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Risk assessment and risk management for dams

Evaluation et gestion des risques pour les barrages

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ABSTRACT: Current practice makes use of deterministic analyses to evaluate the safety and potentially the unsatisfactory behaviour of a dam. In recent years, probabilistic analyses and risk assessment for the evaluation of dam safety have received increasing attention. However, there is conflicting information on and criticism of dam risk assessment methods in the literature, which can lead to confusion in the industry. The paper answers "frequently asked questions" on the risk approach for dams, such as risk diagrams, tolerable and acceptable risk, deterministic vs risk-based safety target, and the strengths and drawbacks of risk approach for dams. The paper concludes that the reliability-based analyses neither need to be complicated, time-consuming nor "for experts only". As society and design standards increasingly require "risk-informed" decisions, risk assessment leads to more robust decisions on dam safety by addressing the uncertainties in a more systematic manner than conventional analyses can do alone.

RÉSUMÉ : La pratique actuelle utilise des analyses déterministes pour évaluer la sécurité et le comportement d'un barrage. Ces dernières années, l'approche fiabiliste et l'évaluation des risques associés à la sécurité des barrages font l'objet d'une attention croissante. Cependant, il existe des informations contradictoires et des critiques sur les méthodes d'évaluation des risques dans la littérature, ce qui prête à confusion pour l'industrie. Cet article répond à des questions fréquemment posées, abordant les diagrammes de risques et les niveaux de risque tolérable et acceptable, et les avantages et désavantages de l'approche fiabiliste pour les barrages. L'article conclue que les analyses fiabilistes ne sont ni compliquées, ni chronophages, ni "réservées aux experts". Alors que la société et les normes de conception exigent de plus en plus des décisions «informées sur les risques», l'évaluation des risques conduit à des décisions plus robustes en incluant les incertitudes de manière plus systématique que les analyses conventionnelles déterministes.

KEYWORDS: dam, uncertainty, risk assessment, risk management, failure, consequences

1 INTRODUCTION

As society increasingly requires that the risks associated with facilities or infrastructure be made transparent, risk-informed approaches need to become a fundamental component of dam safety programs. The premise is that risk-based methods improve dam safety by enhancing diagnostic capabilities and allocating resources more effectively (Vick 2002). Many risk assessment guidelines exist for dams today, e,g., FERC (2016); BC (2016).

The geotechnical profession has made significant progress in understanding how concepts of reliability-based design can provide more insight into the safety of a construction. Methods have been developed to use probabilistic approaches to solve geotechnical issues. However, there are often frequently asked questions, such as why use a reliability approach, how to obtain the probability estimates, and how to use and communicate the results in practice? This paper attempts to answer some of the most "frequently asked questions".

2 RISK AND RELIABILITY CONCEPTS

2.1 *Definitions*

ICOLD (2005) on "Risk Assessment in Dam Safety Management" defines risk as a "Measure of the probability and severity of an adverse effect to life, health, property, or the environment". Risk (R) is the product of hazard (H) and consequence (C), where parameter H is the likelihood or probability of an event occurring over a period of time, and parameter C includes all elements at risk, their vulnerability and their value (and associated losses). ISO 31000:2018 defines risk as the "effect (positive or negative) of uncertainties on the objectives". This definition shows very clearly the importance of the uncertainties on risk.

A hazard assessment is usually conducted by answering the following questions:

- Which conditions can lead to an undesirable situation?
- Which aspect(s) of geology, foundation, design, dam material, construction or operation can cause a dam breach?
- Which investigations (laboratory, field, numerical) can document the conditions and the properties of the dam and foundation? Can the data be validated?
- Given this information, which failure modes are plausible and how often could they happen?

In newspapers, newscasts and everyday speech today, the term "risk" is used to designate both hazard and risk, which is unfortunate.

2.2 *Margin of safety, uncertainties and failure probability*

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 safety factor, FS. A safety factor of 1.5 is often used to account for the combination of uncertainties in the ground, in the analysis parameters and in the calculation method. There is a general perception that a design with an SF ≥ 1.5 must be "safe". In reality, it is not that simple. A SF of 1.5 represents a spectrum of failure probabilities that depend on the uncertainties in the parameters in the analysis.

The safety margin M, is defined as "Resistance – Load". When the Resistance is greater than the Load (M>0), the construction is safe; when M≤0, the construction is unsafe. M has an uncertainty due to the uncertainties in the parameters defining both Load and Resistance. Because the uncertainties in a design are never zero, the failure probability, $P_f = \mathrm{P}[M \leq 0]$, is not zero.

A design with a high FS can have a higher failure probability than another with a lower FS, because the FS is affected by the uncertainties in the analysis (Lacasse & Nadim 1996; Lacasse & Höeg 2019). With today's prescriptive design, the same value of FS is applied to conditions that involve widely varying degrees of uncertainty. Safety factor is not a sufficient indicator of safety because it does not account for the uncertainties in the analysis.

Most dams are designed in compliance with prescribed standard-based methodologies. The design standards have uncertainty embedded throughout. Dam designers recognize the impact of uncertainty in, e.g., the geology of a foundation, the limited number of punctual measurements on dam performance. Some geotechnical problems are governed by average properties; others are dominated by local seams or discontinuities. Experienced designers can tell of surprises that may not be known for many years after dam impounding. Uncertainties are also introduced by hydrologic and seismic events.

Believing that deterministic methods provide a high degree of certainty is erroneous. Considering the uncertainties in a dam design is a fundamental requirement to identify the critical unknowns that control performance. Christian & Baecher (2011) observed that dam failures occur less frequently than predicted. The difference is believed to be due to (1) an overestimation of the uncertainties in the analyses, (2) the use of conservative values of properties in geotechnical analyses, and (3) method bias and uncertainty in the calculation methods and models.

2.3 *Risk-informed decision-making*

There are two approaches to assessing dam safety: (1) the conventional, standard-based approach; and (2) the risk-informed decision-making" (RIDM) approach. The latter encourages a proactive mindset in identifying potential problem areas, requiring a justified reasoning for the choices in the analysis. RIDM (ISO 2394:2015) quantifies the uncertainties and risks to allow for a decision on whether the risk is acceptable. Because dam failure mechanisms develop over time below ground or below water and are difficult to identify and monitor, and because natural threats are difficult to predict, uncertainties and unknowns must be identified and characterized.

The objective of RIDM is always to minimize the risk of life loss, economical losses and other losses. RIDM recognizes that human judgment plays an important role in decisions, and that technical information cannot be the only basis for decision-making. Gaps in knowledge and data are unavoidable, and decision-making is an inherently subjective, value-based task, integrating technical and non-technical elements. RIDM focuses on sequences of possible events, characterizing both the likelihood and the potential consequences of each scenario.

3 ASSESSING PROBABILITIES

3.1 *Risk analysis*

A risk analysis of an existing dam usually includes the following steps (often with one or two iterations):

1) Site visit and inspection of the dam including geology, topography, dam location and site conditions.
2) Review of observations and earlier events and behaviour.
3) Brainstorming on triggers and failure modes, and screening of the plausible failure modes or triggers (called scenarios).
4) Discussion and agreement on scales or categories to describe uncertainties and probability estimates.
5) Construction of a logical diagram (e.g. matrix, event tree, fault tree, bowtie diagram etc.), estimating likelihood and potential consequences for each event in a scenario.
6) Continuation of each sequence of events until failure (or non-failure) and development of consequences.
7) Calculation of probabilities for each scenario leading to a failure and the ensuing consequences.
8) Evaluation of results (comparison with guidelines and recent dam failure statistics) (e.g., ICOLD 2020; Fell *et al.* 2015).

The result of a quantitative risk analysis is a set of temporal probability of occurrence − consequences. In dam safety, the risk is expressed as, for example, the probability that N fatalities (or other consequence metric) occur in the event of a dam failure with a certain likelihood. The risk assessment is best carried out by a team, often in a workshop format, regrouping persons with diverse relevant expertise on the dam. The failure mode screening in Step 3 is often the most important step of the analysis.

3.2 *Assigning probabilities of events*

The probabilities estimated for an event 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, deformation or earthquake response analyses.
- Earlier experience with similar constructions, processes (like internal erosion) etc.
- Discussion at the workshop and consensus reached.
- Engineering judgment and expert opinion.

The assigned probabilities need to be justified and based on a demonstrable chain of reasoning and should not be based on speculation. Consensus is reached through discussion, using standard descriptors for probabilities. The descriptors, agreed to by consensus, reflect orders of magnitude and are used throughout the discussion to make specific and consistent estimates of probability. Vick (2002) stated that "the collective judgment of experts, structured within a process of debate, can yield as good an assessment of probabilities as mathematical analyses".

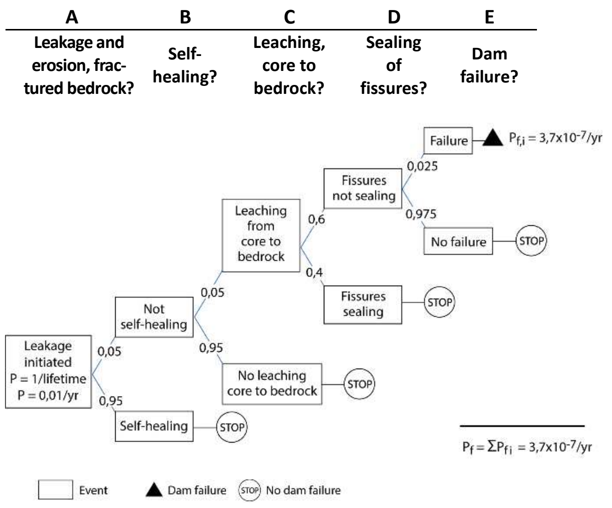
3.3 *Event tree analysis*

The most frequently used quantitative method for the risk assessment of a dam is the event tree analysis (ETA). Great strides have been made, as ETA and similar methods are used more frequently and results are calibrated against historical records (Davidson 2015). Figure 1 gives an example of an event tree for leakage and erosion through the core and the rock foundation of an 89-m high rockfill dam. At each node, a probability was estimated. The boxes above the event tree show the sequence of events in the analysis: (1) Is there leakage and erosion in the fractured rock? (2) Does self-healing occur? (3) Is there erosion from the core into the bedrock? (4) Do the fissures heal? (5) Does failure occur? The probabilities at each node are based on the chain of reasoning shown in the explanation table below the tree. The failure probability along one branch of the tree is calculated from the product of the probabilities along the branches leading to failure. The failure probability for one failure mode is the sum of the probabilities on the branches leading to dam failure in one tree. The total failure probability is the sum of the failure probabilities for all failure modes (all event trees).

3.4 *Expert opinion and engineering judgment*

One of the more contentious issues is how to make subjective estimates of events that have little to no statistical basis. Building an event tree by expert elicitation is a significant part of the quantitative risk assessment. The experts must rely on their experience of similar events to make those judgments. This requires thinking through the logical conditions that must exist or take place for a dam to fail, including design features, operator interventions and time delays that can prevent failure.

The risk process, like the dam design, relies on engineering judgment. Humans use judgment in all aspects of life. Engineers collect and evaluate the relevant data and do analyses. There are, however, always gaps in the information, and engineers use judgment to fill these gaps and develop recommendations. The engineer's professional judgment is the exercise of clear, logical and justified thinking, weighing assumption, known facts and contradictory information and bridging where information is lacking. Engineering judgment inherently includes a subconscious risk calculator that weighs uncertainty and assesses the potential consequences of outcomes of decisions and recommendations. Hence, judgment and risk are closely related.

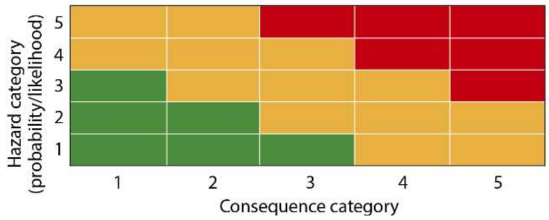


Event	Explanation	Probability
A **Leakage through the rock foundation**	Leakage that could cause erosion of the core initiates in the rock foundation: this has not happened in the first 40 dam-years; unlikely that this will get worse or better with time; life of dam is 100-150 years.	P = 1% during the 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

Figure 1. ETA example with justification for the probabilities: case of leakage and erosion in dam core and rock foundation.

4 RISK DIAGRAMS AND ACCEPTABLE RISK

As risk analysis became more common in dam safety assessment, guidelines were needed to help evaluate the results of the analyses. In a qualitative analysis, risk is usually divided in three zones described as simply 'low', 'medium' and 'high' risk (Fig. 2), in which different scenarios of dam breach are placed. The division in the three zones is the choice of the user.



Hazard category (probability/likelihood)	1	2	3	4	5
5	🟧	🟧	🟥	🟥	🟥
4	🟧	🟧	🟧	🟥	🟥
3	🟩	🟧	🟧	🟧	🟥
2	🟩	🟩	🟧	🟧	🟧
1	🟩	🟩	🟩	🟧	🟧

Figure 2. Qualitative risk diagram: 5x5 risk matrix with low (green), medium (orange) and high (red) risk zones.

With several decades of experience with risk analysis, USACE (2014) published individual (in green) and societal (in blue) risk guidelines (Fig. 3), consisting of two measures: annual failure probability (P_f) and average life loss for societal risk and individual incremental risk of life loss.

Societal risk is illustrated in a risk diagram showing the annual P_f (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. The consequence axis can be fatalities, costs, environmental damage, number of closed roads, interruption of infrastructure etc. Two risk zones are identified in a quantitative risk diagram: 'acceptable risk' and 'unacceptable risk'.

Figure 4 brings together the guidelines for acceptable and unacceptable risk from several countries (grey area). Not all guidelines are for dams, several are of a more general nature. The figure also shows the current NGI recommendation for acceptable risk for Norwegian dams (Lacasse & Höeg, 2019). The recommended limit for Norwegian dams is the same as the guidelines in Canada, USA and Australia and for man-made slopes in Hong Kong. Even if there are differences in the guidelines from different countries, the acceptable risk is quite comparable for one and 10 fatalities:

- For a single fatality, the acceptable P_f is 0.01/yr to 0.001/yr.
- For 10 fatalities, the acceptable P_f averages 0.0001/yr (or 10^{-4}/yr).
- For 100 fatalities, the acceptable P_f is 0.0001/yr to 0.000001/yr (10^{-4} to 10^{-7}/yr), reflecting varying risk aversion levels.

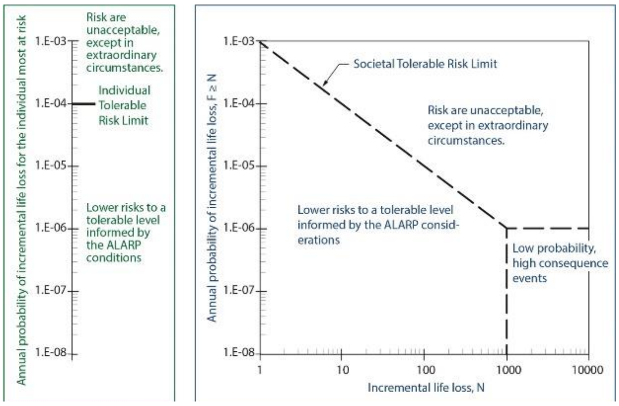


Figure 3. USACE (2014) quantitative guideline for incremental risk: (left) individual risk; (right) societal risk.

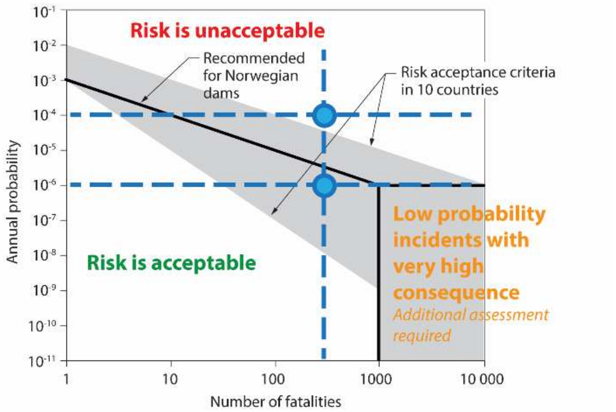


Figure 4. Quantitative risk diagram with risk acceptance criteria (grey area gives existing criteria in 10 countries) (Lacasse & Höeg, 2019).

4.1 *Significance of risk level*

Acceptable annual P_f-values of 10^{-3} (=$1 \cdot 10^{-3}$/yr) for one fatality person and of 10^{-4} (=$1 \cdot 10^{-4}$/year) for 10 fatalities is not unreasonable: statistics of the annual probability of human mortality in Canada and the US show that the annual probability of death from all causes is lowest between age 5 and 10, and is about 10^{-4}/yr. At age 20 to 30 in the US statistics, the annual probability of death is 10^{-3}/yr. If a person is 90 years old, there is a 10% probability that he/she will die in the next year.

Agencies publishing quantitative risk guidelines recognize that the quantitative risk analysis results involve uncertainty. As such, the limits between acceptable and unacceptable risk are a tool to facilitate informed decision-making. USBoR/USACE (2015) pointed out that the risk analysis needs a good balance of engineering judgment and calculations, and to understand and "build the case" for what most influences the behaviour of the dam. The numbers, while important, are less important than understanding the major risk contributors and how they occur.

Many regulations today use only the severity of the consequences to classify dams and prescribe rehabilitation needs. The drawback of this approach is that it gives an incomplete picture of the risk (Fig. 4) Two dams having the same consequences, i.e., along the same blue vertical line in the risk diagram. can have very different P_f . In Figure 4, the failure probability for each dam is shown with the two blue circles (P_f of 10^{-4} and 10^{-6} per year). One dam has acceptable risk, the other unacceptable risk. The difference in the P_f is due to the difference in characteristics and uncertainties of the two dams. The example shows clearly that, despite the two dams being in the same consequence classification class, there can be a very large difference in the failure probability, and thereby their level of risk, the safety of the two dams and their need for rehabilitation.

One needs to recognize that risk changes with time: e.g., if one builds a dam in the middle of nowhere, the risk associated with dam failure is low, even if the P_f is medium or high. If a house is built downstream, the dam suddenly passes from low to high risk. Nothing has changed in the hydrology or the dam itself, but the potential consequences have increased dramatically.

ASCE (2020) published an updated version of Whitman's 1984 risk diagram (Fig. 5). In the update, daily life individual risks are added, e.g., death due to heart disease and cancer, car accident and the estimated risk associated with the New Orleans dikes prior to Hurricane Katrina in 2005.

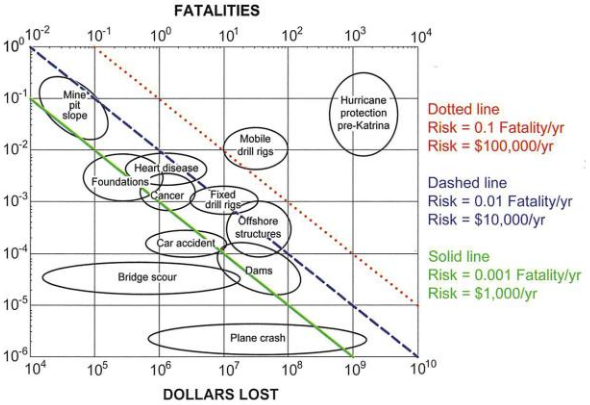


Figure 5. Whitman 1984 risk diagram with equi-risk lines and daily risks (ASCE, 2020) (economical losses in 1984 USD).

The F-N curves (log-log scale) with a slope $\alpha = -1$ are curves describing equal risk (called equi-risk lines). For the case where there is no loss of life (to the left of 10^0 on the upper scale denoted 'Fatalities'), other consequences, e.g., economical losses, loss of trust etc. will be determinant for the decision on acceptable risk. Usually such decisions are based on a cost-benefit assessment.

4.2 *Tolerable risk and ALARP principle*

Society needs to take risks to exist. When risks have the potential of loss of life, society does not like to call these outcomes acceptable. However, society is prepared to tolerate or "live with" the potential that consequences may occur provided that substantially economical and sustainable benefits are achieved.

In between the acceptable and unacceptable risk zones, one can add a 'Tolerable risk' zone, where the risk needs to be managed as far as possible, with analyses, follow-ups and risk reduction measures. The risk reduction, following the ALARP-principle ("**A**s **L**ow **A**s **R**easonably **P**racticable").

The decision on what is reasonably practicable should consider (1) costs and cost-effectiveness of further risk reduction measures; (2) the level of safety and uncertainty in different aspects of the dam and its surroundings; (3) any precedent of comparable decisions for other dams; (4) whether or not it is practically possible to rectify the weaknesses; (5) large uncertainties and low chance of success for the measures that would reduce the risk; (6) Insufficient time to implement the improvement, and any other considerations.

4.3 *Risk communication*

Risk is not absolute, nor static, and is not perceived uniformly by all stakeholders. There is a need for common understanding. Beyond technical and analytical decision-making, there are societal values. Risks are perceived as higher when unknown, involuntary, unfamiliar, catastrophic, acute and uncontrollable. The skills required for communication of engineering risk are not a part of the usual engineering education today. Effective communication is two-way communication, communication about people and their frame of mind and gaining trust with consistent and easy to understand terminology.

5 SAFETY FACTOR OR RISK-BASED TARGET?

A conventional analysis looks at nominal case (one scenario), without considering the entire spectrum of outcomes, and does not quantify the likelihood of the outcomes. A probabilistic analysis identifies the uncertainties that are key for safety, and tries to include all plausible failure scenarios and their likelihood.

What should be the safety target during the lifetime of a dam? Is a fixed deterministic safety factor sufficient to ensure the same safety margin throughout the lifetime of a dam? For dams, there are often discussions of the safety target to achieve, and whether the safety target should remain the same during the entire life. The individuals downstream of a dam should not be exposed to a higher risk with time, and any risk to the environment should not increase with time.

A target annual failure probability allows a more consistent comparison of the safety margin at different times of the life of a dam. A dam already in operation for 50 years, represents 50 years of evaluated experience, not unlike a prototype test on site under the loads experienced over 50 years. In most cases, the uncertainties at the time of design and construction will have reduced with time as more information and data have become available, and as a satisfactory performance of the dam is experienced over 50 years. A reliability-based approach can account for the observations and experiences during the operation of the dam.

An alternative to an annual failure probability, P_f, as a target is an annual reliability index, β. The two are directly related. Reliability index refers to the number of standard deviations (*SD*) between the mean safety factor (SF) and failure. Assuming that the SF is normally distributed, Figure 6 shows the relationship between P_f and β. The authors recommend that a target reliability index be used in practice. Reliability index has a more positive connotation than failure probability by referring to the reliability of a dam ("*Fiabilité*" in French, which means "trustworthiness"). Trustworthiness is the "ability to be relied on, honest or truthful".

6 ADVANTAGES AND DRAWBACKS OF THE RISK-BASED APPROACH FOR DAMS

The authors recommend that reliability-based analyses be done together with conventional deterministic analyses, because the two approaches are complementary. The conventional analyses are well-established and are an integrated part of most of the risk assessments. A risk analysis brings more information and thereby provides a more complete picture of the risk than deterministic analyses alone. Since the risk-based analysis comes in addition to the conventional analyses and provides more insight on the safety of a dam, there are no drawbacks per se. It is, however, possible to discuss advantages and drawbacks of the risk-based approach on a general basis.

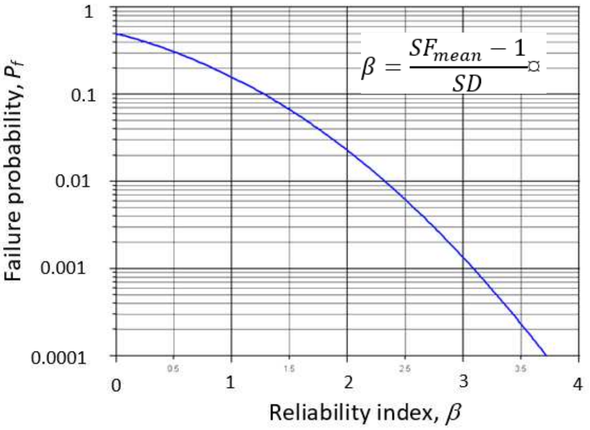


Figure 6. Relationship between failure probability $P_{f,}$ and reliability index, β, for a normal distribution.

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

- Risk assessment does a systematic review of all uncertainties, elements of the dam, their interrelationship and potential failure modes.
- The risk assessment process requires a debate on the uncertainties which helps understand 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 qualitative analysis will help identify the uncertainties and add insight. Discussing uncertainties always leads to an improved understanding of what is important for safety evaluation,
- The results from risk assessment provide a snapshot for a dam with the hazard (likelihood) and the consequences. The risk diagram can help to compare the safety of several dams with international acceptance criteria (Fig. 4).
- The risk assessment can easily be adjusted over the entire life of a dam (as risk changes with time).
- Many of the analysis methods are simple, e.g., risk matrix, event tree and fault tree analyses, bowtie analysis etc.
- The systematisation of uncertainties and expert advice is more manageable in reliability-based analyses than in conventional analyses.
- Risk concepts and terminology are an effective communication tool across different disciplines.

Risk assessment can present the following difficulties:

- A robust risk assessment, with a risk diagram, requires more work, time and resources than a conventional analysis alone.
- Some of the uncertainties and probabilities needed for a quantitative analysis can be difficult to evaluate. (However, the same uncertainties are found in the conventional analyses).
- The uncertainties and judgment required mean that the quantitative risk results are not exact, but give an approximate estimate of the 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.
- It is important to avoid complacency: Vick (2017) presented three case histories of failure or near failure of dams that used various risk-based procedures. For the three cases, the actual failure mode was recognized but disregarded. The 2017 Oroville Dam spillway incident is a recent additional example. Robust risk management was defeated by a "normalization of deviance", whereby departures from desirable conditions became accepted, imparting a false sense of security and complacency. The "normalization of deviance" (a potential hazardous event happening enough times without adverse effect until a former anomaly becomes the new norm).can be controlled by embedding risk-based thinking and processes in organizational culture. Improvements to dam safety evaluation processes must recognize this organizational risk. For example, ICOLD (2020) presents statistics where dam failure is attributed to organisational weaknesses.
- To have completed a risk assessment does not mean that the risk is satisfactorily managed. It is equally important to invest in an effective and sustainable management of the dam safety and involved risks.

There are also "false" drawbacks. Three aspects, reported as drawbacks are omnipresent in conventional analyses:

- Use of engineering judgment in risk-based analyses: yes, risk-based analysis uses experience and engineering judgment. However, a conventional analysis cannot be done without engineering judgment and experience either.
- Need for more knowledge on the dam: the same knowledge is required for both conventional and risk-based analyses.
- Need to update the risk assessment with time: the risk, just like a FS, do not remain the same during the dam's lifetime.

7 SUITABILITY OF RISK-BASED APPROACH FOR DAMS

Risk assessment is especially useful for dams in the following situations (non- exhaustive list):

- Dams which failure causes large consequences or cascading effects, e.g. where there is a risk of life loss or large societal costs, and where stakeholders need to demonstrate that a dam has an acceptable risk level.
- Dams where there are important or large uncertainties. Larger uncertainties always increase failure probability.
- Dams which experience behaviour changes or significant external loads change.
- Dams where efficacy and cost-effectiveness of various rehabilitation measures need to be compared.
- Dams in a portfolio to compare their safety margins and rank the urgency of rehabilitation.
- To establish emergency preparedness and response plans.

Experience with recent risk assessments of five dams in Norway illustrated the importance and variety of learnings from the process (Lacasse & Höeg 2019). For each, the risk assessment contributed to an increased insight in the dam safety:

Dravladalen Dam (Statkraft Energy AS): The failure mode screening and reliability assessment led to the identification of a so far unidentified, but significant, failure mode. Rehabilitation was required. The analyses documented the effect of rehabilitation on the failure probability. After rehabilitation, failure probability was shown to be lower or comparable to the international failure frequency of other dams worldwide.

Nyhellervatn Dam (E-CO Energy): The continuous leakage monitoring provided enough information to confirm no progression of internal erosion. The dam was seen as solid, robust and well-behaved. Consideration of the failure probability of the downstream slope documented that there was no need for rehabilitation, even if the conventional 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 more critical failure mechanism. The risk assessment showed that an optimal rehabilitation would be achieved if one planned for controlled overtopping of Saddle Dam 4 (with no life loss and much smaller consequences than the Main dam) under an extreme flood event. Discharge at Saddle Dam 4 reduced considerably the risk of a breach at the Main Dam.

Strandfossen Dam for Eidsiva Vannkraft AS: The risk assessment identified the most critical breach mechanisms and examined the effect of risk reduction measures. The analyses showed high annual failure probability, compared to other dams. The risk reduction measures were quickly implemented.

Viddalsvatn Dam for E-CO Energi: The now 50-year old dam had had 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 flood wave caused by a massive rock slide into the dam reservoir. The analyses quantified the risk reduction potential of five different rehabilitation schemes and documented that the most expensive measure was not necessarily the most risk-reducing one.

The geotechnical aspects of current dam design are rapidly being transformed by advances in instrumentation, real-time monitoring, remote sensing, and interpretation of data including machine learning, all supported by increased ability to model and interpret deformation and seepage regimes. This will lead to design procedures that overcome some of the conceptual limitations associated with the Factor of Safety concept and, by sequential history-matching of performance and implicit Bayesian updating, will result in a more reliable basis for projecting future performance. This can be described as a "performance-based risk-informed design process".

Morgenstern (2018) recommended, as part of reaching a target of zero failures for tailings dams, the development of Performance-Based, Risk-Informed, Safe Design, Construction, Operation and Closure (PBRISD). The approach requires integrated uncertainty assessment (e.g., geological model, hydrogeological model, geochemical model, geomechanical model, stability model), potential failure mode analysis, and risk analysis, risk assessment, quality management, transparent decision-making, and, none the least, appropriate documentation.

7.1 *Why is the profession hesitant to embrace risk assessment?*

Reasons, which are not considered valid, include:

- Dams are designed based on deterministic standards.
- There is no international consensus.
- Probabilistic methods are said to be too subjective, prone to error, too complex, too expensive and too lengthy to do.
- "If we know the risk, we need to do something about it, and how does one deal with the consequences?"

8 SUMMARY AND CONCLUSIONS

The purpose of risk assessment is to improve dam safety and risk management. Recent dam failures show that the profession can no longer avoid quantitative risk-based decision making. Quantitative risk-based dam safety decision-making provides a powerful means of not only identifying critical potential failure modes but also prioritizing how to address potential dam safety deficiencies in an objective, rational and cost effective manner.

Historically, dam safety has been ensured by applying a conventional a factor of safety as a way of reducing risk.

However, as society expects to be informed of the risk, the focus is shifting from dam safety to public safety, environmental safety and risk reduction. This is a significant shift, that should result in a more rapid and more cost-effective risk reduction.

France & Williams (2017) stated that risk analysis is fundamentally changing the landscape of dam safety in the US. The increasing use of risk analysis and risk-based considerations has resulted in the dam safety community openly recognizing the many ways a dam can fail and the consequences of those failures. Risk-based dam safety analysis has become holistic:

- Rather than evaluating a dam with limited, prescribed safety factors or other criteria, the potential ways a dam can fail are evaluated, and risk reduction measures can be implemented more effectively.
- Risk analysis is a tool for recognizing, understanding, and managing uncertainties and risks.
- The risks posed by a dam and its changes with time can be considered and taken care of.
- For a portfolio of dams, a risk assessment helps identify which dams and which specific failure modes cause the greatest risk. Available resources can then be allocated to more effectively reduce the risks.
- Risk analysis helps develop effective surveillance and monitoring programs and emergency response tuned to the key potential failure modes. Alternative solutions have become better informed by using a risk-informed process.
- Visual portrayals of risk for a dam or dam portfolio are effective communication tools for stakeholders and public.

The authors recommend that reliability index rather than failure probability be used in practice to estimate risk. Reliability index provides a positive connotation by referring to the reliability of a dam. Reliability is "*Fiabilité*" in French, which means "trustworthiness" or the "ability to be relied upon".

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