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Tailings dams quantitative risk prioritization

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Abstract

This paper assesses the quantitative risks of a portfolio of four dams. It is based on case histories and shows a predictive risk prioritization approach. Dams interdependencies are explicitly considered as interdependent scenarios significantly alter the portfolio risk prioritization. Stability analyses in static and pseudo-static conditions performed by the engineers as well as observations/inspections reports are used as input data. It is shown that the Factor of Safety is not a good discriminant to evaluate safety and thus risks. A documented and published symptom-based simplified probability of failure estimate is used to evaluate the probability of failure of each dam. Dams are benchmarked in relation to the world-wide historical performance as well as using a theoretical dewatered and slurry state tailings dams' probabilities of failure. Consequences of dams' breach are quantitatively evaluated using a multidimensional function. Potential for loss of lives is of course included and discussed as well as reputational damages. Indeed, a comprehensive risk metric is the cornerstone in risk communication which is becoming a crucial part of any risk assessment. Enhanced transparency, sensible information, better risk communication will help foster robust Corporate Social Responsibility, Social License to Operate and NI43-101. The risk portfolio is prioritized using various approaches, including a portfolio owner's risk tolerance threshold. A discussion of the impact on possible prioritizations and decision-making is introduced as well. The paper shows that gut-feeling risk prioritization may be misleading and careful consideration of multiple parameters must be introduced before a sensible and sustainable roadmap can be delivered and communicated to the stakeholders and the public. Finally, a roadmap to portfolio mitigation is defined.

Introduction

This paper describes the risk prioritization of a real-life dams' portfolio. The "map" of the system is schematically (no scale) displayed in Fig. 1. The four dams used as an example are real dams from various confidential owners. Their profiles and parameters have been altered to preserve confidentiality.

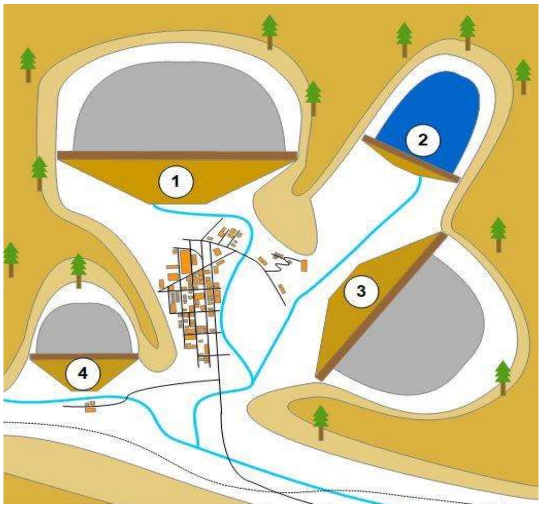

Figure 1 The system of dams constituting the portfolio

The map helps to define the boundaries of the dam systems and the overarching portfolio. Tailings are depicted in grey, water of pond 2 and watercourses in blue. Some of the dams present internal and/or external interdependencies (possible concatenated failures). Valley bottoms are white and major residential and industrial structures are displayed as orange rectangles. Roads appear as single black lines, and a railroad, denoted by a dotted line, crosses the map from East to West in the South end of the map. The map has the objective of allowing a preliminary estimate of potential consequences by looking at the land-use downstream of each dam. It is very important to focus on the consequences as engineering analyses oftentimes privilege the hazard side of the risk equation and neglect the consequence side.

For obvious space limitations we will develop each case to the level required for the discussion and the points we want to make. We use extant engineers' stability analyses and geotechnical characterization. For all the dams the engineers declared the bedrock to be competent and free of weak layers and unfavourable discontinuities.

Dams general descriptions

Dam 1 is a rockfill downstream dam with a height of 162m. Dam 1A is an intermediate situation, i.e. the raise of Dam 1 at 100m height (Fig. 2 left). Phreatic levels are at bedrock in zones 1, 2, and no significant deformations are detected. Dam 1B is the same dam as Figure 2 left, but at its final altitude of 162m.

Dam 2 (Fig. 2 right) is a water retention dam which displays an external inter-dependency with Dam 3. The external interdependency between Dam 2 and Dam 3 exists because a failure of Dam 2 would provoke an erosion at the toe of Dam 3 as we will describe later. Dam 3 is an upstream structure constituted by a compacted till started berm on which upstream compacted waste rock berms have been built. Due to its construction it has significant internal interdependencies.

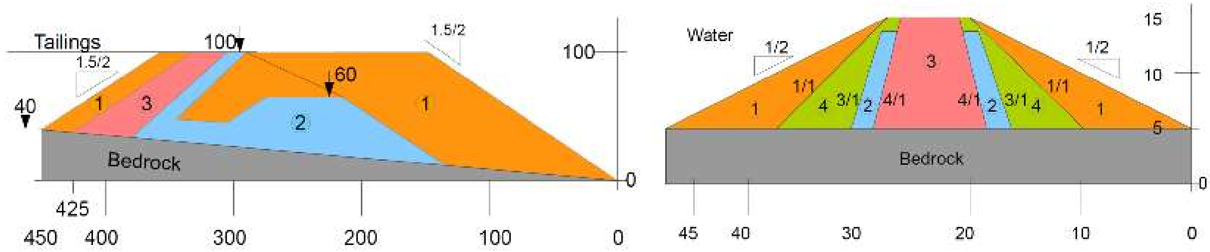

Figure 2 (Left) Dam 1A cross section: Raise at altitude 100m of Dam 1 (final height 162m) (Right) Cross section of Dam 2, a water retention dam.

Finally, dam 4 is an upstream dam of obsolete design, with penstock, similar to recently failed dams.

There are tailings pipelines at the crest of Dam 1A, 1B, 3 while Dam 4 is in the process of deactivation, thus there are no active spigots at its crest. There are vehicular and subcontractor's traffic at the crest of all dams. The engineers defined the Factor of Safety (FoS) for the various dams under various conditions, i.e.: USA (undrained strength analysis), ESA (effective stress analysis) and pseudo-static as shown in Table 1, i.e for Maximum Credible Earthquakes (MCE) and Operating-Basis Earthquake (OBE).

Exception made of Dam 4 which is clearly a “bad apple”, the FoS have very similar values in USA for Dams 2, 3, in ESA for Dams 1A, 1B, 2, and finally very similar FoS under pseudo-static conditions for Dams 1, 2, 3. We will see later that the image derived from the probability of failure is way more defined, with more evident variations from one Dam to the next. This extra definition is very important when a risk prioritization of a large portfolio is sought. This will avoid falling in the trap of calling “safe” dams that have a probability of failure in the top range of credibility.

Table 1 Results of the engineers’ stability analyses (FoS) for the various dams of the portfolio.

Dam	USA	ESA	Pseudo-static
1A	n/a	1.61-1.68	1.18-1.23 for 1/475 Operating Base Earthquake (OBE) and 1:1500 MCE
1B	n/a	1.59-1.65	1.15-1.26 for 1:475 OBE
2	1.63-1.76	1.59-1.68	1.28-1.33 for 1:1000 MCE
3	1.6	1.29-1.35	1.2 for 1:2,475 MCE
4	1 to 1.35, average 1.17		

Dams conditions since inception to the date of analysis (physical and governance)

The conditions over the known history of the dams, resulting from extant reports and records, interviews and other classic means were summarized. Table 2 displays such a summary for Dam 1A, 1B. Should modern hazard identification and monitoring data such as Space or drone Observation history be available (Oboni et al. 2018), then those results could be integrated in the Dams' descriptions. IoT and other data analyses would also complement this information. Of course, all the data and interpretations contained herein should be stored in a Portfolio's database (Hazard and Risk Register) allowing easy retrieval by queries, and updates.

Table 2 Dam 1A, Dam 1B summary of conditions

Construction:

Centerline-rockfill tailings dam analyzed at two stages (100m, 162m). Non-erodible by assumed extreme meteorological conditions. Pipeline and traffic at crest. Supervision of the dam is excellent both in terms of frequency and of skills of the supervisor. No geometric divergences have been noted between the plans and the actual structures and minor intermittent seepage is monitored at one location at the toe. There are no known errors and omission in this project, which has been third party reviewed by competent independent reviewers.

Geotechnical Investigations & testing:

Boreholes along the dam layout were regular, however less than 1/100m, they were rather short, barely entering the bedrock. No continuous sampling was performed. Vane tests and cone tests were numerous but poorly distributed due to access reasons. Soil classification tests were performed in reasonable number and frequency, Geomechanical tests were numerous and distributed. A significant number of residual strength, oedometer and triaxal tests were performed.

Analyses & documentation:

The project is deemed of good quality by a competent engineering firm and a skilled team. The “as-built” plans display no significant imperfections and variations. The alteration plans have also been regularly updated.

Stability analyses:

As shown in Table 1 above effective and pseudo-static stability analyses were performed by the engineers. Settlement analyses were performed. Liquefaction was dismissed by the engineers. Internal erosion analysis estimated by engineers as not being a problem.

Operations and monitoring:

Pore pressure is measured with numerous vibrating wire piezometers. Deformations are monitored by topographic observations and inclinometers. There is an active Independent Geotechnical Review Board (IGRB). There is an annual inspection ran by a reputable third party.

Maintenance and repairs:

Repairs are timely carried out when damages are pointed out by the inspection.

Probability of failure of the portfolio's dams

Two approaches for the evaluation of the probability of failure of each dam were used. Table 3 displays the evaluation of the Category of dam (Dam 1A, 1B) using a method (Silva et al. 2008, Altarejos-García et al. 2015) we call SLM, leading to the evaluation of the probability of failure. The SLM methodology is general and of proven applicability, but should be used with caution for dams' slopes, where dam-specific hazards (e.g. water balance upsets, liquefaction, freeboard loss, etc.) are present.

Table 3 SLM (Silva et al. 2008) results for Dam 1A,1B

Investigation 0.2 to 0.3, Testing 0.2 to 0.3; Analysis and documentation 0.2: Best category I
Construction 0.4 Operations and monitoring 0.4: Above Average category II
Category min (best estimate) = 0.2+0.2+0.2+0.4+0.4= 1.4
Category max (worst estimate) = 0.3+0.3+0.2+0.4+0.4= 1.6

Thus, more tailings dam-specific approaches are to be preferred (Oboni, Oboni, 2019; Oboni et al. 2019) as they include those "missing" factors. Like in SLM, the tailings dam specific approaches use "symptoms" or diagnostic "points" in the history of the dam from inception to the day of the evaluation. The 30 diagnostic "points" are summarized in Table 4. For each point the tailings specific methodology allows a pre-determined set of answers and these are mathematically combined to deliver an estimate of the probability of failure, including uncertainties. Explicit consideration of uncertainties is indeed a fundamental step towards reasonable, transparent and ethical risk assessments (Oboni, Oboni, 2017a 2017b, 2019).

Table 4 summary of diagnostic points (Oboni et al. 2019) used in tailings specific approach.

Physical aspects of the dam and its equipment (weirs, pipes, spigots, penstocks, etc.).
Construction: type of materials, cross section, supervision, berms & erosion, divergence from plans, etc.
Geotechnical investigations and testing.
Prior analyses and documentation of the project.
Various stability, deformation, erosion, liquefaction aspects:
◦ stability analyses (of various types, ESA, USA, pseudo-static, etc.),
◦ instability symptoms,
◦ settlements (actual and analyses),
◦ liquefaction and
◦ internal erosion.
Operations, monitoring, maintenance & repairs.

Based on the list above, evaluations can be easily updated as they consider generally available or observable data (e.g. on site, monitoring, and satellite). The lack of knowledge (missing data) is explicitly entered in the evaluations.

The tailings specific approaches deliver, for dams 1A, 1B category 1.45 to 2.22, instead of 1.4 to 1.6, mainly because of the short, relatively far apart boreholes performed during the investigations. The rockfill nature of the dam downstream body makes it insensitive to erosion, as pointed out by the engineers, and to a possible crest pipeline breach. Using the SLM Categories together with the FoS (Table1) for the various dams of the portfolio, Table 5 can be built. Values are cut at the credibility threshold of one in a million or

10^{-6} (NUREG 1990). For Dam 4 a simple evaluation of the probability of failure (p_f=p(FoS<=1)) delivers a probability of failure between 6% and 13%. Generally speaking, the SLM and dams-specific methodologies deliver similar values of the categories for the portfolio's dams. However, the application of the dam-specific application yields higher categories values because it considers the uncertainties, lack of monitoring, repairs and maintenance surrounding a dam, and the uncertainties on the geotechnical investigations that are not at all included in the FoS determination, as well as water balance, weirs and penstocks, freeboard considerations.

That is to say that a probabilistic stability analysis based on the variability of the FoS is not sufficient to characterize a dam. The mere FoS is not sufficient either, of course. Indeed, SLM is a lot more deterministic in the sense that the range of probability of failure is narrower (Fig. 3 left).

Table 5 Annual probabilities of failure for select Dams (1A, 2, 3) in the portfolio using SLM

Dam	SLM Cat	Annual p_f USA/rapid draw down	Annual p_f ESA	Pseudo-static per event (to be divided by return)
1A	1.4	n/a	≤10^{-6}	$2.03*10^{-3}$ to $5.6*10^{-3}$
	1.6	n/a	≤10^{-6} to $2*10^{-6}$	$4.83*10^{-3}$ to $1.16*10^{-2}$
2	2.2	$6.53*10^{-6}$ to $5.12*10^{-5}$	$2.32*10^{-5}$ to $9.65*10^{-5}$	$5.93*10^{-3}$ to $1.31*10^{-2}$
	2.4	$2.44*10^{-5}$ to $2.64*10^{-4}$	$7.49*10^{-5}$ to $2.64*10^{-4}$	$1.01*10^{-2}$ to $2.32*10^{-2}$
3	1.6	$3.32*10^{-6}$	$4.64*10^{-4}$ to $1.37*10^{-3}$	$7.84*10^{-3}$
	1.7	$6.74*10^{-6}$	$6.60*10^{-4}$ to $2.06*10^{-3}$	$1.14*10^{-2}$

Also, for a few cases the SLM give completely different values as the SLM lack critical data input specific to tailings dams. As it can be seen from Table 5 short boreholes (Dam 1A) deliver higher probabilities of failure to an overall well-designed, built, maintained and managed dam under constant FoS. Needless to point out that this corresponds to observations in various recent catastrophic failures. The same occurs (Dam 3) if liquefaction is suspected, again in compliance with recent observations

To allow comparisons between SLM and the tailings specific approach, Figure 3 (left) includes ESA results with the probability of failure as a function of a FoS. The effect of ignoring dams specific hazards becomes evident, as the difference of probability of failure estimates is sometimes over an order of magnitude between the two approaches.

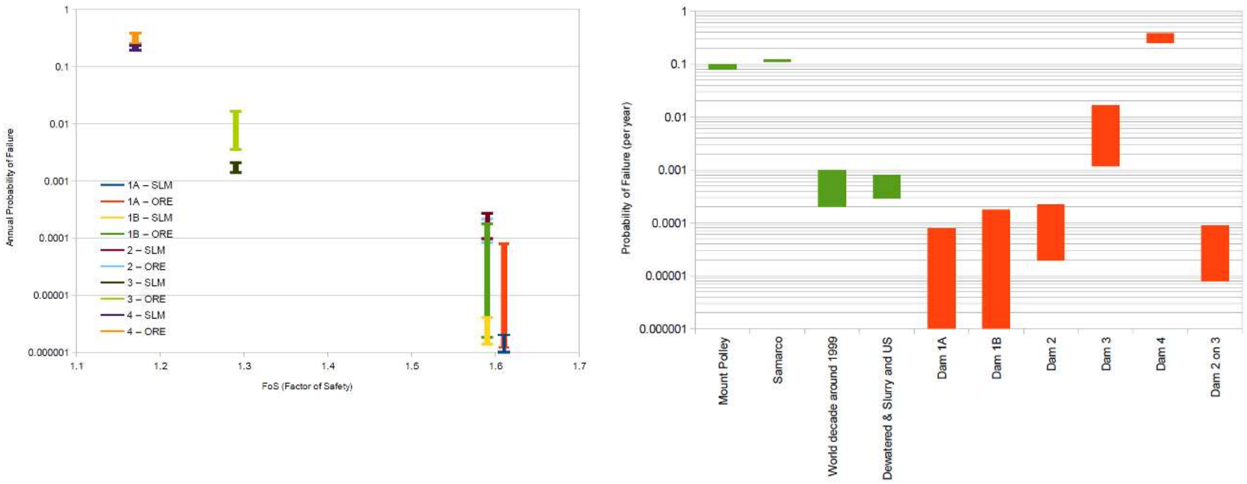

Figure 3 (left) SLM vs. dam specific methodology Optimum Risk Estimates (ORE) FoS vs Annual probability of failure for ESA (right) Portfolio probabilities. In the vertical axis the annual probability of failure -pƒ- of various dams (horizontal axis) under the form of red vertical bars. Green bars are benchmarking

It is easy to see from Figure 3 (right) that the difference between "optimistic" vs. "pessimistic" category classification delivers probabilities of failure which lie within one or two orders of magnitude. That variation is compatible with extant uncertainty on the performance of the world-wide portfolio over the last hundred years, leading to the conclusion that the portfolio prioritization does not require systematic optimistic/pessimistic range evaluation but more importantly requires consistency in the evaluation for each single item. In the case of Dam 2, where there are little tailings dam-specific features, the correspondence of SLM with the dam specific application very good. As SLM does not consider liquefaction, in Dam 3 the divergence with dam specific method is again significant, when liquefaction hazard is included. For Dam 4 ORE penalizes the probability of failure as it is characterized by the paucity of data and ignorance on many aspects of its history SLM does not look at specific tailings dams' deficiencies. Similar conclusion can be derived from USA rapid draw down and pseudo-static.

If the failure criteria have been carefully selected, benchmarking becomes a powerful tool of comparison. Whereas risk comparison amounts to showing different activities of comparable risks, benchmarking corresponds to rate a given activity's risk related to other similar activities. Benchmarking of a tailings dams portfolio probability of failure can assume the aspect shown in Figure 3 (right) (Oboni et al. 2018). The extreme of the bars in Figure 3 (right) represent the minimum and maximum estimates of the probability of failure for each dam. Hence, the length of the bars measures the uncertainty on the evaluation of the probability at the time of the assessment and with the data available at that time. The vertical axis shows four benchmark values described in prior publications (Oboni, Oboni, 2019; Oboni et al. 2019), namely the world-wide performance of the tailings dams' portfolio (around 1999 and following published theoretical approaches (Taguchi, 2014)), as well as Samarco and Mount Polley probability of failure evaluated using the symptom based methodology with data publicly available before the respective failures.

The portfolio benchmarking in terms of the probability of failure shows that in the considered case there are dams below the historical benchmark. Some dams overlap the benchmarks limits, and some are above the upper limit, however still significantly lower than the Mount Polley or Samarco estimates made with available pre-failure data. Additional studies and information would allow narrowing of the uncertainties (length of the orange bars).

Mitigation would push the bar down, an aspect we will discuss later. Long term lack of maintenance and climate change effects will tend to push the bars up, as it has already occurred with Dam 4.

Consequences

The Mackenzie Valley Review Board (MVRB 2013: Appendix D, June 2013, see Section 5.2) defined what a modern risk assessment should include, based on public hearings results. Thus, it becomes clear that partial components of the consequences such as: Biological Impacts and Land Use, Regulatory Impacts and Censure, Public Concern and Image, Health and Safety, Direct and Indirect Costs have to be included in the analyses in an additive consequence function. Since risk data are often highly uncertain, ranges are strongly advisable with respect to "magic" single numbers.

Based on the system map (Figure 1) the following consequences were evaluated:

Dam 1A: Extensive damages to the town, town infrastructure and tailings runout to the river stream with river transportation mechanism (e.g. 75% town full loss damage).

Dam 1B: Full loss of the town, town infrastructure and tailings runout to the river stream with river transportation mechanism (e.g. 95% town full loss damage).

Dam 2: Inundation of the low areas of the town due to water flooding, industries and loss of service of transport infrastructures (e.g. 35% town full loss damage).

Dam 3: tailings runout blocks the valley, then floods the low areas of the town industries and loss of service of transport infrastructures (e.g. 20% town full loss damage).

Dam 4: damages in the mine perimeter, road failure, personnel safety, mining infrastructure (e.g. 60% mine full loss damage).

Interdependent failure of Dam2 and 3: The combination of water and tailings flood makes the tailings more fluid, important scouring occurs, wider areas are impacted because of the combined volume and higher energy (compound damages to be carefully evaluated).

Risk tolerance or Acceptability Thresholds

In Figure 4 we display as an orange line the risk tolerance curve (Oboni, Oboni, 2014) selected by the owner of the portfolio. For this particular corporation a 100M$ loss event with a frequency of one out of ten years is intolerable. Also intolerable is an event generating a loss of 4,500M$ (4.5B$) with a probability at the limit of credibility (10^{-6}).

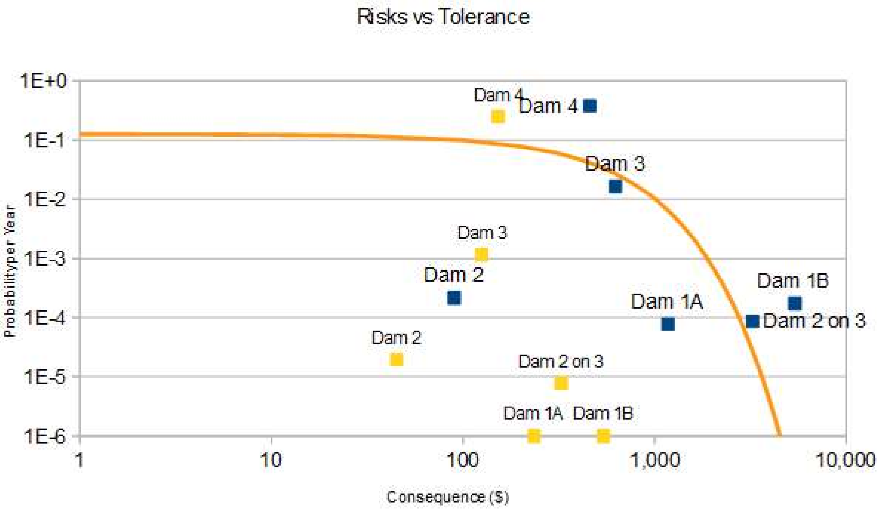

Figure 4 In blue p_{fMax} and C_{max} for each dam, and in yellow p_{fmin} and C_{min} for each dam. Risk tolerance is displayed in orange.

In Figure 4 the yellow squares depict the C_{min} scenarios (i.e. without reputational damages RD) and the optimistic probability of failure (p_{fmin} and C_{min}) for each dam. Only Dam 4 is intolerable under these conditions. However, as history has demonstrated in various occurrences, neglecting the reputational damages is a flawed and unrealistic approach. Out of prudence, from this point on we will focus the discussion on the results including RD.

Figure 4 shows that Dam 1A, Dam 2, Dam 3 are below the selected corporate tolerance. Also, Dam 4, Dam 1B, and Dam 2 on 3 are all above tolerance. Figure 5 displays the total risk for each structure as the sum of the tolerable part, i.e. the portion below tolerance (blue) and the intolerable portion (orange), i.e. the portion of the risk above the tolerance.

Common practice simplistic statements equating bigger dams to bigger risks are to be left aside as they can easily be disproven, as clearly shown in Figure 5. Indeed, for example Dam 4, which is smaller than Dam 1A, 1B generated significantly larger risks. Furthermore Figure 5 shows that prioritizing a portfolio mitigation plan based on total risk (blue+orange), i.e. without considering the corporate tolerance to risk would be far than optimal and lead to squandering of mitigation capital because Dam 3 (tolerable) would be mitigated before Dam 1B, which has an intolerable portion of risk, and Dam 3 would also be mitigated before the interdependence of Dam 2 on 3 which has an intolerable portion of risk, despite its probability being two orders of magnitude lower.

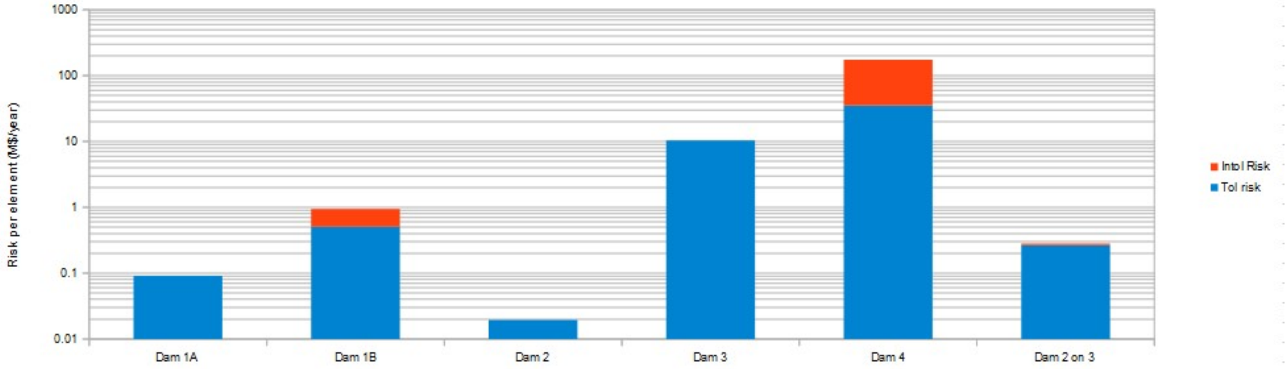

Figure 5 Total risk for each dam is equal to the sum of tolerable (blue) and intolerable (orange) risks.

From the above we note that risks, and in particular risk prioritizations, cannot be ranked by gut-feelings and intuition. The reason is simple: our human brain has already enough trouble understanding the simultaneous effect of two parameters, i.e, probability of failure and cost of consequences, and the introduction of a third vital one, which is the tolerance, certainly does not help the brain to make optimal decisions. Thus, it is paramount to use rational approaches to make decisions involving risks, even for simple portfolios of four dams like the one discussed here, where decisions seem a priori obvious!

Defining strategic tactical and operational risks

Risk Informed Decision Making (RIDM) is necessary to decide on which dams to act in priority, which mitigations to implement. Risk Based Decision Making (RBDM) would be used to prioritize actions and select mitigations, but it would not be sufficient to evaluate the effectiveness of the mitigative investment in order to optimize it. When it comes to mitigation, actions need to be efficient, efficacious and finally effective i.e. producing the desired results (within clear financial goals, covered by RIDM). The idea is to develop effective risk reduction strategies implementation using Risk Informed Decision Making (RIDM). The first step of RIDM is to gain an understanding of which risks are operational, tactical and strategic. This classification is paramount, is an important result of a modern risk assessment, and should not be the result of an arbitrary selection

Operational

Dam 4 can be mitigated, i.e. brought under tolerance with minimal effort at operational level. A reduction of the probability by only 1.5 order of magnitude would make it tolerable. In the case of Dam 4 two options could be attempted: reduce uncertainties and thus decrease the appalling Category of the structure, that is intensive monitoring, repairs, and possibly historical research and investigations (with attention not to trigger a failure), and/or increase the FoS by building, if space and other conditions allow, a berm. The final choice should be carefully examined using probabilistic cost estimates (Oboni et al., 2006).

Tactical

Interdependencies of Dam 2 on 3 can be lowered below tolerance by adding a mitigation on Dam 3 that would change the likelihood of failure of Dam 3 if Dam 2 failed. One example could be an armored toe, preventing erosion of Dam 3, after careful consideration of the liquefaction potential. Here again the portfolio risk assessment allows to allocate resources avoiding paralysis by analysis and feeling overwhelmed.

Strategic

Finally, Dam 1B is considered intolerable independently of possible implementable mitigations (black arrow in Figure 6 remains above tolerance all the way down to human credibility threshold).

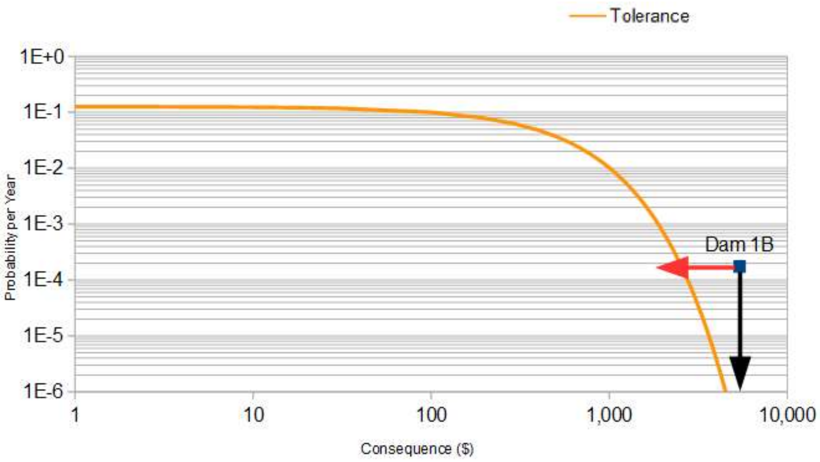

Figure 6 Mitigation Dam 1B effects on risks

Dam 1B represents a strategic risk as only an alteration of the system would make it tolerable (red arrow). A solution could be moving the population, enhancing protection against environmental damages, lowering the dam etc. Thanks to the quantitative approach strategic shifts can be evaluated.

Closing remarks

Simplistic statements equating bigger dams to bigger risks are to be left aside as they can easily be disproven, as clearly shown in Figure 5, and do not help any constructive dialogue. Indeed, as structures become larger, their probability of failure should go down towards the values commonly accepted for major hydro-dams. That reduction necessitates acting on all aspects of the dam investigation, design, construction, monitoring, inspections and management, as all contribute to the chance of failure. Increasing the FoS does not clearly reflect any of the above necessary improvements.

Population increase, land use shifts and environmental constraints will increase consequences of failures and therefore tend to increase risks. Again, the probability of failure will have to be lowered, especially considering that tailings dams have a long-life span during service and post-service, and, again, the FoS cannot help measuring the changes. Predictive prioritization methodologies are the way to bring back credibility to the industry.

It is time for mining companies, governmental agencies to benefit from better understanding the risks they are exposed to and expose the public to. Furthermore, we have to consider that: i) Unless proper methodologies are used it will be very difficult to evaluate progress, as factors such as climate change, seismicity and increase in population will further complicate the situation; ii) Public outcry and hostility toward the mining industry, fuelled by the diffusion of Information and Communication Technology will likely increase; iii) the effects of any risk mitigation program will only become visible over long-time spans, because any portfolio will contain mitigated and unmitigated (legacy) dams; iv) During that time the public, regulators and legal authorities will perceive at best a status-quo, with obvious nefarious consequences to the owners and operators.

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