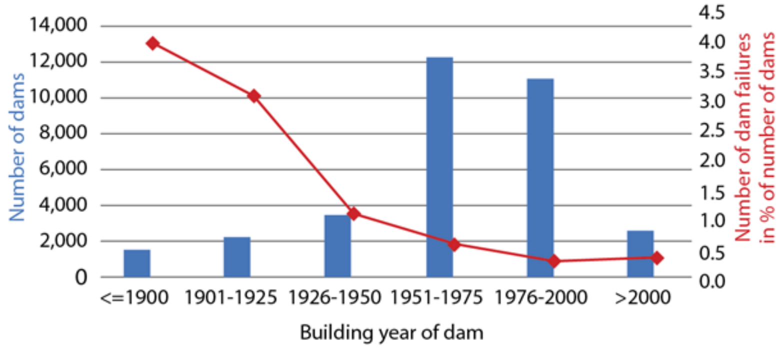
Fig.	Statistics
D15	Number of dam failures for concrete and masonry dams (1900 – 2020)
D16	Failure modes for concrete and masonry dams (1900 – 2020)
D17	Number of dam failures and technical causes of failure for concrete and masonry dams (1900 – 2020)
D18	Number of failures and failure causes in % of total number of concrete and masonry dams (1900–2020)
D19	Causes of failure versus age of dam, concrete and masonry dams (1900 – 2020)
D20	Age of dam at failure, concrete and masonry dams (1900 – 2020)
D21	Failure modes and failure conditions, concrete and masonry dams (1900 – 2020)

Statistics on causes of failure, failure conditions and failure mechanisms, all dam types

Table D4. ICOLD statistics on failure causes, failure conditions and failure mechanisms, all dam types (Figs D22–D23).

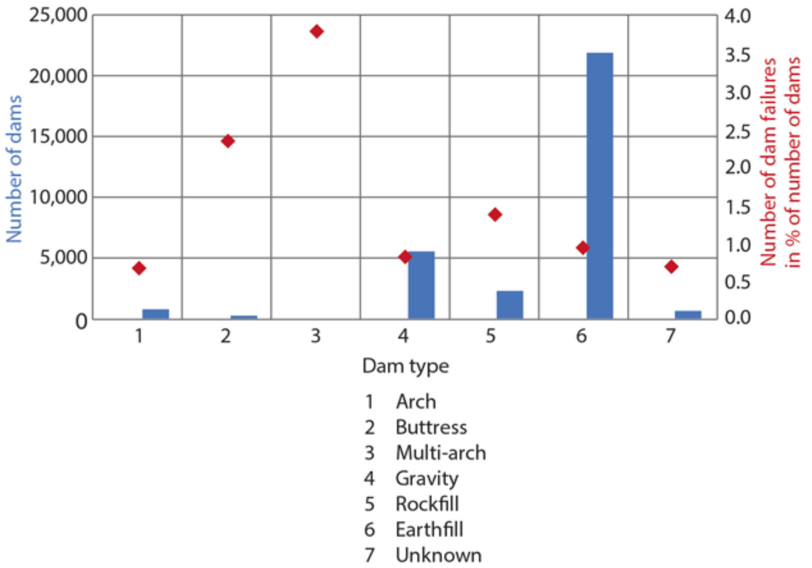
Fig.	Statistics
D22	Causes of failure, all dam types (1900 – 2020)
D23	Causes of failure as a function of construction year, all dam types (1900 – 2020)
D24	Failure modes per dam type (1900 – 2020)
D25	Failure modes per dam type in the first 10 years of the dam life (1900 – 2020)
D26	Failure conditions as a function of construction year, all dam types (1900 – 2020)
D27	Failure conditions as a function of the age of the dam, all dam types (1900 – 2020)
D28	Factors causing failure as a function of age of dam, all dam types (1900 – 2020)
D29	Factors causing failure in % of total number of dam failures, all dam types (1900 – 2020)

D2.4 Statistics in graphs, all dam types



Period	Number of failures	Number of failures (% of total number of dams)
≤ 1900	67	4.2%
1901 – 1025	73	3.3%
1026 – 1950	41	1.2%
1951 – 1975	73	0.6%
1976 – 2000	32	0.3%
≥ 2000	10	0.4%

Figure D1. Total number of dams and number of failures in % of total dams (1900 – 2020), all dam types (ICOLD Bull. 99, 2020).



Dam type	Number of failures	Number of failures (% total number of dams)
Arch dam	6	0.7%
Buttress dam	8	2.3%
Multi-arch dam	4	3.8%
Gravity dam	46	0.8%
Rockfill embankment dam	33	1.4%
Earth fill embankment dam	209	1.0%
Unknown	5	0.7%

Figure D2. Total number of dams and frequency of dam failure per dam type (1900 – 2020) [for each dam type: blue column: total number of dams; red data: number of dam failures in % of total number of dams] (ICOLD Bull. 99, 2020).

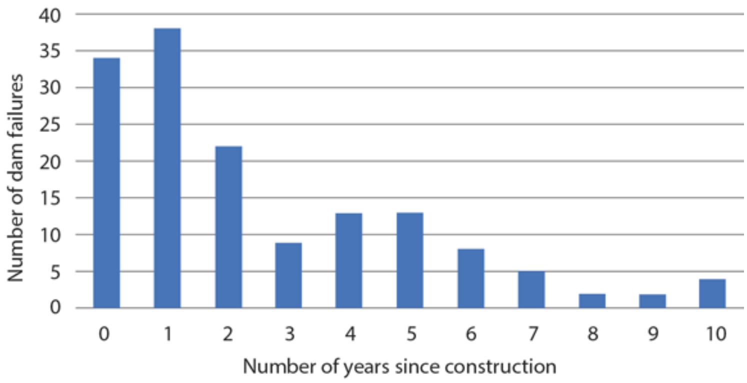


Figure D3. Number of dam failures in the first 10 years of the dam's life, all dam types (1900 – 2020) (ICOLD Bull. 99, 2020)

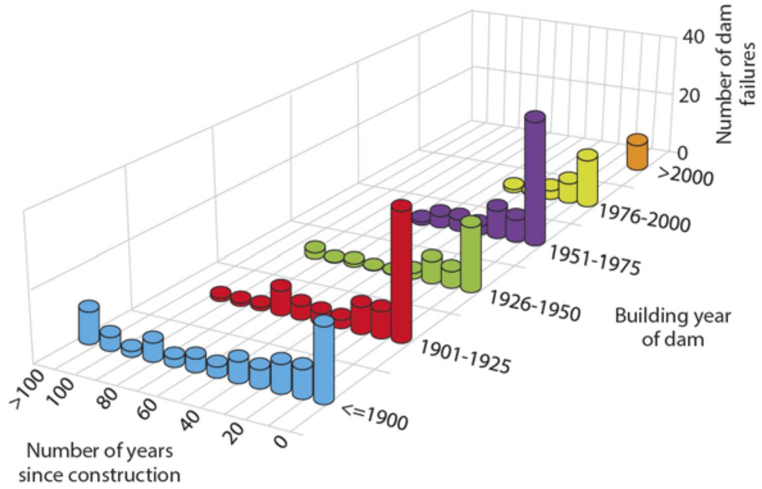


Figure D4. Number of dam failures as a function of construction year and age of dam, all dam types (1900 – 2020) (ICOLD Bull. 99, 2020)

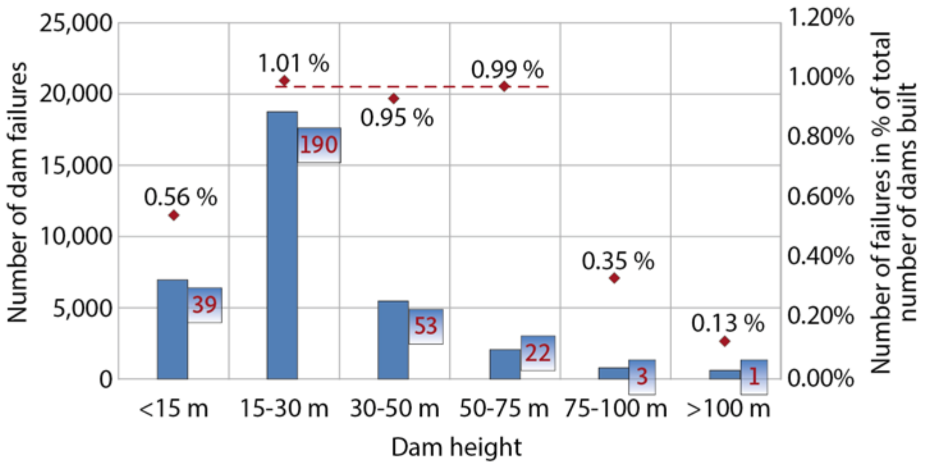


Figure D5. Number of dam failures versus dam height, all dam types (1900 – 2020) (ICOLD Bull. 99, 2020)

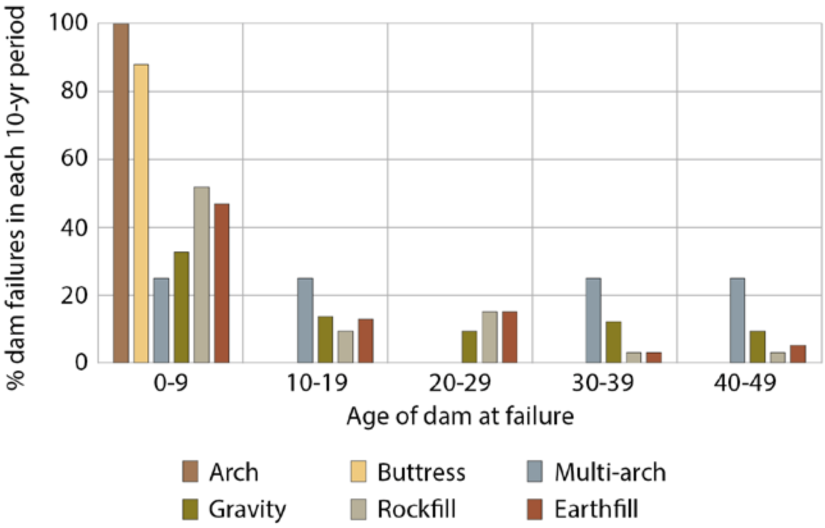
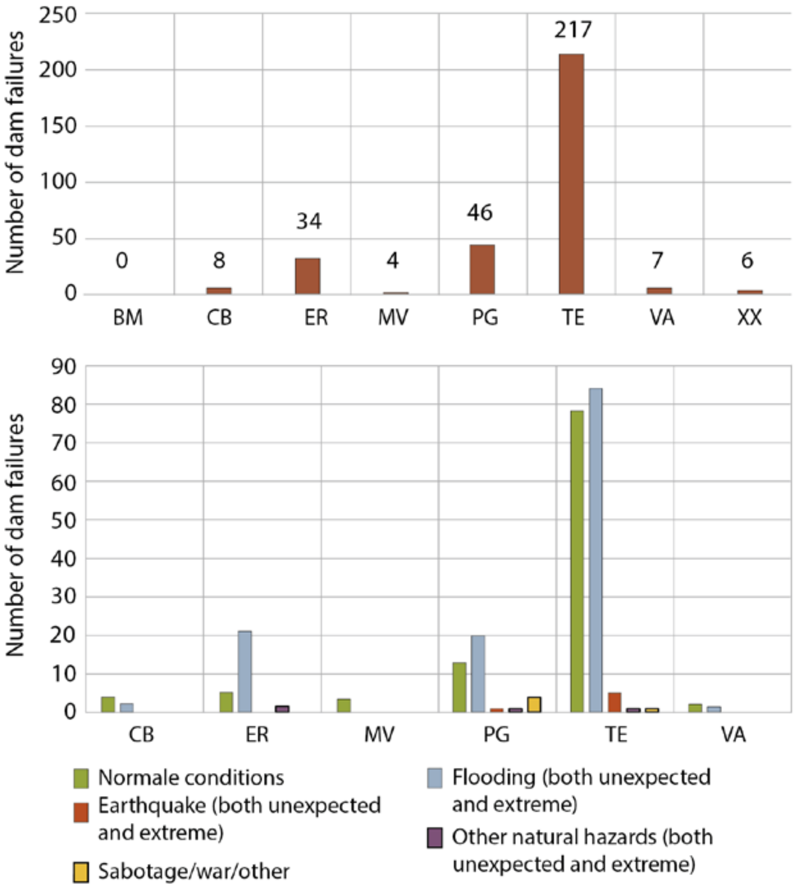


Figure D6. Number of dam failures (in %) as a function of the age of the dam at failure, per dam type (1900 – 2020) (ICOLD Bull. 99, 2020)



Notation	Dam type	Number of dams	Number of failures	No. failures (% of total No. dams)
BM	"Barrier"-dam	224	0	0
CB	Buttress dam	340	8	2.4%
ER	Rockfill embankment dam	2378	34	1.4%
MV	Multi-arch dam	105	4	3.6%
PG	Gravity (concrete) dam	5571	46	0.8%
T	Earth fill embankment dam	21977	217	1.0%
VA	Arch dam	890	7	0.8%
XX	Unknown	715	6	0.8%

Figure D7. Number of dam failures per dam type and per cause of failure (1900 – 2010) (ICOLD Bull. 99, 2020)

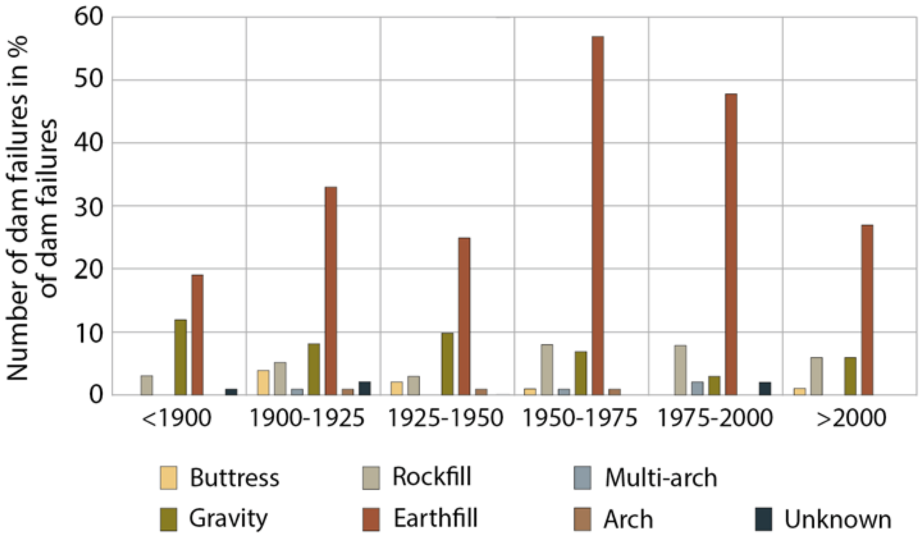


Figure D8. Number of dam failures as a function of the time of construction, per dam type (1900 – 2020) (ICOLD Bull. 99, 2020)

D2.5 Statistics in graphs, embankment dams

Figure D9 shows the annual failure probability due to internal erosion for embankment dams, based on observations of failures in the USA, ICOLD statistics and a worldwide review carried out by Fell *et al.* (2015). Factors that can increase or reduce progression of internal erosion and failure probability, according to ICOLD, are listed below Figure D9.

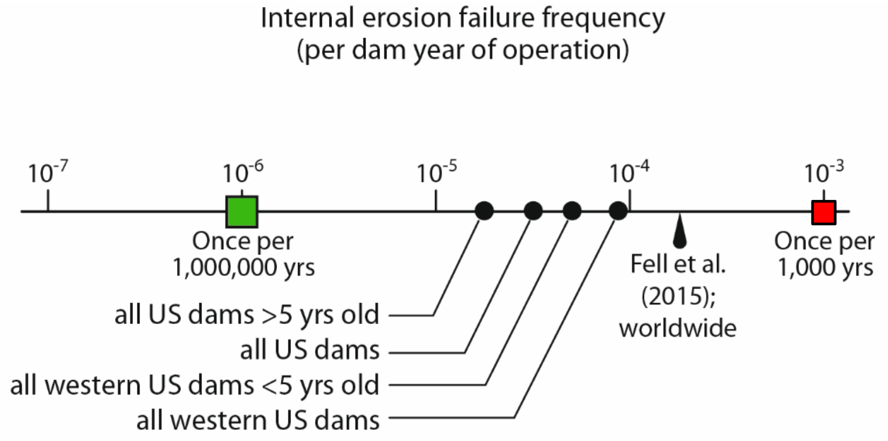


Figure D9. Annual failure probability of embankment dams due to internal erosion (Von Thun, 1985; Vick, 2002).

Reduces probability of erosion and failure	Increases probability of erosion and failure
Processed filters	Uncontrolled seepage exit
Surface treatment of foundation	No processed filters
Impervious foundation	Open, untreated foundation joints
Foundation grouting	Open granular foundation soils
Shaping of rock foundation	History of seepage carrying fines
Long operation at maximum pool	"Dispersive" soils in dam or foundation
Well-graded core	Structures penetrating embankment
Plastic core	Irregular or steep foundation profile
Positive cut-off into rock	Fine grained erodible core
Low gradients	High gradients
Minor seepage	High seepage quantity
Good and reliable monitoring	No or poor monitoring

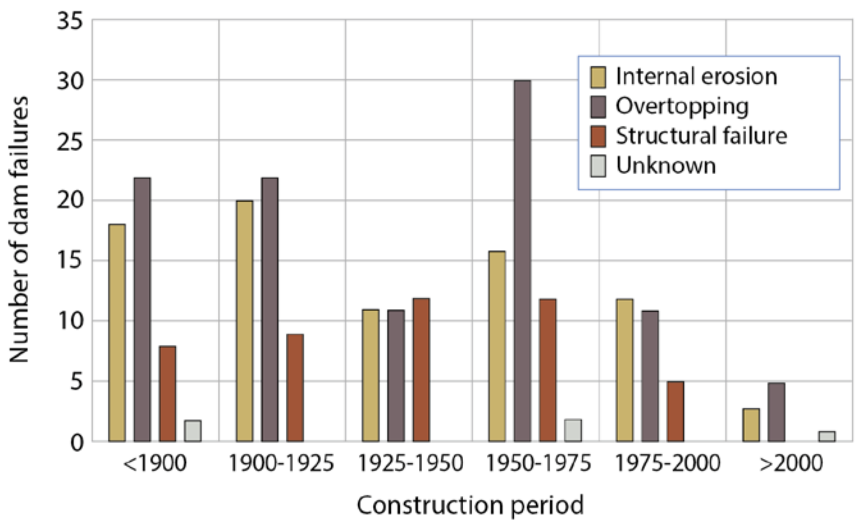


Figure D10. Technical causes of failure in embankment dams (1900 – 2020) (ICOLD Bull. 99, 2020)

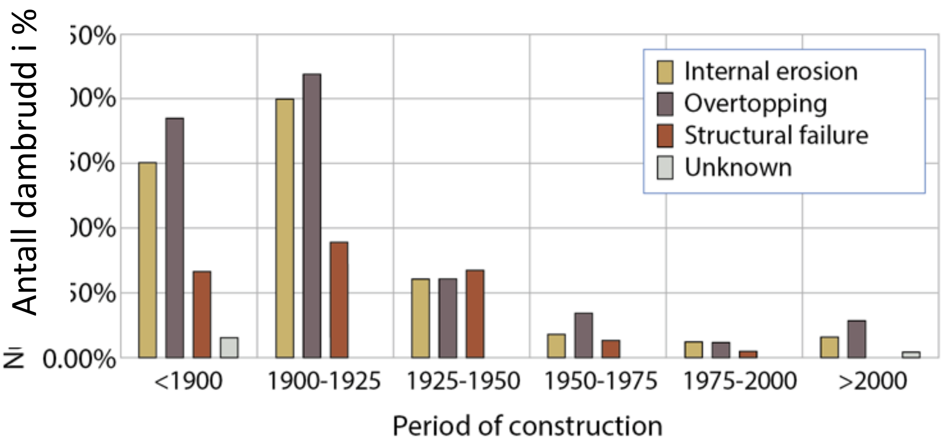


Figure D11. Number of dam failures in % and technical causes of failures in embankment dams (1900 – 2020) (ICOLD Bull. 99, 2020)

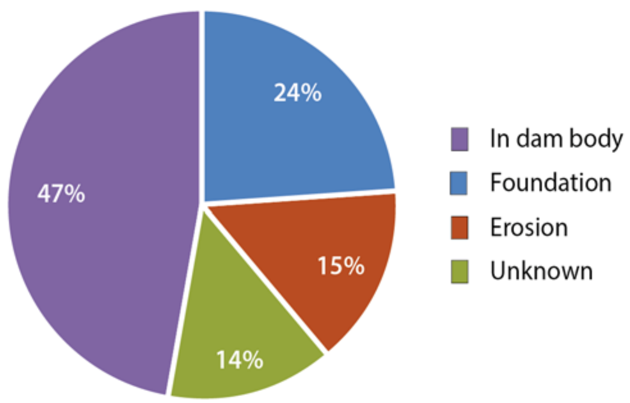


Figure D12. Causes of internal erosion in embankment dams (1900 – 2020) ICOLD Bull. 99, 2020)

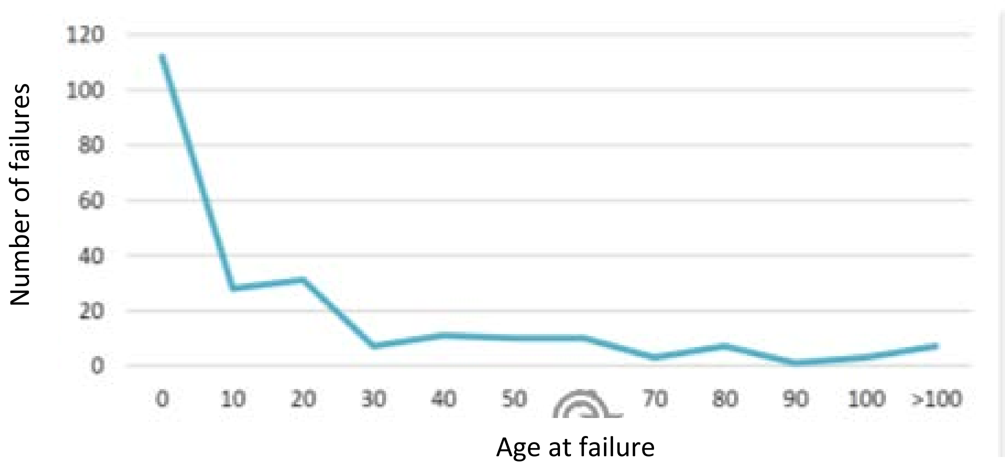


Figure D13. Age of dam at failure, embankment dams (1900-2020) (ICOLD Bull. 99, 2020)

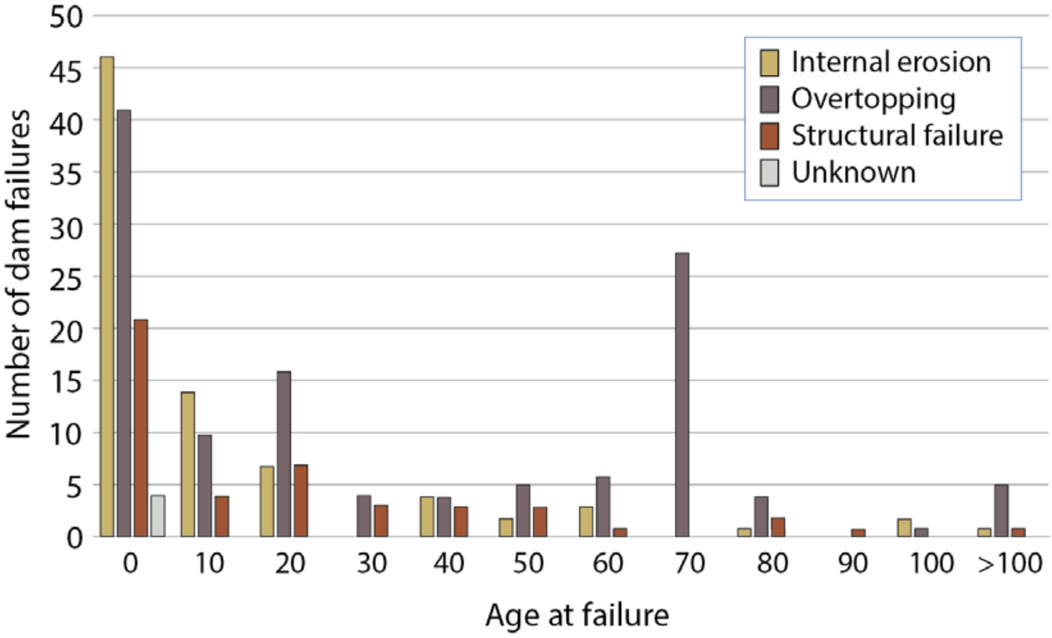


Figure D14. Number of failures, causes of failures and age of dam, embankment dams (1900-2020) (ICOLD Bull. 99, 2020)

D2.6 Statistics, concrete and masonry dams

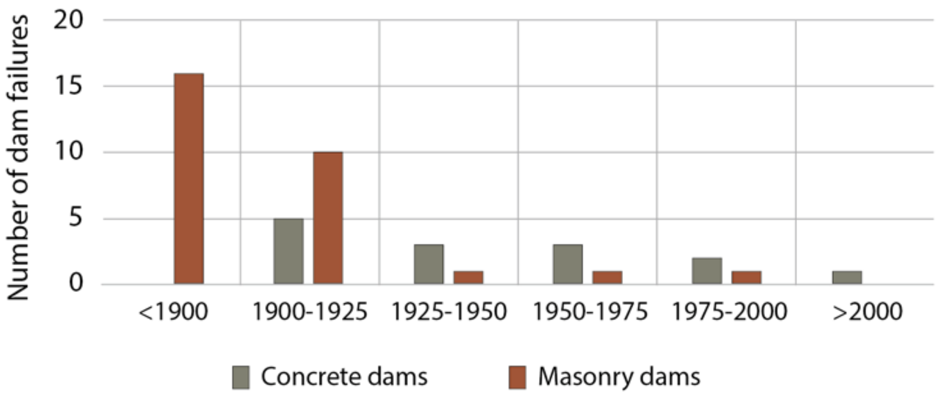


Figure D15. Number of dam failures for concrete and masonry dams (1900-2020) (ICOLD Bull. 99, 2020)

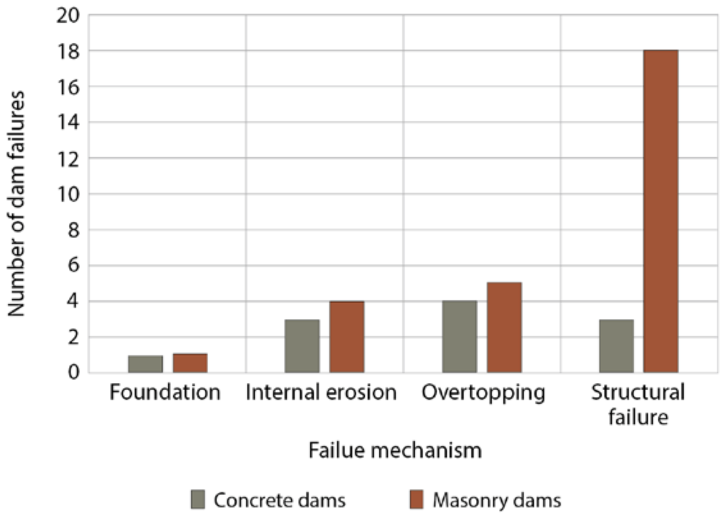


Figure D16. Failure modes for concrete and masonry dams (1900 – 2020) (ICOLD Bull. 99, 2020)

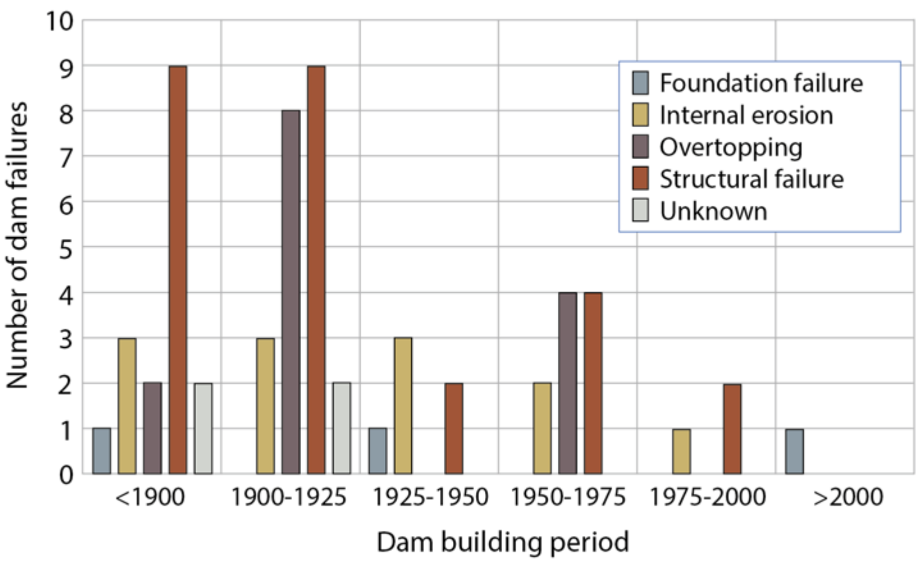


Figure D17. Number of dam failures and technical causes of failure, concrete and masonry dams, (1900-2020) (ICOLD Bull. 99, 2020)

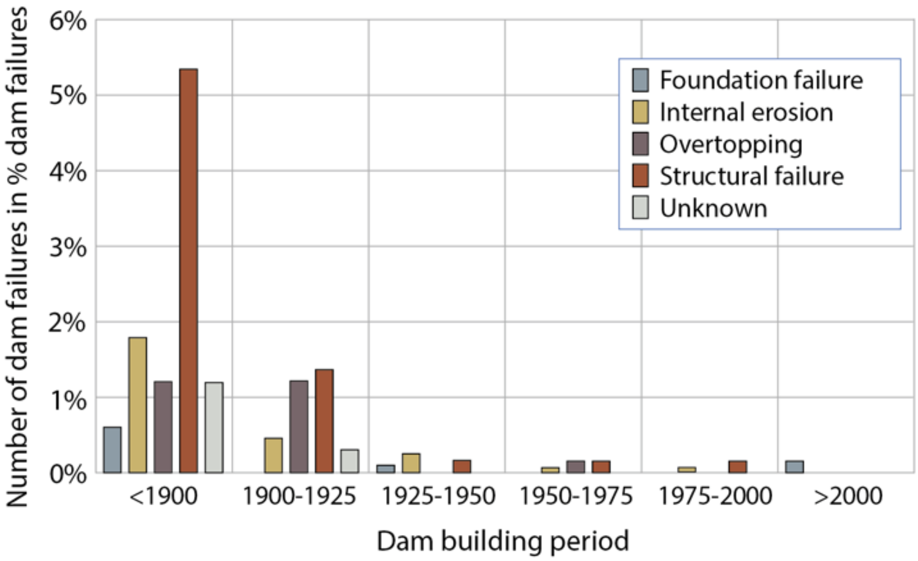


Figure D18. Number of failures and failure causes in % of total number of concrete and masonry dams (1900-2020) (ICOLD Bull. 99, 2020)

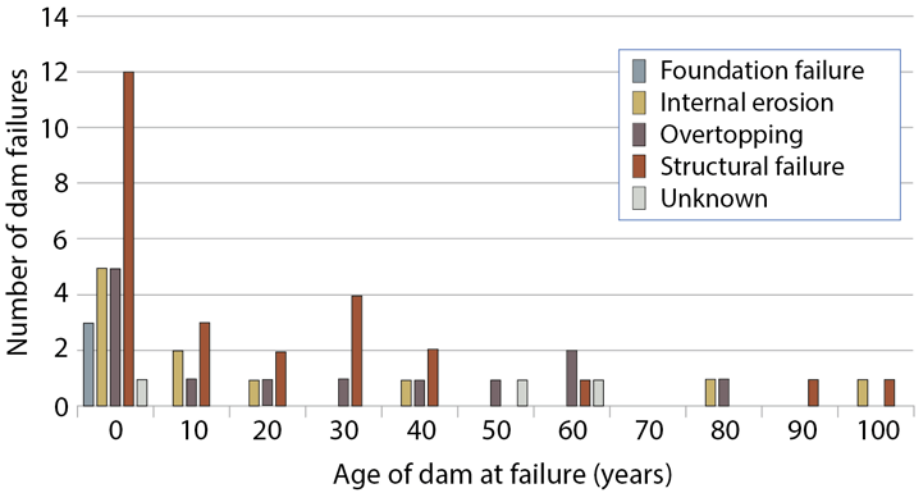


Figure D19. Causes of failure versus age of dam at failure, concrete and masonry dams (1900-2020) (ICOLD Bull. 99, 2020)

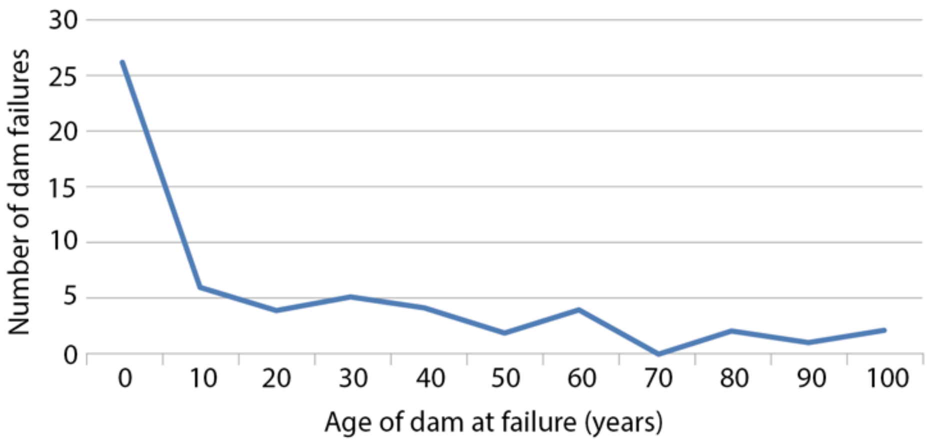


Figure D20. Age of dam at failure, concrete and masonry dams (1900–2020) (ICOLD Bull. 99, 2020)

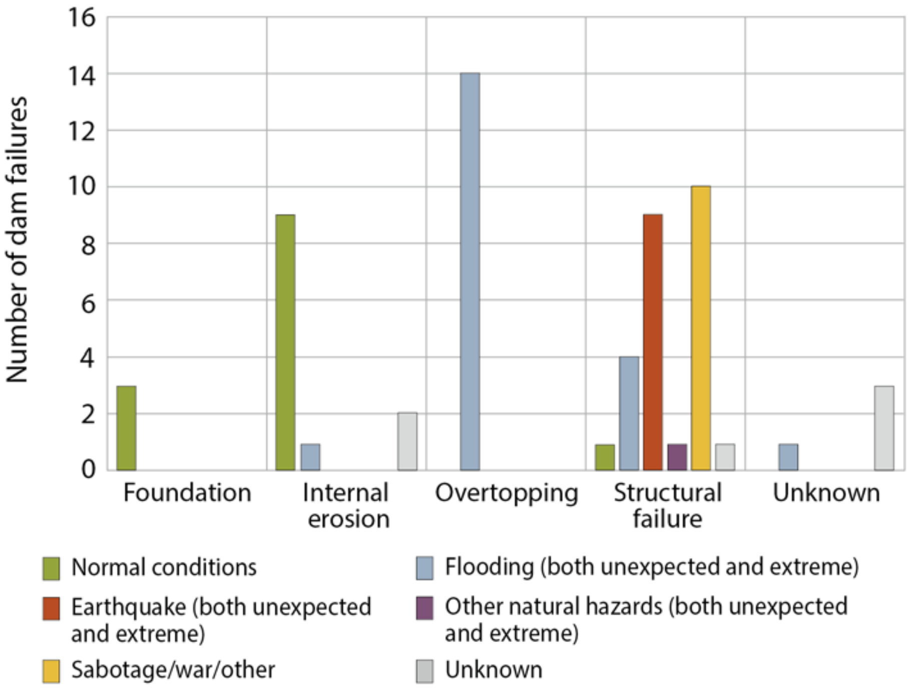


Figure D21. Failure modes and failure condition, concrete and masonry dams (1900 – 2020) (ICOLD Bull. 99, 2020)

D2.7 Statistics on causes of failure, failure conditions and failure mechanisms, all dam types

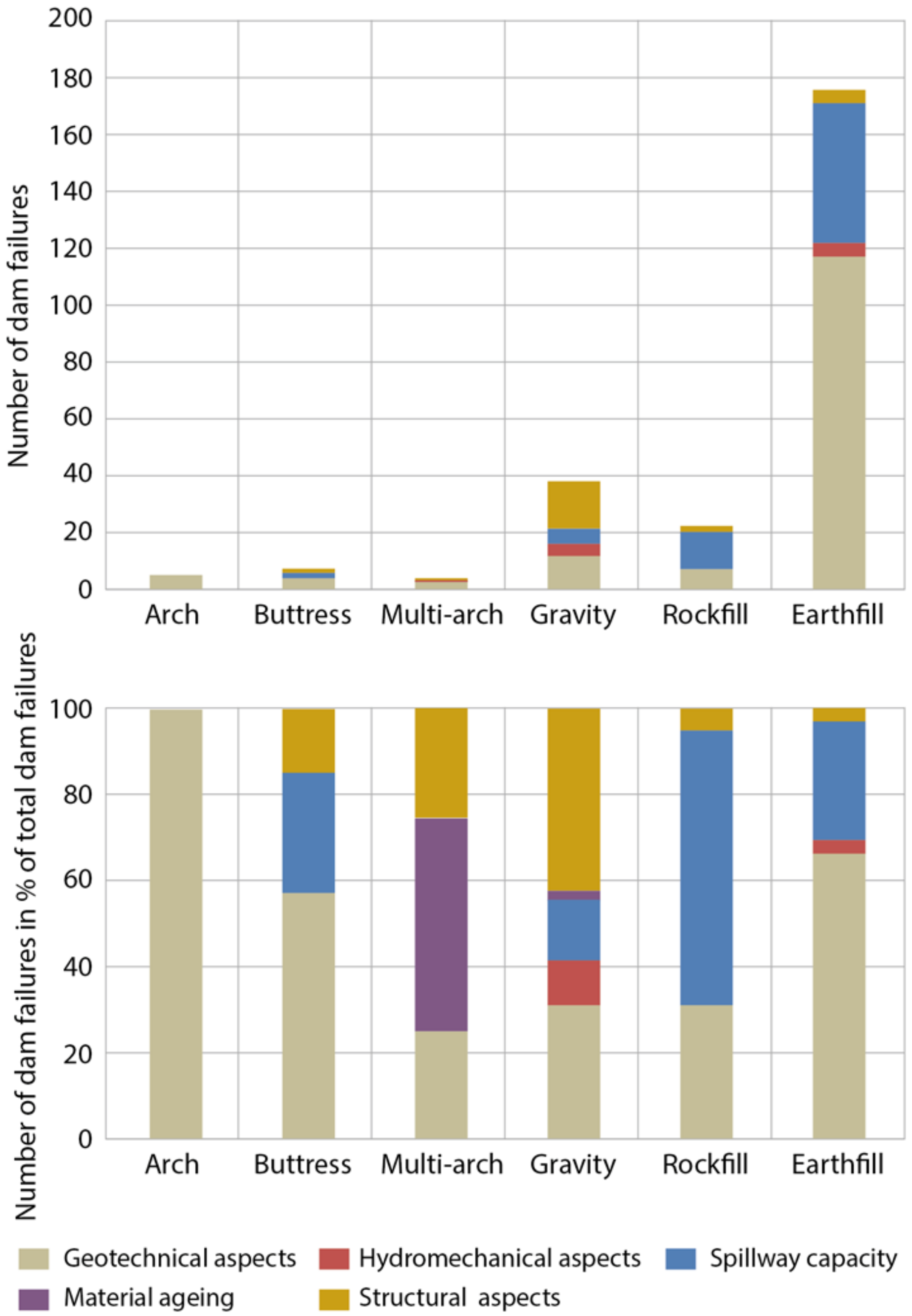


Figure D22. Causes of failure, all dam types, (in numbers (upper) and in % (lower) (1900 – 2020) (ICOLD Bull. 99, 2020)

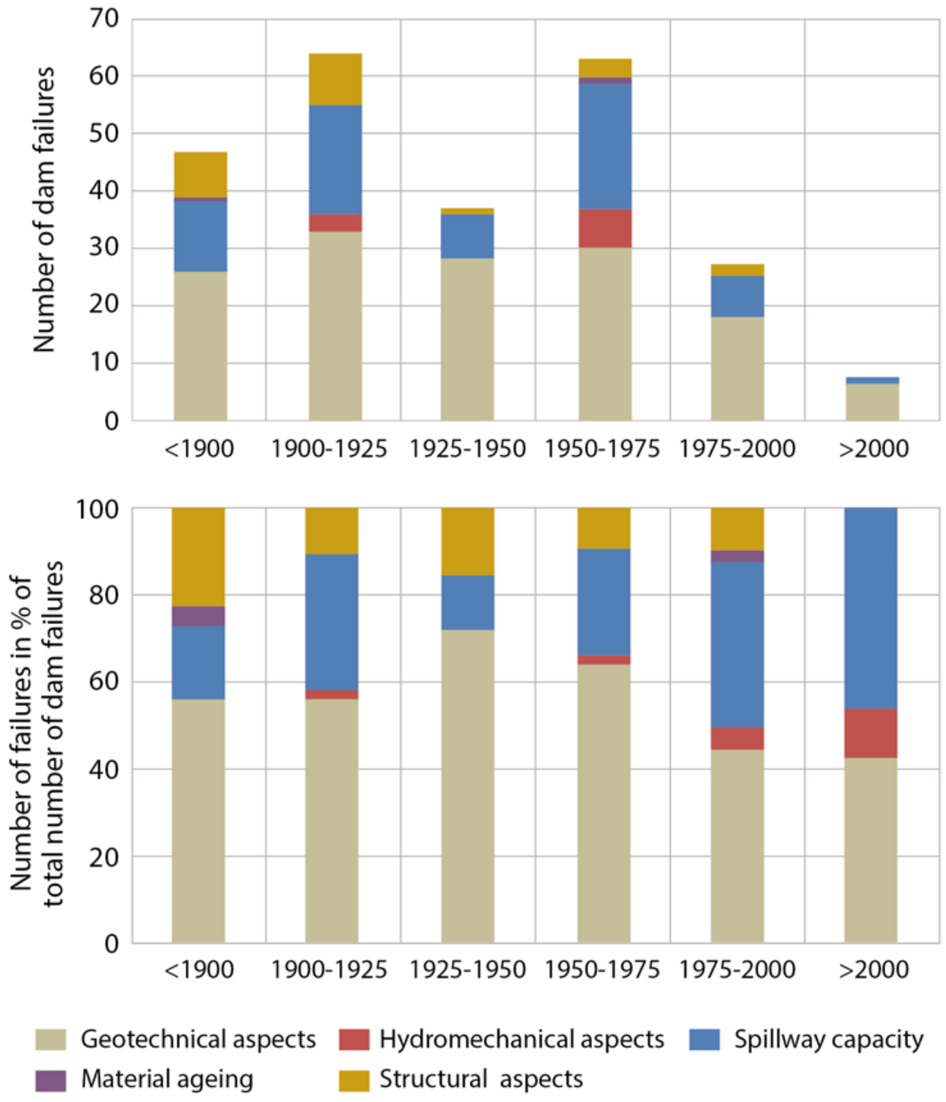


Figure D23. Causes of failure as a function of construction year, all dam types (1900 – 2020) (ICOLD Bull. 99, 2020)

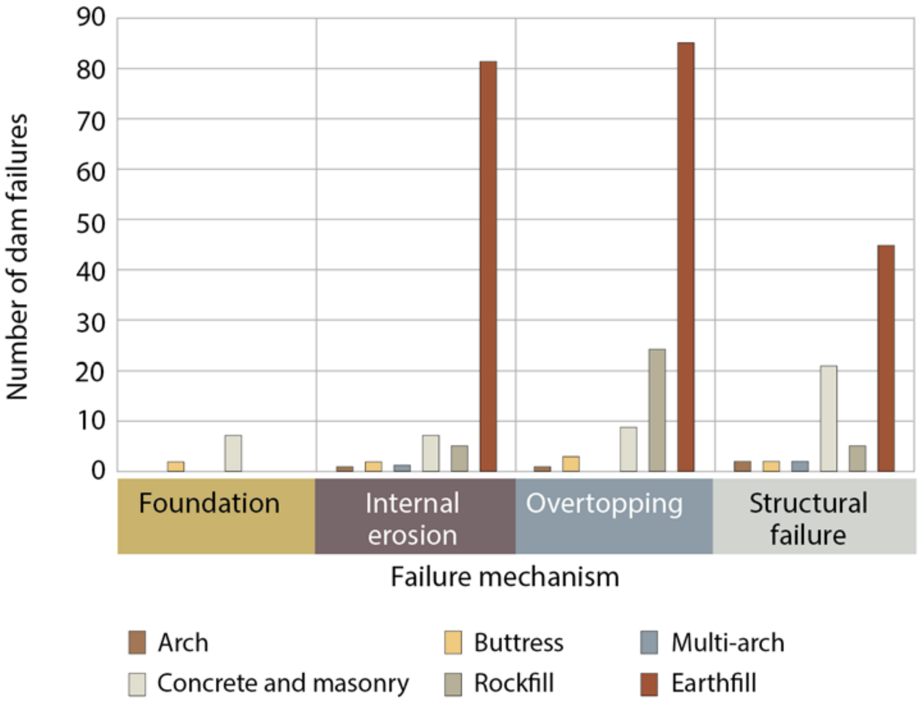


Figure D24. Failure modes per dam type (1900-2020) (ICOLD Bull. 99, 2020)

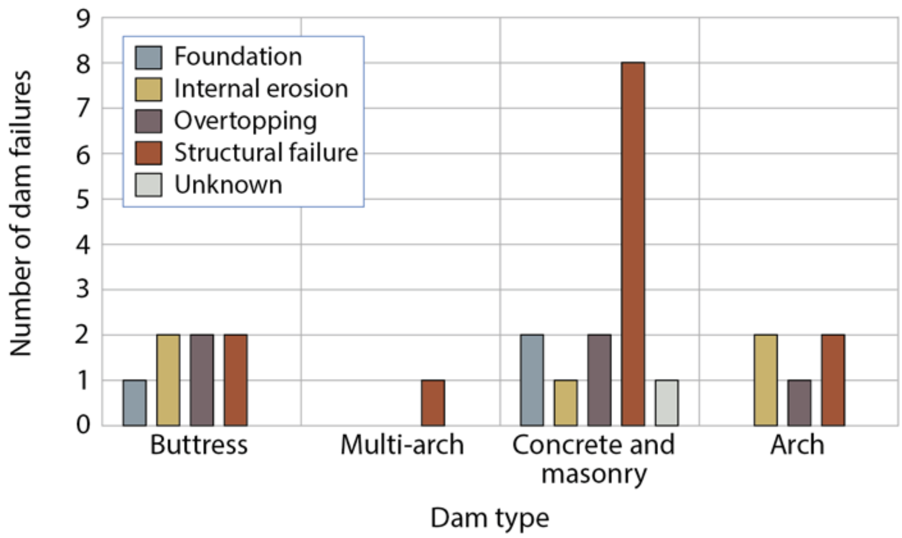


Figure D25. Failure modes per dam type in the first 10 years of the dam life (1900 – 2020) (ICOLD Bull. 99, 2020)

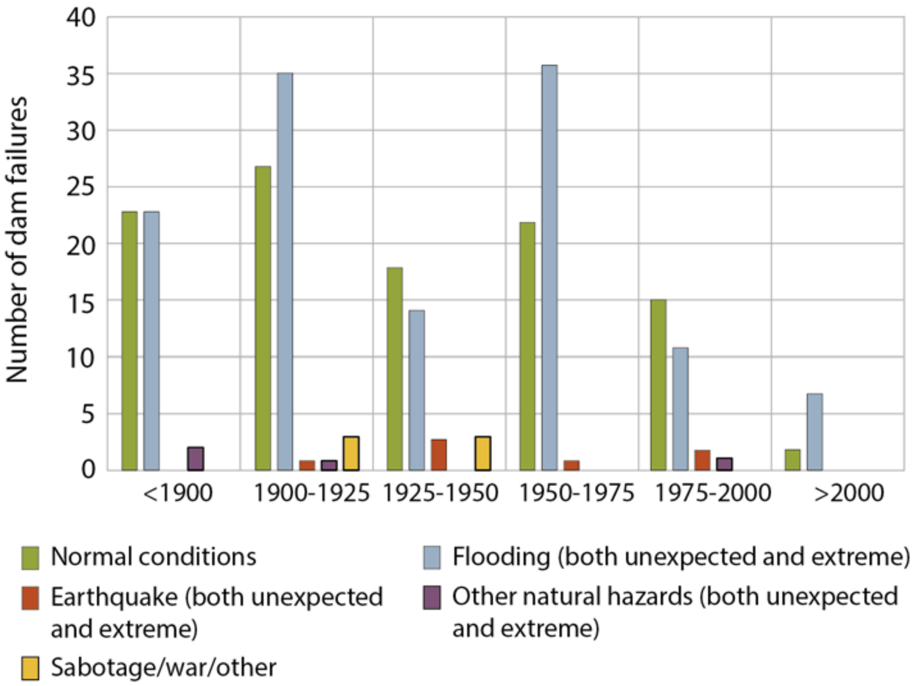


Figure D26. Failure conditions as a function of construction year, all dam types (1900 – 2020) (ICOLD Bull. 99, 2020)

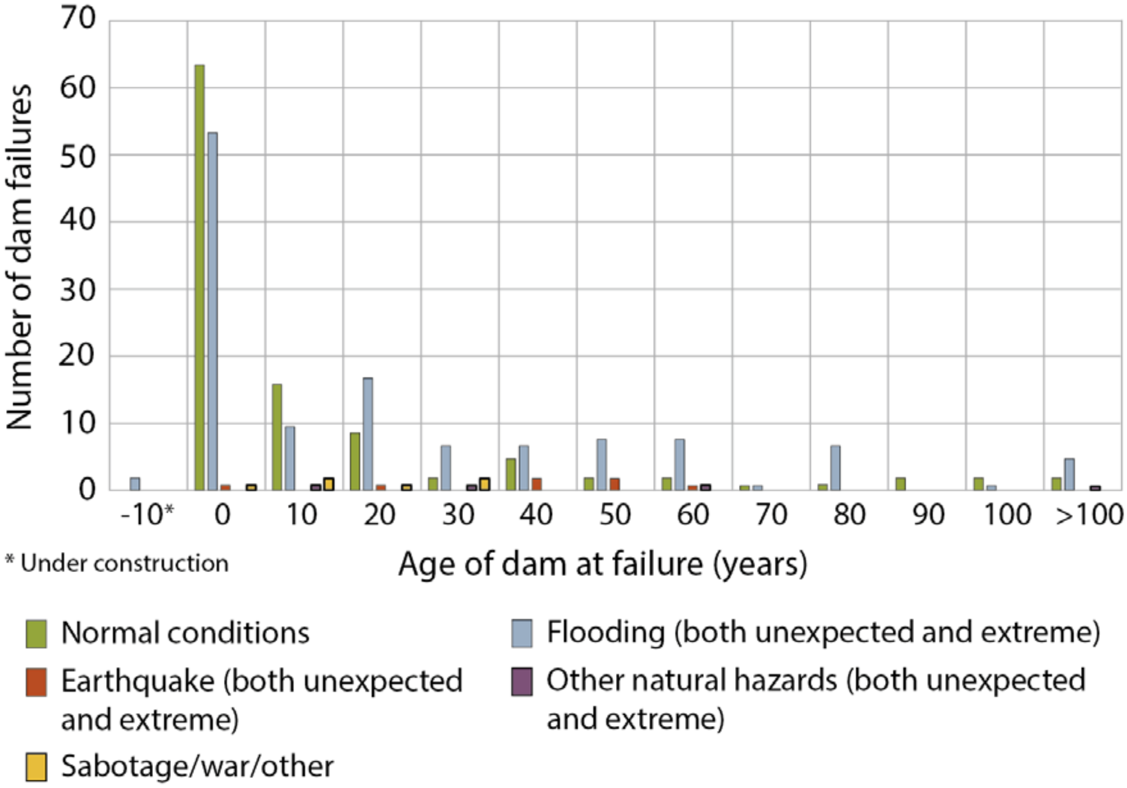


Figure D27. Failure conditions as a function of the age of the dam, all dam types (1900 – 2020) (ICOLD Bull. 99, 2020)

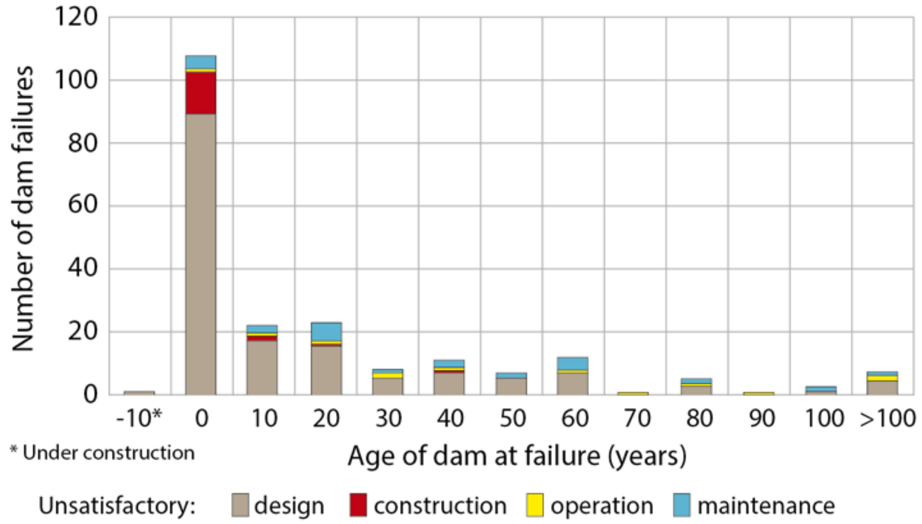


Figure D28. Factors causing failure as a function of the age of the dam, all dam types (1900 – 2020) (ICOLD Bull. 99, 2020)

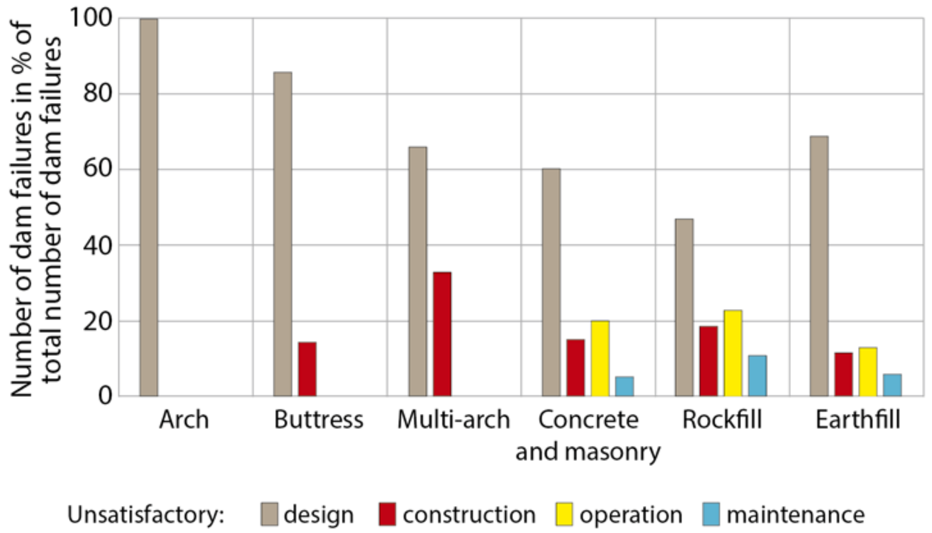


Figure D29. Factors causing failure in % of total number of dam failures, all dam types (1900 – 2020) (ICOLD Bull. 99, 2020)

D3 Statistics from the literature

D3.1 Embankment dams

Based on the observed frequency of internal erosion and the life of the dams in the USA, ICOLD published that dams in the USA have an annual failure probability due to internal erosion between 3 and $9 \cdot 10^{-5}$ /year, so close to 10^{-4} /year (Fig. D9). These numbers were confirmed by Londe (1993), ICOLD (1995), Foster *et al.* (2000) and Høeg (2001). Peck (1980), based on the work by Baecher *et al.* (1980 a and b) reported that the failure probability for dams both in the USA and the rest of the world was between 2 and $7 \cdot 10^{-4}$ /year. Foster *et al.* (2000) reported that the probability of an accident due to instability in the downstream slope was between 1 and $5 \cdot 10^{-4}$ /year and that the failure probability was $1.5 \cdot 10^{-5}$ /year.

Fell *et al.* (2015) reported statistics for embankment dams covering the period of 1800 to 1986, based on Foster *et al.* (2000). The number of dams in the database was 11,192 "large" dams. Fell *et al.* (2015) calculated an annual failure probability during the same period (1800 to 1986): the failure probability after first reservoir filling was $2 \cdot 10^{-4}$ /year. Fell's annual failure probability (shown in Fig. D9) is higher than the ICOLD statistics.

A selection of several of Fell *et al*.'s statistics for embankment dams is reproduced in Table D5, showing average occurrence of failures and undesirable events (in %) for different failure mechanisms and at different times in a dam's lifetime. For embankment dams, about 67% of the dam failures are due to internal erosion and "piping". Approximately 50% of the internal erosion and "piping" events occur either during the first filling of the reservoir or during the first five years of operation. The statistics also show that there are much more frequent failures in smaller dams (less than 30 m high) than in large dams.

Table D5. Statistics for dam failure and undesirable incidents for embankment dams (Fell et al., 2015).

Failure mode	**Average annual probability**		**Number of incidents/failure (in %)**							
			Failure				Incident			
	Failure	Incident	Constr ue	1st fill.	0-5 yr	>5 yr	Constr	1st fill.	0-5 yr	>5 yr
Internal erosion and/or piping										
-In the embankment	$3.5 \cdot 10^{-3}$	$6.7 \cdot 10^{-3}$	2%	48%	14%	36%	0%	26%	13%	61%
-In the foundation	$1.7 \cdot 10^{-3}$	$6.2 \cdot 10^{-3}$	5%	20%	50%	25%	0%	30%	24%	46%
-Embankment to foundation	$0.2 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$	0%	50%	50%	0%	0%	20%	27%	53%
Slope stability										
-Downstream	$0.5 \cdot 10^{-3}$	$5.3 \cdot 10^{-3}$	18%	18%	0%	64%	15%	11%	25%	49%
-Upstream	$0.1 \cdot 10^{-3}$	$4.2 \cdot 10^{-3}$	0%	0%	100%	0%	22%	2%	26%	50%

Constr means under construction
1st fill. means under the first reservoir filling
0-5 yr means during the first 5 operative years of the dam
>5 yr means after the first 5 operative years of the dam.

D3.2 All dam types

The US Bureau of Reclamation (USBoR, 1998) in the United States provided the annual failure probabilities in Table C4 in the western United States. For USBoR dams only, the same source indicates an annual failure probability of $4.5 \cdot 10^{-3}$ for all types of dams, and $7.6 \cdot 10^{-3}$ for concrete dams.

Table D6. Annual failure probability for US western dams (USBoR, 1998).

Dam type	No. of dams	No. of failures	No. of incidents*	Annual failure probability
Earth fill embankment	7,812	74	100	$6.5 \cdot 10^{-4}$
Rockfill embankment	200	17	14	$4.1 \cdot 10^{-3}$
Arch	200	4	8	$1.3 \cdot 10^{-3}$
Concrete gravity	285	4	2	$4.5 \cdot 10^{-5}$
All dam types	8,497	99	124	$7.5 \cdot 10^{-4}$

* Type of incident not specified

Douglas *et al.* (1999) presented the statistics in Table D7 for concrete dams, based on a worldwide database. Fell *et al.* (2001) presented the same historical numbers for dams until 1986.

Table D7. Annual failure probability for concrete dams (Douglas et al., 1999).

Period	Annual failure probability		
	First 5 years	After 5 years	Total
1700-1929	$100 \cdot 10^{-5}$/yr	$9 \cdot 10^{-5}$/yr	$15 \cdot 10^{-5}$/yr
1939-1992	$14 \cdot 10^{-5}$/yr	$1.4 \cdot 10^{-5}$/yr	$3.5 \cdot 10^{-5}$/yr

Fell *et al.* (2015) reported statistics for both embankment and concrete dams during the period 1800 to 1986, based on Foster *et al.* (2000). The number of dams in the database was 11,192 large dams[1]. Figure D30 presents Fell *et al.*'s (2015) newest statistics for all types of dams.

[1] According to ICOLD's definition, large dams are those with heights > 15m.

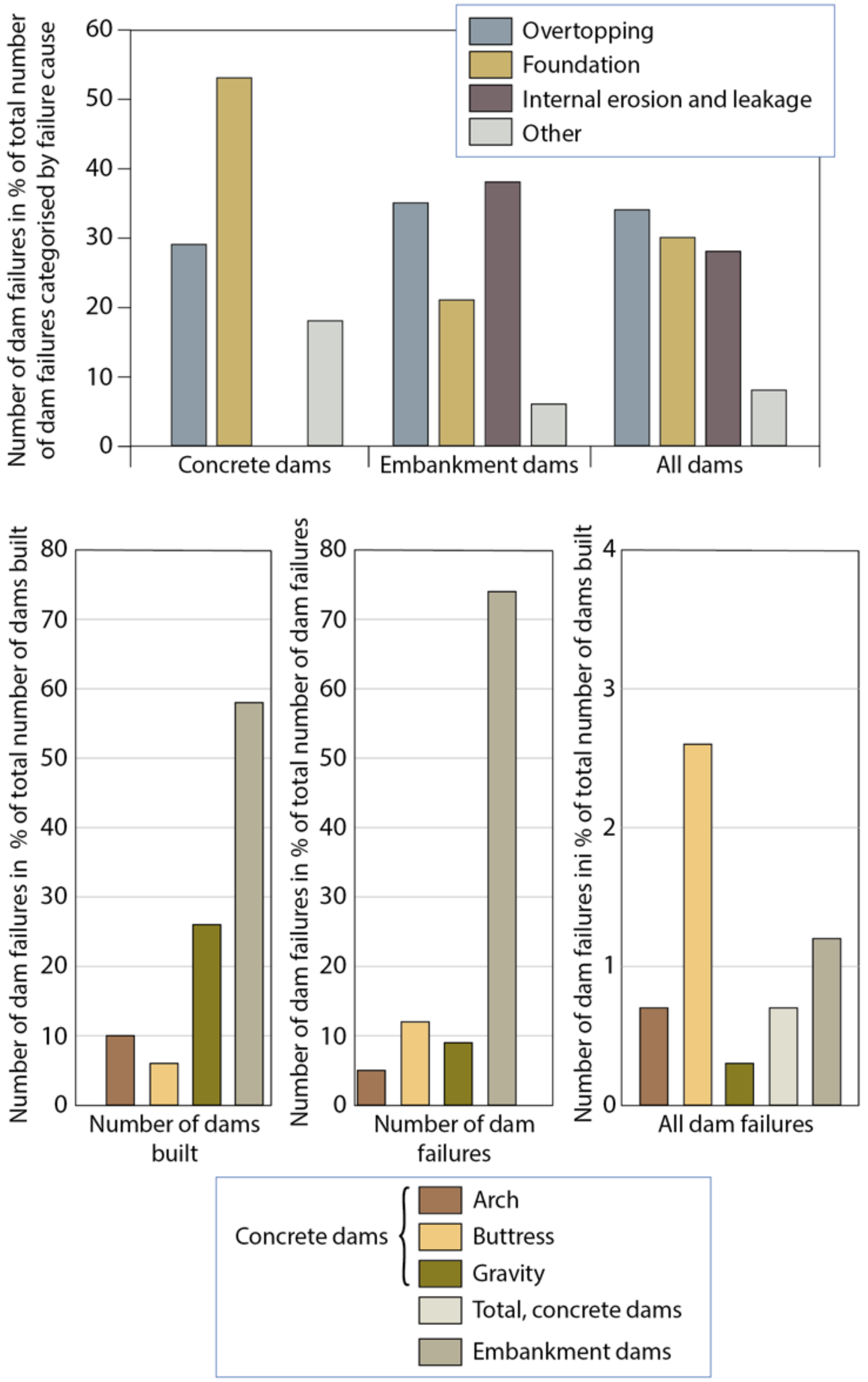


Figure D30. Causes of dam failure and number of dam failure for dams over 15m high (1900-1975) (NRC, 1983; Fell et al., 2015)

Annexes

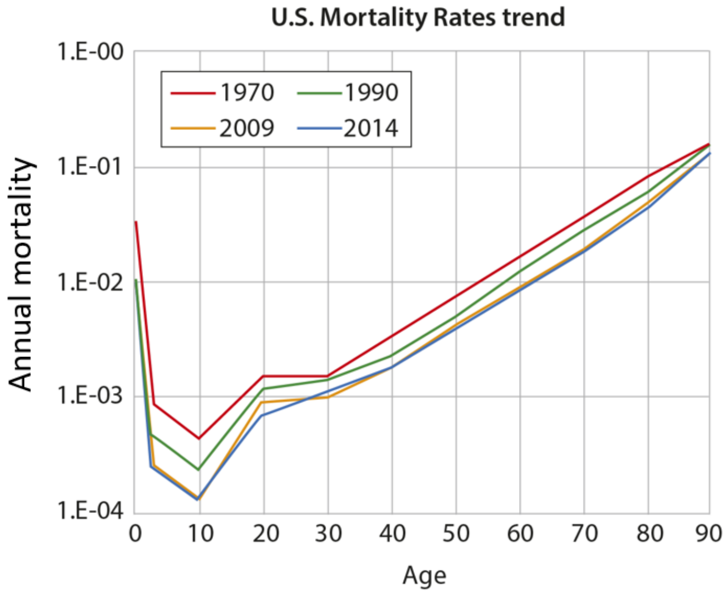
Annexes

Pålsbu concrete dam (photo: Statkraft Energi AS)

Storvass embankment dam (photo: Statkraft Energi AS)

Annex E Exponential numbers and fatality statistics

Contents


U.S. Mortality Rates trend
1.E-00
1.E-01
1.E-02
1.E-03
1.E-04
Annual mortality
1970
1990
2009
2014
0
10
20
30
40
50
60
70
80
90
Age

Annex E Exponential numbers and fatality statistics

E1 Exponential numbers (Table E1)

Table E1. Explanation of exponential numbers

Probability: Exponential expression	Probability: How often can it happen
10/year	10 times per year
10^{0}/year	Once in 1 year
10^{-1}/year	Once in 10 years
10^{-2}/year	Once in 100 years
10^{-3}/year	Once in 1,000 years
10^{-4}/year	Once in 10,000 years
10^{-5}/year	Once in 100,000 years
10^{-6}/year	Once in 1,000,000 years
10^{-7}/year	Once in 10,000,000 years
10^{-8}/year	Once in 100,000,000 years

E2 Fatality statistics

E2.1 Loss of life

Figure E1 shows the annual probability of human mortality in Canada. All causes of death are included. From birth to approximately 2 years, the annual probability of death (that is the probability of dying in the next year) is rapidly reduced from 10^{-2} to 10^{-4}. Between age 5 and 10, a person experiences the safest period in its life. Thereafter, the annual probability of death increases more or less evenly over the years. Figure E1 shows that if a person is 60 years old, there is a 1% probability that he/she will die in the next year; if a person is 90 years old there is about a 10% probability that he/she will die in the next year. The United States use similar numbers, without differentiating between men and women (Fig. E2).

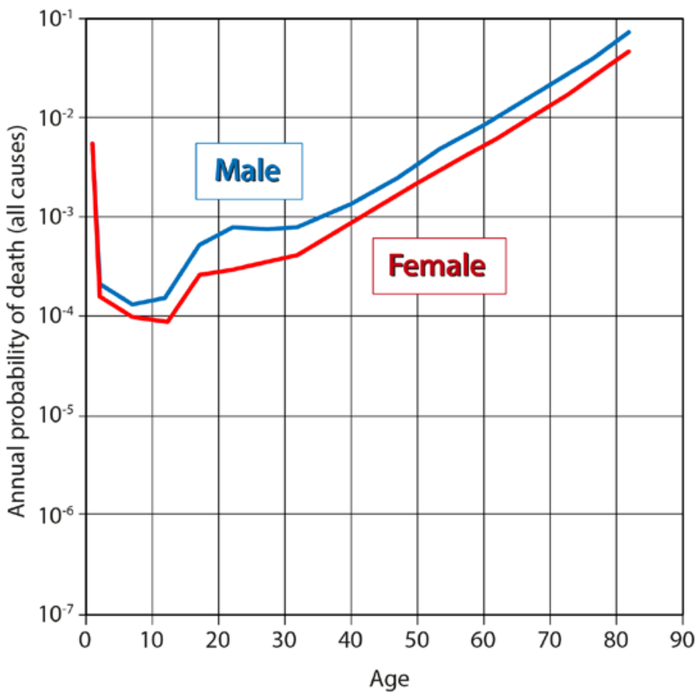


Figure E1. Annual death probability for males and females, all causes of death (Statistics Canada, 2018)

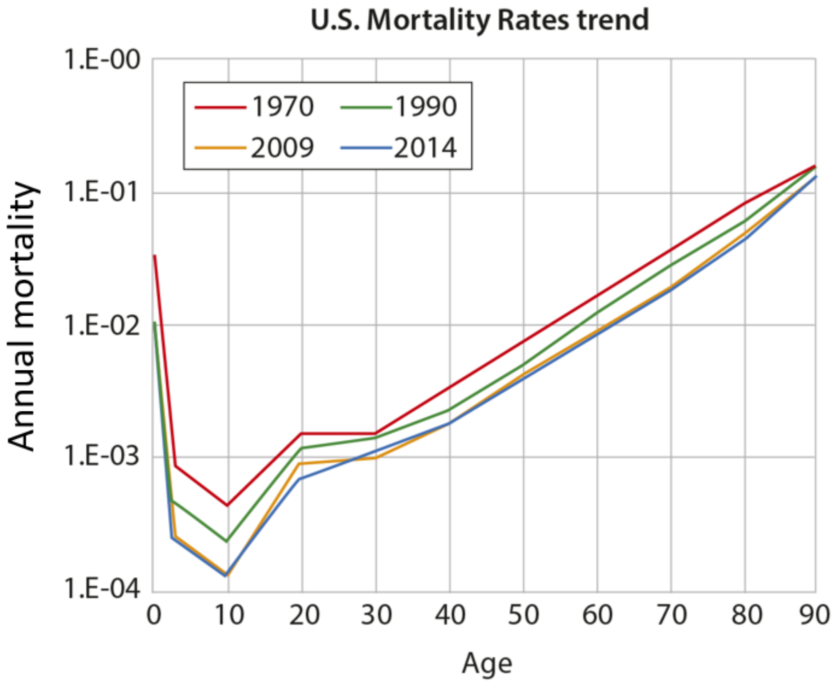


Figure E2. Annual death probability for males and females, all causes of death (CDC, 2005)

E2.2 Where does the failure probability of 10^{-4}/year come from?

The probability of 10^{-4}/year (0.0001/year) is often used as an upper limit for tolerable failure probability for larger constructions. The value of 10^{-4}/year is the same as the annual probability of death for a child 5-13 years old, due to all causes of death.

E2.3 Statistics for daily activities (see also Fig. A34)

Table E2 lists annual death probabilities for several daily activities. Figure E3 illustrates similar statistics.

Table E2. Death statistics for daily activities and accidents (Insurance Information Institute USA - https://www.iii.org/fact-statistic/facts-statistics-mortality-risk (2018)

Cause	$P_{death\ annual}$	Cause	$P_{death\ annual}$
Poisoning	$1.9 \cdot 10^{-4}$	Fall in stairs	$7.7 \cdot 10^{-6}$
Narcotics	$1.9 \cdot 10^{-4}$	Drowning	$2.3 \cdot 10^{-6}$
Car accident	$1.3 \cdot 10^{-4}$	Airplane crash	$1.1 \cdot 10^{-6}$
Pedestrians	$2.4 \cdot 10^{-5}$	Floods	$1.3 \cdot 10^{-7}$
Motorcycle accident	$1.4 \cdot 10^{-5}$	Lightning	$7.0 \cdot 10^{-8}$

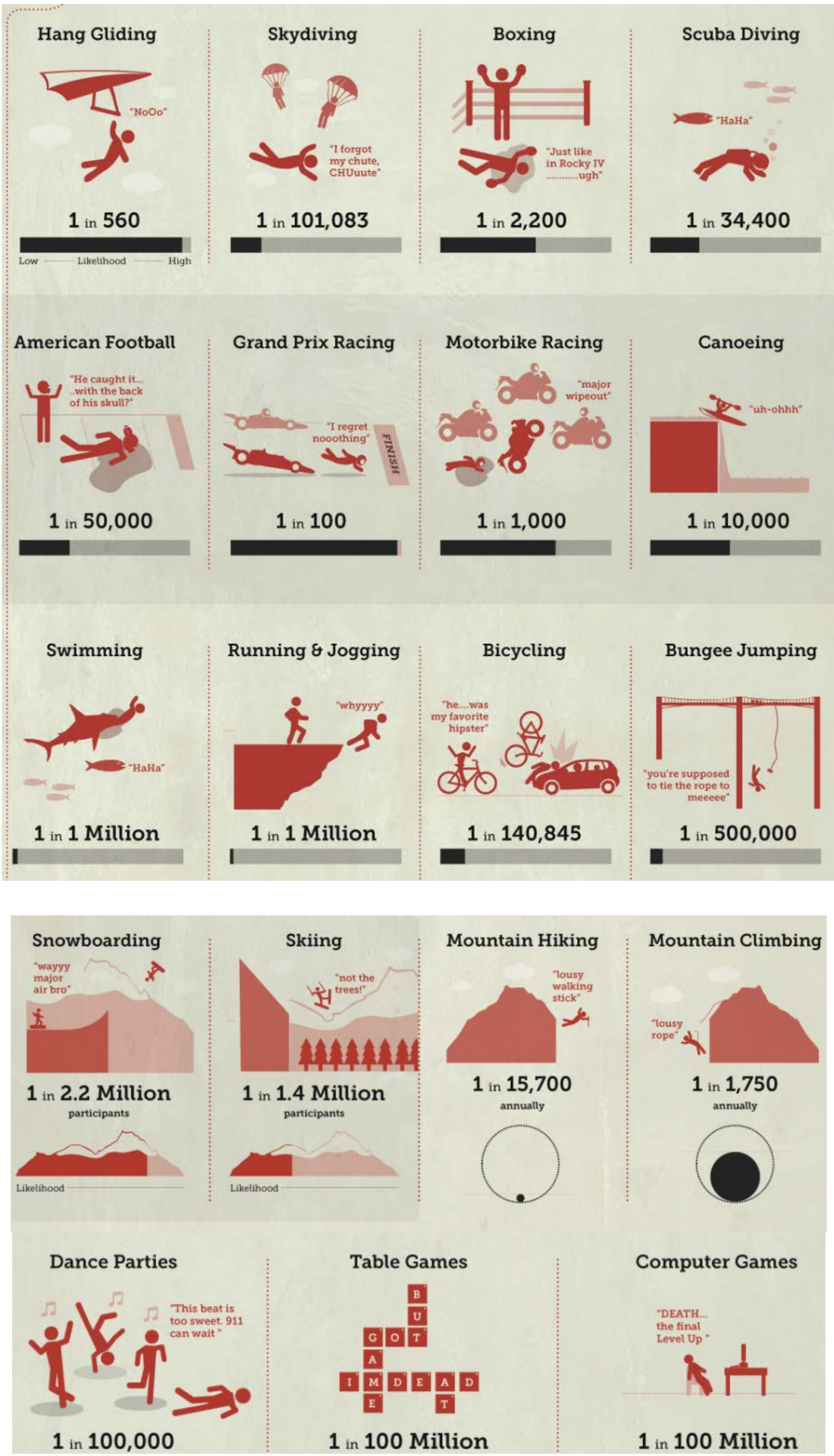
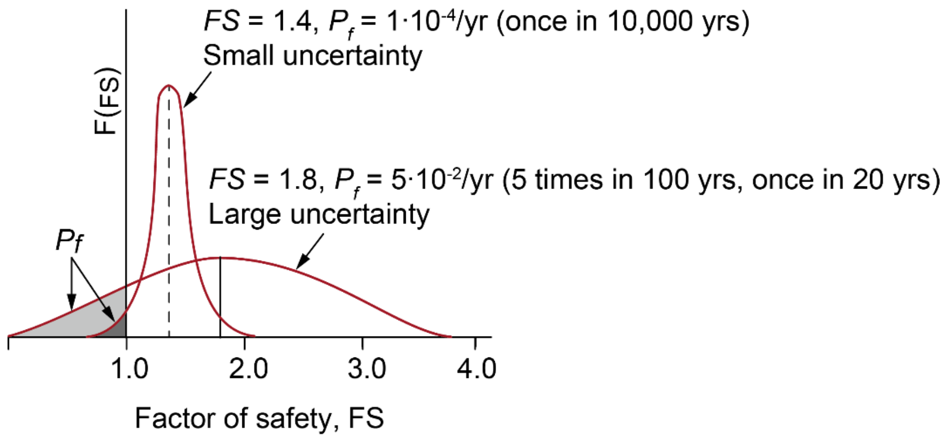


Figure E3. Death probability for different activities, including "computer games".

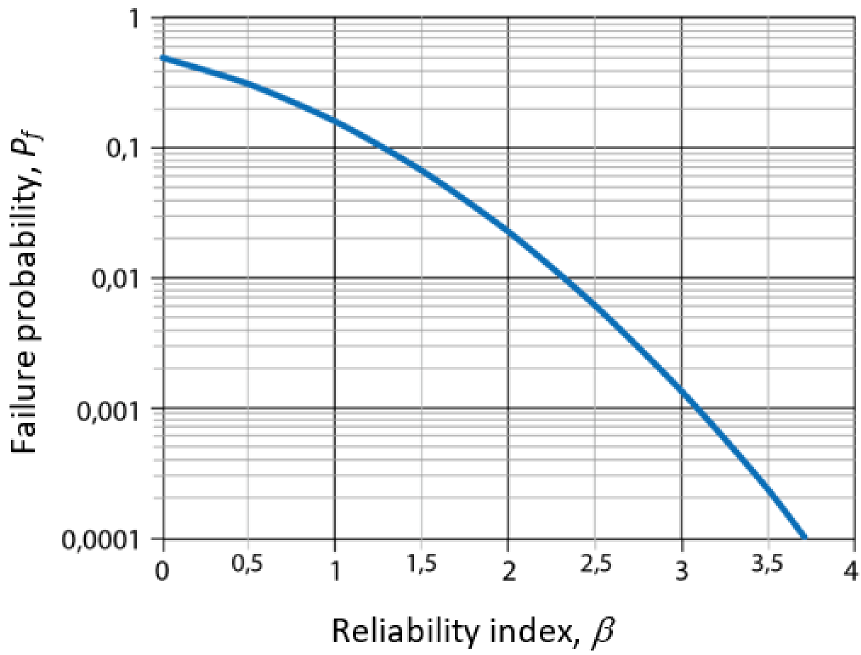
(In the lower part, the probability is given as one in 100,000 "dance parties" and one in 100 million "computer games played". National Centre for Health Statistics (CDC, USA)) https://www.besthealthdegrees.com/health-risks/

Annex F Risk terms and concepts

Contents



Safety factor (FS) and failure probability (P_f) for two embankment dam slopes.



Relationship between probability of failure, P_f, and reliability index β (normal probability distribution).

Annex F Risk terms and concepts

F1 Uncertainties

A statistical distribution is a practical tool for quantifying uncertainty (Fig. F1), with an average μ, a standard deviation (*SD*) and a coefficient of variation, CoV. The coefficient of variation is the ratio of the standard deviation to the mean (CoV = SD/μ), is often expressed as a percentage and is a good indicator of the uncertainty. Figure F2 shows the significance of one standard deviation: for a normal distribution, ± one standard deviation covers approx. 68% of all the data; ± 2 SD covers 95% of the data and ± 3 SD covers nearly 100% of data.

Both load and resistance have uncertainties (Fig. F3). The failure probability is related to the potential overlap of the two uncertainty distributions. In order to be able to do risk-based assessments, there is a need to quantify the uncertainties.

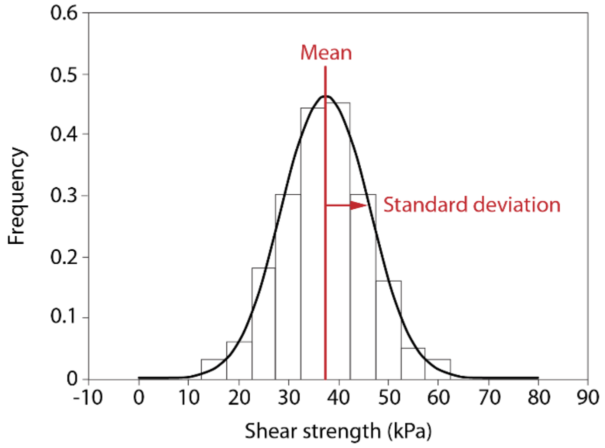


Figure F1. Example of uncertainty in shear strength.

F2 Safety margin

The objective of a safety assessment is to demonstrate that the risk associated with a facility is acceptable. The conventional way is to use a "deterministic" safety factor, FS. A safety factor of 1.5, for example, is often used to account for the combination of uncertainties in the ground, in the analysis parameters and in the calculation method.

There is, for example, a general opinion that a design with a safety factor greater than or equal to 1.5 must be "safe". In reality, the safety goal is not that simple. A safety factor of 1.5 actually represents a range of failure probabilities that depend on the uncertainties in the input parameters in the analysis. In a safety assessment, the engineer looks to quantify the safety margin (*M*). Safety margin is defined as:

$$M = \text{Resistance - Load}$$

When M is greater than zero, the construction is safe; when *M* is less than or equal to zero, the construction is unsafe. The safety margin itself has an uncertainty (Fig. E4) due to the uncertainties in the parameters defining the safety margin, and a failure probability, P_f, which can be represented by the zone where *M* is less than zero in Figure E4.

Because the uncertainties in a design are never zero, the failure probability is never zero.

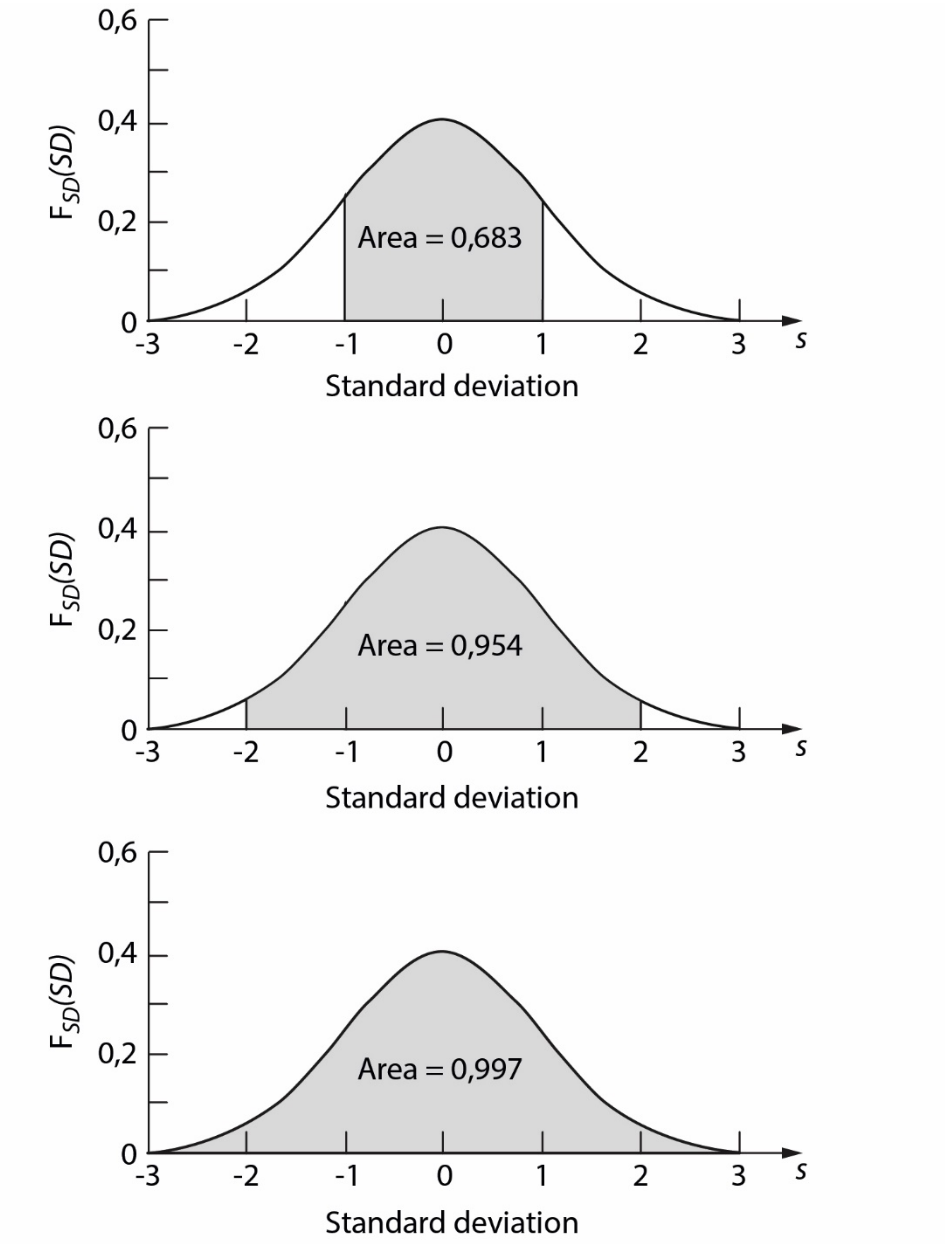


Figure F2. Meaning of one, two and three standard deviations (SD) in a normal distribution of parameters

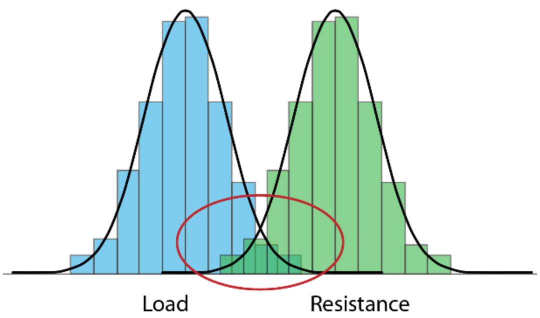


Figure F3. Uncertainty in load and resistance and values that lead to failure (overlap in red ellipse)

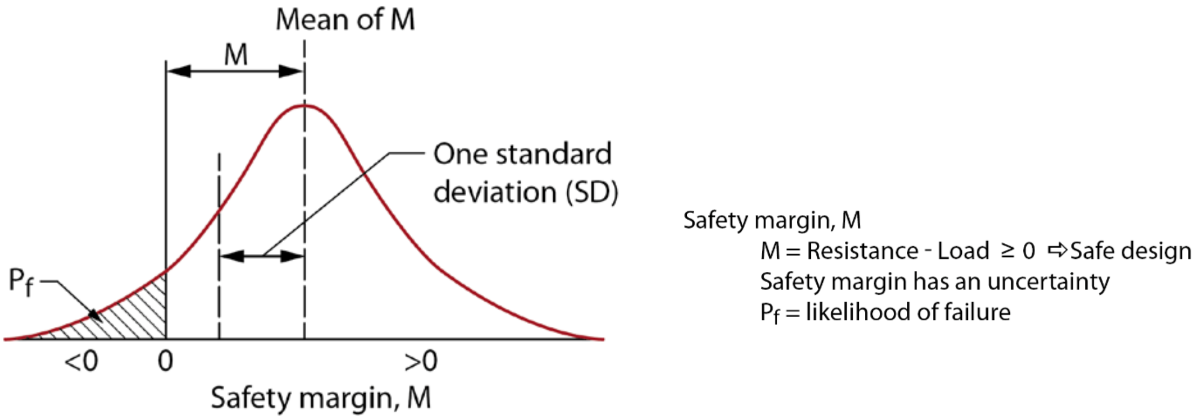


Figure F4. Safety margin and failure probability P_f (zone under the curve where M < 0)

F3 Failure probability and safety factor

Figure 5 illustrates that a design with a high safety factor may have higher failure probability than another design with a lower safety factor. A higher safety factor does not necessarily mean a lower risk than a low safety factor, because it is affected by the uncertainties in the analysis, and the uncertainties are different for the two cases. Through regulation or tradition, the same value of the safety factor is applied to conditions that involve widely differing levels of uncertainty. This is not logical.

The safety factor is thus not a sufficient indicator of safety because it does not account for the uncertainties in the analysis.

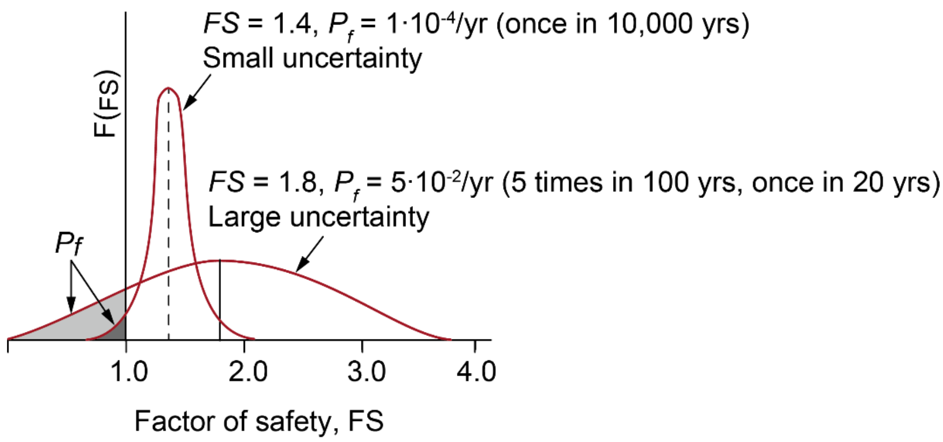


Figure F5. Safety factor and failure probability for the slope of an embankment dam.

F4 Reliability index and failure probability

An alternative to using failure probability, which can give a negative impression, is to express the safety target in the form of an annual reliability index, β. The "reliability" index gives a more positive terminology than "failure" probability, and the two terms are directly correlated. Reliability index refers to the distance of the average safety margin to failure in terms of the number of standard deviations. Reliability index therefore refers to the distance to the zone where $M \leq 0$ in Figure F4. Reliability index is defined as:

$$\beta = \frac{FS_{ave} - 1}{SD}$$

Figure F6 shows the relationship between the failure probability and the reliability index for a normally distributed safety margin. For example, a reliability index (β-value) of 3.7 corresponds to a failure probability (P_f) of 10^{-4} and a β-value of 4.3 to a P_f of 10^{-5}. For a normal probability distribution, the relationship between the reliability index(β) and the failure probability (P_f) is:

P_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1,28	2,32	3,09	3,72	4,27	4,75	5,20

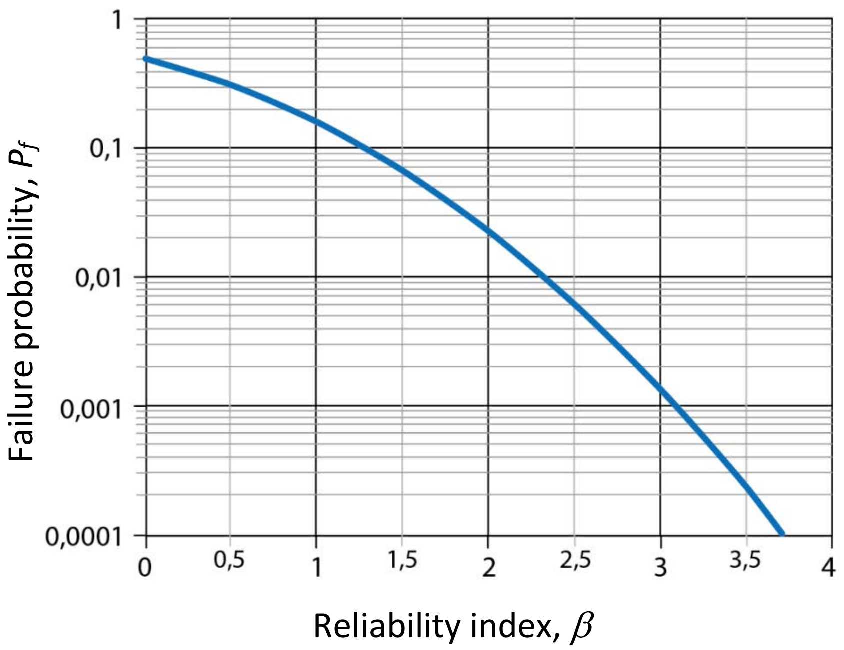


Figure F6. Reliability index and failure probability (normal probability distribution)

F5 Effect of uncertainties on reliability index

Figure F7 shows the effect of low and high uncertainties in the safety factor (FS) on the reliability index. Uncertainties in the analysis parameters and analysis method are expressed with a coefficient of variation, C_{oV}, of 10, 15, 20 and 30%. For a safety factor of 1.5 for a slope in Figure F7, the reliability index decreases from 3.2 to 1.1 when C_{oV} is increased from 10 to 30%. This means that the failure probability increases from 10^{-3} to approximately 10^{-1} due to the higher uncertainty. A failure probability of 10^{-1} is much too high and cannot be tolerated.

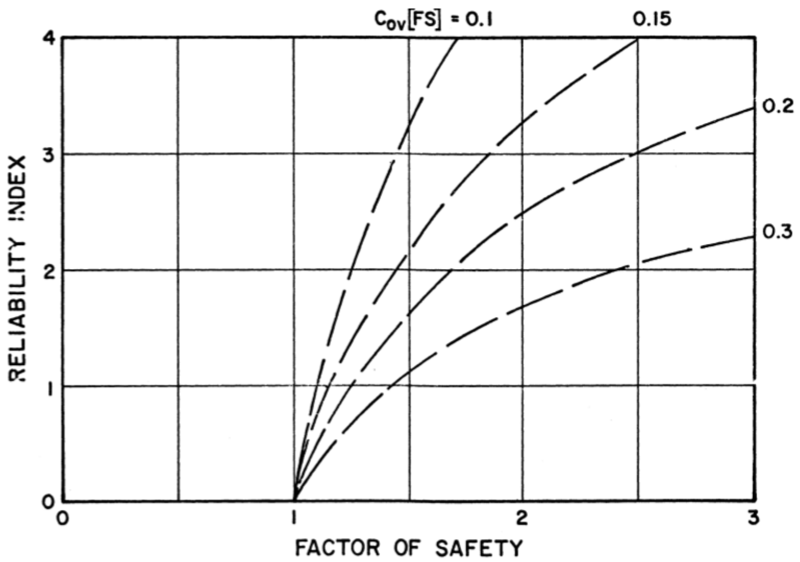


Figure F7. Reliability index and safety factor for a slope as a function of the uncertainty in the safety factor (expressed here as C_{OV} [FS)].

F6 Risk diagrams

Qualitative risk is expressed by risk matrices (Appendix A). Quantitatively, risk is most often expressed by so-called *F-N* curves or *f-N* curves, where *F* is the cumulative frequency of events and *f* is the frequency of events. *N* describes the consequences of the incidents. Cumulative frequency or frequency of events, that cause for example at least *N* deaths, is plotted as a function of *N* in a coordinate system where both axes are logarithmic[1].

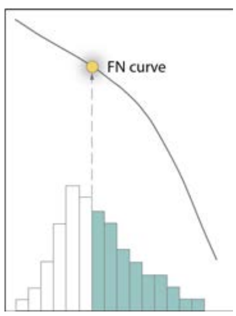
In a quantitative risk analysis, Figure F8 is often used as a guideline for acceptable risk. The figure put together the guidelines for acceptable risk from several countries (see also Annex A, Section A4). Not all guidelines were developed for dams, several are of a more general nature. Most risk acceptance criteria do not operate with a sharp distinction between acceptable and unacceptable risk. The dotted black line is the guideline most frequently used in several countries and for man-made slopes in Hong Kong (after Lacasse & Høeg, 2019).

---

[1]

Construction of the *F-N* curve

To construct an *F-N* curve, historical data are compiled by listing a series of events within some period of time and the corresponding number of fatalities. The data are sorted and plotted on a log-log grid to form a frequency diagram. The *F-N* curve is constructed by summing the areas of the histogram to the right of a given point on the *F-N* curve to obtain the complementary cumulative distribution.



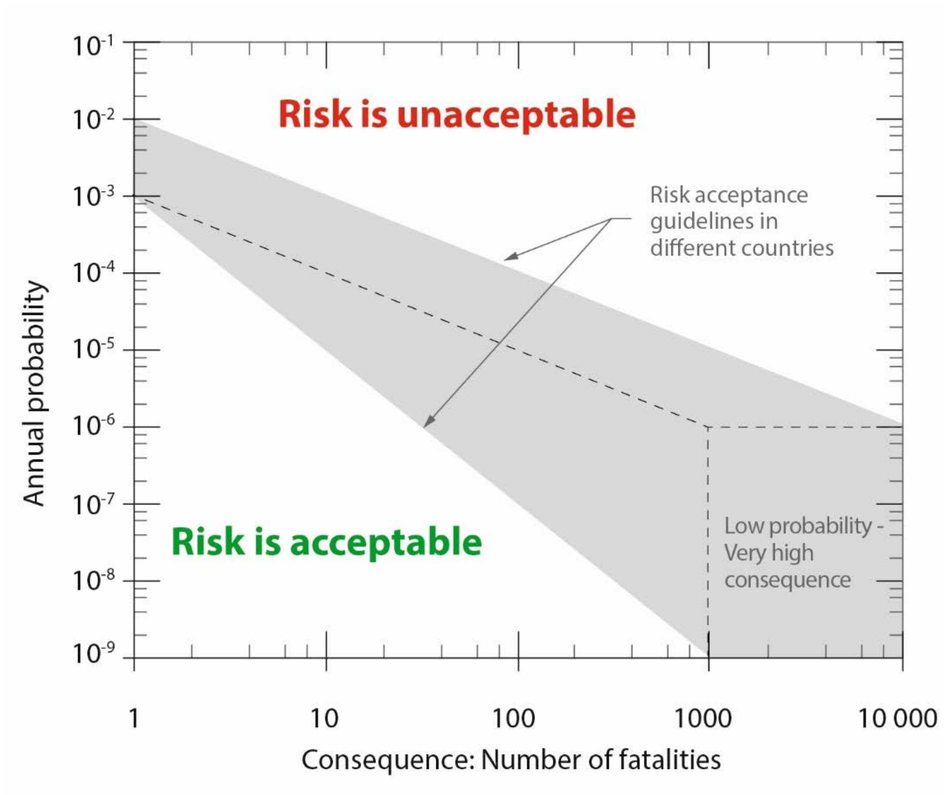


Figure F8. Recommended acceptable and unacceptable risk in international guidelines

F7 Individual and societal risk

It is common to differentiate between individual and societal risk:

Individual risk is the risk to any individual who lives within a given distance from a hazard, or who follows a pattern of life that subjects him/her to the consequences of the hazard. The most usual connotations are the average individual risk over all those individuals significantly exposed, and risk to the most exposed individual (right and left diagrams in Fig. F9).

Societal risk refers to the possibility of multiple, simultaneous fatalities from a single event (e.g., from a dam failure or a plane crash). The usual definition of societal risk is .“the relationship between frequency of a hazard and the number of people suffering from a specified level of harm in a given population.

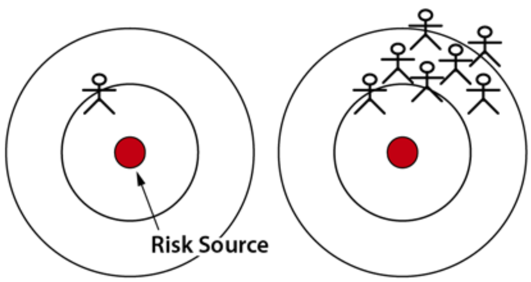


Figure F9. Individual and societal risk exposure illustrated with distance from a risk source: both conditions have the same individual risk; the case on the right has lower average individual risk (Baecher et al., 2015).

F8 ALARP principle

In the UK (and many other countries), three risk areas are used: acceptable risk, unacceptable risk, and an area in between called tolerable risk.

As a rule, unacceptable risk must at least be reduced to a "tolerable" level (down into the **ALARP** area - where the risk is as low as reasonably practicable)[1].

If risk is unacceptable, risk reduction measures are implemented to reduce the risk down to an acceptable level.

Acceptable and unacceptable risk:

– Acceptabe risk ("*Broadly acceptable risk*", UK guidelines)

– Unacceptable risk

In between, there can be a Tolerable risk zone, where the ALARP principle should be followed (ALARP = "***A****s* ***L****ow* ***A****s* ***R****easonably* ***P****racticable*").

Alternatively, an ALARP analysis can be done and the ALARP principle can be used: the risk should be reduced as far as is practically reasonable. The decision on what is reasonably practicable should consider the following aspects:

- Costs and cost-effectiveness of further risk reduction.
- The level of safety and uncertainty in different aspects of the dam and its surroundings.
- A precedent of comparable decisions for other dams.
- It is not practically possible to rectify the identified weaknesses.
- Large uncertainties and low chance of success for the measures that would reduce the risk.
- Time to implement the improvement.
- Other considerations.
-

ALARP analyses:

An ALARP analylses should demonstrate the risk level for all plausible hazards and dam response. The analysis should explain:

- The level of safety that is achievable, i.e. what is reasonably practically possible.
- Why the safest of the alternatives are not chosen.
- Justification for the selected solution to the regulators and society (solidity, societal value and optimal selection among alternatives).

F8 Risk-informed decision-making (RIDM)

There are two approaches to assessing dam safety (see main text):

1) Standard-based approach (conventional approach); and
2) "Risk-informed decision-making" (RIDM).

RIDM considers risk by looking at probabilities, possible weaknesses in or around the dam and consequences. Risk assessments are used together with the conventional calculations to determine further steps. RIDM promotes an increased understanding of safety aspects, identifies areas of vulnerability that have not been identified by conventional analyses and prioritises rehabilitation measures to reduce risk. The purpose of RIDM is always to minimize the risk of loss of life and other consequences.

Many important decisions are based on risk assessments, where risk is defined as 'the probability multiplied by the (severity of) the consequences'.

Having to make any decision almost always involves taking a risk. It is therefore absolutely crucial, in situations involving uncertainties, to base decision-making on risk assessments.

---

[1] ALARP = "***A****s* ***L****ow* ***A****s* ***R****easonably* ***P****racticable*".

How does one make robust and good decisions when there is a lack knowledge? In some cases, one can postpone the decision in anticipation of more knowledge. However, not everything can be quantified or postponed (in a number of environmental problems, for example, it is important to act quickly). In many situations, uncertainties cannot be reduced.

Risk-informed decision-making (RIDM):
The objective of RIDM is always to minimize the risk of loss of life and other consequences. The RIDM process recognizes that human judgment plays an important role in decisions, and that technical information, often insufficient, cannot be the only basis for decision-making. This is due to unavoidable gaps in knowledge and data, and because decision-making is an inherently subjective, value-based task. In dealing with complex decision-making involving competing goals, the cumulative knowledge of experienced personnel is crucial to integrate technical and non-technical elements to produce robust and reliable assessments and decisions.

F9.1 RIDM for dam safety

The objectives of RIDM include:

- Systematically identify and understand potential failure mechanisms.
- Identify, justify and prioritize studies and analyses to reduce the uncertainty in the risk.
- Strengthen the formulation, justification and prioritization of risk reduction measures for either individual dams and a portfolio of dams.
- Justify operational decisions.
- Identify ways to improve dam safety through changes in operations, monitoring and surveillance, safety management systems, employee training, contingency planning and business decisions related to dam safety.
- Identify opportunities to improve the effectiveness of warning and evacuation plans.
- Identify cost-effective alternatives to achieve risk reduction more effectively.
- Justify spending on improvements to dam safety
- Identify and understand the risks that exist during normal operation of a dam.
- Provide a framework for quantifying the engineering assessment and to improve communication of technical problems with dam owners in a more transparent way.
- Facilitate the evaluation of risks for the dam and enable comparisons with other infrastructure and constructions.

RIDM is a structured process:
RIDM consists of:
- aiming to achieve "project" success by informing about the decision options;
- ensuring that decisions between competing alternatives are made with awareness of the risks associated with each alternative and thus helps avoid excessive costs, time delays etc;
- addressing some of the following issues:
  - possible "incongruence" between expectations and resources,
  - possible misunderstanding of the risk that a decision maker accepts,
  - inadequate communication about the risks associated with competing alternatives.
- promoting the development of a robust decision basis (technical and otherwise) by:
  - linking the proposed decision alternatives to the goals that define "project" success;
  - assessing all important aspects of the alternatives in an integrated way;
  - contributing to the assessment of a wide range of decision-making options;
  - performing quantitative assessment of the advantages and disadvantages of each decision alternative in relation to the identified objectives;
  - taking into account the uncertainties associated with each decision alternative and quantifying their impact on the achievement of the objectives.

- Provide a non-technical basis for communicating dam failure risk to the public.
- Assess the adequacy of insurance coverage.
- Strengthen the exercise of the dan owner's duty of care, diligence and soundness with regard to dam safety incidents or dam breaches.

The advantages of RIDM are:

- A greatly improved and holistic understanding of the safety of a dam.
- Systematic analysis of logic about failures modes: it is not only the numerical results, which involve, sometimes, large uncertainties, but also the risk analysis process that present real advantages and insight in the risk.
- Reasoned approach to deal with areas that are difficult to quantify.
- It helps form the basis for demonstration of due diligence.

Figure F10 illustrates some of the questions asked during a RIDM process (USACE, Lecture 2019, Calgary).

F10 Use of engineering judgment

Humans use judgment in all aspects of life. Engineers use professional judgment to move forward in their work. Engineers collect and evaluate all the data, complete the analyses, but there are some gaps in the information and results, so engineers use technical assessment and judgment to develop its recommendations. The engineer's professional judgment ('Engineering judgment') is important and essential in most evaluations.

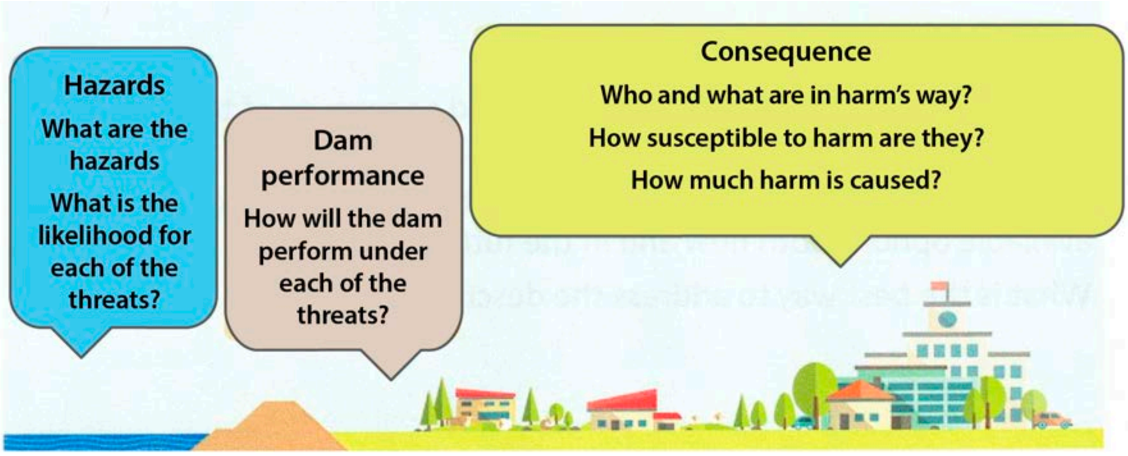


Figure F10. RIDM-process for a dam risk assessment, Can one define the professional judgment of the engineer? Professional judgment is the exercise of clear, logical and justified thinking, weighing known facts, assumptions, lack of information and consequences of the assessments. Professional judgment provides the opportunity to come to sensible conclusions in the presence of incomplete and conflicting information. Synonyms for professional judgment include common sense, perception, wisdom, judgment, understanding and reasoning.

Engineering judgment in a project:

- Determine the size of the project, develop a sense of proportion.
- Be well acquainted with the theoretical basis for the models and their limitations, and use simple methods to check results.
- Identify and understand the gaps in the knowledge and data, and their consequences for the assessments.
- Avoid impulsive decisions and "sleep on" important decisions, as subjective assessments can change with additional reflection.
- Stay receptive to questions, review, reflection, learning and error.
- Use independent experts or peers to review novels and complex designs.
- Ensure that all decisions can be justified.

Professional judgment is used to build a bridge between data, information and knowledge. Judgment uses reasoning and calculation to develop conclusions. Judgment inherently includes a subconscious risk calculator that weighs uncertainty and assesses the potential consequences of outcomes of decisions and recommendations. These characteristics are fundamental to critical thinking. The process introduces subjective assessments of the relative importance of the different uncertainties.

Geosciences require a lot of professional judgment, from ground investigations to interpretation of data, geo-mechanical analysis, design, plans for instrumented monitoring and interpretation of the observations. The engineer's professional judgment is based on both empiricism and theory. Good judgment comes from evaluated experience. Good sense in the geosciences comes from experience.

The most important aspects of good judgment include:

- An ability to see the actual problem.
- An ability to establish the adequate performance criteria for design.
- A perception of proportion (i.e. does this result seem to be correct?)

Like many other civil engineering constructions, dam facilities rely on professional judgment. Judgment and risk are closely related. Good technical judgment builds on many years of seeing, learning, applying, and re-learning when things do not go as planned, and most importantly, transferring this acquired skill to new issues. The engineer's professional judgment involves risk. That is why it is so important to recognize and, where possible, quantify the uncertainties underlying the assessments.

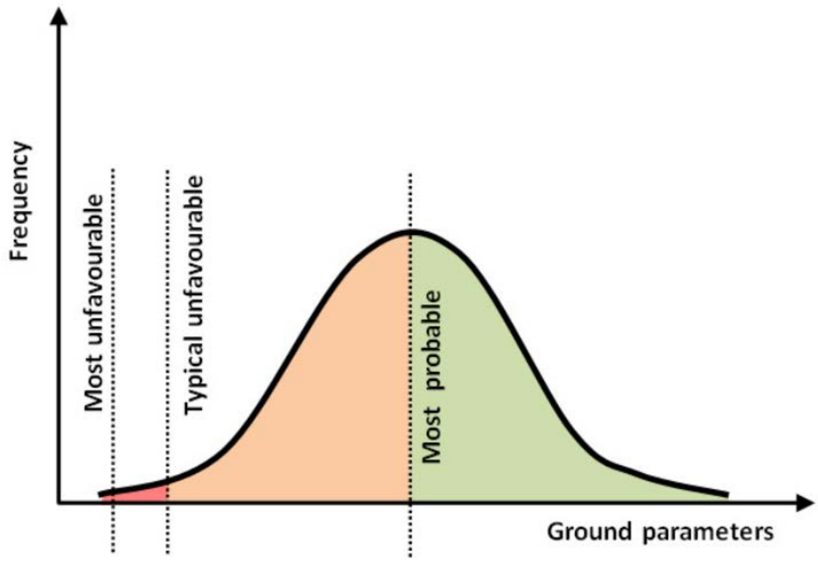
F10 Incremental risk

It is important to point out that a potential dam failure under extreme conditions imposes an incremental risk, in addition to the other "background risks" to people and material values, which are already exposed to risk under extraordinary events such as floods and earthquakes. The incremental risk is described n ICOOKD Bull 130:

> *"Incremental losses or damage, which dam failure might inflict [...] over and above losses which might have occurred for the same natural event or conditions, had the dam not been there or not failed"* (ICOLD Bull. 130. 2005).

Annex G *The "Observational Method"*


Observe


Frequency
Most unfavourable
Typical unfavourable
Most probable
Ground parameters

Annex G The "Observational Method"

Karl Terzaghi (1961) wrote:

"Soil engineering projects […] require a vast amount of effort and labor securing only roughly approximate values for the physical constants that appear in the equations. The results of the computations are not more than working hypotheses, subject to confirmation or modification during construction. In the past, only two methods have been used for coping with the inevitable uncertainties: either adopt an excessively conservative factor of safety, or make assumptions in accordance with general, average experience. The first method is wasteful; the second is dangerous. A third method is provided that uses the experimental method. The elements of this method are 'learn-as-you-go:' Base the design on whatever information can be secured. Make a detailed inventory of all the possible differences between reality and the assumptions. Then compute, on the basis of the original assumptions, various quantities that can be measured in the field. On the basis of the results of such measurements, gradually close the gaps in knowledge, and if necessary modify the design during construction."

The Observational Method, described by Professor Ralph B. Peck in his Rankine Lecture in 1969, is a formalisation of Terzaghi's philosophy. The Observational Method consists of:

- Exploration sufficient to establish at least the general nature, pattern and properties of the deposits.
- Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.
- Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.
- Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.
- Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.
- Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observations from those predicted based on working hypothesis.
- Measurement of quantities to be observed and evaluation of actual conditions.
- Modification of design to suit actual conditions.

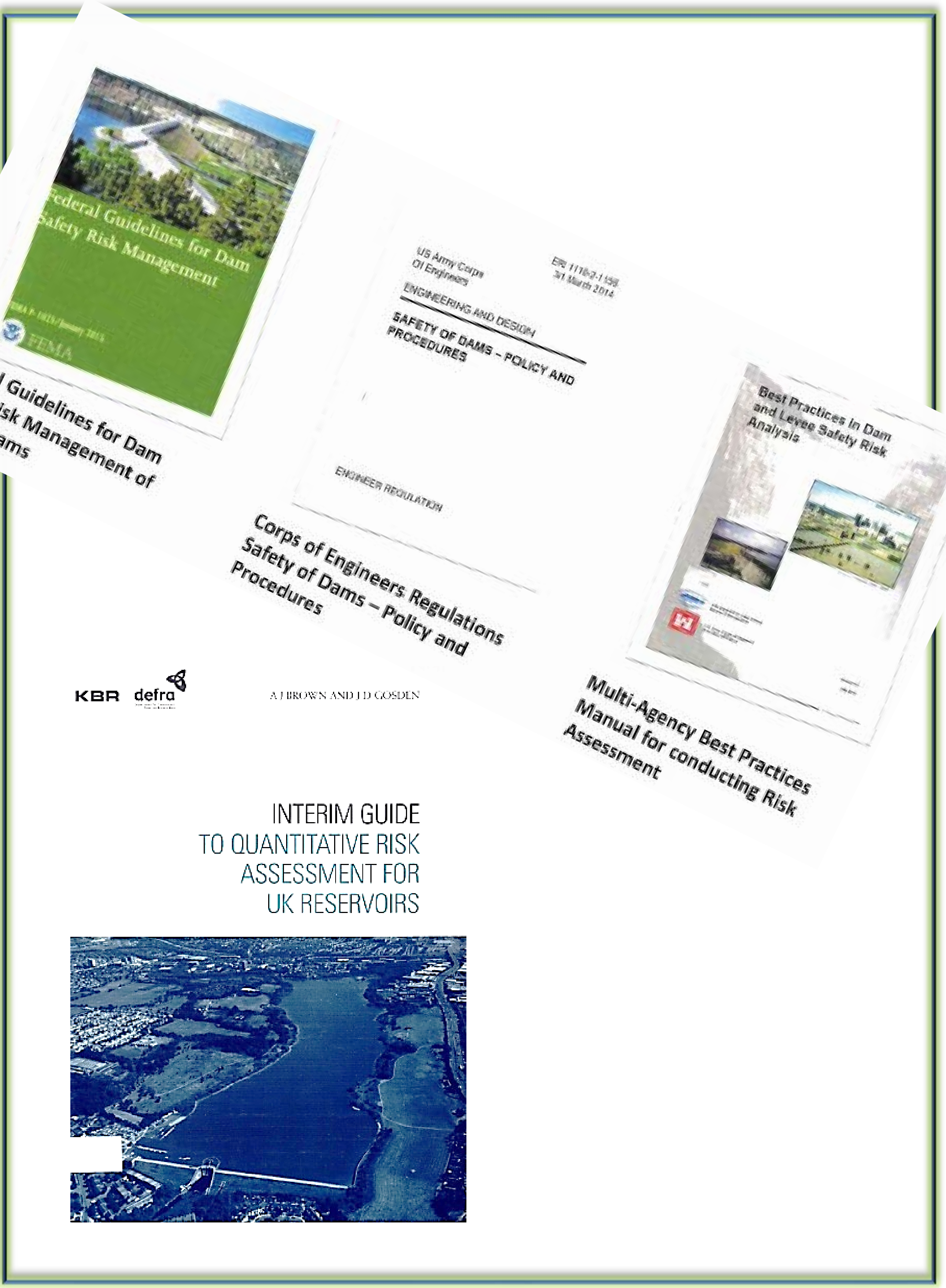
The Observational Method (OM) is useful in design. In many cases, the results of the early design computations are not more than working hypotheses, subject to confirmation or modification during construction, with the help of the OM. The degree to which each step is followed depends on the nature and complexity of the project. Geotechnical engineers work in both a theoretical and practical dimension. Both have aleatoric and epistemic uncertainties[1], which can never be completely eliminated. Because of the uncertainties, there is a finite, even if small, probability that a failure may occur.
The OM has many advantages, but requires a robust set of procedures throughout a project: the method adopts the "most probable" design parameters, as opposed to conservative parameters; it assesses a range of probable behaviour; it sets out modifications in construction to be implemented if the parameters or the behaviour turn out to be less favourable than assumed in the design; it monitors the behaviour of the structure and soil, providing indication of whether mitigation measures are required or not; and it analyses the data and triggers the implementation of contingency plans. Costly overdesign can be avoided without compromising on safety or the environment. One key aspect is the selection in advance of a course of action for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.

1 *Aleatoric* uncertainty (also known as statistical uncertainty) is the natural randomness of a property or a load, e.g., soil strength and ocean wave height. The aleatoric uncertainty cannot be reduced.

Epistemic uncertainty (also known as systematic uncertainty) is the uncertainty due to lack of knowledge, e.g., measurement uncertainty and model uncertainty. The epistemic uncertainty can be reduced by, for example, increasing the number of tests, improving the measurement method and/or verifying the calculation procedure with model tests.

Annex H Dam risk assessment in other countries

Contents


Federal Guidelines for Dam Safety Risk Management
FEMA
Federal Guidelines for Dam
Safety Risk Management of
Federal Dams
US Army Corps
Of Engineers
ER 1110-2-1156
31 March 2014
ENGINEERING AND DESIGN
SAFETY OF DAMS – POLICY AND
PROCEDURES
ENGINEER REGULATION
Corps of Engineers Regulations
Safety of Dams – Policy and
Procedures
Best Practices in Dam
and Levee Safety Risk
Analysis
Multi-Agency Best Practices
Manual for conducting Risk
Assessment
KBR
defra
A J BROWN AND J D GOSDEN
INTERIM GUIDE
TO QUANTITATIVE RISK
ASSESSMENT FOR
UK RESERVOIRS

Annex H Dam risk assessment in different countries

H1 Introduction

The dam industry abroad has experienced that failures and malfunctions have occurred on large dams that were apparently built according to specifications, or with dams where it was not practically feasible to satisfy all the criteria, or with older dams where not all aspects of construction are known. With such experience, risk-informed decision making has become an accepted supplement to conventional analyses of dam safety. The use of risk diagrams and *F-N* curves, to evaluate risk began in the 1990s under the influence of ANCOLD, BC Hydro and USBoR[1].

In Australia, risk assessment is not an alternative to deterministic analyses, but is carried out together with deterministic analyses. In Canada, documentation of dam safety is accepted based on documentation of dam safety through risk analyses. In USA, risk analyses are also used for risk-informed decision-making as part of the in documentation of dam safety. For prioritizing the rehabilitation of dams in a portfolio, risk-based methods are used to a large extent, especially if all the dams in the dam portfolio have the same owner. The purpose of the studies and measures is to achieve the greatest risk reduction for the entire portfolio with the available funds and attempt to achieve a uniform level of risk for comparable dams.

H2 Historical development

Baecher *et al*. (2015) summarized the development of the criteria for acceptable risk, especially in the Netherlands (for dikes), UK, Hong Kong, USA, Canada and Australia. The historical development of the beginnings of risk assessment and risk diagrams is summarised in Figure H1.

H3 Risk frameworks

All risk frameworks from abroad use a form of the five steps illustrated in Figure H2. Figure H3 shows four levels of risk framework which can be applied. Level 1 risk assessments are appropriate only for early stage projects. Level 2, 3 and 4 become relevant as more information is acquired and as the need for documentation of the dam safety evolve, and perhaps the requirements for documentation from society increase.

Figure H4 exemplifies the steps in the UK in a semi-quantitative or quantitative risk assessment.

H4 ICOLD Bulletins 130 and 154

H4.1 Bulletin 130

ICOLD (2005, Bull. 130, *"Risk assessment in Dam safety assessment"*), presented an overview of benefits, methods and applications (in 2005) of the risk-based approach for dams. In particular, the Bulletin addresses

- What does risk assessment add to traditional analyses.
- The importance of the decision context in a risk assessment.

Bulletin 130 presents principles of risk assessment, concepts, methods and a number of applications, but the text reflects the perception and expectations of the period 2000-2005. Method descriptions and applications are provided but not in enough detail to enable one to understand how to run a risk

[1] Acronyms are defined in Annex I.

assessment. AS described in the bulletin, the text gives a "high level" overview of principles of risk assessment

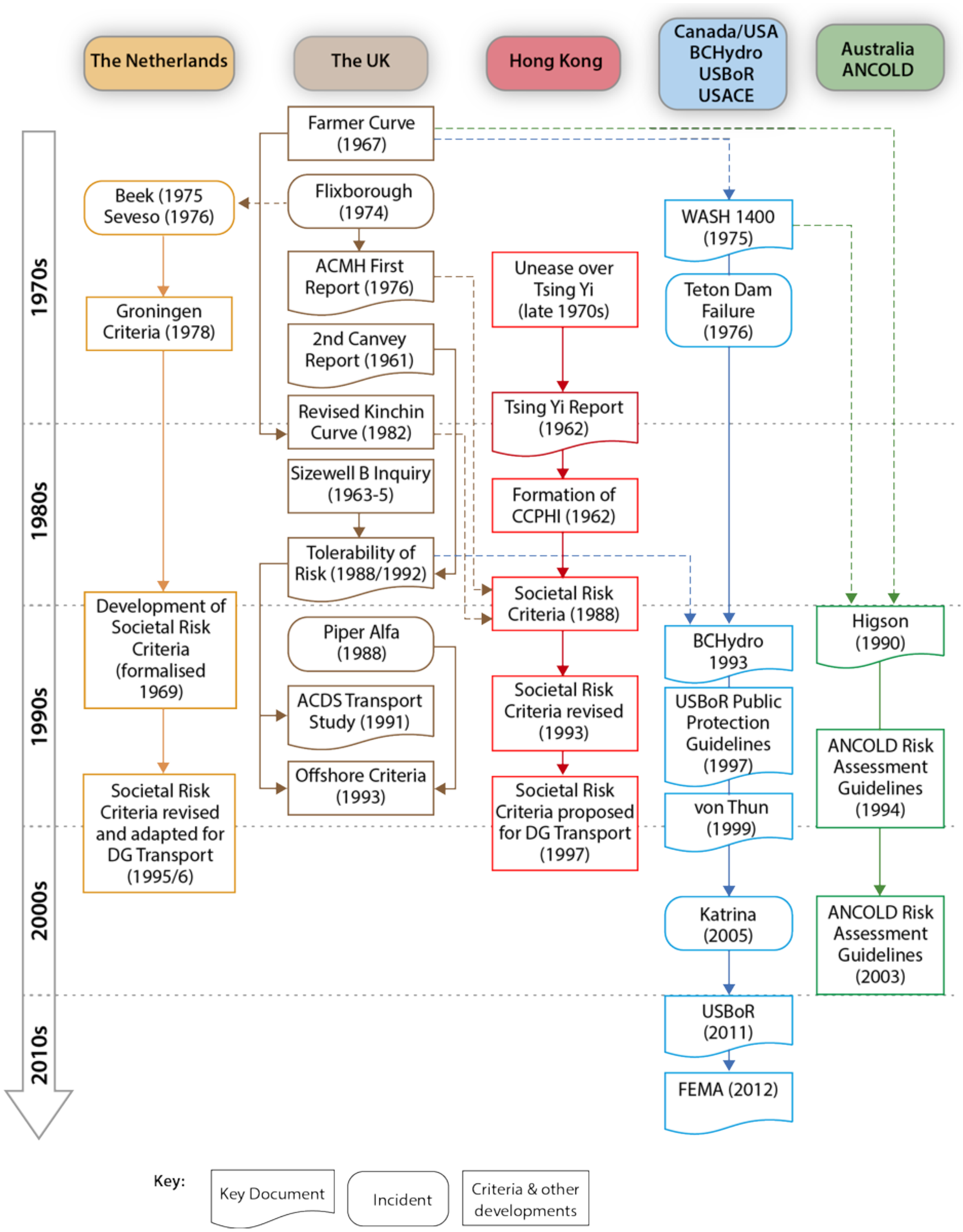


Figure H1. Historical development of societal risk criteria (adapted from Baecher et al. (2015).

Figure H2. Steps common to all risk assessment and risk management frameworks.

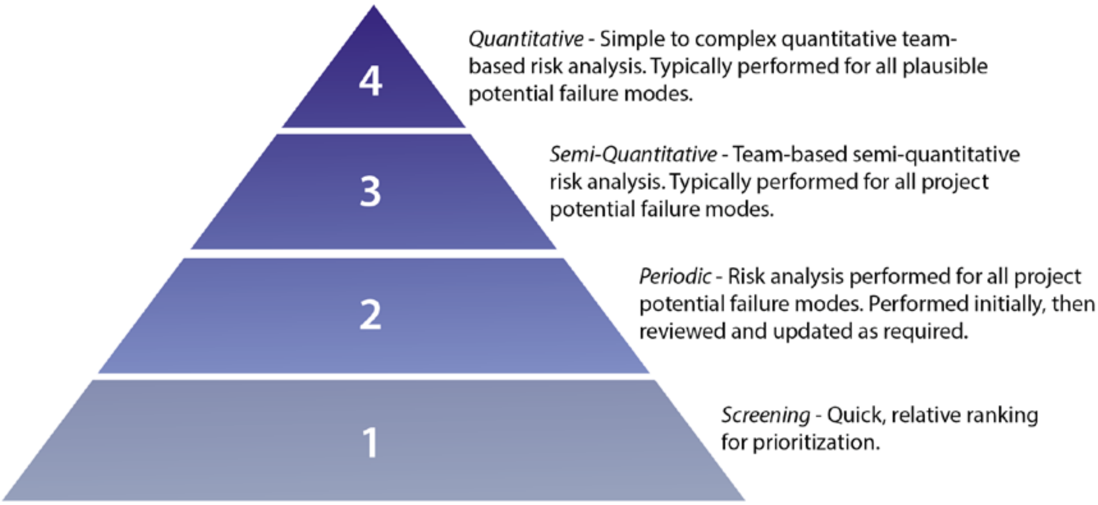


Figure H3. Levels of risk framework (adapted from FERC, 2016)

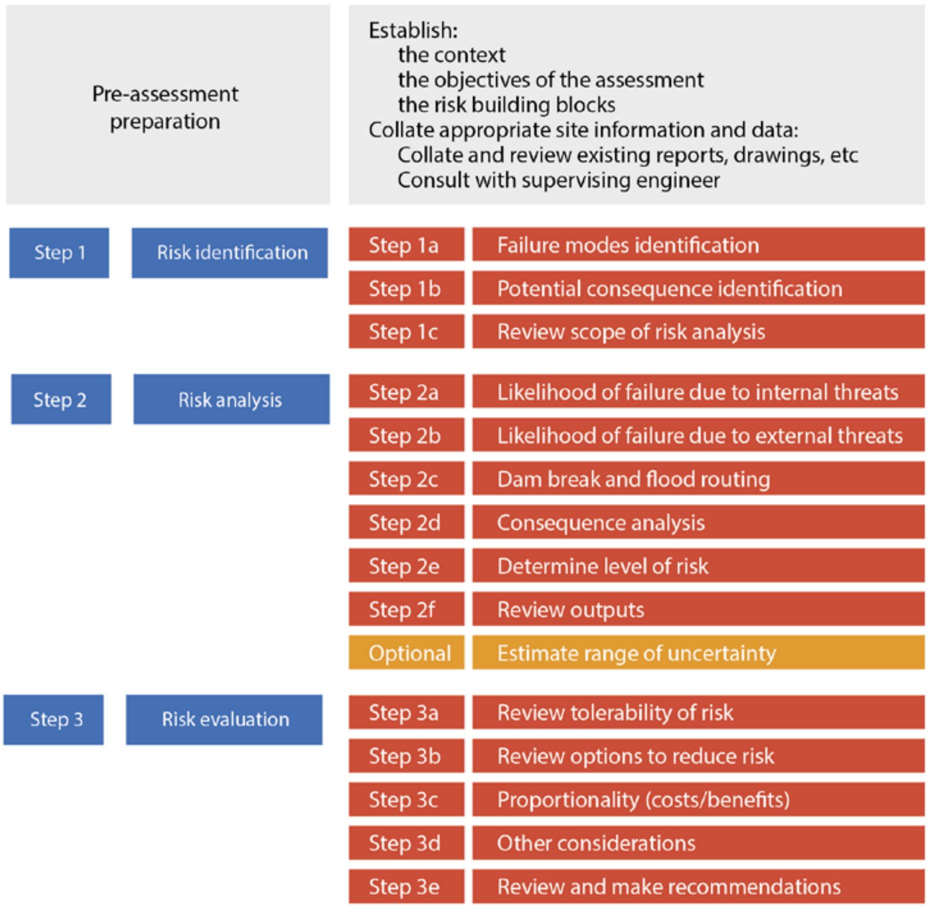


Figure H4. Details of safety management of dams in the UK.

ICOLD Bulletin 130 concludes that, since risk assessment for dams was in its infancy (in 2005), the bulletin is not a code or manual of established practice. Nevertheless, risk assessment is presented as an enhancement of the traditional approaches and as a benefit to dam safety management programs. Bulletin 130 saw risk assessment as a means to quantify the degree of conservatism inherent in engineering judgment and to identify key sources of uncertainty that can influence dam safety investment decisions. The improved understanding of dam performance was singled out as one of the great benefits of ta risk assessment .

The Committee on dam safety (CODS) of ICOLD collected the information from the CODS members on the state of their national practice within risk assessment, risk management and risk-informed decision-making for 14 countries, in a so far unpublished report (2020). The questions addressed the following areas of practice: (i) legal, regulatory and enforcement arrangements, (ii) general risk considerations, (iii) risk analysis, (iv) risk evaluation, (v) risk management and (vi) risk communication. Results should become available soon.

H4.2 Bulletin 154

ICOLD (2017, Bull. 154, "*Dam Safety Management: Operational phase of the dam life cycle*") illustrated the aspects that should enter into the process of risk-informed decision-making (Fig. H5). In section *§B*.2.1 "Sa*fety decision making – explicit consideration of risk (general concept)",* writes ICOLD:

> "*At the foundation of risk-based frameworks is the principle that ultimately all decisions about safety are risk management decisions. As zero-risk decisions are not practicable and most of the time simply not affordable some trade-offs between the costs of reducing risk and the benefits from risk reduction are unavoidable. […].*
> *A Responsible Entity who elects to demonstrate dam safety with the help of this framework [explicit consideration of risk] has to conduct the safety assessment in such a way as to ensure that all measures necessary to avert the risk must be taken until the cost of these measures is disproportionate to the risk, which would be averted. As a result, the risk must be reduced to a level, which is ALARP (as low as reasonably practicable) […]".*

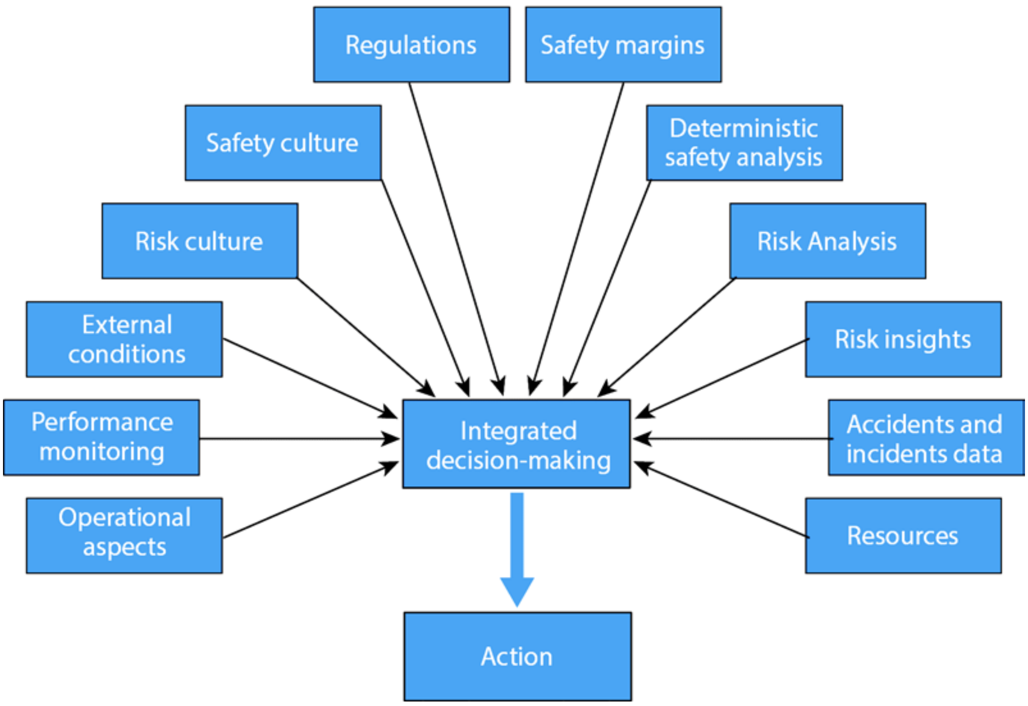


Figure H4. Integrated risk-informed decision -making (after ICOLD, 2017).

H5 Risk assessment in Australia

In Australia, dam safety is the responsibility of each of the states. Some states (such as New South Wales, NSW) have developed specific regulations, while other states have more general regulations that define liability. The Australian National Committee on Large Dams (ANCOLD) issued risk assessment guidelines and design guidelines in relation to earthquakes and floods (ANCOLD, 2003) which are very good. The New South Wales Government Dam Safety Committee (2006) presented the "Risk Management Policy Framework for Dam Safety" which regulates dam safety. The safety requirements distinguish between target-based regulation (based on risk acceptance criteria) and standard-based regulation (based on explicit requirements). Normally, 'standard-based' documentation of safety is required, but in some cases 'target-based' documentation of safety is used. In these cases, acceptance criteria for New South Wales apply with an annual failure probability (Annex A, Section A4).

The trend is towards increased use of the target-based approach with risk assessment. The latest changes are:

- Risk assessment is accepted as a tool in dam safety management.
- Failure Mode and Effects Analysis (FMEA) is required as part of the safety documentation for dams where loss of life can be a consequence.
- Safety requirements for dams have improved through the addition of risk management systems.

H6 Risk assessment in Canada

Regulation of dams in Canada is a provincial or territorial responsibility[1]. Canada does not have a federal regulatory body or overarching program that governs the requirements for the safe management of dams. The Canadian Dam Association (CDA) is a non-profit organization formed in the 1980s that offers dam owners, operators, consultants, suppliers and government agencies a national forum for discussing dam safety. The CDA prepared Dam Safety Guidelines (CDA 2007; 2013) with five main themes:

- dam safety management,
- operation,
- maintenance and monitoring,
- preparedness,
- dam safety review, including analysis and assessment.

None of Canada's provinces explicitly refer to the CDA's dam safety guidelines in legislation or regulation, but some provinces have used parts of these to develop their own legislation and regulation. The regulations in Alberta and British Columbia do not require explicit risk assessments, but do not exclude them either.

The authorities accept documentation of dam safety through risk analyses. For example, the results of risk analyses in various forms have been presented to the authorities in British Columbia for various BC Hydro projects. The analyses have helped to increase the understanding of dam safety and has improved communication, but have not been used as the sole basis for the dam owner's decisions and legal approval. In British Columbia, dam safety is regulated by the "Water Act". The dams are classified on the basis of severity of the worst potential consequence according to loss criteria for life and health, environment, cultural values, infrastructure and economy. The consequence severity class determines how often review and other activities related to dam safety, such as inspection, instrumentation and dam safety review, are required.

Guidelines for risk assessment were first published in Canada in 1995. In the latest revision (2013), CDA supports the use of risk-informed decision-making. The recommendation states that safety

[1] Canada has 10 provinces and three territories.

management depends on risk management and should provide answers to the following three questions:

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

To understand how the structures are expected to perform and what level of deviation from the normal condition is tolerable, dam safety analyses should consider the full range of current conditions. In view of the major uncertainties, a risk-informed approach to dam safety is encouraged in addition to conventional methods.

The guide says:

> The general framework for dam safety must ensure that no individuals or local communities are unduly affected in terms of broader societal interests. On the other hand, society does not have infinite resources to spend on managing risk. Often, resources that are used inefficiently in one area can be more beneficial if invested in another area. Effective application of a balanced approach to efficiency requires the recognition that both economic efficiency and social justice are legitimate goals that society wants to pursue.

Risk assessment for dam safety should assess the risk diagram shown in Figure H1, which presents guidelines for risk of loss of life that are in accordance with values used in other hazardous industries and with the principle that risks should be made as low as practicable (ALARP) (Appendix F).

Figure H1 is based on the assumption that the maximum tolerable level of societal risk shall be such that the annual probability of loss of *N* or more lives shall be less than the probability of loss of life that was not explicitly identified in advance of the failure. A higher risk that this value is considered as unacceptable.

A high societal aversion to catastrophic casualties should be reflected in setting the maximum performance target in cases where more than 100 lives would be endangered. Risks should be kept as low as practicable until they fall within a "generally acceptable" range set 100 times lower (Fig. H1). Actions to reduce the risk is clearly necessary if the risk is not acceptable. The ALARP principle is based on the duty to reduce the risk to life to the point that further risk reduction is impossible or requires actions that are grossly disproportionate in time, difficulty, costs and efforts to reduce the risk.

The maximum level for individual risk is usually given as less than 10^{-4} /year. To calculate the risk to an individual, probability methods must be available to quantify each factor in the following equation to calculate the probability of loss of life (PLOL) for the highest exposed individual:

$$P_{LOL} = P_{Event} \; x \; P_{Failure/Event} \; x \; P_{Fatality/Failure}$$

P_{LOL} = Unconditional fatality probability for the most vulnerable person, due to event;
P_{Event} = Unconditional probability of occurrence of the event (for specific event type and size);
$P_{Failure/Event}$ = Conditional probability of a failure, given the occurrence of the specific event;
$P_{Fatality/Failure}$ = Conditional probability of loss of life, given that the failure occurs.

The risk calculated with the above formula must be aggregated over all the threatening events that may occur during the life of the dam in order to obtain the total risk for the individual.

In Canada, it is considered that risk assessment is an appropriate framework for managing dam safety. The approach has significant advantages in offering well-defined and sound safety targets. In the CDA guidelines, the dam owner is expected to demonstrate that the resulting risk level is justifiable and that the safety management of the dam is in accordance with the principles in the guideline.

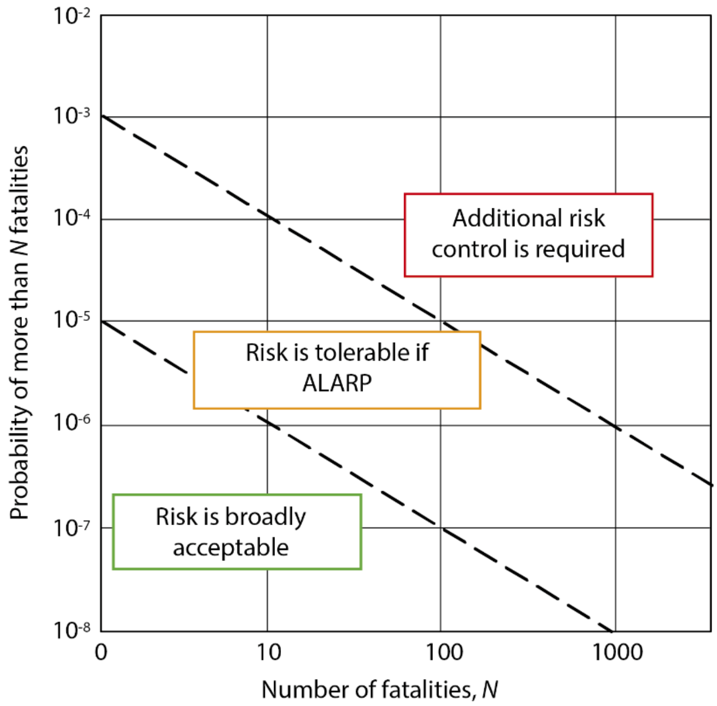


Figure H5. Risk diagram recommended in Canada (CDA 2007; 2013)

The authorities in British Columbia (BC) provide guidance in conducting risk assessments. On the other hand, there is no requirement for risk assessment in BC's dam regulations from 2016. BC Hydro has been an active and advanced user of risk assessments since the 1990s (Fig. H1). BC Hydro uses risk assessments to support decision-making on dam safety and dam portfolio management. Methods used by BC Hydro include:

- Potential Failure Mode Analysis;
- Fault Tree Analysis to identify vulnerability;
- Quantitative methods such as Event Tree Analysis;
- Semi-quantitative risk matrix, Bowtie analysis or Risk Register for dam portfolio management.

In Ontario (Ontario Power Generation), risk assessment is used for:

- Portfolio management (quantitative analysis);
- Assessment of specific safety aspects (quantitative analysis);
- As decision support for rehabilitation (quantitative analysis);
- Assessment of safety or risk reduction measures for 3rd parties (qualitative analysis).

In addition, the authorities carry out risk assessment at an overall level.

H7 Risk assessment in the UK

The Health and Safety Executive (HSE) in the UK has a well-known framework for evaluating risk, the so-called "Tolerability of Risk" diagram (Fig. A29 in Annex A). In the United Kingdom, risk assessments have been carried out for large dams with quantitative risk assessment methods using both simplified and detailed quantitative analyses. British Standard (BS EN 31010 (BSI 2010)) stipulates the following:

> "Risk assessment is the part of risk management, which provides a structured process that identifies how goals can be affected, and analyses the risk in terms of consequences and their likelihood before deciding whether further treatment (risk reduction) is necessary."

In the UK, dams are classified on the basis of impact assessments. There is no requirement for risk assessment. When using risk assessment, it is recommended that the PFMA method (Potential Failure Mode Analysis) be used. The risk assessments should be used in advance of inspections to ensure that focus is placed on the most critical aspects of the dam during the inspection. Dam owners can choose to control the dam with either standard loads differentiated by consequence classes or probabilistically based loads.

H8 Risk assessment in the USA

Laws and regulations on dam safety vary from state to state in the US (50 states). The Federal Emergency Management Agency (FEMA) administers the National Dam Safety Program, which coordinates all federal dam safety programs and assists states in improving their dam safety regulations and programs. FEMA (2015) presented the "Federal Guidelines for Dam Safety Risk Management" with guidelines for dam risk management. The guidelines provide the general principles for risk management and risk-informed decisions. Guidelines for dam safety were published jointly by the U.S. Bureau of Reclamation (USBoR) and the U.S. Army Corps of Engineers (USACE). Several of the recommended risk charts have already been shown in Annex A.

Following the Teton Dam breach in 1976, the US Bureau of Reclamation was asked to develop a risk analysis methodology for dams (risk is mentioned in the US Dam Safety Act). USACE recognized the need to implement risk analysis following the breaches in the dikes in New Orleans during Hurricane Katrina. In particular, USACE highlighted:

- The need to improve and balance risk-reducing measures with a limited budget (e.g., upgrading a few specific dams to sustain extraordinary floods versus using available budgets to reduce the risk associated with several dams).
- The need for more transparency and justification for decisions about dams and levees.

Figure H6 illustrates the dam safety risk management process put forward jointly by FEMA, FERC and USACE. Table H1 presents the joint federal risk categories used in the USA. In the joint federal US guidelines, the objectives and guiding principles for dam safety are:

- Life safety is paramount.
- Risk assessment should inform the decision-makers and improve the status of safety of the dams.
- Identify and reduce the risk to life and property, and reduce those risks following ALARP.
- The urgency of completing dam safety actions should be commensurate with the level of risk.

USBoR and USACE concluded that risk analysis procedures, although quantitative, do not provide accurate numerical results. The risk assessment will be advisory, not prescriptive, so that site-specific considerations, good logic and all relevant external factors can be used in decision-making processes, rather than relying on a 'cookbook' with a numerical criteria approach. The numbers, although important, are less important than understanding and clearly documenting what the biggest risk is.

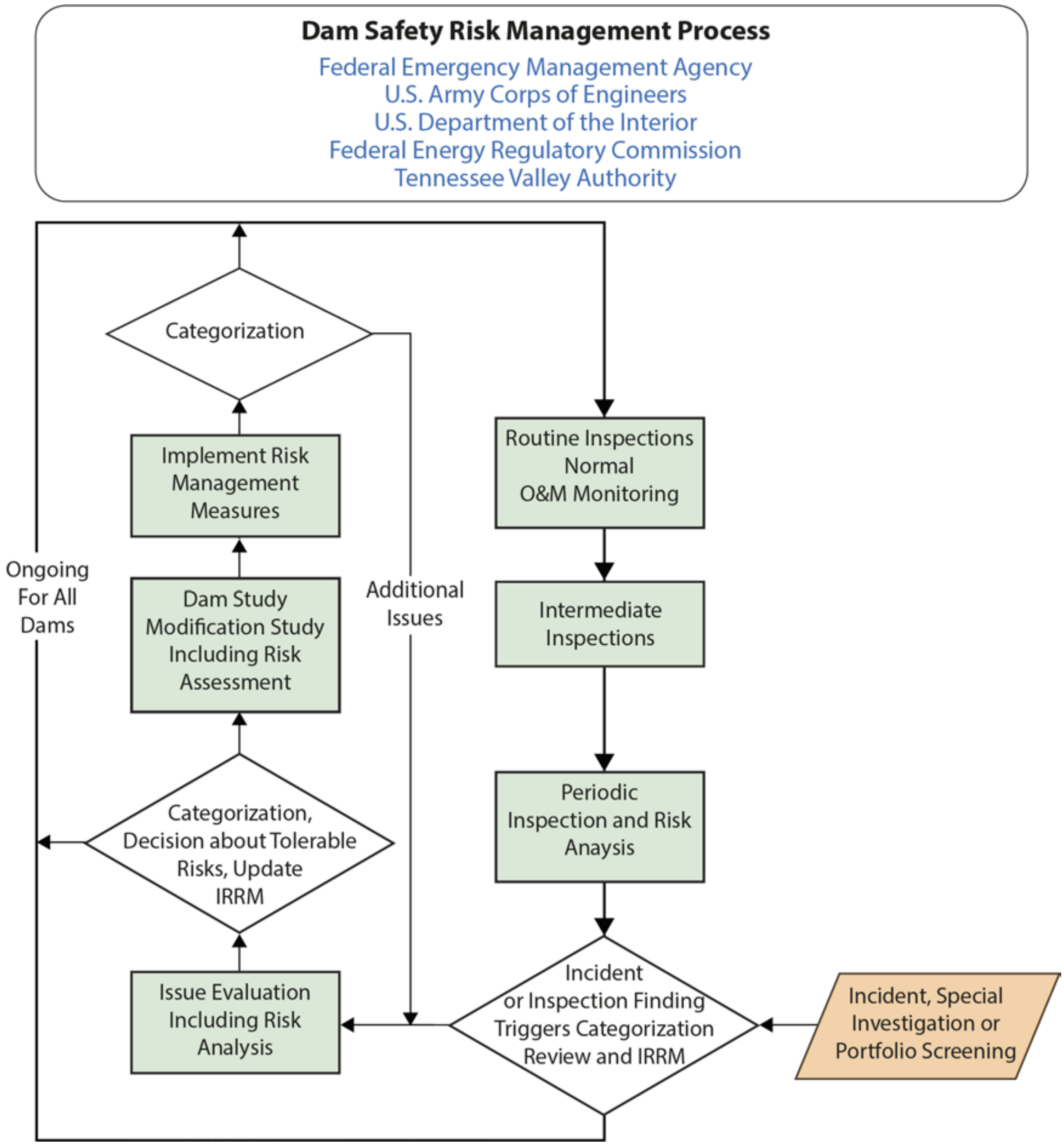


Figure H6. Joint risk management process adopted by FEMA, USACE, USDI, FERC and TVA in the USA

Table H1. Urgency table of US joint federal guidelines, including risk classes and potential actions.

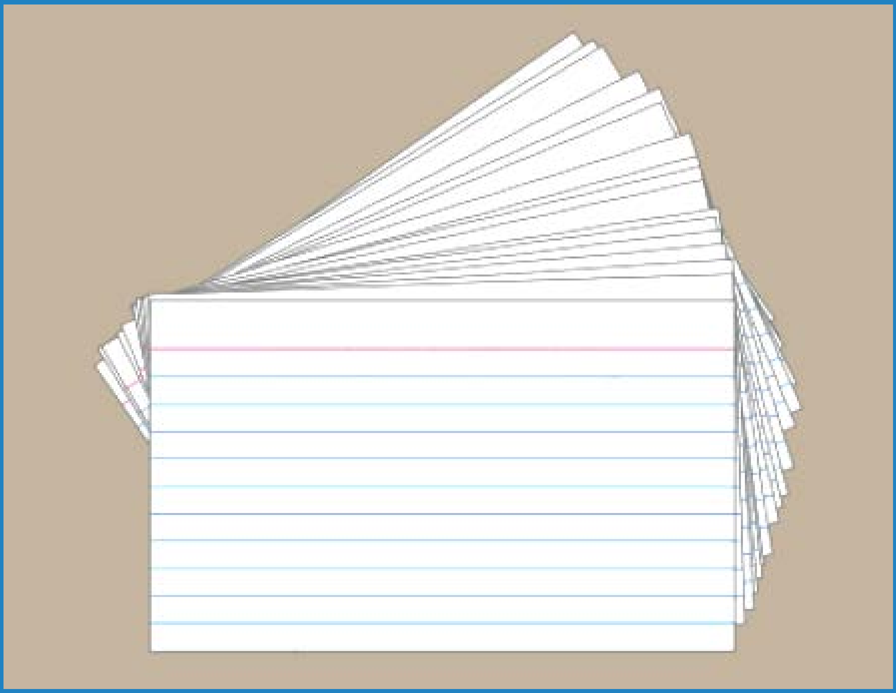
Urgency of action	Characteristics and consequences	Potential actions
I Very high urgency	Critically near failure: There is direct evidence that failure is in progress, and the dam is almost certain to fail during normal operation if action is not taken quickly, or Extremely high risk: Combination of life and economic consequences and likelihood of failure is very high with high confidence.	– Take immediate action to prevent failure. Communicate findings to potentially affected parties. – Implement interim risk reduction measures. – Ensure that the emergency action plan is current and functionally tested. – Conduct heightened monitoring and evaluation. Expedite investigations and actions to support long-term risk reduction. – Initiate intensive management and situation reports.
II High urgency	Risk is high with high confidence or Risk is very high with low to moderate confidence: The likelihood of failure from one of the occurrences, prior to taking action, is too high to delay action.	– Implement risk reduction measures. – Ensure that the emergency action plan is current and functionally tested. – Give high priority to heightened monitoring and evaluation. Expedite investigations and actions to support long-term risk reduction. – Expedite confirmation of classification.
III Moderate urgency	Moderate to high risk: Confidence in the risk estimates is generally at least moderate, but can include facilities with low confidence if there is a reasonable chance that moderate risk estimates will be confirmed or confidence will potentially increase with further study.	– Implement risk reduction measures. – Ensure that the emergency action plan is current and functionally tested. – Conduct heightened monitoring and evaluation. Prioritize investigations and actions to support long-term risk reduction. – Prioritize confirmation of classification as appropriate.
IV Low to moderate urgency	Low to moderate risk: The risks are low to moderate, and confidence in the risk estimates is high with the potential for the classification to move less urgent, with further study.	– Ensure that routine risk management measures are in place. – Determine whether action can wait until after the next periodic review. – Before the next periodic review, take appropriate interim measures, and schedule other actions as appropriate. – Give normal priority to investigations to validate classification , but do not plan for risk reduction measures at this time.
V No urgency	Low risk: The risks are low and are unlikely to change with additional investigations or studies.	– Continue routine dam safety risk management activities and normal operations and maintenance.

Annexes

Part I Tools for risk assessment

Part II Additional information

Part III Reference material



Annex I Definitions, acronyms and notation

I1 Definitions

Acceptable risk

A risk which everyone impacted is prepared to accept. Action to further reduce such risk is usually not required unless reasonably practicable measures are available at low cost in terms of money, time and effort.

Accident

Sudden unintentional action or event occurring at an unpredictable point in time causing harm to a person or persons.

ALARP (As Low As Reasonably Practicable) principle

That principle which states that risks, lower than the limit of tolerability, are tolerable only if risk reduction is impracticable or if its cost is grossly in disproportion (depending on the level of risk) to the improvement gained.

Annual exceedance probability

The estimated probability that an event of specified magnitude will be exceeded in any year.

Availability

The probability that an item will be able to function according to specification under stated conditions at a particular point in time.

Bayes theorem

A theorem that provides the logical basis for updating a probability on the basis of new information.

Breach

Failure of a dam, uncontrolled release or water.

Cascade failure

One of a sequence of failures following closely after the other, from a common cause.

Conditional probability

The probability of an outcome, given the occurrence of some event. For example, given that a flood has reached the crest of an embankment dam, the probability of the dam failing is a conditional probability.

Consequence

In relation to risk analysis, the outcome or result of a hazard being realised. Impacts in the downstream, as well as other, areas resulting from failure of the dam or its appurtenances (ICOLD, 2005).

Countermeasures

All measures taken to counter and reduce a hazard or consequences of a hazard. They most commonly refer to engineering (structural) measures but can also include other non-structural measures and tools designed and employed to avoid or limit the adverse impact of natural hazards and related environmental and technological disasters.

Cumulative distribution function (CDF)

The integral of the probability density function calculated in the direction of increasing values of the random variable. Thus, the probability that the random variable takes on values less than or equal to a particular value can be read from the CDF.

Dam failure

Uncontrolled release of contained water.

Danger (Threat)

The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The danger can be an existing one (such as a creeping slope) or a potential one (such as a rockfall). The characterisation of danger or threat does not include any forecasting.

Decision-maker

The person or organizational unit who decides on a course of action in relation safety.

Deterministic

Describing a process with an outcome that is always the same for a given set of inputs, i.e. the outcome is "determined" by the input. Deterministic contrasts with random, which describes a process with an outcome that can vary even though the inputs are the same. Deterministic analysis contrasts with probabilistic analysis.

Elements at risk

Population, buildings and engineering works, infrastructure, environmental features and economic activities in the area affected by a hazard.

Environmental risks

Risks to natural ecosystems or to the aesthetics, sustainability or amenity of the natural world.

Event

A change in the state of a system taking place in a period of time which is sufficiently short for the time to be ignored (sometimes the word 'incident' is used as a synonym).

Event tree analysis

Inductive analysis process that utilises an event tree graphical construct that shows the logical sequence of the occurrence of events in, or states of, a system following an initiating event.

Extreme event

Event, which has a very low annual exceedance probability. Sometimes defined as an event beyond the credible limit of extrapolation and therefore dependent on the length of record and the quality of the data available.

Factor of Safety

The ratio of resistance to peak design loads, often calculated in accordance with and measured against established rules.

Failure

The inability of a system, or part thereof, to function as intended. In the context of structural safety (including geotechnical structures), failure is generally confined to issues of structural integrity, and in some contexts to the special case of collapse of the structure or some part of it.

Failure mechanism

A mechanism describing the physical processes and states that must occur for failure to develop.

Failure mode

A way that failure can occur, described by the means by which element or component failures must occur to cause loss of the sub-system or system function.

Fault tree analysis

A systems engineering method for representing the logical combinations of various system states and possible causes which can contribute to a specified problematic (fault) event (called the top event).

f, N pair

Refers to "f', the probability of life loss due to failure for each scenario studied, and "*N*", the number of lives expected to be lost in the event of such a failure scenario. The term "*N*" can be replaced by any other quantitative measure of failure consequences, such as monetary measures.

F-N curves

Curves relating the probability per year of causing *N* or more fatalities. This is the complementary cumulative distribution function. Such curves may be used to express societal risk criteria and to describe the safety levels of particular facilities.

Frequency

A measure of likelihood expressed as the number of occurrences of an event in a given time or in a given number of trials (see also likelihood and probability).

Hazard

Probability that a particular danger (threat) occurs within a given period of time. “Threat" or condition which may result from either an external cause (e.g., earthquake, flood, or human agency) or an internal vulnerability, with the potential to initiate a failure mechanism. A source of potential harm or a situation with a potential to cause loss (ICOLD, 2005).

Hazard analysis

Systematic way of identifying hazards in a system.

Human factors

Human factors refer to environmental, organisational and job factors, and human and individual characteristics which influence behaviour in a way which can affect safety.

Incident

Synonym of event.

Individual risk

The increment of risk imposed on a particular individual by the existence of a hazard. This increment of risk is an addition to the background risk to life, which the person would live with on a daily basis if the facility did not exist.

Involuntary risk

A risk imposed on people by a controlling body and not assumed by free choice of the people at risk.

Joint probability

The probability that two or more variables will assume certain values simultaneously or within particular time intervals.

Judgment

Contribution to decision-making which depends on a person's experience, technical know-how, and ethical or moral values.

Likelihood

Conditional probability of an outcome given a set of data, assumptions and information. Also used as a qualitative description of probability and frequency.

Limit

In relation to level of risk, that level which, when exceeded, is unacceptable. Higher risks cannot be justified except in extraordinary circumstances (typically where the continuation of the risk has been authorised by government or a regulator in the wider interests of society).

Loss

Any negative consequence, financial or otherwise.

Mitigation

Measures undertaken to limit the adverse impact of, for instance, natural hazards, environmental degradation and technological hazards.

Monte Carlo simulation

A procedure, which seeks to simulate stochastic processes by random selection of input values to an analysis model in proportion to their joint probability density function.

Owner

Legal entity which either holds a government license to operate a facility or retains the legal property title on the facility, and which is responsible for the safety of the facility.

Population at risk

All those persons who would be directly exposed to the consequences of failure of a structure or facility if they did not evacuate.

Potential failure mode

A way that dam failure can occur (i.e., the full sequence of events from initiation to failure) for a given loading condition" (FEMA, 2015).

Preparedness

Activities and measures taken in advance to ensure effective response to hazards and their consequences.

Prevention

Activities to provide outright avoidance of the hazards and their consequences.

Probabilistic

A description of procedures, which are based on the application of the laws of probability. Complementary to deterministic.

Probability

A measure of the likelihood, chance, or degree of belief that a particular outcome or consequence will occur.

A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event. There are two main interpretations:

- *Statistical frequency or fraction* – The outcome of a repetitive experiment of some kind like flipping coins. It includes also the idea of population variability. Such a number is called an "objective" or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
- *Subjective probability (degree of belief)* – Quantified measure of belief, judgement, or confidence in the likelihood of an outcome, obtained by considering all available information honestly, fairly, and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes.

Probability density function

A function describing the relative likelihood that a random variable will assume a particular value in contrast to taking on other values.

Random variable

A quantity, the magnitude of which is not exactly fixed, but rather the quantity may assume any of a number of values described by a probability distribution.

Redundancy

Having two or more components capable of carrying the sane function.

Regulatory agency

Usually a government ministry, department, office, directorate or other unit of government entrusted by law or administrative act with the responsibility for the general supervision of the safe design, construction and operations of structures or facilities, as well as any entity to which all or part of the executive or operational tasks and functions have been delegated by legal power.

Reliability

The probability that an item will perform a required function under stated conditions for a stated period of time. It is the likelihood of successful performance of a given project element. Mathematically, Reliability = 1 - Probability of failure. See definitions of “probability” and “failure”.

Reliability analysis

An analysis (qualitative or quantitative) concerned with the reliability or availability of a technical system or man/machine system.

Residual risk

The remaining level of risk at any time before, during and after a program of risk mitigation measures has been completed.

Risk

Measure of the probability and severity of an adverse effect to life, health, property, or the environment. Quantitatively, Risk = Hazard * Potential Worth of Loss. This can be also expressed as "Probability of an adverse event times the consequences if the event occurs". ISO expresses risk at the "effect of uncertainties on the objectives".

Risk analysis

The use of available information to estimate the risk to individuals or populations, property or the environment, from hazards. Risk analyses generally contain the following steps: definition of scope, danger (threat) identification, estimation of probability of occurrence to estimate hazard, evaluation of the vulnerability of the element(s) at risk, consequence identification, and risk estimation. Consistent with the common dictionary definition of analysis: "A detailed examination of anything complex made in order to understand its nature or to determine its essential features", risk analysis involves the disaggregation or decomposition of the system and sources of risk into their fundamental parts.

- *Qualitative risk analysis:* An analysis which uses word form, descriptive or numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur.
- *Quantitative risk analysis:* An analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

Risk assessment

The process of making a decision recommendation on whether existing risks are tolerable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation phases.

Risk-based decision-making

Decision-making, which has as a main input the results of risk assessment. It involves a balancing of social and other benefits and the residual risks.

Risk control

The implementation and enforcement of actions to control risk, and the periodic re-evaluation of the effectiveness of these actions.

Risk evaluation

The stage at which values and judgement enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Risk-informed decision-making

Decision-making that is made considering risk estimates and many other contributing factors that might include confidence in the risk estimates **and** risk uncertainty**.**

Risk management

The systematic application of management policies, procedures and practices to the tasks of identifying, analysing, assessing, mitigating and monitoring risk.

Risk mitigation (risk treatment)

A selective application of appropriate techniques and management principles to reduce either likelihood of an occurrence or its adverse consequences, or both.

Safety coefficient
See “Factor of Safety”.

Safety factor
See “Factor of Safety”.

Scenario

A unique combination of states. A scenario defines a suite of circumstances of interest in a risk assessment, for example loading scenarios or failure scenarios.

Sensitivity analysis

An analysis to determine the range over which the result varies, given unit change in one or more input parameters.

Societal risk

The risk of widespread or large scale detriment from the realisation of a defined risk, the implication being that the consequence would be on such a scale as to provoke a socio/political response.

Standards-based approach

The traditional approach to engineering, in which risks are controlled by following established rules as to design events and loads, structural capacity, safety coefficients and defensive design measures.

System

Assembly that consists of interacting elements.

System response

How a system responds. May be expressed as a conditional probability of failure, to a given scenario of applied loads and concurrent conditions (see also fragility curve).

Temporal probability

The probability that the element at risk is in the area affected by the danger (threat) at the time of its occurrence.

Tolerable risk

A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

Trigger event

The event which activates an accident response (failure, Breach).

Uncertainty

The result of imperfect knowledge about the present or future state of a system, event, situation, or population under consideration. Uncertainty describes any situation without certainty, whether or not described by a probability distribution. Uncertainty is caused by natural variation and/or incomplete knowledge (lack of understanding or insufficient data). Uncertainty can be attributed to: (1) *aleatory uncertainty:* inherent (or natural) variability in properties and events, and (2) *epistemic uncertainty:* incomplete knowledge of parameters and the relationships between input and output values.

Undesirable event

Event or condition that can cause undesirable consequences for e.g., people, constructions, infrastructure, equipment, of other resources.

Voluntary risk:

A risk that a person faces voluntarily in order to gain some benefit.

Vulnerability

The degree of loss to a given element or set of elements within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). Also, a set of conditions and processes resulting from physical, social, economic, and environmental factors, which increase the susceptibility of a community to the impact of hazards.

I2 Acronyms

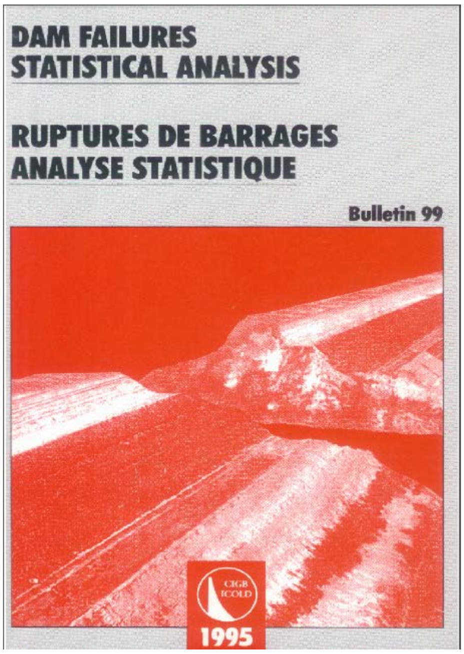
ALARP	As Low As Reasonably Practicable.
ANCOLD	Australian National Committee on large dams
ASCE	American Society of Civil Engineers
BoR	Bureau of Reclamation (USA)
FEMA	Federal emergency Management Agency (USA)
FERC	Federal Energy Regulatory Commission (USA)
ICOLD	International Commission On Large dams
NSW	New South Wales (Australia)
RIDM	Risk-informed decision making
TVA	Tennessee Valley authority (USA)
USACE	US Army Corps of Engineers
USBoR	US Bureau of Reclamation
USDI	US Department of the Interior

I3 Notation

C	Consequence
CoV	Coefficient of variation
$C_{OV}[FS]$	Coefficient of variation of factor of safety, FS
f	Frequency
F	Cumulative frequency
FS	Safety factor
H	Hazard
H	Probability, likelihood
$LLOL$	Likely Loss of Life
LOL	Loss of Life
M	Safety margin
N	Number of fatalities
PDF	Probability density function
P_f	Failure probability
P_{LOL}=	Unconditional fatality probability for the most vulnerable person
P_{Event}	Unconditional probability of occurrence of the event
$P_{Failure/Event}$	Conditional probability of a failure, given the occurrence of a specific event
$P_{Fatality/Failure}$	Conditional probability of loss of life, given that the failure occurs.
R	Risk
s	Probability
S	Total probability
SD	Standard deviation
α	Exponent (slope of line in log-log risk diagram)
β	Reliability index
μ	Average

Annex J ICOLD Bulletins with main focus on dam safety


DAM SAFETY
GUIDELINES
SÉCURITÉ DES BARRAGES
RECOMMANDATIONS
BULLETIN 59
1987
CHECK-LISTS


DAM FAILURES
STATISTICAL ANALYSIS
RUPTURES DE BARRAGES
ANALYSE STATISTIQUE
Bulletin 99
CIGB
ICOLD
1995

Annex J ICOLD Bulletins dealing with dam safety

Table J1 makes a matrix of the ICOLD Bulletins dealing with dam safety, statistics of dam failure, embankment dams and concrete dams, internal erosion, snow and ice loads, stability and deformations, and rehabilitation.

Table J1. ICOLD Bulletins dealing with dam safety

ICOLD Bull. No./yr	**Title**	**Dam safety**	**Damages and other incidents**	**Rehabilitation and upgrading**	**Embankment dams**	**Leakage, internal erosion**	**Stability, deformations**	**Concrete and masonry dams**	**Ice and snow loads**	**Contents in Bulletin**
15 1960	*Frost resistance of concrete – Results obtained in different laboratories*							X		Resistance of concrete under freeze-thaw cycles
29 1982	*Report from the committee on risks to third parties from large dams*	X								Dam failure, risk elements and risk reduction
30 1987	*Finite elements methods in analysis and design of dams*	X			X			X		Method, hypotheses and challenges
41 1982	*Automated observation for the safety control of dams*	X								Automated surveillance
48 1986	*River control during dam construction*	X		X						Dam safety under building
49 1986	*Operation of hydraulic structures of dams*	X								Operation and inspection
51 1985	*Filling materials for watertight cut off walls*				X	X				Methods and materials for cut-offs
53 1986	*Static analysis of embankment dams*	X			X		X			Earth and rockfill dams, no foundation analysis
55 1986	*Geotextiles as filters and transitions in fill dams*				X	X				Geotextiles as filter for an embankment dam
56 1986	*Quality control for fill dams*	X			X					Quality assurance under construction
59 1987	*Dam safety – Guidelines*	X	X							Guidelines for dam safety
94 1994	*Computer software for dams – Validation*	X			X			X		Considerations for numerical analysis of dams
99 2000	*Dam Failures - Statistical Analysis (1995, updated 2020)*		X							Statistics of incidents and failure (Annex D)
105 1996	*Dams and structures in cold climate - Design guidelines and case studies*								X	Ice loads damaging a dam and mitigation measures
111 1998	*Dam break flood analysis - Review & recommendations*	X								Downstream consequen-ces of a flood wave
118 2000	*Automated dam monitoring sys-tems - Guidelines and case histories*			X						Guidelines for automated surveillance
122 2001	*Computational procedures for dam engineering - Reliability and applicability*	X			X			X		Overview of models to assess dam safety

ICOLD Bull. No./yr	**Title**	**Dam safety**	**Damages and other incidents**	**Rehabilitation and upgrading**	**Embankment dams**	**Leakage, internal erosion**	**Stability, deformations**	**Concrete and masonry dams**	**Ice and snow loads**	**Contents in Bulletin**
124 2000	*Reservoir landslides: Investigation and management - Guidelines and case histories*	X								Historical landslides in dam reservoir and guidelines
125 2003	*Dams and floods - Guidelines and case histories*		X							Historical cases of floods and guidelines
130 2005	*Risk assessment in dam safety management (benefits, methods and current applications)*	X								Introduction and termino-logy – risk assessment
131 2006	*Role of dams in flood mitigation - A review*		X							Risk associated with floods
133 2007	*Embankment dams on permafrost - A review of the Russian experience*				X				X	Experience with dams built on permafrost in Russia
138 2009	*Surveillance: Basic elements in "dam safety" process*	X								Principles for dam safety and surveillance
142 2012	*Bulletin on safe passage of extreme floods*	X	X							Direct and indirect consequences of floods
154 2017	*Dam safety management: Opera-tional phase of the dam life cycle*	X								Guidelines for dam safety management over life cycle
155 2013	*Guidelines for use of numerical models in dam engineering*	X								Guidelines on modelling of new and older dams
156 2014	*Integrated flood risk management*	X								Assessment of risk associated with floods
157 2016	*Small dams: Design, surveillance and rehabilitation*	X								Guidelines for small dams
158 2018	*Dam surveillance guide*			X						Guidelines on surveillance
164 2017	*Internal erosion of existing dams, levees and dikes, and their foundations*				X	X				Instrumented surveillance of internal erosion and observations made
167 (2020)	*Regulation of dam safety: An overview of current practice*	X								Dam safety: Current practice worldwide
170 2018	*Flood evaluation and dam safety*	X								Flood calculations and how floods affect dam safety
175 (2020)	*Dam safety management: Pre-ope-rational phases of the dam life cycle*	X								Dam safety in the early phases of the dam life
180 2017	*Dam surveillance - Lessons learnt from case histories*		X							Surveillance of dams: historical experience
185 2019	*Challenges and needs for dams in the 21st century*	X			X	X		X	X	Freshwater, energy and climate change

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