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OPTIMIZING TAILINGS DAM SAFETY: INTEGRATING HUMAN FACTORS AND EVOLVING HAZARDS

Franco Oboni[1]
SRK Consulting

Cesar Oboni[2]
SRK Consulting

ABSTRACT

The mining industry faces significant challenges in managing both inactive and active tailings storage facilities (TSFs), which vary widely in size, environmental parameters, and maintenance issues. Traditional risk assessment methods for TSFs often rely on incomplete and inconsistent historical data, leading to potential misclassifications and a false sense of security. This paper introduces a comprehensive quantitative risk assessment model for TSFs that addresses these limitations by incorporating human factors and evolving risks due to maintenance, operations, and climate change. The model leverages a probabilistic causality analysis to evaluate the failure processes of tailings dams, emphasizing the importance of human factors over natural events in determining failure probabilities. By analyzing a global portfolio of dams, the model provides a robust framework for assessing and mitigating risks, offering practical insights into the effectiveness of various mitigation strategies. Comparative analyses of three similar dams—categorized as “The Good, Bad, and Ugly”—demonstrate the model's capability to differentiate risk levels based on care and understanding in design, construction, and maintenance. The paper also explores the potential for preparing scripts to study mitigative alternatives, such as buttress construction or less significant ones, and discusses the application of ALARP (As Low As Reasonably Practicable) analyses in optimizing risk management. This work aims to enhance the reliability and safety of TSFs by providing a more accurate and holistic approach to risk assessment.

Keywords: Tailings Storage Facilities (TSFs), Quantitative Risk Assessment, Probabilistic Causality Analysis, Human Factors, ALARP (As Low As Reasonably Practicable)

[1]foboni@srk.com, Canada
[2]coboni@srk.com, Canada

1. INTRODUCTION

The Mining industry deals with thousands of inactive/closed heritage storage facilities and a significantly smaller number of modern active/inactive ones. The size of the facilities is extremely variable, both in terms of volume, height, length and shapes without even mentioning major “environmental” parameters such as geology, hydrogeology, seismicity, climate, topography and land use (especially downstream). In addition maintenance issues, in particular but not limited to water management subsystems further complicate any attempt to define a “simple” taxonomy of TSFs.

Despite numerous efforts by several institutions and authors [1], [2], [3], [4], [5], and [6] it appears that:

- data are incomplete and present very significant gaps,
- records do not deliver enough details to elicit proper taxonomies,
- causality/failure mode classification are inhomogeneous and doubtful to say the least with significant percentages of “unknown” cases.

As a result, when extracting information from these databases there still is a clear hazard of reaching fuzzy results due to the mixing of different populations of dams and past accidents.

On the risk assessment front, practitioners, including the authors of this paper, have dealt with single dams using various approaches going from qualitative to semi-quantitative, semi-empirical and quantitative [7]. Many of these approaches deal separately for each failure mode (stability, internal erosion, seismic, etc.) and adopt mono-dimensional consequences evaluations, which are misleading. Indeed, the accidents consequences are the sum of dimensions such as harm to people, environmental damages, business interruption, direct and indirect losses, third parties losses, etc. and neither the worst of one of these dimensions, nor merely harm to people as some guidelines suggest. In 2014 a MSc Thesis at UBC [8] linked various failure modes using a well-known reliability formula known as the series-system equation, which assumes the various failure modes were totally independent from each other, and each failure mode occurrence could be fatal to the structure. Following the same idea the US Federal Energy Regulatory Commission [9] states that failure modes should be combined by summation of their probabilities, an approximation of the series-system equation result only valid if the probabilities are all very small (NB: if that is not the case the sum could become greater than one, which is against the basic axiom of probabilities).

Only in the last years the idea of portfolio risk assessment has been pushed forward [10]. In this paper we describe how we built a general model for TSF risk assessment which allowed to develop a “world model” covering to date more than hundred tailings dams of various types, age and built, which apparently mimics the behavior of the world-wide tailings dams portfolio.

2. DRIVING CONCEPTS

Linking specific types of failures to a potential failure mode or cause taxonomy is challenging because only a few failures might fit into a category of that taxonomy. For example, as demonstrated in [11], the "Failure distribution by cause" shows a small sample size. Similarly, the "Failure distribution by dam height" also has a limited sample size. When we try to analyze correlations, such as "Failure distribution by cause" given a certain dam height, the sample size becomes so small that one ends up with either a single case or no case at all.

From a risk point of view, i.e. when consequences of failures are included, risk is constantly evolving in both directions: probabilities (quality of design, evolving standard of care, lack of maintenance, operations, climate change, etc.) and consequences (demographic pressure, land use, public opinion, legal, etc.).

2.1. Databases may be misleading and give a false sense of security

The above always made us uneasy about blindly relying on historical data, but one should take advantage of extant data, after careful considerations of the limitations stated earlier.

Furthermore the goal of the approach was to provide simple, deconvoluted probabilities estimates of single “basic events/situations” and not “failure mode” range, to avoid confusing the users. The approach also had to stay as close as possible to “standard engineering” understanding of the very convoluted issues that may arise in dams quantitative risk assessment, as it will be discussed in the following sections.

2.2. Past different than future

In addition, it was understood that using databases without any checks would likely lead to neglect three important points, namely that:

- the quality of dams, especially the most modern “big” ones has improved over time,
- over time ancillary water management facilities may have deteriorated, as maintenance and design deviations may have developed,
- climate change will make the statement “past different from future” even more true than it is today [12].

2.3. Human factors do not show up in databases

Furthermore, it must be considered that traditional databases were not prepared with a "human factor" focus, whereas, based on numerous examples of catastrophic failures we were inclined to think that these were paramount to explain why a world portfolio of dams generally designed with the same FoS generated enough failures to stir public opinion (and regulatory/ political) outcry**.** That is why we started looking at the human factors first, followed by all the other hazards, root causes and elements/sub elements discussions.

3. FAILURE CHAIN PROCESS DRIVEN BY HUMAN CAUSES

Dams failure processes, which included "soft" root causes were studied [13]. A systemic approach of the "failure chain process" of tailings dams using a probabilistic causality analysis based on publicly available incident and accidents data from the last 60 years was presented after considering valid the particular use of the database made as it looked at very specific aspects of the failure process. Citing directly [13]: "The predictive model, geared toward filling the gap between common practice and "path to zero failures" requirements (as "requested" in the aftermath of major failures), accommodates data-mining analytics. The model "constructs" the probability of failure of a dam which is consistent with factual historical world-data. The causality of various factors entering in the dam's service life can then be individually discussed with a sensitivity analysis." Then the 2016 paper [13] showed where and how mitigative actions can benefit the most with a practical example. Attention was focused on Common Cause Failure (CCF) in operations, risk assessment, peer reviewing and inspections of tailings dams during the service life of dams. Investigations, Design and Construction extended to Management, Monitoring & Water Balance control of the dam (shortened to e-IDC in [13]) were analyzed with a probabilistic causality analysis based on publicly available incident and accidents data from the last hundred years. It was noted that a significant number of risk studies do not start with the considered tailings system definition, its functional analysis, and they oftentimes confuse hazards, risks and consequences [14] leading to misleading results. For instance it was noted: "it is for example rather common to see "insufficient FoS" considered as a hazard (or a risk), whereas such deficiencies are generally the result of deliberate human choices (excessive audacity, errors and omissions, insufficient efforts)".

The 2016 paper [13] therefore took a rather extreme, but logical line of thinking, stating that dams' failures find, in the vast majority, their root-causes in human choices and not in natural events. At the center of this reasoning there is the concept of credibility threshold. Many industries consider the limit of credibility at around 1/100,000 to 1/1,000,000 (10^{-5} to 10^{-6}) [15], [16], [17], [18] so it can be stated that any event above that limit is not an "Act of God" (or, following modern times buzz-words a "Black Swan") and should be therefore foreseen/

planned for. It was also noted that, reportedly, most dam failures have occurred for other causes than "Black Swan" natural events, but again for "chains" of gradual deviances, which become "normalized" over time, stemming from investigations, design, construction, management and long-term monitoring.

For the e-IDC four different functions (Geotechnical Investigations, Engineering, Construction, Management (including Water balance), Monitoring) constituting the chain of elements responsible for success/failure of a dam were identified. A "causalities network" was built as shown in Figure 1 using the same concept of a Bayesian network.

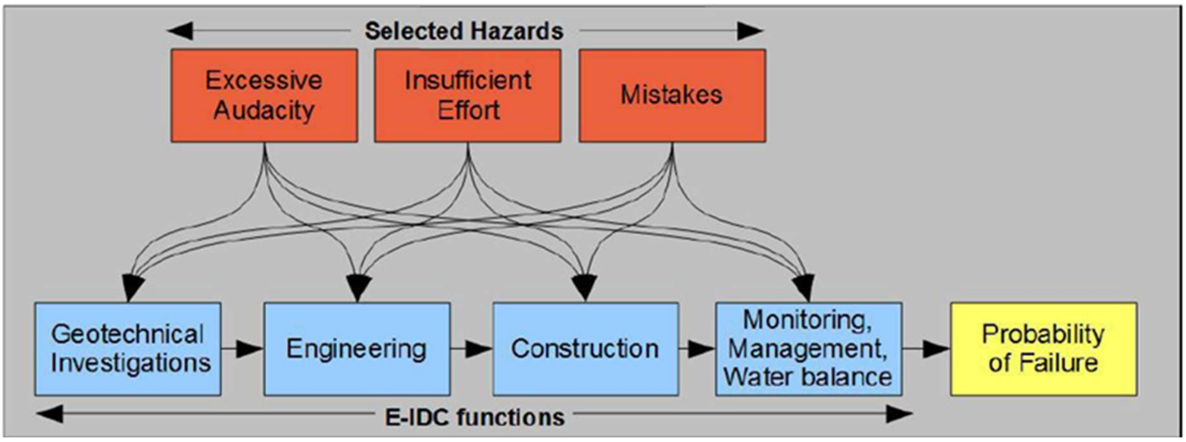


Fig. 1 – Functional scheme of the e-IDC with the hazards selected (Oboni, Oboni, 2016)

Various hazards (root causes) are lurking on each element of Figure 1 such as, in the specific approach adopted in that paper: Insufficient effort, Mistakes, Excessive Audacity, etc. leading to a probability of failure PoF for each element evaluated using a reliability model. Of course, the list of selected hazards should be discussed project by project. Failure modes previously identified in the literature, for instance ICOLD [19]) and from a 1910-2009 compilation [11] due to the selected hazards were selected as:

- Slope Instability,
- Earthquake and Mine Subsidence,
- Overtopping,
- Foundation,
- Seepage and Structural.

In Table 1, the rater wide difference in the percentage split of causality is due to the databases poor quality, requiring the study to proceed with a range rather than a single value to include uncertainties.

Table 1 –Attributed Causality Scenario stemming from project inception based on ICOLD and world-wide 1910-2009 data. NB: data had to be reorganized to comply with the selected taxonomy [13].

	ICOLD		World-wide 1910-2009 data	
Attributed Causality Scenario	Recorded failures	Failures in %	Recorded failures	Failures in %
Poor investigation	9	13	12	13
Engineering error & omission, excessive audacity	44	63	32	35
Poor Construction	17	24	48	52
Total	70	100	92	100

Two possible types of mitigations M1, M2 were then considered [13] , for the sake of an example. Their implementation was assumed to occur during the e-IDC development:

- M1: Engineering performance can be enhanced with an independent peer review (including sensible risk based decision-making procedures and risk assessment from project inception). Engineering and Peer Review become a parallel subsystem, possibly fraught by Common Cause Failure (CCF).
- M2: Monitoring, Management, Water balance function can be enhanced with Inspections paired to sensible risk based decision-making procedures and risk assessment from project inception.

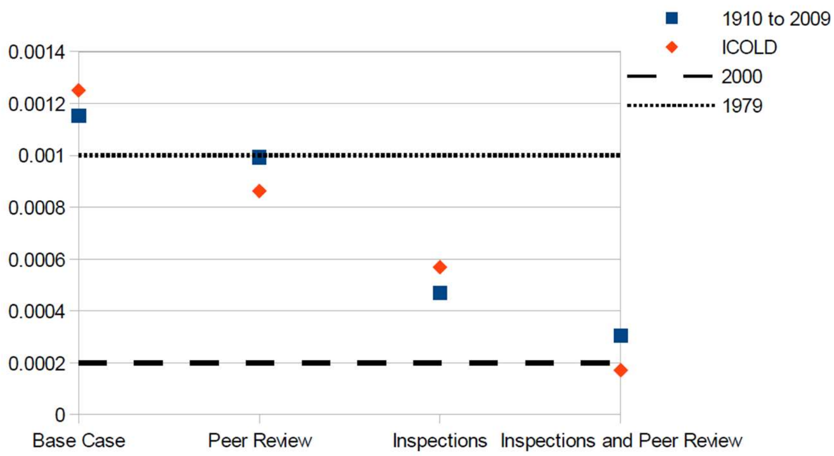


Fig. 2 – Results of the annual probability of failures derived from the model for mitigation level A,B,C,D including attributed causalities (Table 2, 3) derived from factual data (Fig. 2, 3). NB: numbering of Tables and Figures refer to the original paper [13].

Again CCF has nefarious potential on this additional parallel subsystem. Adopting a very simplified approach to CCF it was possible to assume that insufficient rigor, complacency, conflict of interest, common excessive audacious approach in M1, M2 could reduce the expected positive result of any mitigation to nil. Four levels of mitigation were studied.

As it can be seen from Figure 2 the paper concluded that a dam sporting a probability of failure PoF of 10^{-3} could see it reduced to $2*10^{-4}$ by simply adding rigorous and unbiased peer-review and detailed inspections with swift follow-up without any changes to its geomechanical FoS or geomechanically derived PoF. Obviously this result was and is generic and should be integrated with all the dam-specific details of a candidate dam to be risk assessed: the devil is indeed always in the details!

Based on the above and more experiences made in risk analyses, a number of features aiming at describing the "devils" were introduced in the methodology. A summary is delivered in the next section.

4. ROOT CAUSES, UNDERLYING HAZARDS, MEASURES, PARENT-OF SUMMARY

A list of root causes (leftmost two columns) that appeared to cover the set of world-wide dams studied to date was introduced. The list is of course subject to changes in the future but represents in our eyes the minimum set that is absolutely necessary to deliver an image of the risks generated by a tailings dam.

As it can be seen in table 2, there are many hazards that cover the entire system, and many common "parents" within the system. Indeed governance, human errors and other "soft issues" have ubiquitous effects on a dam system and become "parents" to other hazards within the considered system. These constitute the Key Performance Indicators of the dam (KPIs).

Table 2 – Summary of Root Causes, Deficiencies, and Causalities in Tailings Dam Failures

Hazard & Deficiencies	Measurable as	Applies to...	Parent to...	Participates to...
Poor quality/documentation	Probability	Foundation, dam body	Foundation	All stability failures: ESA, USA, seismic, residual/liquefaction
Poor quality, excessive audacity	Probability	Foundation, dam body, dam crown	Dam body	ESA, USA, seismic, residual/ liquefaction, internal erosion
Poor geotechnical, hydrological understanding	FoSs probabilities	Foundation, water table, dam materials	Dam body	PoF for ESA, USA, seismic, residual/ liquefaction
Poor quality/documentation (Construction)	Probability	All dam system elements	Dam body, d/s face	All stability failures, erosion of D/S face

Poor quality/deficient analyses	Probability	All dam system elements	Dam body	All stability failures: ESA, USA, seismic, residual/ liquefaction
Poor quality/documentation /operations	Probability	All dam system elements	Dam body, water manage-ment	All stability failures: ESA, USA, seismic, residual/ liquefaction
Supernatant pond (engineering deficiencies)	Anomalies	Dam body, dam crown	Dam body	Overtopping failure, oversteepening
River at toe (hydraulics/climate change)	Erosion	Dam body	Dam body	“Wet” stability failure
Weir/spillway (operational deficiencies)	Mainte-nance	Dam d/s slope	D/s face	Overtopping failure
Penstock/gallery (operational deficiencies)	Mainte-nance	Dam internal structure	Dam body	Overtopping, internal erosion
Diversion ditches (operational deficiencies)	Mainte-nance	Dam crown	D/s face	Overtopping failure, catastrophic
Pipeline at crest (operational deficiencies)	Mainte-nance	Dam crown	Dam d/s face	Erosion, stability failure
Active/Inactive deposition (human error)	Aggrava-tion	Dam body	Dam body	Static liqu./ residual failure
Heavy equipment vibrations (human error)	Vibrations	Dam body, dam toe	Dam body	Static liqu./ residual failure
Blasting operations (human error)	Vibrations	Dam body, dam toe	Dam body	Static liqu./ residual failure
Exceedance of piezometric levels (human error)	Piezo-metric	Dam body, dam toe	Dam body	Static liqu./residual failure
Pre-existing weak layer (geology/geomor-phology)	Pmin-Pmax	Foundation	Dam body	All stability failures
Pre-existing landslide (geology/geomor-phology)	Pmin-Pmax	Foundation	Dam body	All stability failures

Footnotes:

1. ESA: Effective stress Stability Analysis
2. USA: Undrained Stability Analysis
3. Pmin Pmax: Probability min., max.4. d/s: Downstream
4. FoS: Factor of Safety

5. EVALUATION WORKFLOW

The methodology's compact algorithm is a quantitative semi-empirical approach.

The various hazards, elements constituting the homogeneous dam system to be evaluated are combined following the logic described in table 2, organized in such a way to reduce redundant calculations and to avoid double counting. This leads to results that have been shown to match, to date, the world-wide portfolio behavior. Human factors and governance issues are of course built-in together with other paramount details.

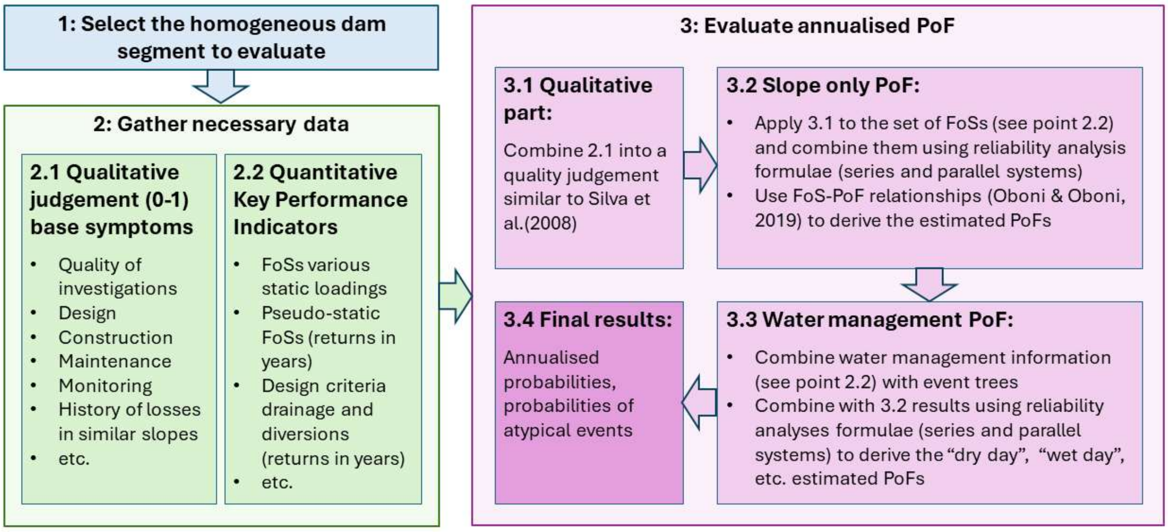


Fig. 3 –. Systemic probability evaluation workflow

As we will see later, this workflow makes it possible to establish pre-set values of families of underlying hazards to deliver a priori orders of magnitude of dams probabilities of failure, guide new users as shown in the example of "The Good, Bad and Ugly" dam below.

Also, as discussed later it is possible to prepare "scripts" guiding the formulation of what-if scenarios for mitigations such as for instance buttresses, as shown in the last section of this paper.

6. COMPARATIVE ANALYSIS OF THREE SIMILAR DAMS

6.1. Dams description: The Good, Bad and Ugly

In this section we focus on the comparative analysis of three active, centerline dams, bearing a main tailings distribution line, designed with the same FoS stability criteria:

- FoS drained (ESA): 1.4-1.6
- FoS undrained (USA): 1.3-1.4
- FoS pseudostatic : 1.2 for return =10,000 and 1.3 for return= 2,475

The three dams are under the same climatic conditions, with no water course at the toe. They have berms on the downstream face to control face erosion and are built with selected materials, well-engineered rockfill/earth fill, and a clay core with drainage blanket.

Table 3 – Example of the good, the bad, the ugly, to show the impact on the results using the methodology described in Figure 3.

The good	The bad	The ugly
Top of the line care for investigation, design, testing, construction, water balance return of anomalies 200yrs, excellent analysis. Excellent water management: weir (1:10000), diversion ditches (1:1000), no penstock, Pipeline at crest well protected (1:1000). Conventional monitoring and maintenance, inspections and reviews. No deviances from original design, no defects. Water levels under control. No liquefaction suspicions, no pre-existing slopes movements.	Average care/understanding for investigation, design, testing, construction, water balance is fair, same return (200yrs), Fair water management: weir (1:10000), diversion ditches (1:1000), no penstock, Pipeline at crest fairly protected (1:1000) All KPIs ok, also from the understanding point of view, but not excellent: Conventional monitoring and maintenance, inspections and reviews. No deviances from original design, no defects. Water levels under control. No liquefaction suspicions, no pre-existing slopes movements.	Poor care/poor understanding for investigation, design, testing, construction, water balance is poor, same return (200yrs), Poor water management: weir (1:10000), diversion ditches (1:1000), no penstock, Pipeline at crest poorly protected (1:1000) All KPIs below standards/poorly understood. Conventional monitoring and maintenance, inspections and reviews. No deviances from original design, no defects. Water levels under control. No liquefaction suspicions, no pre-existing slopes movements.

6.2. Comparative results (Good→Bad→Ugly)

As shown in Figure 4, the “good” dam lies at the bottom of the world-wide benchmark range, the “bad” dam at the top of the same range and finally the “ugly” is above the benchmark upper bound [20].

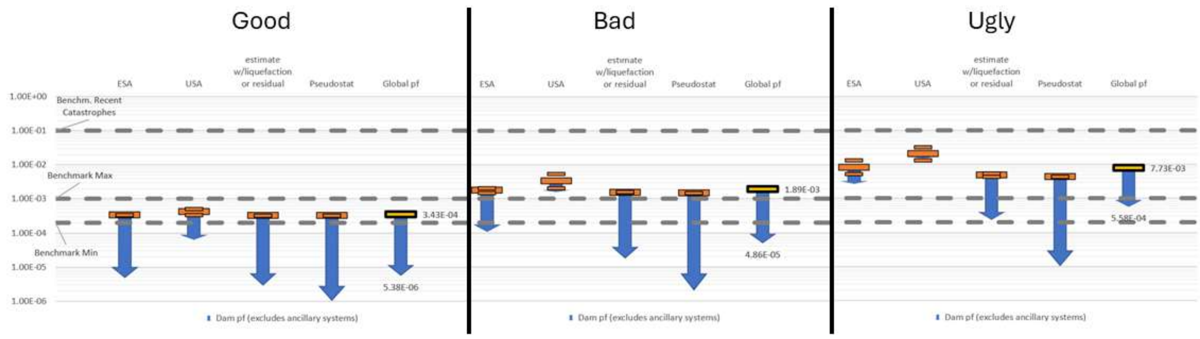


Fig. 4 – Estimated annualized probabilities of failure

It is interesting to compare the composite scenarios (Table 4, sunny day, extreme rain, etc.) among the three dams. as well as the relative causalities (Table 5). Note that the causalities are relative values and always add up to 100% by definition.

Table 4 – The good, bad and ugly failure mode and annualized PoF.

	Annualized PoF		
Failure Mode”	The good	The bad	The ugly
Sunny day	4.70E-06	4.86E-06	5.58E-04
WET day no AWTM failure	1.74E-05	4.07E-04	6.43E-03
Extreme rain event	3.65E-04	2.26E-03	1.00E-02
Quake<MCE	3.18E-04	1.45E-03	4.36E-03
MCE quake	3.18E-04	1.45E-03	4.36E-03
Liq stat/res	3.22E-04	1.53E-03	4.91E-03

Table 5 –Main causalities per dam.

Area	Themes/ comments	Good	Bad	Ugly
Investigations	Sampling; insitu testing; on site vane; soil classification, lab testing (shear, triaxial and oedometers)	24%	28%	28%
Design	Boreholes depth, density, trenches; cross section material; cross section type; berms & erosion control; project depth of analysis & detail; as built plans, alterations plans; stability analyses reasonableness	51%	42%	42%
Construction	Construction supervision; divergence from plans; known errors and omissions.	5%	5%	10%
Oper. Mon. Inspec., maint. & repairs	Deformations; pore pressure; operations and maintenance; inspections and review; repaired defects/damages	20%	20%	20%

In the good dam the “design” causality leads with 51%, Investigation 24%, Construction 5% and Inspections, monitoring and maintenance are at 20%. This last value does not change for the bad and the ugly, because the other factors variations are more significant in the specific case. Indeed, in the Bad and the Ugly dams investigation grows to 28%, while design reduces to 42% (because there are many factors of ignorance that impact the other key performance indicators). Hence Investigations and construction increase respectively to 28% and 10%.

7. PREPARING SCRIPTS TO STUDY MITIGATIVE ALTERNATIVES

7.1. Example for an existing inactive dam undergoing a possible buttress construction.

In this section we examine which data would change if a buttress were built at a dam, leading to the possibility of preparing a script for buttress mitigation.

Indeed, a number of dam's data will be better due to the studies to undertake to design the buttress and the enhanced stability conditions. Operations, maintenance, monitoring etc. should also improve.

For instance it can be assumed that the buttress would be based on enhanced geological and geotechnical understanding, selected materials, new stability analyses, deformations analyses and would be monitored under a well-designed inspections schedule and oversight by a competent EoR and independent review board.

This exercise has been conducted in various real-life cases and, as shown in the next sections has led to the evaluation of the ALARP level in cooperation with the EoR and the owner.

7.2. Other possible scripts

There are no limitations to the scripts that could be written to facilitate new users and quick scenario building for single dams, and even portfolios.

It appears that a good approach could be to develop three identical scripts per scenario, offering a good-bad-ugly set of alternatives to pick from.

The user would then:

a) Decide is the dam belongs to the "good-bad-ugly" quality category to start with

b) Insert the "as is" set of factors of safety delivered by the engineers for the dam.

c) Run as many scripts as needed to test alternative mitigations on the dam, including alternatives that may provoke a "jump" of quality category.

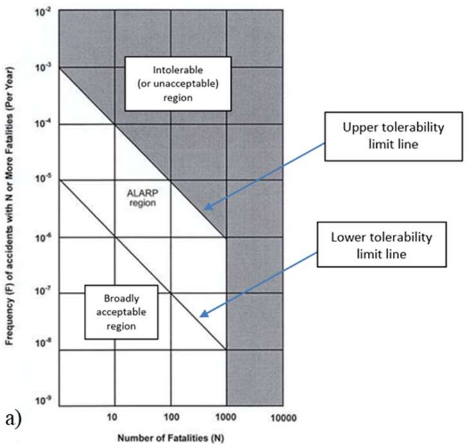
7.3. ALARP analyses

Several examples of ALARP (As Low as Reasonably Practicable) quantitative analyses have been published to date [21] including a development [22] that looks at the evolution of ALARP over time. Indeed, defining the ALARP should not be seen as a static process, as it has to encompass various time horizons along the life of a project/facility. Short term ALARP mitigation level may indeed be very different from the long term one due to different uncertainties, changing system conditions and external evolution, such as for example land use around the considered facility which will require adaptation.

The term ALARP is present in various guidelines, such as the Canadian Dam Association (CDA), the Mining Association of Canada (MAC), and the Australian National Committee on Large Dams (ANCOLD), as well as in GISTM/ICMM. In some older literature ALARP was defined as a probability level linked to harm to people; then it was defined as the trade-off equilibrium between risk mitigation costs and risk reduction. This has unfortunately introduced confusion among users and even regulators, oftentimes stemming precisely from the evolution of the definition (see Figures 5, 6 for an example). Let's note that ALARP should not be confused with tolerance thresholds. Indeed both the tolerability of the risk generated by a dam as well as its mitigation level reaching ALARP should be demonstrated.

In its most modern definition ALARP is reached when it is possible to demonstrate disproportion between mitigative cost and the risk-benefit gained.

Being able to demonstrate ALARP status, is paramount to various stakeholders such as owners, Engineer of Record (EoR), insurers, lenders, regulators and finally the public.



a)

Fig. 5 –. Generic harm to people tolerance also called f-N curve. This curve features an obsolete definitions of ALARP.

b)

Fig. 6 –. ICMM 2021's Concept of assessing benefit of mitigation effort to residual risks with ALARP at trade-off point, called LMALARP [22].

To evaluate the ALARP level of a structure mitigation measures proposed by the EoR with input from the TSF's owner and his technical Team must be used. Each proposed mitigation measure must be cost evaluated by the engineers/EoR, and then their effect on the dam system risks must be analyzed. This process requires constant interaction between the EoR, the technical Team and the risk assessment team following the steps below:

- The EoR proposes mitigation measures.
- The risk analysis team possibly makes other mitigation proposals.
- The mitigations are discussed and checked for constructability and possible sequence (say minimum 3 alternatives, max 6).
- The risk analysis team generates the PoFs of the mitigation alternatives.

Using the results of the previous step, the EoR and the technical team will then rank the mitigation measures by increasing risk mitigation effectiveness and cost, allowing to evaluate the minimum ALARP mitigation level (see Figure 6), i.e. the level that corresponds to the "equilibrium" between risk reduction and mitigative cost.

Figure 7 displays the ranking of various composite mitigation actions sorted by decreasing probability of failure of a real-life dam. Once the results of Figure 7 are available, the risk analysis team builds point by point (that is 3 to 6, depending on how many alternatives were selected) the risk vs. mitigative cost curves and evaluates the minimum ALARP, that is the trade-off point of Figure 6. Figure 8 displays an example of Risk reduction vs. CAPEX graph for the real-life dam discussed in Figure 7. In this example the minimum ALARP is therefore located at the completion of the "erosion protection" mitigation task and the final ALARP will be located to the right of that level.

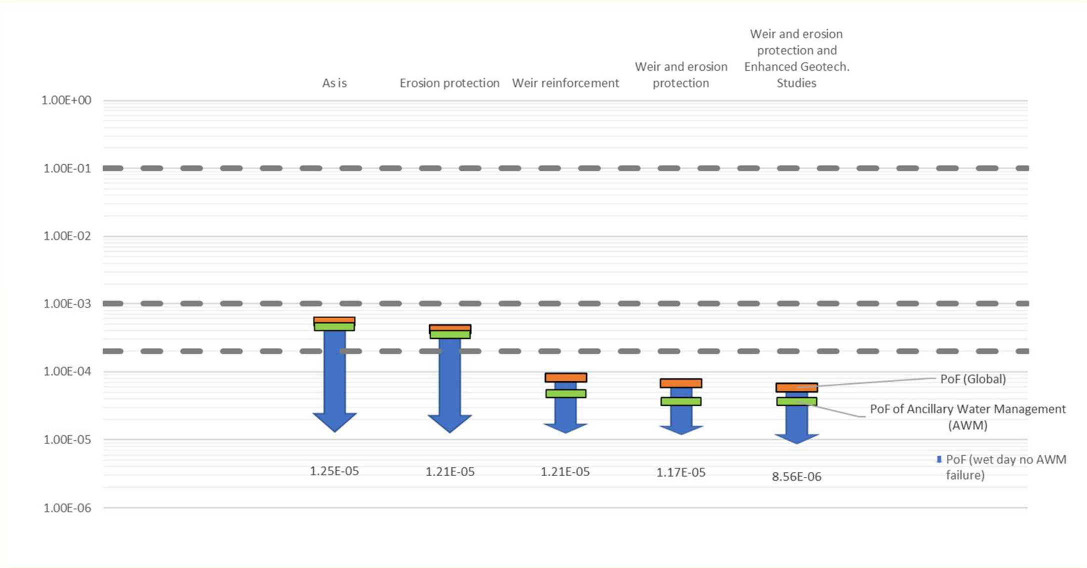


Fig. 7 –. Reduction of the PoF as a function of the chain of mitigations starting from "as is" state.

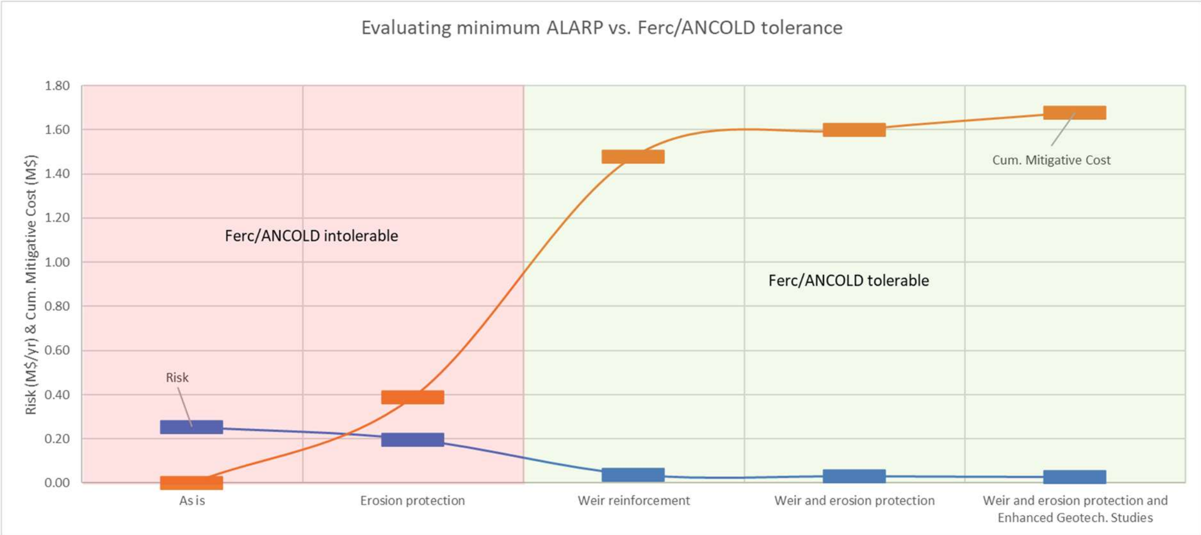


Fig. 8 –. Finding the "minimum ALARP" (intersection of the risk reduction (blue curve) vs. mitigative investment (orange curve). The pink area corresponds in this example to mitigation levels that are still intolerable from the harm to people point of view, i.e. FERC/ANCOLD intolerable.

It is paramount to remember that, as it is expected that all mitigations may have side-effects, these should be carefully studied before the final decisions are made.

The ALARP process, as described above, is iterative and demands a nuanced evaluation that balances risk reduction and constructability with cost considerations. By systematically analyzing each mitigation's effectiveness and cost impact, the process ensures that the selected level of mitigation is both economically viable and aligned with safety objectives. As already mentioned, this approach allows stakeholders—owners, engineers, and regulatory bodies alike—to make informed, responsible decisions regarding dam safety. The model's flexibility in adapting to new mitigation measures and evolving risk thresholds underscores its value in TSF management, providing a structured yet adaptable framework that upholds safety as system conditions change. The resulting ALARP assessment, when conducted transparently and in collaboration with the EoR and risk analysis teams, strengthens the decision-making process and facilitates an approach that is both justifiable and resilient over time.

8. CONCLUSIONS

This paper presents a quantitative approach to tailings storage facilities risk assessment that integrates evolving hazards and human factors, bridging gaps left by traditional methodologies. The probabilistic causality model described in this paper quantitatively demonstrates the central role of human factors, underscoring how design choices, maintenance practices, and operational decisions influence risk in some cases more significantly than natural events alone. The comparative analysis of three dam cases – "Good," "Bad," and "Ugly" – highlights the robustness of the model in differentiating risk levels and in guiding practical mitigations. Indeed, the model effectively demonstrates its capacity to differentiate hazard and hence risk levels based on real-world operational variables.

By enabling tailored risk assessment scripts and scenario planning, this approach offers a replicable framework that can support TSF owners, engineers, and stakeholders in pursuing a risk-informed strategy toward enhancing dam safety and resilience. The model not only contributes to a more nuanced understanding of TSF risks but also aids decision-making, offering pathways toward achieving safety standards that align with public, regulatory, and environmental expectations.

The implementation of ALARP concepts using the presented model further enhances its utility, offering a structured approach to evaluate and balance risk mitigation efforts against practical constraints and costs. This adaptability is a key contribution, as it enables decision-makers to apply the model in diverse scenarios, from new project planning to the assessment of existing facilities. The capability to perform quick scenario planning is essential for identifying effective risk mitigation strategies, particularly as TSF operations face increased scrutiny and evolving regulatory demands.

Beyond immediate applications, the model paves the way for future improvements in TSF safety, emphasizing the importance of continuous monitoring and adaptation as conditions change over time. This dynamic approach to risk assessment aligns with the growing need for sustainable practices and resilient infrastructure, particularly as climate change and demographic shifts alter the environmental and social context in which TSFs operate. By integrating this advanced risk model, practitioners can achieve a comprehensive understanding of risk factors and proactively manage uncertainties, thereby supporting TSF safety goals that are responsive to both public and environmental concerns.

This work not only provides a more reliable method for assessing TSF risks but also lays a foundation for further research into the role of human factors and complex causality in industrial safety. By advancing these insights, the paper contributes to the development of TSF risk management practices that better meet the expectations of regulators, insurers, and communities, ultimately fostering a path toward safer and more sustainable dam operations globally.

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