Optimizing mitigation of tailings dams portfolios

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ABSTRACT: Mitigative investments are a finite resource and mining companies owning large portfolios of active and inactive/closed tailings storage facilities (TSFs) find themselves in a mitigation conundrum. That is, where to act first and get the best sustainable mitigation RoI within the framework of GISTM and other codes? Unfortunately, every consequence-based prioritization, such as GISTM, biases the issues at TSF portfolio level by not looking at the probability of failure, making it harder to find a pathway for sustainable and rational mitigation of tailings dam's portfolios. In this paper we show the effect of discretization of the TSF portfolio and suggest it is paramount to start the analyses with the Homogenous Dam Segments (HDS) composing each TSF as well as explicitly with their ancillary water management subsystems. Keeping client's confidentiality, we show a case story of an international tailings storage inventory portfolio spanning four continents and six macro-geographic areas including a total of approximately a hundred active/non active/closed dams of various type, age, maintenance, monitoring and care level. We examine it against tailings dam reliability benchmarks and then discuss how the granular (HDS) and subsequent aggregated deployment is useful to swiftly identify quick and efficient risk reduction opportunities, and to support long-term risk-informed mitigation strategy. Indeed, we will identify the critical TSF asset(s) from our case story and then look at different portfolio mitigation strategies and simulate their implementation to see the effect on the portfolio and against the benchmark. In other words, we show how to identify the path for prioritization of de-risking initiatives, quick wins, current controls effectiveness and possible additional controls aiming at reducing the overall TSF portfolio risk exposure. This is fundamental to communicate residual risks to regulators and stakeholders, evaluate mitigation methods and comply with the GISTM As Low As Reasonably Practical (ALARP) criteria for a given TSF or TSF portfolio aggregation. Thus, the conundrum of mitigative effort allocation can be solved in a rational, efficient and sustainable manner also allowing TCFD and TNFD credible and sensible reporting.

1 INTRODUCTION

In this day and age of IoT, big data, remote monitoring and all-encompassing reporting applications, oftentimes using arbitrarily-set alert thresholds, we live in a paradox. Indeed, tailings dams' mitigation efforts risk paralysis by analysis because management may be misled by data "indigestion" and other biases (Woodhouse 2018). This may result in mitigative investments misplacement and, very unfortunately, in an illusion of safety.

This paper shows what ICMM's GISTM (GISTM 2020) aims to solve and how the process could be enhanced. Indeed, the terms of reference for the Global Tailings Review asked for a global and transparent consequence-based TSF classification which would include the expected number of fatalities, extent of environmental damage, infrastructure etc. Let's also note that the consequence-based GISTM system by definition ignores the probability of failure of the considered dam, another a priori arbitrary decision.

For the sake of this paper, we will use a case story of an international tailings storage inventory (portfolio) spanning four continents and six macro-geographic areas including a total of approximately a hundred active/non active/closed dams of various type, age, maintenance, monitoring and care level. We will introduce a few notions necessary to avoid confusion and missteps as needed.

The paper then shows the mitigation conundrum in which mining companies owning large portfolios find themselves. Indeed, mitigative investments are a finite resource and mining companies need to decide where to act first and get the best sustainable mitigation RoI within the framework of GISTM and other codes. Unfortunately, as hinted above, any consequence-based prioritization, such as GISTM biases the issues at TSF portfolio level by not looking at the probability of failure and working with discrete classes of consequences, making it harder to find a pathway for prioritization leading to sustainable and rational mitigation of tailings dam's portfolios

Finally, the paper describes dam's benchmarking which helps formulating risk triaging plans. The portfolio is examined against tailings dam reliability benchmarks and then discuss how the granular homogeneous dam segments (HDS) and subsequent aggregated deployment is useful to swiftly identify quick and efficient risk reduction opportunities, and to support long-term risk-informed ALARP mitigation strategies.

2 THE TAILINGS CONUNDRUM

2.1 *ICMM Standard GISTM does not really solve the conundrum*

The GISTM requires dam break analyses to be run following the logic exemplified by the flowchart below.

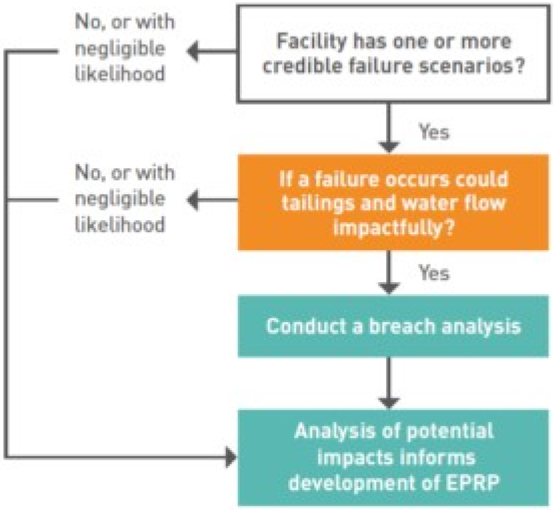

Figure 1. GISTM flowchart

These are notoriously based on many assumptions and can lead to an array of diverse conclusions, let alone the fact that "negligible likelihood" is not defined and therefore open to interpretation. Despite the dam break studies, GISTM then proposes an oversimplified way of classifying a dam, which leads to many dams being in the very high to extreme category (see GISTM Requirement 4.1 and Annex 2, Table 1).

Under these conditions, mining companies simply do not get enough guidance on where to act first and may then resolve to allot excessive funds to programs that will not solve their "real" problems. For instance, only monitoring future conditions while neglecting dam's system "birth defects" or mitigating potential brittle failures by increasing the factor of safety to vaguely specified levels (see ICMM conformance protocols requirement 4.6, 7.2 (ICMM 2021). Certainly, the requirements of GISTM focus the attention of mining companies in the good direction, but we see the possibility that many will fall to the temptation of "interpreting", "documenting" rather than "solving" issues.

We also note that risk tolerance remains a vague notion through the GISTM, while its definition is invoked to justify the "position" of the ALARP "point"! This is odd, since F-N curves exist for catastrophic accidents in various industries (Vasconcelos et al. 2015; Haastrup & Rasmussen 1994), CDA has their version of tolerance (Baecher et al. 2015), and studies exist on corporate tolerance (Oboni et al. 2021).

Finally stricter construction standard, QA/QC, inspections, care, maintenance, and monitoring do lead to smaller probabilities of failure and there are rational and sustainable ways to ensure that risk to life (probability times fatalities) remains constant or even decreases.

2.2 *How to support ICMM standard on tailings management and triage risks*

In order to support GISTM and triage risks over a portfolio, we need a platform that focuses on a convergent (Oboni and Oboni 2021) prioritization of risks allowing for tactical and strategic planning considering hazards, causalities and divergent hazards, such a climate change and finally creates a portfolio hazard and risk register providing information on interdependencies as needed.

In order to achieve the goals above we need to define the success/failure criteria. Indeed, without clear definition of success, failure cannot be defined, and one does not know what "risk" means. For example, one can consider a dam successful if it: a) stands as built and does not break allowing for catastrophic tailings release in static and seismic conditions; b) features slow "stable" deformations without evolving into condition a) above, due to excessive strain and finally; c) does not develop ancillary water management issues potentially leading to the appearance of severe damages. Generally, the evaluation of the tailings dams slopes stability follows various conditions as applicable (ESA, USA, Pseudostatic, residual strength, static and dynamic liquefaction) and as the available data allow. These conditions may possibly evolve into a catastrophic releases alone or in combination with surface water management failures (overtopping, scouring, toe erosion) including potential liquefaction or residual strength failures (earthquake or storm induced).

The next step is to evaluate consequences. We strongly advise to use a complete and realistic consequence formulation, which includes simultaneous and additive multiple dimensions considering at least:

harm to people,
environmental losses,
physical losses,
reputation and finally,
crisis potential,

transformed into a single composite metric allowing rational comparisons across various TSFs, large portfolios. Let's note that following the mantra that you cannot manage what you 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 et al. 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).

2.3 *Using Knowledge to Evaluate Risks*

The dam system knowledge base includes all the archival documentation since inception of the project. This in addition to inspections, incident and near-misses reports (Caldwell et al. 2015), monitoring results, space observation (Oboni & Oboni 2021; Oboni et al. 2018), etc.

Encoding these into the data is a step of paramount importance. In our experience, a third-party eye is necessary to distill a balanced set of data and avoid biases. This is required as GISTM promotes demonstrably objective engagement free of conflict of interest or undue influence of others to override professional or business judgments. Let’s note that “self-assessments” based on unsupervised data feeds into a “software” go against these requirements.

Monitoring data also require expert third party review in order to ensure they are meaningful and as unbiased as possible. We have too often seen stakeholders censor “unfavorable” results, discard them leaving the way to unwanted exposures.

3 CASE STUDY: A PORTFOLIO OF TSF

The TSFs selected for this sample portfolio are owned/operated by different companies. The identity of owners/operators and locations are strictly confidential. The portfolio includes appx. hundred homogenous dams’ segment in 27 TSFs located in Central Asia, Europe, Latin America, North America, Oceania and South-East Asia. The TSF have a variable number of dams, i.e., between 1 and 9. The TSFs are labelled on the horizontal axis of Figure 2 where aggregated probabilities of failure results are shown. The sites are anonymized, their name replaced by the country followed by a cardinal number.

3.1 *Definition of the HDSs*

In order to be amenable to rational analysis, focus on well targeted mitigation, TSFs must be discretized. For example, a perimeter dam should not be evaluated as a single dam, but split to consider variations in geology, potential consequences, etc. Thus, it is paramount to start the analyses with the Homogenous Dam Segments (HDS) composing each dam in each TSF as well as explicitly with their ancillary water management subsystems.

Each dam in each TSF system, is split in Homogeneous Dam Segments (HDS) as appropriate, based on geometry, geological/geotechnical/hydrogeological conditions, and potential consequences. Indeed, a dam is not a mere cross section, but a system including a “homogeneous” segment of tailings retaining barrier (homogeneous cross section, foundation, topography, and potential consequences) and its ancillary surface water management facilities (spillways, penstock, weirs, diversions, etc.), possible lines and “traffic” running at its crest. Missing any of those points would miss some vulnerabilities and thus bias the risks.

The potential triggers of liquefaction/residual events should be explicitly considered. We generally consider eight of these triggers for which the engineer and owner have to estimate potential “frequencies” (see Oboni, Oboni, 2020, Section 9.3, page 136-138). For instance, one of these is “access of heavy equipment working on dam”. The engineer could likely state, for example, “once a year” or perhaps “every two years”. The composite probability of the triggering event is then evaluated. Of course, this evaluation must pair with strict SoPs the owner should publish and enforce on the system, in order to avoid catastrophic blunders during service life and after closure. This is covered in GISTM Requirement 5.2.

3.2 *Dam System Portfolio Inventory*

The dams were built following upstream, downstream, center-line types of cross-sections. The stored tailings are the result of base- and precious metals extraction. The dams are active, inactive and in some cases closed. We aggregate each TSF’s dams (HDSs) by considering the extreme min-max scenarios for probability and consequences. This allows to depict a “rectangle perimeter” display of the risks of the HDSs present at the specific TSF.

Oftentimes risks have significant inverse correlation between consequences and probability. As a result, small consequences have high probabilities and larger consequences have a smaller probabilities, of a given hazard. A good example of this are car accidents: fender-bender are way more likely than full loss of the vehicle. However, in the case of tailings one can assume that probability of catastrophic failure and their consequences are rather uncorrelated at least at the standard level of analysis that data generally allow. Indeed the consequences of a catastrophic failure are not dependent on the probability of the failure, but rather on the population density downstream, land use (PAR, PLL), the topography, etc. Indeed, in the next sections we identify the critical TSF asset(s) from our case story and then look at different mitigation strategies and simulate their implementation to seek the ALARP levels.

4 TAILINGS RISK BENCHMARKINGS AND ROADMAP CONSIDERATIONS

In this section, we show how to identify the path for prioritization of de-risking initiatives, quick wins, current controls effectiveness and possible additional controls aiming at reducing the overall TSF portfolio risk exposure. This is fundamental to communicate residual risks to regulators and stakeholders, evaluate mitigation methods and comply with the GISTM As Low As Reasonably Practical (ALARP) criteria for a given TSF or TSFs portfolio aggregation. Thus, the conundrum of mitigative effort allocation can be solved in a rational, efficient and sustainable manner also allowing TCFD and TNFD credible and sensible reporting (Oboni & Oboni 2022 b) as well as climate change evaluations (Gloor et al, 2022).

4.1 *Probabilities Benchmarking*

Figure 2 shows the aggregated annualized probabilities estimates for the TSFs case study portfolio inventory described in Section 3. All the analyses were developed using ORE2_Tailings™ (© Oboni Riskope Associates Inc.), a well documented procedure object of numerous papers (Oboni, Oboni 2016, 2017, 2020). It uses “symptoms” or diagnostic “points” (KPIs, KRIs) in addition to factual and numerical results 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.

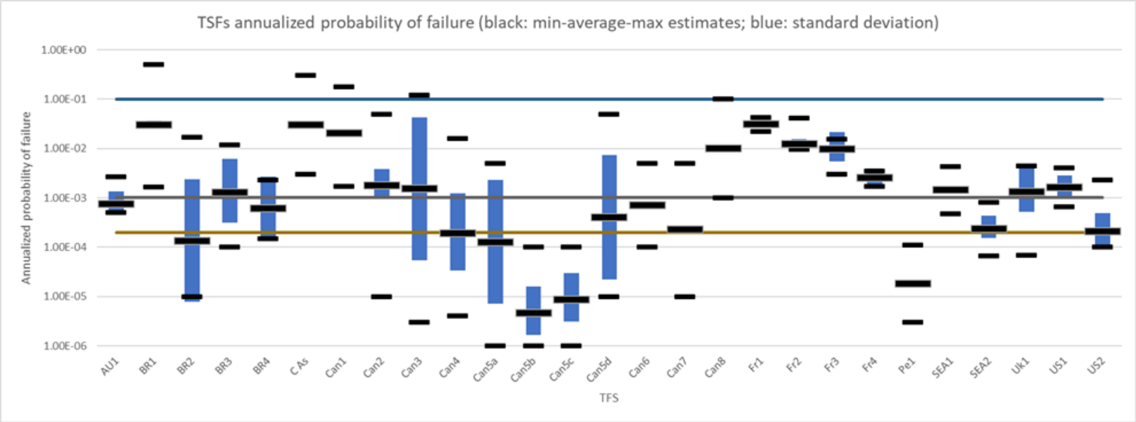

Figure 2. Annualized probabilities estimates for a portfolio of selected active/non active/closed TSFs around the world.

The vertical axis in Figure 2 bears the aggregated annualized probability of failure. Three horizontal continuous lines indicate world-wide benchmarks developed by analyzing historical failure data. The bottom two display a range ($1.2*10^{-4}$ to 10^{-3}) of the historic rate of failure of tailings dams around the world (Oboni, Oboni, 2013; recently confirmed by Rana et al. 2022). The top one corresponds to the pre-catastrophic level and was determined by evaluating Mount Polley and Samarco using information that was publicly available before their failures (Oboni, Oboni 2020).

The thick horizontal black segments correspond to the “average” aggregated estimate of the probability of failure for each TSF, with the thin black segments indicating the min-max estimates. The blue vertical band shows the “standard deviation”. If large uncertainties are present, the min-max range and the standard deviation are larger. The lack of the blue bar means there were not enough data to establish a standard deviation at the time of the assessment.

As it can be seen, based on the data available at the time of each TSF analysis, many TSF were “at the benchmark” (or barely above or below) with their “average”. Some TSF were way better (Can5b, Can5c, Pe1) while some were way worse: Br1, C As, Can1, Can8. Mostly this was due to lacking/poor quality data, while Fr1,2,3 poor results were due to unrepaired damages and/or compliance to excessively optimistic jurisdictional codes (in particular water management design criteria).

Note that the probabilities range (Figure 2) for this world-wide summary goes from $1*10^{-6}$ to several percent, which is equivalent to saying that the studied dams varied from “the limit of credibility” to very near to pre-catastrophic levels. Notice how many sites “straddled” the min-max world benchmark band, meaning that, after all, there is a sort of planetary convergence on the performance of tailings dams. This is not a surprise because engineers around the world designed their dams using similar factor of safety criteria. However, what comes as a surprise is the wide range of resulting probabilities. That range is the effect of varying level of care, maintenance, governance, management from site to site. Figure 2 enables to start a dialogue with the owner, the EoR. But again, it is not enough to really define a sensible roadmap to portfolio mitigation because it does not help discerning which sites/dams can really “hurt” the owners and the public.

4.2 *Risks Benchmarking*

In Figure 3, we reproduce the same probability landscape of Figure 2, with the world-wide benchmark thresholds we developed complemented by their respective consequences (additive quantitative consequences model). The resulting “raw” risk landscape delivers general information on ranges but again does not allow to make any risk informed decision making yet. We need to add information to increase its value as it is shown in Section 4.3. As one can see in Figure 3, consequences cover a very wide range, spanning from 10M$ up to over 10B$. Interestingly there are two strong concentrations in the sample portfolio, one of consequences around 100M$ and other consequences between 1B$ and 10B$.

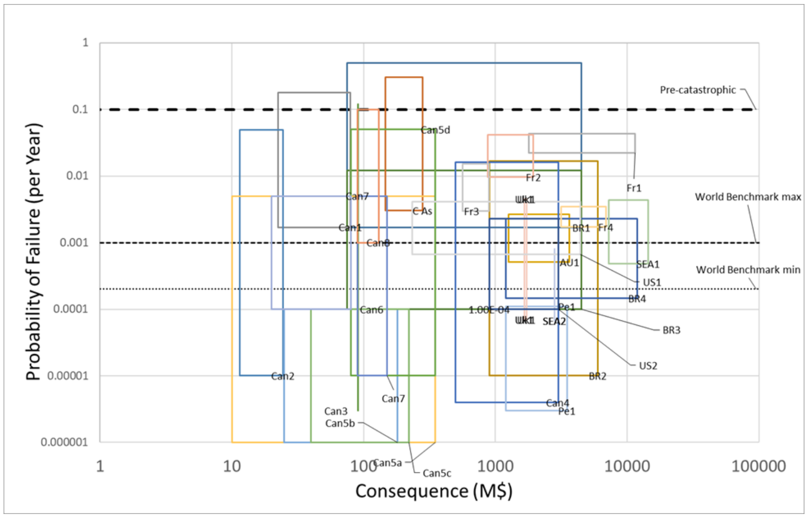

Figure 3. Raw risk landscape with annualized probabilities of failure (vertical axis) and consequences (horizontal axis) together with the probabilities benchmarks.

4.3 *Risk Triaging Plan*

Prioritizing the risks is performed using the client’s corporate tolerance threshold, the “harm to people” threshold (e.g. CDA or other jurisdictional thresholds) and a combination of them. At the end, tolerable, intolerable but manageable and strategic risks are clearly defined to support clients’ decisions. Strategic risks are intolerable risks which cannot be brought under tolerance by reducing the probability of failure within the credible range of analyses (e.g. before hitting $1*10^{-6}$). In order to reduce strategic risks the system has to be altered (for instance, remove the population, reduce the height of the dam, etc.).

The selection of the mitigation level to be reached for intolerable but manageable risks or strategic risks should be based on the ALARP concept. The ICMM Tailings Management: Good practice guide includes the following definition of As low as reasonably practicable (ALARP):

> *ALARP requires to take all reasonable measures with respect to ‘tolerable’ or acceptable risks. … reduce them even further until the cost …are grossly disproportionate to the benefit. [based on the definition provided in the Standard]*

and also Page 15…

> *One can then evaluate the acceptability of the risks considering the potential consequences for health and safety, social, environmental, financial and other factors that may occur (risk evaluation). …The goal is to eliminate, reduce or mitigate, and communicate the risks.*

We can see that following ICMM/GISTM tailings dam risk management must include the notion of tolerable risk, however the standard does not include any solid guidance for these terms. Tolerable and acceptable risks are indeed left open to interpretation and not transparently defined, which can lead to communication problems with the potentially exposed public. Thus, we reproduce in Figure 4 once again the risk landscape adding an example of explicit risk tolerance threshold developed for a large mining company. We show it in red in Figure 4 which uses the same data as Figure 3.

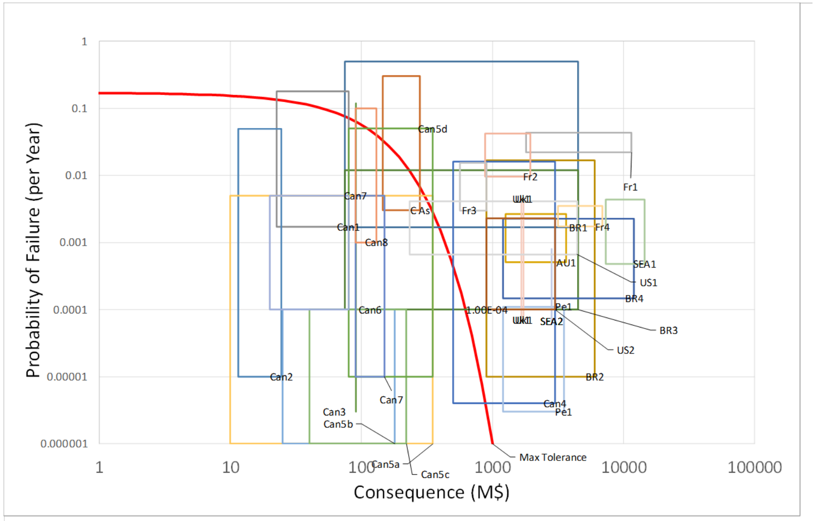

Figure 4. The case story portfolio risk landscape superimposed with the corporate risk tolerance threshold selected for this example/

As it can be seen in Figure 4, many North American sites in the portfolio fall into corporately tolerable territory for large companies (left and under the red curve) due to their location, land use and topography despite their quite high probabilities of failure. However, a majority of sites in the case study portfolio fall in the intolerable territory (above and right of the red curve). Armed with Figure 4 we can also swiftly evaluate which sites represent strategic, tactical risks and therefore require varying degrees of attention.

Focusing on the intolerable risk sites we note that sites like Can 4, US 1 are intolerable but partially manageable. Indeed, mitigation can be carried out by reducing the probability of failure of some of their dams. Hence, they represent tactical risks for they owners. Sites like EU, BR 1,2,3,4. are mostly intolerable and unmanageable within the realm of credibility. Therefore they represent strategic risks and their mitigation requires strategic shifts as explained earlier.

4.4 *Risk Tolerance Roadmap*

Another reason to consider risk together with risk tolerance is that this can deliver a roadmap for large portfolio in a systematic and transparent manner. Figure 5 is generated by ranking the sites by decreasing intolerable risks. This constitutes a clear prioritization roadmap for management.

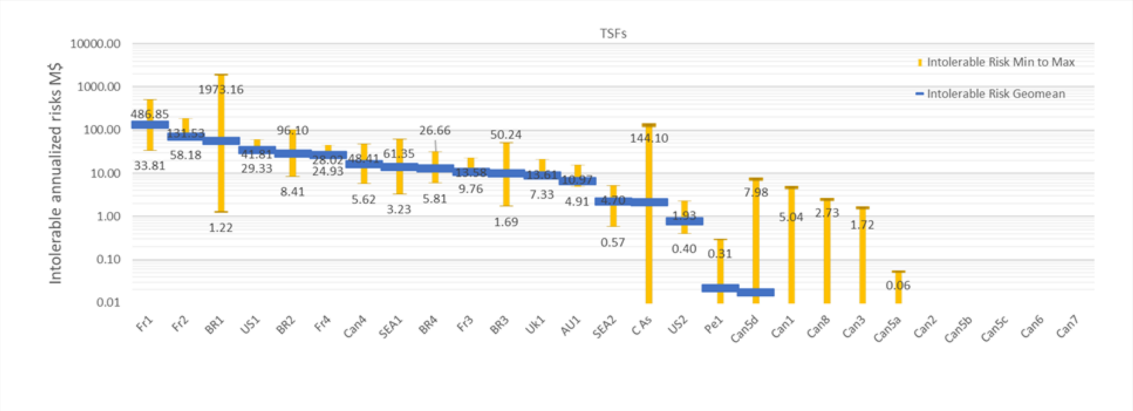

Figure 5. Ranking of the portfolio by decreasing aggregated intolerable risks.

For example, one can immediately see that 12/27=44% sites of the case study portfolio generate an aggregated risk of more than 10M$/yr, and only 3/27=11% generate aggregated risks of more than 50M$/yr. Now, let’s suppose the owner decides to tackle one of the most intolerable risk HDS and mitigate it.

4.5 *ALARP Considerations, Quick wins*

Given the risks linked to a dam, generated by its probability of failure and cost of consequences, mitigation may be required at present or during the closure and post-closure phases. Previously we have discussed how to quantitatively evaluate risks, decide if a given dam constitutes a tactical or strategic risk, and if mitigation is necessary based on explicit and formal definition of corporate and societal tolerance.

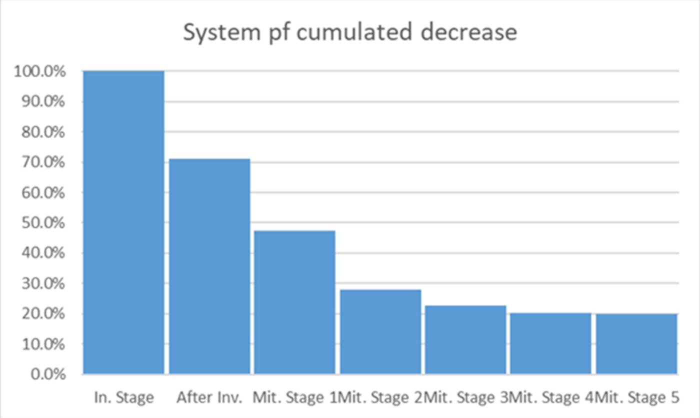

Figure 6 Probability of failure P_f cumulated decrease

The same quantitative approaches can be deployed to enable what-if scenarios and develop sustainable and efficient roadmaps towards reduced risks. Indeed, it is possible to express the risk and the associated mitigative costs for each alternative, allowing for risk estimates for each alternative, evaluation of risk differential and efficiency (Oboni & Oboni 2022 a). One can also find the optimum ratio between the annualized risk decrease and the mitigative CAPEX for each mitigation alternative and/or stage.

The process consists in systematically evaluating the risks for each mitigative stage, the related mitigative CAPEX and deriving risk abatement-mitigative investment graphs to determine the ALARP "point". Figure 6 shows the cumulated reduction of the probability of failure of a dam system when n stages of mitigation are evaluated. Figure 7 shows the related mitigative CAPEX per each stage. Once the risks are included together with the costs of each foreseen mitigative step, a true cost benefit analysis can be discussed. Figure 8 shows the combined annualized risk reduction-CAPEX curves. The crossing of the two curves in Figure 8, i.e. risk and mitigation cost vs. mitigation level, represents the theoretical "Optimum" and is sometimes indicated as the ALARP point.

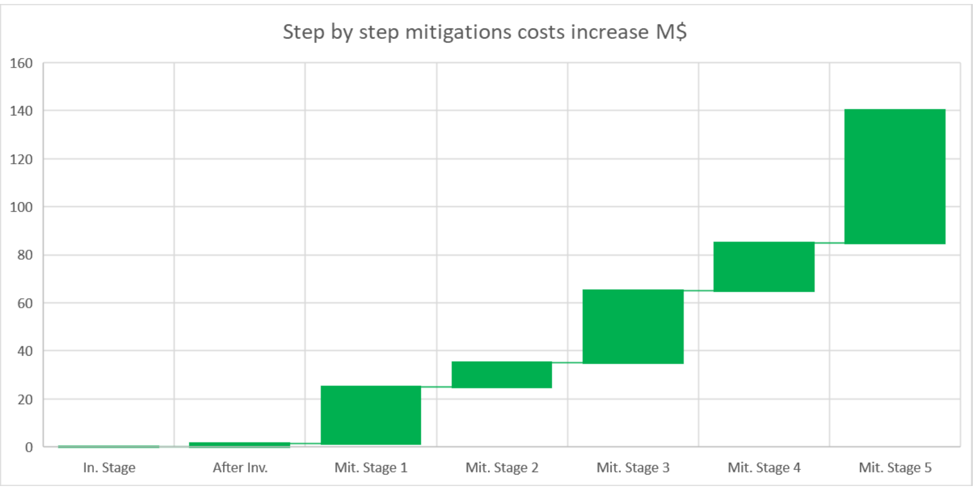

Figure 7 Stepped mitigation increase

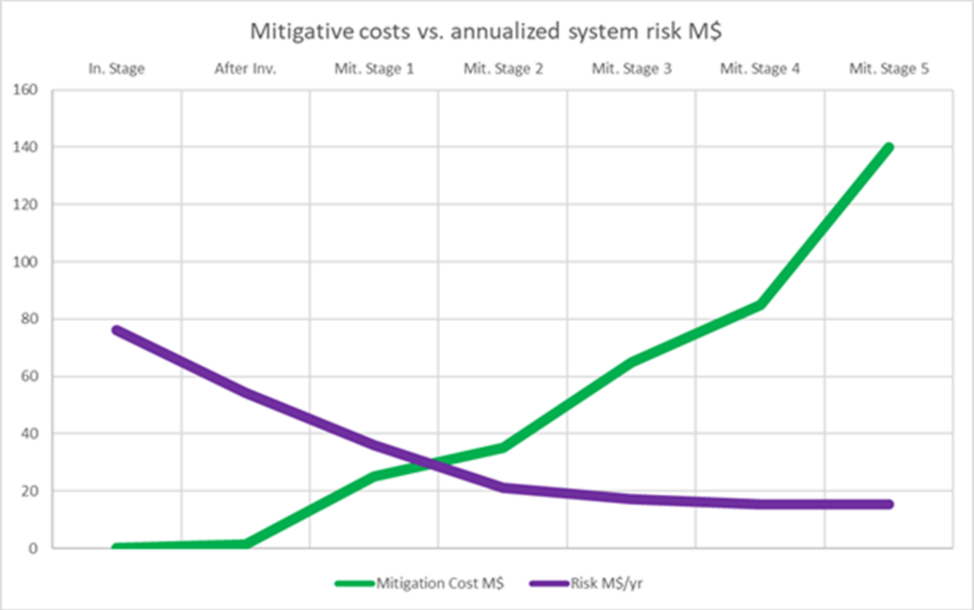

Figure 8 Risk and mitigation cost vs. mitigation level

Incidentally, that point corresponds to the legal negligence test used in some jurisdictions. However, it is not a critical test when confronted to risk perception and public reactions and therefore the "advisable" ALARP will generally lie at higher mitigation levels. (Oboni & Oboni 2022 a). Indeed, the ALARP selection discussion boils down to the following: is selecting a certain mitigation stage (the crossing point in Figure 8) enough from a pure risk-engineering point of view, if we do not consider jurisdictional and perception issues? Actually, the stakeholder's perception could easily indicate that dam risks should be mitigated "anyways, at any cost" to higher levels. This deployment would offer a solid ground of discussion and negotiation to state that a certain stage represents a possible choice for risk mitigation level which is proportional to the gain and constitutes a "well thought argument". It can foster healthy technical and perception-based discussion on the level of risk mitigation that should be attained, based on GIST ALARP concept, the legal negligence test and finally the mitigative stages "efficiency". Thus, ALARP considerations, "quick wins" can be easily and efficiently evaluated in a rational and defensible manner that goes beyond the highly disputable "trust us" statement.

5 CLOSING REMARKS

The selected case study portfolio indicates that, despite similar deterministic criteria (National codes stating factors of safety) were used during the design, significant ranges of probabilities arise due to varying standards of care, monitoring, and maintenance. Prioritizing based on consequences-only can lead to wasting precious resources, time and oftentimes targets the "wrong dams". Every dam is special and statistical approaches generating blanket statement, generalized software solutions have to be taken with caution. Tailings dams include too many "variants", actually, many more than the types of cross-section and basic materials; ancillary water management systems are complex and cannot be oversimplified.

As a matter of fact, each element of the TSF split into HDSs systems has to be carefully evaluated, including all possible interdependencies, especially since their performance is crucial to the survivability of the system in case of extreme, climate change related, events. Dams are indeed systems and cannot be simplified into a "stability problem" without considering the various conditions they undergo during their life, such as, for example: drained, undrained, seismic, residual/liquefaction in an explicit manner, together with the ancillary water management elements potential failure and effects.

The dam system knowledge base must include all the archival documentation since inception of the project. This in addition to inspections, incident and near-misses reports, monitoring results, etc.

Encoding these into the data is a step of paramount importance. In our experience, a third-party eye is necessary to distill a balanced set of data and avoid biases. This is required as GISTM promotes objective, conflict of interest-free engagements avoiding undue influence of others to override professional or business judgments. Thus, "self-assessments" based on unsupervised data feeds into a "solve it all" solutions go against these requirements.

Monitoring data also require expert third party review in order to ensure they are meaningful and as unbiased as possible. We have too often seen stakeholders censor "unfavorable" results, discard them leaving the way to unwanted exposures.

Tailings dam risk management must include tolerance/acceptable threshold to provide meaningful answers.

The paper has shown that one can use quantitative risk assessment approach in full conformance with GISTM. The process delivers risk-informed decision-making indications to optimize, if feasible from a constructional point of view, the phasing of the various mitigation stages and alternatives. It can foster healthy and rational internal and external communication on the: i) level of risk mitigation, conforming with GIST minimum ALARP concept and beyond, ii) legal negligence test and finally the iii) mitigative alternative risk informed "efficiency".

We hope this showcase has given a clear view of risk triaging for a large portfolio of TSF. In particular we hope it shows where and how to support GISTM points 10 and 15, as it fosters better, repeatable and reality anchored communication.

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