Risk Assessment of the Long-Term Performance of Closed Tailings Facilities

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ABSTRACT: A risk assessment of the long-term, post-closure performance of a tailings facility may be undertaken to compare alternative closure scenarios or to guide design of the closure works. A post-closure risk analysis of a closed tailings facility may be used to understand if the closed facility generates societally acceptable risks. The results of such a risk assessment depend significantly on the post-closure performance period specified for the comparison or design. This paper explores the question of appropriate periods to be considered in a risk assessment of the performance of a closed tailings facility. Specifically, the paper looks at the outcome of various risk assessments for various closure design periods of 200, 500, and 1000 years during which periods a statistically-determined number of Maximum Credible Events occurs. We show that design of closure works for different time frames may result in significant cost differences and perceptions of what constitutes a good closure approach. Risk-based decision making based on rational and conceptually-sound risk assessment methodologies proves to be an invaluable tool in bringing clarity to the ongoing debate on how best to assess the consequences of mine closure.

1 INTRODUCTION

The portfolio of the world's historic buildings, bridges, defensive walls, cathedrals, aqueducts, and other great works is a memorial to good engineering, human intuition, and the sense of proportions of their builders. None of their designs was proven by calculations; none was the object of risk assessments. They are the few survivors of the scores that failed and disappeared. Some of the failures were so bad that the buildings were never completed, or required significant alterations or even reconstruction during the decades they took to complete.

It has been only a few centuries since we learned the science of static analysis. We have only recently “invented” geotechnical engineering and have started analytically proofing our designs. This has greatly improved the chances of success of new structures of all kinds, including, dykes, dams etc. In the meantime, we have hopefully never stopped learning from our short-term bad experiences, i.e. “unexpected” failures of code-compliant structures which, in most cases, underwent some “unexpected” (geotechnical) conditions or loading combination (man-made, natural, climatological).

Our societies have evolved and as a result nowadays we are asked, for example, to design larger and higher long-term storage facilities for tailings. Regulators and the public want to know how these structures will survive their few decades of operational life. In some cases we are requested to demonstrate that our structures will survive closure design periods of one thousand years and beyond.

We can react to these “new” challenges in various ways:

- As we are again venturing in *terra incognita*, like the cathedral builders did when they challenged the skies with their towering structures, we can revert to the old model and trust our intuition and good engineering sense, convincing regulators and the public they have to trust our genius.

- We can try to convince the same stakeholders that a matrix-based risk assessment, fallacious and misleading to start with, will help shed light on a distant future (FAA, 2002, Cox et Al., 2005, Cox, 2008, Chapman, Ward, 2011, Cresswell, 2011, Hubbard, 2009, NASA, 2007) Even though we know that this approach does not even solve “immediate” issues.
- We can try to put together a transparent procedure that enables us to rationally compare designs, foster an understanding of what we know and what we do not know, measures chances of success in comparable-reproducible manner, which, together with our good engineering sense will give the necessary comfort to our proposed ideas in a way that can be explained to the public and regulators.

This paper explores the third alternative.

2 A SMALL NOTE ABOUT TIME AND PERSPECTIVE

Just to keep things in perspective, let us examine “the state of the world” thousands of years ago, then 1000, 500, and 200 years ago, imagine what the requirements were in those times, and what that would mean for the tailings storage facilities you would have built then.

2.1 *Forty-five thousand years ago*

You would have been mining hematite at Bomvu Ridge in Swaziland. Your small-scale mining would have produced insignificant waste and no societal concerns. Much later archaeologists would come and record your efforts, glad to dig through your debris for clues about how you did it. And then miners would come to reopen the mine to provide the King and his forty concubines with money to play.

2.2 *Three thousand years ago*

You would have been bidding for the rights to mine silver at Laurentia just east of Athens. The 28,000 slaves would have worked to your command to provide the money to build the Parthenon and support philosophers of democracy for the wealthy mine owners. No money was set aside for waste management. Today nobody goes to see the abandoned mine workings; they all go to see the structures built with mining profits. As an Egyptian Pharoe you would have raided Ethiopia for slaves to build a pyramid of rock for your perpetual glory. There was only human waste.

2.3 *One thousand years ago*

If your mining company had existed 1,000 years ago, you'd probably been asked to sponsor the crusades. Thanks to your sponsorship, the Europeans would gain Greek and Latin medical and scientific texts from the Muslims. The Europeans would learn about advanced technologies like the windmill, water wheel, Damascus steel, and Arabic numerals. As an American you would have been building the Cahokia mounds near East St Louis. You used soil, for there was no rock to build like those others were doing in Central and South America. Today those mounds persist: well-vegetated, although much eroded by gullies. Total world population was around 300M souls. Languages used in those times have disappeared.

2.4 *Five hundred years ago*

If your company had existed 500 years ago you could have written a congrats card for the well-deserved retirement of Mr. W. Shakespeare who went home to Stratford-on-Avon. Christopher Columbus "discovered" America for the last time ever. Total world population had increased to 500M souls. Leonardo da Vinci was living his last years, having just painted the Last Supper which has since been in a permanent process of restoration, due to its state of decay. Perhaps only fifteen of Leonardo's paintings survive, because of his constant, and frequently disastrous, experimentation with new techniques. Leonardo conceptualized the double hull, flying and other machines, concentrated solar power, also outlining a rudimentary theory of plate tectonics. Few of his designs were constructed or were even technologically feasible during his lifetime.

2.5 *Two hundred years ago*

If your company had existed 200 years ago, you'd been concerned because slavery was abolished in the UK, and Ireland was incorporated into Britain. The world was also distraught by the Battle of Trafalgar, Napoleon's retreat from Moscow, and the Battle of Waterloo. The world's population had reached 950M inhabitants.

The Robert C. McEwen U.S. Custom House in Ogdensburg, N.Y., was built and is nowadays recognized as the oldest operating federal office building in the US. The building started out as a simple store and warehouse in an unsettled and remote area, with few roads to transport goods. Local waterways and the St. Lawrence River served as avenues of commerce for goods that were brought up the river and warehoused in Ogdensburg for local distribution. The U.S. Customs Service, founded by the First United States Congress in 1789, occupied space in the McEwen building as early as 1811.

2.6 *What about the Tailings Storage Facilities?*

If you had closed your tailings facility 1,000, 500, or 200 years ago you would have expected that the tailings should still be right there where you dumped them, unattended, not maintained, not monitored? And that despite the fact that major buildings under everyone's nose failed and required reconstruction, cherished masterpieces vanished in dust or require continuous care, and the oldest operating federal office building has certainly undergone multiple maintenance, capex refurbishments and upgrades.

Oh, we were forgetting one thing, had you left an SOP and Maintenance manual for "future generations". Now the manual would be in a difficult (impossible) to understand language. The documents might have turned to dust or have been heavily damaged. And if you think digital transcriptions of your documents may have saved you, well the solar flare of 1859 (Carrington event) would probably have erased them all if fires, floods, and wars had not done it earlier.

Keep the information above in mind as you will go through the rest of the paper.

3 A MODEL FOR THE AGING PROCESS OF A GEOSTRUCTURE.

In this section we focus our attention on modeling the aging process of a geostructure as a series of discrete hits by hazardous conditions (these could be anything, from an earthquake to flooding, to icing, etc.). We assume that hazard specialists (seismologist, climatologist, hydrologist) can deliver a probabilistic estimate of the Maximum Credible Event (MCE), and we will work with this data, assuming different life spans for the structure. We will consider that, by using standard geotechnical analyses, an estimate of the reduction of the factor of safety (FoS) can be evaluated for each hit to the structure (in some cases extant designs around the world have been selected in such a way that after one MCE the residual factor of safety would have a code compliant value, sometimes as low as 1.1, following, for example, ANCOLD, 2011).

At the end of the step-by-step process described herein we will have at hand:

1. The evolution of the probability of failure "over time" (i.e. after a certain number of probabilistic hits), and the evolution of risks.
2. It will be possible to evaluate designs that would have different initial conditions, standards of care, and costs of repairs.
3. Should the future show that the initial estimates by the hazard specialist were not that correct, say because of climate change, for example, the evaluations will be easily and transparently updated, or scenarios evaluated.

In a real-life case, engineering skills will allow to design structures that experience only a small decrease of the FoS at each hazard hit, at an economically sustainable and defensible implementation cost.

This approach is certainly more complex than a common practice PIGs (Probability Impact Graph) or FMEA (matrix approaches), but it is our opinion that, despite all the necessary assumptions, it is a very useful way to "measure intuitions", evaluate our beloved "good engineering sense," and promote transparent discussions about risk, particularly over the long term. Finally the approach described herein bypasses the well-known pitfalls and misleading biases brought by the arbitrary choices and hidden assumptions common to matrix approaches (Oboni, Oboni, 2012).

3.1 *Estimates of the Probability of Failure*

The vast majority of geotechnical structures worldwide are nowadays designed deterministically. One assumes prudent single values of the driving parameters, and one sometimes performs parametric studies to show the impact of one or more parameters on the Factor of Safety (FoS). Still rare are the case where the Probability of Failure (p_f) is evaluated (Oboni, 2006).

In order to perform a Risk Assessment, the probability of failure (p_f) has to be determined, as Risk is defined, in its simplest form, as the product of p_f and consequences. Any deterministic model (for example any classic slope stability method like Bishop, Morgenstern & Price, etc.) can deliver an estimate of p_f of the form p_f=p(FoS<=1) by using, for example, Monte Carlo simulations with assumptions on the distribution of driving parameters, their correlations, etc. Thus it is possible to evaluate that a given structure, which has a FoS=x, has a p_f=y.

More sophisticated probabilistic slope stability methods, which consider local failures progression within the sliding mass, have been proposed and used for over more than three decades (Oboni, Bourdeau, 1983, Oboni, et Al., 1984, Bonnard, Oboni, 1985, Oboni, et Al., 2006). These methods produce estimates of the probability of "first" failure or of reactivation, estimates of the position of tension cracks, etc. Figure 1 shows an example of results, where the probability of failure (of a certain part of Cassas (Italy) large Alpine landslide) is linked to the height of the water table. This study, developed for the Olympics 2006 transportation corridor, lead to the decision to build a drainage gallery and was the object of detailed monitoring for years.

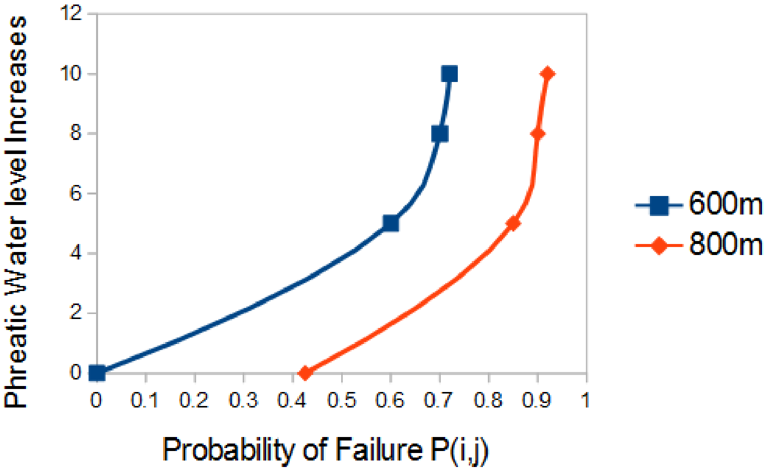

Fig. 1 Local Probability of Failure (P(i,j), horizontal axis) vs. phreatic water level increases (vertical axis in meters) in a large Alpine landslide (Oboni et Al., 2011) at 600m and 800m above the toe of the slope.

In this paper, where the discussion is a general one, we focus on slope stability as it is considered the most frequent cause of dam failure (USCOLD 1994, UNEP 1996, 1998). We select a set of general FoS-p_f relationship (Silva & Al., 2008) that is referred to as the SLM methodology. In a specific real-life case we would opt for probabilistic analyses to yield probabilities of failure. SLM, however, has the advantage of delivering FoS-p_f curves calibrated for various standards of care which allow us to put structures into four Categories (I is the best, IV is the worst) (Fig. 2).

SLM also defines a set of “rules” to class structures that are “between” categories either from inception, or because the standard of care decreases over the structure’s life. Again, the decision to choose SLM relationship is a practical one, as it facilitates a general discussion. For a specific case it is strongly recommended, past the screening level, that a case-specific probabilistic analysis should be developed to link the dam's p_f to its FoS at various stages.
In this paper we consider a Maximum Credible Event (MCE) with an annual probability given by a hazard specialist, for example 1/475 (approximately. $2*10^{-3}$). Of course the methodology can accommodate any MCE probability like, for example 1/100, 1/200, etc.

We assume that for any single event of smaller magnitude than the MCE, the structure will undergo limited damage/deformation that could be repaired without significantly disrupting service and would not lead to a FoS decrease. We do not delve into liquefaction cases in this paper, as this would obviously bring the story to a fast end, and leave us with little to discuss.

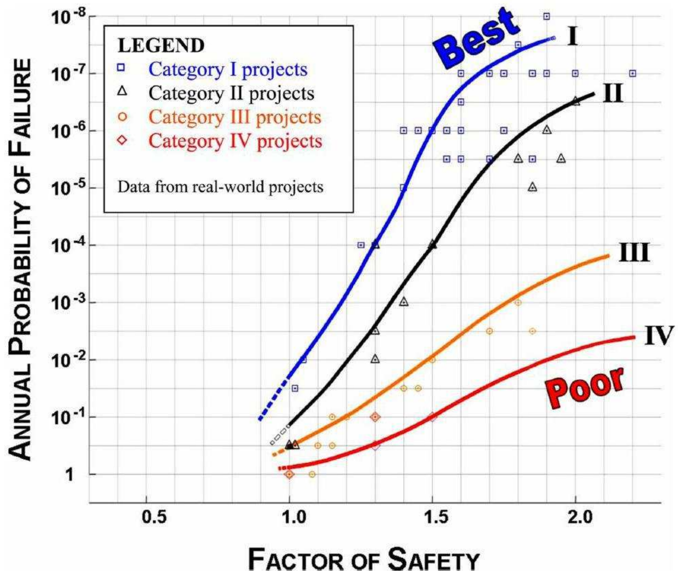

Fig. 2 Annual Probability of Failure vs. Factor of Safety following the method proposed by Silva, Lambe, Marr (SLM) (Silva et Al., 2008). Note that the p_f scale is logarithmic, while the FoS scale is decimal. If a structure is in an intermediate Category, say 1.4, then linear interpolation of p_f has to be performed between the values of Category I and II.

In the event of the Maximum Credible Event, the dam will show defects, becoming weaker (FoS decreases, p_f increases) if no repairs are undertaken. The nature of the repairs will have to be studied beforehand by the dam’s engineers. In the following discussion, Life Phases are those suggested by Szymanski & Davies (2004) and we summarize the life development of our example structure as follows:

- Structure's life starts with an excellent (Cat I) structure with FoS=1.5 , i.e. an approximate $p_f=10^{-6}$ (See Fig. 2), a value that is generally recognized as being at the limit of credibility by us humans, and which applies to critical water retaining dams (Tailings Dams have displayed much higher rates of failure over the last four decades or so (Oboni, Oboni, 2013)).

- Maximum Credible Events (MCE) hit the structure from time to time, with no short term repetitions, and damage gets repaired during the service life.
- The initial FoS does not change until closure because repairs/emergency repairs are undertaken to restore it as soon as they occur before closure.
- Initial Category decays due to gradual reduction of care after the service life. Over the life of the structure Category goes from 1. “as-built” to 1.6 at Closure/Abandonment.
- Starting at closure, Maximum Credible Events damages are not repaired and FoS gradually decays, by, say, 0.1 per hit. This FoS decay per unrepaired hit is actually very small, and we will see below the effect of assuming a larger one.

For each life span, based on the annual probability of MCE, it is possible to estimate the probability of occurrence of one or more hits. For example, for 200 years we can evaluate, with over 90% confidence, a 28% probability of having one MCE, the probability of having no event being 66%. For 1000 years we can calculate, with over 90% confidence, that 1 MCE event has a probability of 26%, 2 MCE a probability of 27%, 3 MCE a probability of 19%, 4 MCE a probability of 10%, and the probability to see no events is a mere 12%. Armed with these estimates it is possible to evaluate (Table 1) the Category decay and then (Table 2) the average probability of failure over each Phase and how many times more likely the dam is to fail in comparison to the “as-built” value.

Table 1. Dam life phases, duration, performance summary and SLM Category based on the assumptions made for the discussion.

Life Phase	Duration	Performance	Category
Service life	20-50 years	1*	1
Transition toward abandonment	Negligible	2*	1.2
Long Term Treatment	50-200 years	3*	1.4
Closure Abandonment	200-1000 years	4*	1.6

1*Performing as foreseen, well-managed, well-maintained, no defects, Category 1 structure.
2*As for 1 but with uncorrected malfunctions (in case one or more damaging event has/have occurred)
3*Annual inspections, emergency repairs only (in case one or more damaging event has/have occurred)
4*Occasional inspections, no measurements. No repairs after each hit of MCE.

Table 2. Dam closure design period, average probability of failure over the period, and times more likely to fail than “as built,” based on the assumptions made for the discussion (decay of FoS=0.1 per MCE hit, etc.).

Closure Design Period	Average p_f	Times more likely to fail than “as built”
200	$6.0*10^{-5}$	60
500	$1.8*10^{-4}$	180
1000	$2.8*10^{-3}$	2800

From the above we can see that even considering the excellent initial state of the structure, with a FoS=1.5 and outstanding care in its design, investigations, construction, care during service life, and the assumed extremely modest FoS decay of 0.1 at each MCE hit, we can evaluate that the occurrence of hazards and the lack of repairs will impart to the probability of failure the shape of an exponential curve like the one depicted in Figure 3.

Let us discuss the meaning of these results. Prior papers (Oboni, Oboni, 2012, 2013) evaluated that in the 1970s, $p_f = 10^{-3}$ and in the 1990s the probability of failure of tailings facilities had decreased to $p_f = 2*10^{-4}$. Under our set of assumptions, i.e. an “excellent dam” built today, with an initial $p_f = 10^{-6}$, a value bordering credibility and generally attained by critical hydro dams, and the very modest FoS decay of 0.1/MCE, following the analysis developed above, we would have:

- After 500 years a quality comparable to the tailings dams around 1999.
- After 1000 years it would be three times more prone to fail than the tailings dams of this world around 1979.

The only way to reduce the probability of failure to at least the “historical value” of the 1970s would be either to repair the damage at each hit, or to entirely avoid the damage, which is obviously “not feasible” for economic and constructional reasons. Risks, especially long-term ones can never be reduced to nil. Here again, engineering skills, good sense etc. enable us to imagine robust solutions that, in an economically sustainable way, will deliver the best imaginable results.

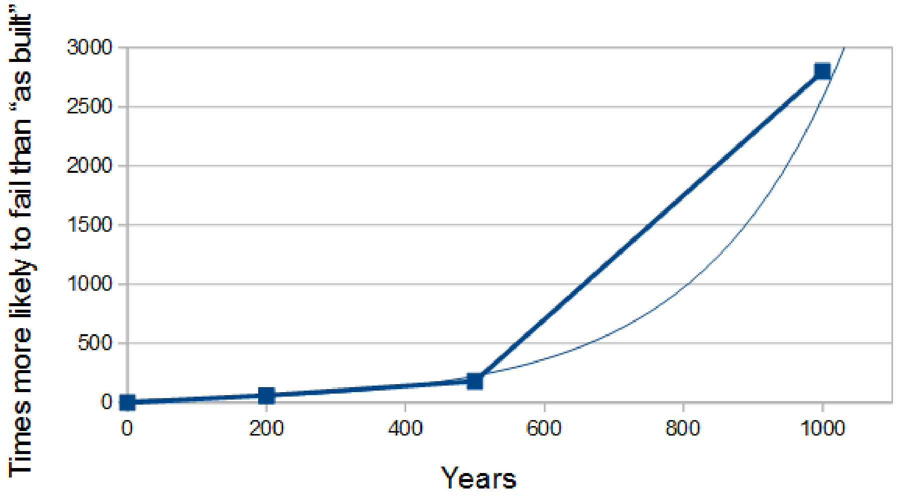

Fig. 3 Exponential evolution of the probability of failure with time for the example described in the text.

Of course not all structures are born equal so let us discuss what would change if a similar outstanding structure (Category I) started its life with FoS=1.3 instead of 1.5. In that case the probability of failure would reach an astoundingly high estimate of 0.15 at the end of the same period. Additionally, an optimistic designer could design in such a way that the decay of the factor of safety (remember, this is not a real dam, we are looking at hypothetical structures) would be 0.15 instead of the prior selection of 0.1. Table 3 summarizes all the results developed for this discussion.

Table 3. Dam closure design period, average probability of failure over the period, times more likely to fail than “as-built,” based on the assumptions made for the discussion (decay of FoS=0.1 per MCE hit, etc.).

Closure Design Period	FoS/decay per MCE hit	Average p_f	Times more likely to fail than as built
200	1.5/0.1	$6.0*10^{-5}$	60
500	1.49/0.1	$1.8*10^{-4}$	180
1000	1.48/0.1	$2.8*10^{-3}$	2800
1000	1.47/0.15	$1.3*10^{-1}$	more than 10,000
1000	1.32/0.1	$1.5*10^{-1}$	
1000	1.31/0.15		failed before end of period

The last rows of Table 3 are quite evidently and indisputably “off-the-chart” with respect to desirable long-term performance of tailings dams.

3.2 *Future consequences evaluation*

Consequences are the second term of the risk equation R= p_f*C. Future consequences, or, to be precise, the evolution of the value of the consequences, are at most uncertain, as they are often locally/regionally driven, or the result of demographic and landuse changes that may be modeled, but not agreed upon, by many institutions like the UN and the FAO. Here is a simplified review.

Casualties to date. Prior studies (Oboni, Oboni, 2012) have shown that the number of victims per Tailings Dams failure were estimated to a minimum of nil, a maximum of ~500, with a long-term historic average at ~80 casualties. An argument could be advanced for using these values for the future; on one hand world population will increase; but on the other hand mines are generally in remote areas. Others would argue that in many cases populations have gathered downstream of mining operations, thus we should increase the tally.

Population growth predictions. The United Nations predicts that by 2050 (that is 35 years from now, i.e. one generation) global population will explode by as much as 40%, from more than 7B (billion) today to 10B. As the world population explodes in the next generation, we will also see increasing per-capita environmental impact. Various estimates have been published for the long-term trend, and sustainability concepts have lead various authors to a long-term estimate limit of 12B humans on Earth. How many of these extra habitants will live within direct (or indirect) reach of a Tailings Dam failure is certainly driven by local/regional parameters, so it is difficult to use these models in a general discussion like the one in this paper.

Land use. Reportedly, First World citizens now consume 32 times more resources such as fossil fuels, and put out 32 times more waste than the inhabitants of the Third World. According to a 2009 report by the United Nations Food and Agriculture Organisation (FAO), the world will have to produce 70% more food by 2050 to feed the projected additional inhabitants (this estimate is far from saying that everyone will live with “First World” standards by then). How much agricultural or simply “productive” land may be impacted directly or indirectly (via a stream, watercourse) by a Tailings Dam failure also lies outside of the general discussion of this paper.

Public opinion and public awareness. In a little more than a hundred years we have gone from “throwing everything to the river” to spending hundreds of millions of dollars for tailings storage facilities and then spending one billion (or more) for environmental rehabilitation of facilities “gone wrong”. Our societies used to consider, up until maybe a couple of decades ago, that death that results from a disaster or accident, is something established by fate, i.e. a “fatality”. Nowadays First World countries have a “willingness to pay” to spare a life of in between 5 and 10M (US Dollars) (Oboni et Al., 2013). Contamination is persecuted and companies lose large parts of their market capitalization because of tailings accidents.

4 RISK ASSESSMENT

Armed with p_f and C (from historic failures) we can now evaluate risks. Figure 4, drawn from a recent publication (Oboni, Oboni, 2014) shows the probability of failure and “best estimates” (average) of casualties for various traffic accidents scenarios, tailings dams around the 1970s and 1990s (decades), nuclear reactors Class 5+ accidents to date compared to published societal tolerability thresholds (Baecher, 1987, Whitman, 1984, Morgan, Lave, 1990).

Figure 5 (a zoom into Fig. 4) shows that the example Category I structure would start its life three orders of magnitude below the lowest probability displayed in Figure 4, i.e. in an area which relates to critical water dams, rather than tailings dams. The probability of failure of that excellent Category I structure would increase over time, due to unrepaired hits of the assumed MCE and the related decrease of the FoS assumed to be equal to 0.1 per hit.

It is easy to notice that, even considering an average number of casualties identical to the historic value (80), the longer terms will mean intolerable societal risks even for the “excellent” structure.

Should the value of consequences increase, for any of the reasons previously discussed, then the “excellent dam” would soon pose a societally unacceptable risk even for shorter terms.

Any dam that starts its life with a small initial FoS or reduced standards of care (lower Category) would see its risk evolve towards intolerable societal risks faster, even if its consequences of failure remain constant. Thus it turns out that it is not necessary, for this discussion, to delve into conjectures related to future consequences.

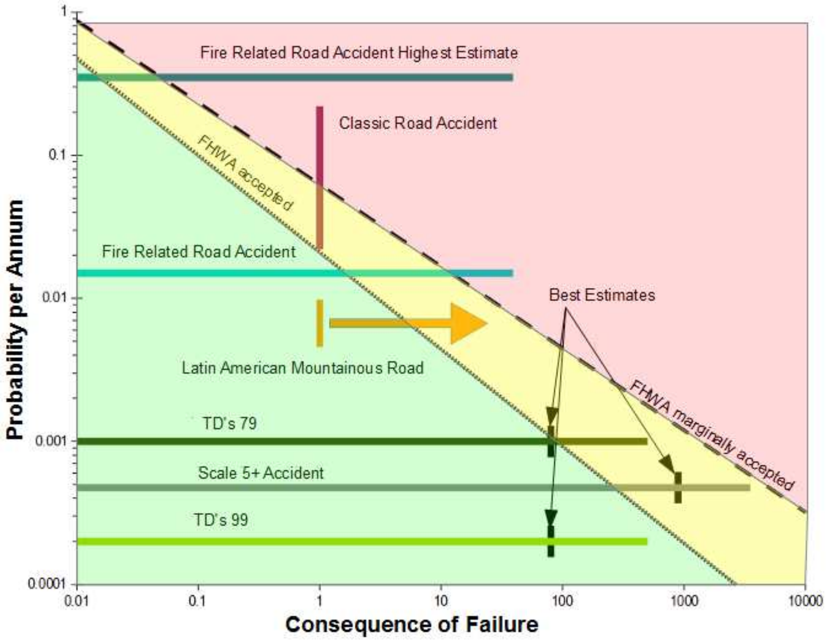

Fig. 4 Various accidents (consequences are casualties only) compared to FHWA/Whitman societal tolerability curves. The black vertical traits represent the position of the consequences "best estimates" (Oboni, Oboni, 2013). The traffic accidents estimates are for specific cases, not large scale statistics.

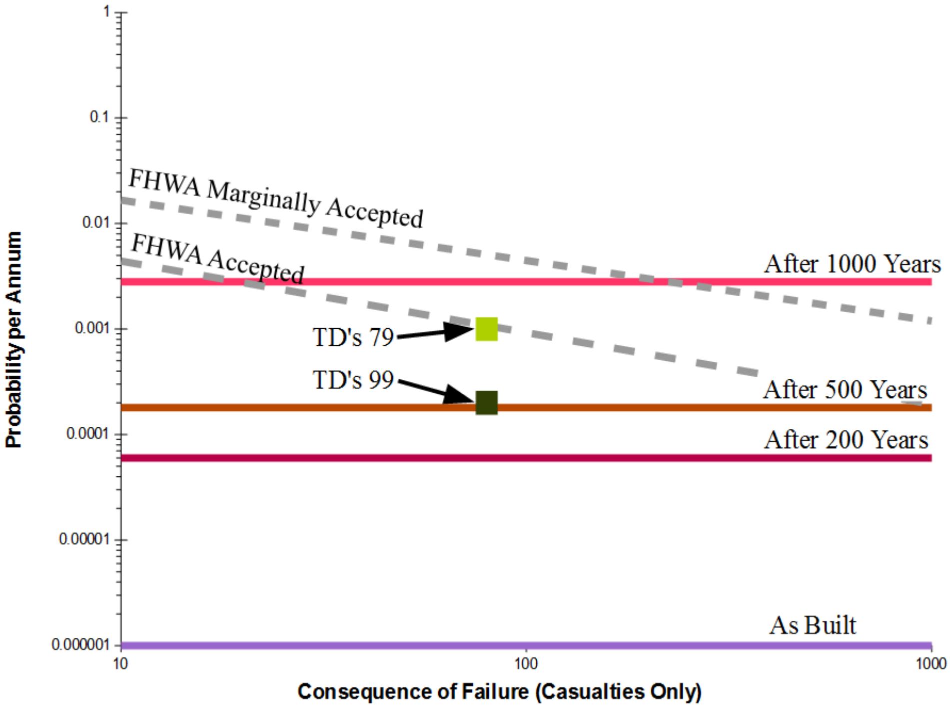

Fig. 5 Probability per Annum vs. Consequences for the "excellent" Category I example. As mentioned earlier the p_f value at 500 years is almost identical to the 1990s historic value, and the p_f value at 1000 years is three times the value of the 1970s. With an assumed tally of the "historic average" of 80 victims, the 1,000 years risks are societally intolerable; any increase of the consequences would push risks toward the intolerable domain. Poorer starting conditions (lower FoS, inferior standard of care) and larger damages (FoS decay per MCE hit) would lead the structure to a faster failure spiral and intolerable long term risks.

The conclusion is simple: the conditions described in our example are a minimum set for a generic example dam to be acceptable in the long run, unless adequate reserves are provided to perform critical repairs/reconstruction/replacement in the future. Any decrease of the initial FoS or release in the standards, any increase in the decrease of the FoS when the dam is hit by a MCE, will take the structure above the selected societal tolerability if the consequences (let us limit the discussion to casualties in this example) are compatible, and not any higher, than the long term historic average.

4.1 *Long-term, Post-closure possible mitigations*

As mentioned earlier the only way to reduce the probability of failure to at least the "historical value" around the 1970s would be either to repair the damage after each MCE/hazard hit, or to entirely avoid the damage. This is obviously "not entirely feasible" for economic and constructional reasons. An option is to reduce the consequences, but that again requires special measures (limit population, land use, or second lines of defense).

Risks, especially long-term ones can never be reduced to nil.

The general analyses developed above show that beyond the initial standards (FoS, standard of care), the decrease of the FoS at MCE hits is the leading parameter for the exponential decay and failure of a structure. Mitigation may mean in this case to foresee (and fund) structural checks, repairs and subsequent monitoring after each MCE hit.

Dams that were built under the assumption of allowable FoS decrease to 1.1 (ANCOLD, 2011) or even less, should be the object of specific checks and preventative works.

4.2 *Comparing alternative closure scenarios*

Thanks to the methodology described in this paper it becomes possible to rationally study the tradeoff between different levels of initial FoS and initial standard of care, long-term monitoring and preventative/reactive maintenance in order to keep the risks to the structure within the tolerable domain.

Rational comparison of alternatives is possible in terms of average probability of failure and detailed risks, if in a specific case, it is possible to consider future modification of landuse, demographics, agricultural pressure, etc. to build an evolutionary consequence model. Sophisticated consequences models can and have been formulated to date, including not only casualties, but direct and indirect environmental, economic consequences.

In many cases mining projects, capital expenditures etc. are evaluated in terms of Net Present Value (NPV). NPV is deterministic, can only accommodate uncertainties by means of an increase of the discount rate, i.e an indirect and opaque way to include risks, and, most critically, this approach makes any future expense that would occur after, say twenty years, "vanish" from the analysis. Because of the above, NPV should not be applied to this type of analyses. Instead, techniques like CDA-ESM (Oboni, Oboni, 2010) should be used.

5 CONCLUSIONS

The results of a risk assessment depend significantly on the period specified for the comparison or design of closure performance and on the level of care that is considered to be reached for the structure. A structure can start its life generating tolerable risks and evolve into an intolerable area.

This paper has explored the question of appropriate periods to be considered in a risk assessment of the performance of a closed tailings facility and has looked at the outcome of various risk assessments for various closure design periods spanning many Maximum Credible Events probabilistic occurrences, and the very long time sometimes referred to as perpetuity.

Most of the conclusions of this paper are well known, intuitive, and accepted: we all know that an abandoned structure will end up failing; we all know that excellent initial standard of care delays the decay, etc. However the methodology developed in this paper enables us to "measure" and give a sense to a complex problem, to transparently compare alternatives, to discuss rationally and openly the survival conditions, or to evaluate the premature failure of a structure.

The only way to reduce the increase of the probability of failure is to repair damage occurring as a result of each hazard hit, or to entirely avoid the damage. The second is generally “not feasible” for economic and constructional reasons. Risks, especially long-term ones, can never be reduced to nil. Engineering skills and good sense enable us to imagine robust solutions that, in an economically sustainable way, will deliver the best imaginable results.

It has been shown that the design of closure works for different time frames may result in significant cost differences and perception of what constitutes a good closure approach in addition to significantly different risk landscapes. Any decrease of the initial FoS or reduction in the standards of care, any increase in the decrease of the FoS when the dam is hit by a MCE, will take the structure above today’s societal tolerability if the consequences (the discussion was limited in this paper to casualties) are compatible, and not any higher than the long-term historic average. The general analyses developed in this paper show that beyond the initial standards (FoS, standard of care) the decrease of the FoS is the driving parameter for the exponential decay towards failure of a structure. Mitigation may mean in this case to foresee (and fund) structural checks, repairs and subsequent monitoring after each MCE hit.

Risk-based decision making founded on rational and conceptually sound risk assessment methodologies proves again to be an invaluable tool in bringing clarity to a complex and sometimes convoluted debate.

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