A Case Study on ALARP Optimization

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ABSTRACT

The risks potentially generated by tailings dams are produced by the combination of probability of failure and consequences. From inception of the design, mitigations and monitoring plans are implemented and followed through as required throughout the life and toward closure. GISTM indicates an ALARP objective for mitigation.

This paper uses an anonymized case to show how a dam's probability of failure and risks evolve with its raising. The search for the ALARP risk level is explicitly discussed for a specific dam elevation.

At the moment of the first evaluation a certain crest level had been reached and several more raises were to be analysed. Thus, the assessment was part backward looking and part predictive.

To support the ALARP mitigation roadmaps, the implemented mitigations, dam raise, and monitoring effects were systematically tested in comparison to the world-wide failures rate benchmark. This helped understanding where the mitigation sweet spot was at any given stage, and where the dam stood compared to other structures, testing, monitoring, and other human factors.

The causality of the potential failures at each stage, a conceptual broadening of the usual "failure-modes" reasoning (how the dam fails) to the "causes" (why the dam fails) proved to be an extremely valuable criterion.

At the end of the day the owner and his EoR had a clear understanding of how their past decisions had influenced the evolution of the probability of failure of the considered dam system and had clear decision-making support for the future stages

INTRODUCTION

Tailings dams quantitative risk assessments should rely on proper evaluation of consequences and probabilities. The goal is to be able to economically and swiftly prioritize a portfolio of dams enabling risk informed decision making for mitigation. During the development of the study presented herein it was decided it would be extremely interesting to show the variation of the probability of failure p_f of the main dam at different crest levels, thus both looking backward to past crest levels and forward to future ones. The concept of assessing benefit of mitigation effort, residual risks, ALARP are closely linked. Indeed, GISTM Requirement 4.7 clearly states the need for risk informed decision making for existing structures. Additionally it requires reaching an ALARP level. We consider that showing the ALARP value as a range with the theoretical at its minimum helps conveying the idea that tailings systems are complex and surrounded by uncertainties and covers stakeholders' anxiety. Furthermore we consider the ICMM guidance (ICMM, 2021) figure 9 (reproduced below Fig.1) is misleading, especially since such a graph cannot be built using "qualitative categories" of risk and resources.

Figure 1 ICMM 2021's Concept of assessing benefit of mitigation effort to residual risks with ALARP

To ensure repeatability and transparency we consider these analyses are feasible only with quantitative risk assessment (QRA) approaches. Fortunately, these are one of the two possible means considered by the ICMM document. Indeed, the other alternative, i.e. a semi-quantitative FMEA does not offer the same level of resolution, repeatability and transparency. Furthermore, especially for owners of large portfolios, semi-quantitative FMEA would lead to paralysis by analysis, excessive costs and deter users from regular updates. Our QRA is compatible with preliminary evaluations and has been proven and tested with respect to standard approaches. It is thus possible to prioritize any portfolio economically and swiftly in terms of probability of rupture.

CASE STORY

The dam cross-section is a downstream construction with a central low permeability core and a vertical filter/drain upstream of a fill made of selected waste rock. The TSF construction came after a detailed design based on a series of geological and geotechnical studies, with a detailed site and laboratory tests, including many boreholes which entered the basal soil/rock mass for tens of meters. During these studies some critical conditions were highlighted on the valley sides which would then progressively be covered by the dam, such as pre-existing instabilities.

The initial design was constantly updated in terms of dam stability and site investigation. The design documents included drained (ESA), undrained (USA) and pseudostatic analyses. No liquefaction analysis was performed as the materials were considered as non-liquefiable. The ancillary water management facilities include diversion channels and a spillway. The TSF was designed to completely contain storm events and longer duration wet periods up to an average return interval of 1 in 100 years 72-hour event. The dam was well monitored from inception, the monitoring mainly aiming at detecting displacements and pore pressure variations. The number of instruments varied over time given the replacements of broken units, the addition of new ones. The tailings are disposed via a large diameter HDPE pipe which runs on the upstream face of the dam, around 1-1.5m from the crest road. The pipe is positioned in such a way that any spill would be directed towards the tailings. Spigotting is performed following a well-established pattern. The ground monitoring is completed by a series of visual inspections of the dam, carried out at regular intervals by the mine personnel and by the designer. These and the analysis of monitoring data lead to corrective measures that were swiftly proposed and enforced. Based on the last available reports these included instruments replacement, increased reading frequency, change of operations in the construction process, etc. The TSF is classified as extreme by GISTM. A dam break study was conducted assuming different scenarios in terms of modes of failure and water content of the failed material. As a result, the study looked at the evolution of the p_f alone as there was only one dam in the portfolio. However, later it appeared that the simplistic GISTM consequence classification was not enough to enable GISTM's own requirements, such as ALARP. Indeed, GISTM define ALARP as a function of tolerance and/or acceptability and those concepts are indissociable from quantitative probabilities and consequences.

Dam success/failure

Reliability is achieved if the p_f is reduced to a certain level, and risks are tolerable or ALARP. Thus it is necessary to clearly state what is considered a successful structure. Indeed, unless success is clearly defined, failure remains an ambiguous term (Adams, 2015). Our study considered the dam successful if: i) it stands as built and does not break allowing for catastrophic tailings release in static and pseudo static (residual) conditions; ii) it features slow "stable" deformations without evolving into condition i) above, due to excessive strain; iii) it does not develop ancillary water management issues potentially leading to the appearance of severe damages, possibly evolving into a catastrophic release (overtopping, scouring, toe erosion, sloughing) perhaps involving liquefaction or residual strength failures.

The nemesis of success is failure, expressed p_f. Failure can occur because of hazards, threats and conditions that are the causes of the failure. As risk assessors we focus on the causes of failure, whereas a designer would normally focus on the modes of failure (Failure Modes) which describe how a failure occurs. This point was brilliantly made by Terry Eldrige (Golder) during his Keynote Lecture at TMW2019. By knowing how a failure occurs, i.e. their causality, the designer can develop countermeasures. By exploring the causality together with the risks, we can guide decisions on where and how to mitigate dam risks.

Causality and probability of failure

The failure causality analysis was performed following a methodology similar to (Oboni 2016).

Table 1 Dam body failures causality analysis valid for all the considered crest elevations

Estimate	Construction	Investigations	Geomechanical Testing	Analyses & documenttation	Operations Monitoring & Maintenance	Total causality [%]
Worst	19%	18%	21%	23%	21%	
Best	18%	17%	20%	22%	21%	
Average	19%	18%	21%	23%	21%	100%

Our dam QRA specific approach has been the object of numerous publications (Oboni 2016, 2017, 2020). It uses "symptoms" or key performance/risk indicators (KPIs, KRIs) in the history of the dam from inception to the day of the evaluation to deliver a set of probabilities of failure of the dam (see Table 2). The over thirty KPIs/KRIs consider the dam system, i.e. includes ancillary water management systems, such as diversions, spillways; pipelines; traffic in the p_f evaluations. The KPIs/KRIs are mathematically combined to deliver an estimate of the p_f, including uncertainties on the knowledge base. Table 1 displays the ORE2_Tailings™ dam body causality factors which always add to 100% for the dam body. These causalities do not consider the ancillary water management, decants, etc., the factors of safety values (but the completeness of the analyses of the dam developed to date) which enter later in the evaluation of the dam system p_f. The causality families we are evaluating are construction; investigations; geomechanical testing; analyses and documentation; and finally operations, monitoring & maintenance. The average causalities for the dam body show a rather equilibrated causality across the spectrum (Table 1), which is a positive characteristic of the considered dam. This means there is not a single area of potential deficiencies which could afflict the body integrity, but rather compounding effects generated by the deficiencies. The set of pf includes drained (ESA), undrained (USA), pseudostatic and residual/liquefaction scenarios (Oboni, 2016, 2017, 2020). Table 2 displays the probability estimates for various analyses as applicable in the specific case of the considered dam at various crest elevations. The values include the water management facility failure, evaluated at a very low value of $6*10^{-4}$/yr for this specific dam. As usual, data lead to various estimates for a specific analysis, meaning the approach always considers min-max ranges to express uncertainties.

Table 2 Central estimates of the annualized probabilities of failure at various crest elevations in drained (ESA), undrained (USA), pseudostatic and residual/liquefaction conditions (Oboni, 2016, 2017, 2020).

Crest elevation	p_f ESA	p_f USA	p_f pseudostatic	p_f residual / liquefaction
290	$6*10^{-4}$	$6*10^{-4}$	$7.4*10^{-4}$	$6*10^{-4}$
315	$6*10^{-4}$	$6*10^{-4}$	$6.8*10^{-4}$	$6.5*10^{-4}$
340	$3*10^{-3}$	$6*10^{-3}$	$3*10^{-3}$	$6.5*10^{-4}$
365	$4*10^{-3}$	$7*10^{-3}$	$3.5*10^{-3}$	$5*10^{-4}$
380	$3*10^{-3}$	$5*10^{-3}$	$3*10^{-3}$	$7*10^{-4}$

However, due to space limitations the cells in Table 2 display a "central estimate" of the various probabilities of failure. Table 2 shows that up to elevation 315 the system failure was not driven by the body of the dam, but by the probability of ancillary water management failure ($6*10^{-4}$), exception made for the pseudostatic loading. At higher dam elevations the stability of the dam body became the driving factor.

Benchmarking of probabilities of failure

Figure 2 displays the results of Table 2 together with the world-wide benchmark for catastrophic failures. Benchmarking of tailings dams exist since at least 2013 (Oboni, 2013). Hazard benchmarking is based on the p_f, disregarding the consequences, hence significantly differs from a full pledged risk prioritization that will be developed in the next sections by using the quantitative estimate of the consequences. Benchmarking uses a "statistical" approach (Oboni, 2013) as well as a theoretical range developed by Taguchi (Taguchi, 2014). The system values (larger orange rectangles) are those attained by the dam combined with its ancillary water management systems. The dam-only p_f (readable at the bottom of the blue arrows) is the value of the dam body alone. This corresponds to a situation where the ancillary water systems have a p_f significantly smaller than the dam body itself. The smaller orange rectangles correspond to the max-min estimates of p_f at a specific crest elevation. The combined effect of ESA, USA and seismic conditions leads the dam to hover above the World Benchmark max level, which is not a desirable condition for a dam of this magnitude and extreme potential consequences.

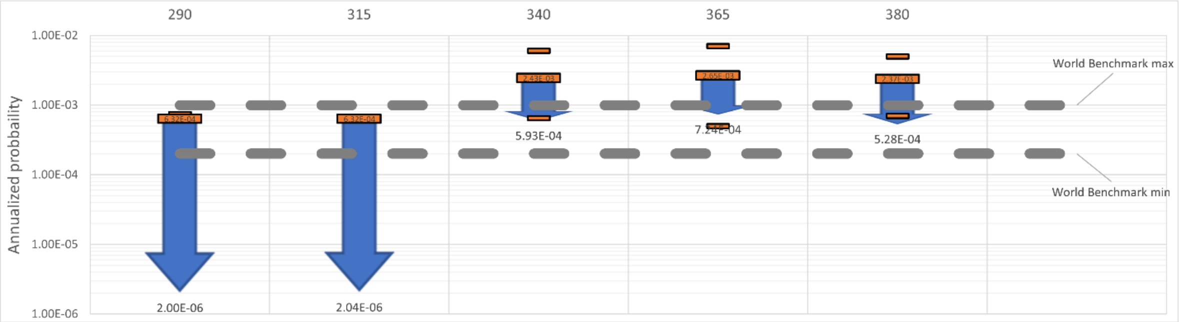

Figure 2 Results of the approach (see Table 2) at different crest levels together with the world-wide benchmarking

Multidimensional consequences of dams' collapses

Following the mantra that one cannot manage what one cannot measure, the value of statistical life has been used for at least 50 years in most industries and more than 20 years by the EPA (EPA, 2022, Lindhjem, 2008). Equally, environmental and reputation damages can be and have been quantified in many industries around the world for at least 15 years (Diermeier, 2008).

As cited earlier, the mining company had already at hand a consequence evaluation carried out following GISTM metric rated as "extreme". Unfortunately, such a verbiage does not allow to evaluate annualized risks or to perform sensible prioritization, or ALARP definition, within a portfolio or a single dam stage. The annualized risk is the combination of the annual p_f and the quantitative consequences. That is why we had to evaluate consequences following a multidimensional analysis. Indeed, the dam failure consequences dimensions to be considered include the addition of:

- BI: Business interruption (e.g., work stoppages for various reasons)
- H&S: Health and safety (e.g., fatalities and injuries etc.)
- PL: Physical losses (e.g., equipment and infrastructure damages, third parties damages)
- ED: Environmental (e.g., clean-up cost and fauna, fisheries and flora rehabilitation, etc.)
- CR, RD: Crisis and Reputation (including legal costs, fines and liabilities)

First rating of risks

Thanks to the quantitative evaluation of annualized p_f and the consequences Table 3 shows that the dam's annualized risk of the dam increased significantly from the beginning of the operation but remained relatively stable at 34-39M$/yr during the final stages of construction/raises. This helped the owner and his EoR to gain a clear understanding of how their past decisions had influenced the evolution of the p_f of the considered dam system and offered clear decision-making support for the future stages.

Table 3 Evolution of the annualized risks of the dam as a function of crest elevation

Crest elevation	**Risk p_f*C M$/yr**	**Comments**
290	9.18	All risks evaluated with central values of annualized p_f and quantitative consequences C
315	9.17	
340	35.34	
365	38.41	
380	34.39	

ALARP evaluation and optimization

Figure 3 shows the ALARP (lower bound) evaluation for crest elevation 380 based on the simulation of six mitigative stages on top of the present conditions (status quo). The simulation was driven all the way to a p_f of 10^{-6} (Stage 6), i.e. to the credibility threshold. Please note how the mitigation costs, delivered by the EoR, evolve almost exponentially, whereas the risk abatement features an asymptotic behavior towards negligible risks.

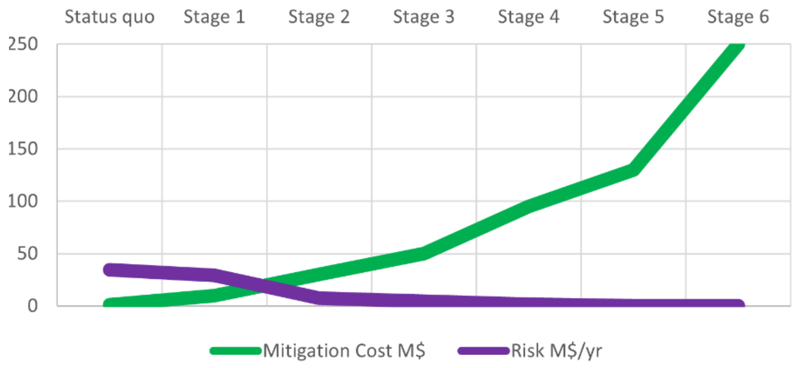

Figure 3 Mitigation costs M$ vs. risk M$/yr (on the same vertical axis). The crossing is the minimum ALARP point as defined in ICMM guidance document (ICMM 2021)

Based on this chart, risk perception and other considerations, the "optimum" ALARP point, most certainly located to the right of the theoretical crossing can be determined. As the mitigations are discrete steps, out of prudence one would be inclined to suggest Stage 2 is indeed the minimum ALARP. However, the discussion may lead to the following question: from a pure risk-engineering point of view is it enough to select mitigation Stage 2 if we disregard jurisdictional issues? The perception of some stakeholder could easily be that the owner should mitigate "anyways" to alternative 3 or 4 or higher. However, going beyond stage 2 requires, based on the costs delivered by the EoR for this example, sharp investment increases for what seems a modest risk mitigation gain. In some cases this reasoning could bring to propose different sequences (as possible and feasible) of the mitigation stages to seek better CAPEX allotment. Thus our deployment would offer a solid ground of discussion and negotiation (with the public and regulators, and, if applicable, with insurers) to state that stage 3 represents a possible "above minimum" ALARP choice for risk mitigation level. Ultimately this deployment example, using assumed initial knowledge and mitigation costs, shows that our QRA can be used in full conformance with GISTM to foster healthy and rational discussions between the owner, the EoR and regulators as well as other stakeholders.

CONCLUSION

The QRA deployment gives useful indications both looking at past and future stages of a dam construction. It can foster solid and rational technical and risk perception discussion, in particular on the level of desirable risk mitigation, based on GIST ALARP concept. In addition, it supports communication between owners, regulators and the public.

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