THE INCREASING NUMBER OF TAILINGS FACILITY FAILURES: NAVIGATING THE DECADE 2020-2029

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ABSTRACT

In 2011 (Chambers & Higman) the authors published the results of their research into worldwide tailings dam failures. This research, which involved developing the most complete list of tailings dam failures publically available (www.worldminetailingsfailures.org), showed the rate of tailings dam failures over the period 1940-2010 was relatively constant. There are two immediate implications of this finding. First, efforts to implement regulatory, engineering, and operating changes to lower the rate of tailings dam failures are not having the desired effect. Second, because the rate is staying the same, and the number of mines is increasing, the number of failures is also rising. In 2017 we (Bowker & Chambers) updated our data to include the half-decade from 2010-2014. We segregated the data into several different categories in accordance with observed impact, and noted that the failure rate remained essentially the same for the most important Serious and Very Serious failures. We also found a correlation between the production of copper ore, an analog often used for metal production in general, and the number of failures. We now have data for next half-decade, 2015-2019, and will show how this new data relates not only to the trends observed in previous decades, but also how it compares to the predictions we made for this time period, and what we predict for the next decade if significant changes to present practices for the design, construction, operation, and closure of tailings dams are not made.

RÉSUMÉ

En 2011 (Chambers & Higman), les auteurs ont publié les résultats de leurs recherches sur les défaillances mondiales de digues à stériles. Cette recherche, qui visait à dresser la liste la plus complète des défaillances de digues à stériles accessible au public (www.worldminetailingsfailures.org), a montré que le taux de défaillances des digues à stériles au cours de cette période 1940-2010 était relativement constant. Cette constatation a deux conséquences immédiates. Premièrement, les efforts visant à mettre en œuvre des modifications réglementaires, techniques et opérationnelles visant à réduire le nombre de défaillances de digues à stériles n'ont pas eu l'effet souhaité. Deuxièmement, comme le taux reste le même et que le nombre de mines augmente, le nombre de défaillances augmente également. En 2017, nous (Bowker & Chambers) avons mis à jour nos données afin d'inclure la demi-décennie de 2010 à 2014. Nous avons séparé les données en plusieurs catégories différentes en fonction de l'impact observé, et avons constaté que le taux d'échec restait essentiellement le même pour les plus importantes. Échecs graves et très graves. Nous avons également constaté une corrélation entre la production de minerai de cuivre, un analogue souvent utilisé pour la production de métal en général, et le nombre de défaillances. Nous disposons maintenant de données pour la prochaine demi-décennie, 2015-2019, et nous montrerons en quoi ces nouvelles données se rapportent non seulement aux tendances observées au cours des décennies précédentes, mais également aux relations que nous avons établies avec les prédictions que nous avons établies pour cette période, prédire pour la prochaine décennie si les pratiques actuelles en matière de conception, de construction, d'exploitation et de fermeture des digues à stériles ne sont pas profondément modifiées.

1 INTRODUCTION & BACKGROUND

In the last 5 years there have been three highly visible tailings dam failures – Mount Polley, British Columbia; Fundao, Minas Gerais, Brazil; and, Brumadinho, Minas Gerais, Brazil. The latter resulted in over 300 dead or missing, many of these mining company employees. What has changed? Unfortunately, the answer is very little. Brumadinho is only the 3rd largest tailings dam failure in terms of lives lost (the Mir mine, Sgurigrad, Bulgaria, is the largest; Los Cedros, Tlalpujahua, Michoacán, México in next). There have been large tailings dam failures in countries with long experience with mining, and with highly developed regulatory systems, including the US, Europe, Canada, and Australia. Fundao was the largest tailings dam failure on record in terms of volume of waste released – 43.7 Mm^3 (Padcal No.2, Luzon, Philippines, is next at 32.2 Mm^3).

What is causing concern is the rate at which these large, highly visible tailings dam failures are occurring. This paper will demonstrate that the rate at which these failures are occurring has, in fact, remained relatively constant since 1940. However, if the rate of failure remains constant, but the number of mines increases, and these mines become larger, then the number of failures, and the size and impact of those failures, will also increase.

2 MINE/DAM FAILURE DATA BASE

2.1 Background

There are some readily available, and sobering, statistics on tailings dam failures. Tailings dam fail at approximately 10 to 100 times the rate of water retention dams (Garbarino et. al. 2018). The major failure mechanisms are overtopping, earthquakes, static failures, etc. (ICOLD 2001). Upstream-type dam construction is associated with a majority of these failures (Rico et.al. 2008).

Yet despite the repeated impacts on public safety, and the financial and environmental impacts to society, both private and public, and the known existence of these failures for over 100 years, a number of very basic steps have not been taken. There is no data base of tailings dams, tailings dam failures, or statistics related to these failures (dam type, height, length, construction materials, etc.) No international or national institution tracks tailings dam failures (e.g. UN, ICOLD, USEPA, CDA, ANCOLD). And, there is no financial surety requirement for tailings dam failures.

The latter is important because society often ends up picking up a large share of the costs of catastrophic dam failures, either in terms of the direct economic costs of cleaning up these failures, or the indirect costs of the impacts when there is only partial or no cleanup. For example, the cleanup of the dam failure at Mount Polley has not only been subsidized by the public sector, but many businesses, tribal groups, and local individuals who suffered economically from the accident, were not compensated for those losses (Lavoie 2017). In 2015, the author estimated the cost of a catastrophic tailings dam failure was $543 million (Bowker and Chambers 2015). The accidents at Fundao and Brumadinho have resulted in multi-billion dollar legal actions by the Brazilian government. Given the immense costs associated with the dam failures in Brazil, the cost of the average catastrophic dam failure could be over one billion dollars now.

A water reservoir dam is an asset to its owners, making care and maintenance an investment, rather than a cost. A tailings dam is a financial liability to a mining company. If mining companies were required to have some form of financial surety, or insurance, for a catastrophic tailings dam accident, not only would the public receive more reliable compensation for their losses, and government for cleanup costs, but mining companies would also have a financial incentive to prevent tailings dam failures.

2.2 Data Limitations

Today there are only a few regional entities, like British Columbia and Alberta, who have accurate inventories of tailings dams within their jurisdiction. Because there are no international entities that track tailings dams, we don't know the number, types, and operational status of most tailings dams. There is no institutional incentive to report, collect, or analyze data on tailings dam failures. This is because for agencies and companies to report this information, they are reporting on their own failures. Few like to publically declare their own mistakes. And, in countries where press censorship is practiced, it is difficult to get information about tailings dam failures (e.g. Russia and China).

In an effort to get just an order of magnitude handle on the problem of tailings dam failures, we were forced to create our own database of mine failures from publically available sources (www.worldminetailings.org), primarily online. This data base of mine failures consists mostly, but not exclusively, of over 300 tailings dam failures beginning in 1915. Data pre-1940 is limited by lack of records; and a smaller number of events as tailings impoundment use increased, and as these dams increased in both number and size. It is also important to note that prior to passage of the Clean Water Act in 1972, it was still legal to dump mine waste directly into streams in the United States.

2.3 Categorization of mine waste failure events

We initially classified impoundment-related failures into 4 categories – Very Serious, Serious, Other Accidents, and Other Failures. The Very Serious and Serious categories encompass the most damaging tailings dam failure events. The number of the Other Accidents and Failures appear to have peaked in the period from 1960s to the 1980s, and have decreased since then, suggesting that improved management approaches and technologies have had a positive effect on these categories of failures. Data plotted for the figures in this paper represent only tailings dam failures, even though non-dam failures data (e.g. waste dump, sinkholes, etc.) do exist in the data base.

We developed the definitions for the different categories of tailings failures based on our own experience, and the definitions seem to provide both a meaningful distinction between failure types, and plausible informational statistical results. For the purposes of this paper, the focus will be on Very Serious and Serious Failures (defined below), since they are associated with events that impact the public.

- Very Serious Failure – multiple loss of life and/or release of $\geq$ 1,000,000 m^3 total discharge, and/or release travel of 20 km or more
- Serious Failure – loss of life and/or release of $\geq$ 100,000 m^3 discharge

These definitions are subjective, but as with all new definitions we had to begin somewhere. Ideally we would have a scale that represented social (human life), environmental (type of habitat and area impacted), and economic (loss). There is seldom any data on the economic value lost in a tailings dam failure, environmental damage data is sparse and selective, but human lives lost is typically precise. Nonetheless, environmental damage needs to be considered. No one would consider Mount Polly, which had no fatalities, a minor accident.

2.4 Data averaging and curve fits for projecting future failures

In order to get meaningful results from the tailings failure data, it must be averaged over a specified interval. Annual, 5-year, 10-year, and 20-year data average windows have been investigated (see Figure 1).

As can be seen in Figure 1, the statistical fit is better the longer the time-average period, but we have used a 10-year data average interval because it provides the best compromise between statistical fit and response to changing event frequency. At some time in the future, in 20 to 100 years, when there is enough data to provide better response for the 20-year data average interval, that period might become more appropriate to provide predictions, but at present there is not enough data recorded to provide an adequate prediction from this interval.

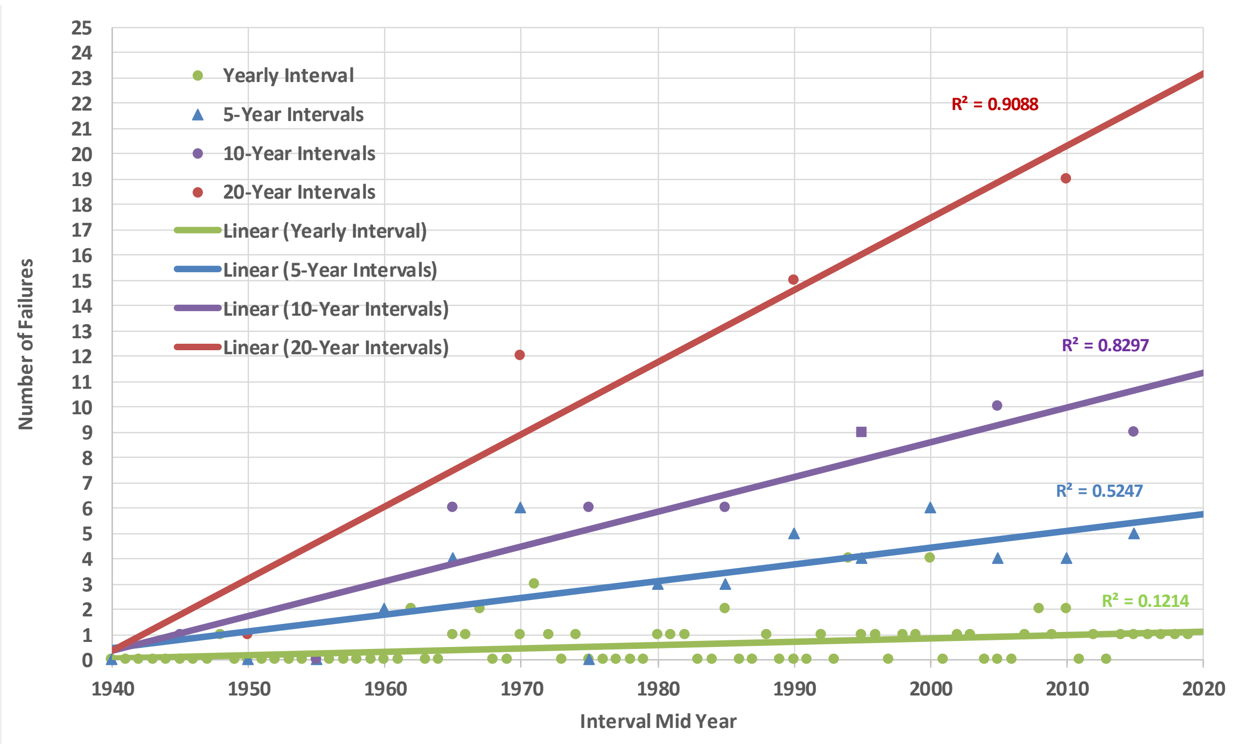

Figure 1: Very Serious Failures by Different Intervals

As can be seen from the intercept of the line fit with the far right vertical axis, all of the time intervals predict approximately 1 Very Serious Failures per year, which is close to the actual rate of occurrence.

It can be seen in Figure 2 that the rate of occurrence for Very Serious and Serious events are quite similar, and we see a relatively constant rate of failure continuing from 1940 to the present. It might also be argued that the two should be combined. However, because all catastrophic events will fall into the Very Serious category, and because the data trend for Very Serious Failures has slightly better regression statistics, it is useful to maintain the distinction between the two categories.

We also have data on lesser failures, but that information is clearly in a different failure cause and impact category, and as previously noted is not presented here.

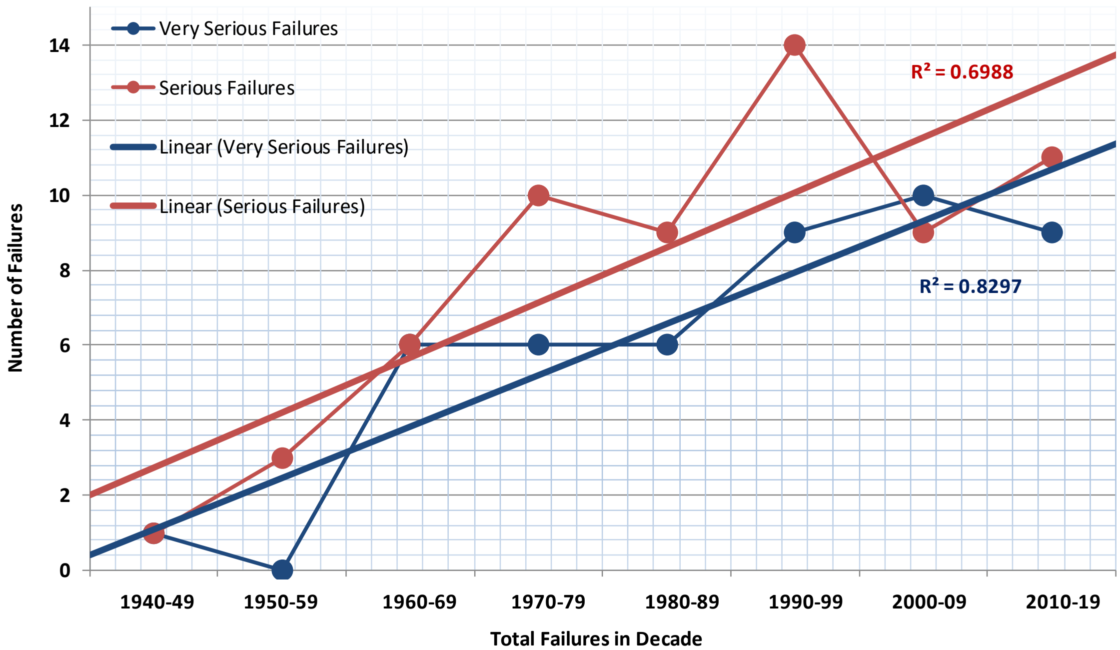

Figure 2: Failure Predictions with Linear Fit

This relatively consistent failure rate is alarming from two perspectives. First, it suggests that changes to management approaches, and in technological improvements, have not had a major impact in reducing the rate of large tailings dam failures. Second, if the tailings dam failure rate remains the same, but as the number of tailings dams increases, we will see more frequent, and as it turns out, larger tailings dam failures. In fact, this is what is happening.

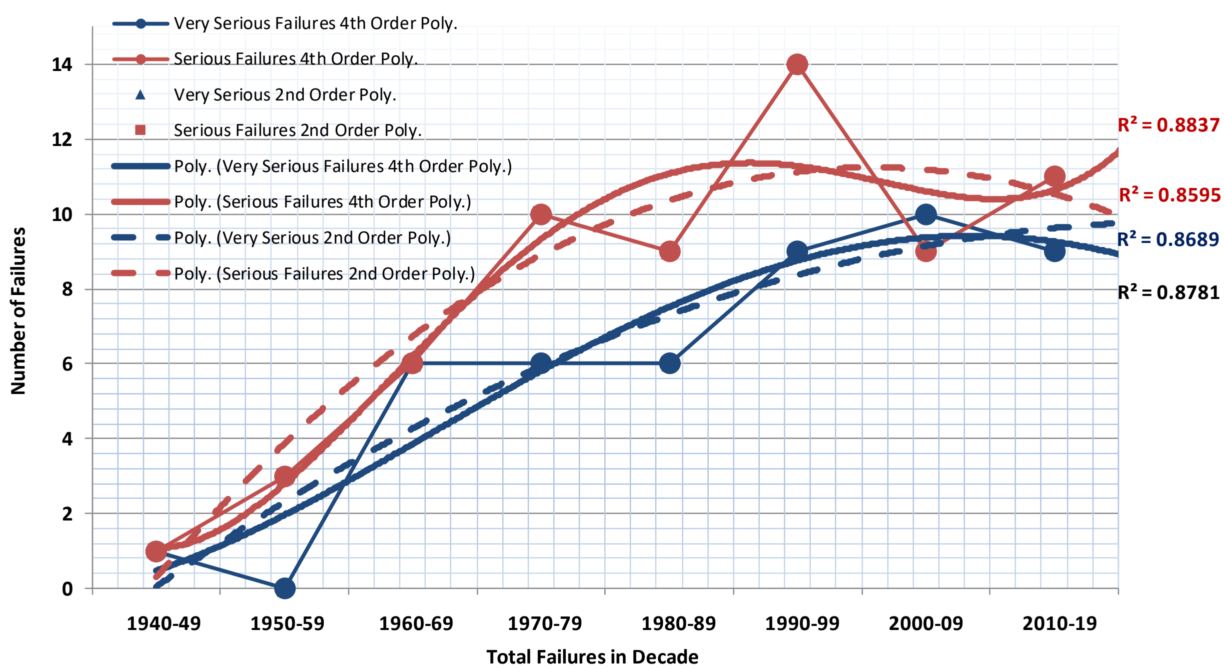

Figure 3: Failure Predictions with 2nd and 4th Order Polynomial Fits

Use of other curve fitting formulas for the data was also investigated. In Figure 3 the use of a second-order and fourth-order polynomial fits to the failure data are displayed. While there is a better fit statistically, it can be seen that the curve fit is being biased by the scatter in the data. We believe that using a linear fit to the data represents the best approach to predicting future events, at least for the present time.

There seems to be a downturn in the data trend beginning in the 1990-99 decade. With a curve fit it is easier to detect a bias in the predictions made from the data trend. By trying different curve fitting routines, including polynomial, exponential, and logarithmic, we believe that the linear fit gave the most consistent trend. Hopefully, with more data, and more reliable data, better interpretation methods can be utilized.

3 ESTIMATING THE NUMBER OF CATASTROPHIC TAILINGS DAM FAILURES

The constant rate of tailings dam failures first became apparent to the author in 2010. At that time the data available on tailings dam failures was even worse than today. In 2011 we (Chambers and Higman 2011) published a paper discussing this trend, but at that time only data on total failures was considered. In 2015 we (Bowker and Chambers 2015) developed our definitions for Very Serious and Serious failures, and published a paper discussing the trends in this segregated tailings dam failure data. It is now 5 years hence, and again we have data from an additional 5 years to analyze.

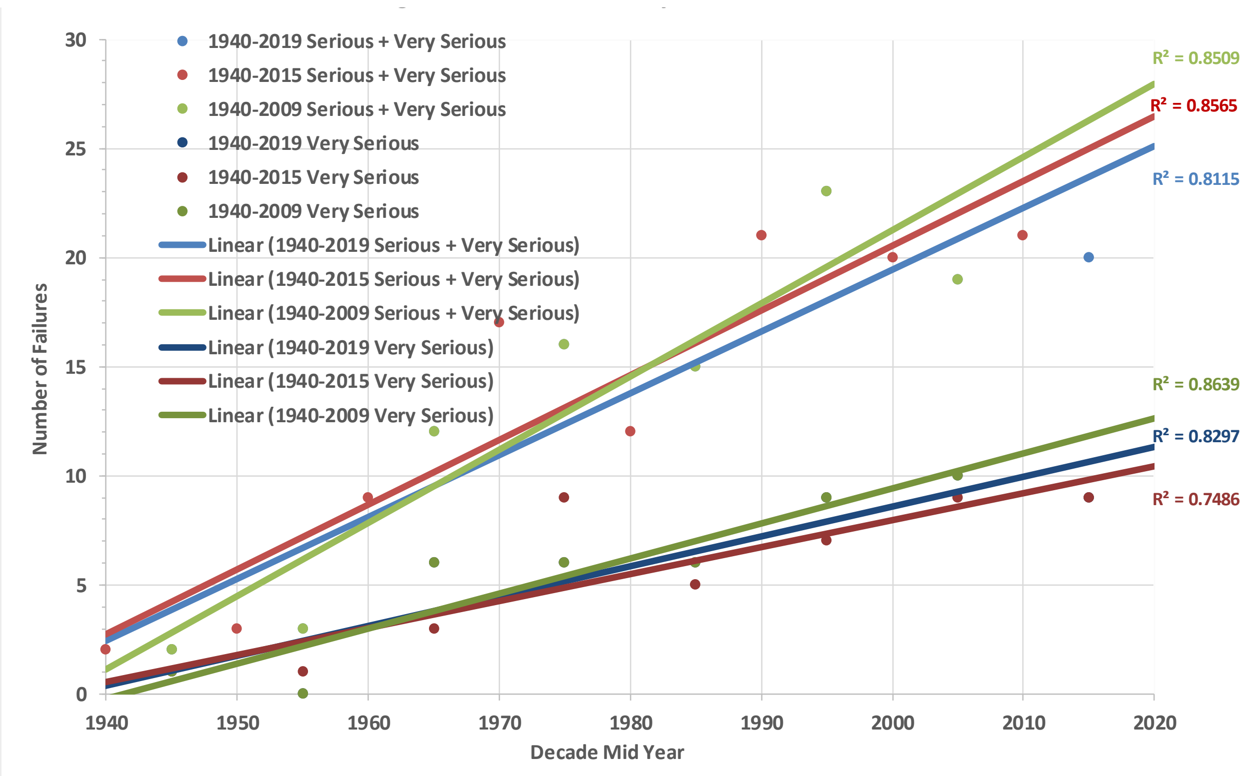

Figure 4: Very Serious Failures

In Figure 4 the Very Serious Failures and Serious Failures data available from 1940-2009 is plotted with associated trend lines. The lower set of lines is for Very Serious data only, and the upper set of lines for both Very Serious and Serious Failures. Similarly, the data from 1940-2014 and 1940-2019 is plotted. The

Very Serious Failure data shows some improvement in the tailings dam failure rate, on the order on one less Very Serious tailings dam failure per decade.

The trends for the combined Very Serious and Serious Failures show a consistent lowering rate over three consecutive periods. There are approximately 30% more Serious Failures than Very Serious Failures, so the Serious Failures data has more influence on the trend, suggesting that improvements to prevent failures are having more influence on the Serious Failures, the less-serious events. While this trend is positive, at this rate of change it would take another 80 years to realize a drop of one order of magnitude for tailings dam failure rate, approximately the failure rate for water supply reservoir dams.

This analysis predicts there will be, on average, approximately one Very Serious tailings dam failure per year. In the decade from 2005-2014 there were 8 Very Serious tailings dam failures, and in the decade 2010-2019 (to date) there have been 9 Very Serious Failures (Brumadinho, Minas Garias, Brazil, 2019; Cadia, New South Wales, Australia, 2018; Vedanta, Jharsuguda, India, 2017; Louyang, Xiangjiang, China, 2016; Fundao-Santarem, Minas Gerais, Brazil, 2015; Mount Polley, British Columbia, Canada, 2014; Padcal No 3, Benquet, Philippines, 2012; Ajka, Kolontár, Hungary, 2010; Xinyi Yinyan, Guangdong, China, 2010).

4 IMPLICATIONS OF TAILINGS DAM FAILURE RATE

Some interesting implications come out of this analysis.

There is no fundamental engineering reason for tailings dams to fail more often than water retention dams. So something is happening with tailings dam design, construction, operation, and/or closure that is not happening with reservoir dams.

There are some significant differences between tailings dams and water retention dams. Tailings dams are almost always constructed with mine waste, either waste rock or tailings, and use three construction types – downstream, centerline, and upstream. It is not possible to use upstream-type construction for water reservoir dams, and it would only be possible to use centerline construction for water retention dams if concrete were utilized. Upstream-type dam construction is associated with most tailings dam failures, yet is probably the most widely utilized dam construction type for tailings dams because of the lower construction cost (Rico et. al. 2008).

In addition to different construction types, tailings dams are almost always constructed in lifts, or stages, one to several years apart. This is related to the availability of dam construction materials (mine waste rock or tailings), but means that many different individuals, sometimes different companies, and often significant design changes, lead to potential complications in integrating the different stages.

The Mount Polley Expert Panel Report offered a number of sage suggestions on how to break the cycle of failure that plagues tailings dams. The overall sense, and explicit observation, of the panelists was that "*The Panel firmly rejects any notion that business as usual can continue*." (Expert Panel 2015).

The Panel left the definition of "Business-as-Usual" open to interpretation, but to this author it means:

- Wet closures are the best option for PAG waste;
- Cost is the primary driver in tailings dam construction;
- Risk is focused on risk to mine operators and regulators, not on risk to public safety; and,
- Better engineering is the answer to these problems.

The author has reviewed the following post-Mount Polley changes to regulatory requirements and professional organization guidance: the British Columbia Mines Act and Health Safety & Reclamation Code Part 10 (2017); the Montana Act Revising Metal Mine Reclamation Laws, Establishing Standards for Tailings Storage Facilities, and Creating Independent Review Panels (2015); Alberta Regulation 205-98 Part 6 Dam & Canal Safety (2018); the Mining Association of Canada Guide to the Management of Tailings Facilities, Third Edition (2017); and, the Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries, European Commission (2018).

The primary response in most of the world to the recommendations of the Mount Polley Expert Panel has been to require Independent Tailings Review Boards, with the major exception of the European Commission, which requires an independent review, by only by an individual (Garbarino et.al. 2018). It is also of note that the failed Fundao tailings dam had an independent tailings review board (Fundão Review Panel 2016). The Mount Polley Expert Panel recommendation for eliminating wet closures are only minimally addressed in post-Mount Polley regulatory revisions, except for the European Commission (2018).

The Mount Polley Expert Panel recommendations for making safety “first” has largely been overlooked. Most post-Mount Polley regulatory changes make safety one of, but not the primary, consideration in risk assessment and the design, construction, operation, and closure of tailings dams.

5 DISCUSSION

What does the tailings dam failure rate data tell us? It says the failure rate for tailings dams is relative constant, but with more mines there are more failures, and with larger mines there are larger, more damaging failures. We can also see that despite the explicit warning issued by the Mount Polley Expert Panel, Business-as-Usual is continuing.

It may not be surprising, but there is also a correlation between tailings dam failures with increasing waste production (Bowker and Chambers 2017). If the average grade of ore minerals declines, as it does for most base and precious metals, and the demand for these metals by society increases, more waste per unit of metal is produced. This increase in waste production requires more waste storage facilities, resulting in more and larger tailings dams – a few of which will fail.

What are potential engineering-related approaches to bringing the tailings dam failure rate down? To make the change from business-as-usual to a new approach to tailings dams will be painful from a process point of view, and will be expensive – but economic costs society should be willing to pay to avoid the catastrophic impact on the individuals affected by a catastrophic dam failure.

Some suggested considerations are:

- Find an organization to put together a data base on tailings dams and tailings dam failures (dam type, height, length, construction material, etc.) so that we can understand the nature of the problem.

- Find a mechanism to organize an international source for catastrophic tailings dam failure insurance. Requiring financial assurance for a catastrophic event would only make the mining industry comply with financial surety requirements that are already levied on similar businesses, like the oil & gas and chemical industries. Right now, mining is getting a big economic break by avoiding a financial surety for catastrophic failures. The industry itself would probably be the best source to organize this funding assurance.

- Make independent tailings review boards truly independent by making their proceedings, or at least their determinations, transparent. There are some entities that argue that the deliberations and recommendations from independent tailings review boards and an operating company should remain confidential in order to foster open dialog (MAC 2017). But if a company can chose to ignore the recommendation of an independent tailings review board, the publics only backstop is regulatory oversight – which didn't work in the recent instances of catastrophic tailings dam failures in Minas Gerais and British Columbia.

- Make dry closure the starting point for all waste impoundments, even for tailings deposited in wet impoundments. Wet closures, even for potentially acid-generating waste, should only be undertaken if it can be demonstrated through formal risk assessment that the long-term risk to public safety is less with a wet closure than with a dry closure. The Mount Polley Expert Panel noted: "*… the Mount Polley failure shows why physical stability must remain foremost and cannot be compromised. ... No method for achieving chemical stability can succeed without first ensuring physical stability: chemical stability requires above all else that the tailings stay in one place*." (Expert Panel 2015)

- Make public safety explicitly the primary (but not the only) consideration in tailings dam risk assessment. Until safety is explicitly made the primary consideration for the design, construction, operation, and closure of tailings dams, cost will continue dominate the process. Here observing human nature is important. For example, it is logical to convince ourselves that upstream-type dam construction can be done safely, that we understand all of the important engineering factors. But in following this path we are in essence assigning a risk to future generations to which they have no input. We build them, but they will ultimately need to take care of them.

- Recognize that human factors must be taken into proper consideration in dam design. Anytime there are people involved in a process, they will inevitably make mistakes. Dam design should minimize the dependence on human involvement, for example the need for long-term monitoring and maintenance, and maximize redundancy for dam safety features. The Mount Polley Expert Panel noted: "*Tailings dams are complex systems that have evolved over the years. They are also unforgiving systems, in terms of the number of things that have to go right. Their reliability is contingent on consistently flawless execution in planning, in subsurface investigation, in analysis and design, in construction quality, in operational diligence, in monitoring, in regulatory actions, and in risk management at every level. All of these activities are subject to human error. Human error is often, if not always, found to play a key role in technological failures. And human error will always be with us, as much as we might wish it to be otherwise*." (Expert Panel 2015).

- Significantly restrict, perhaps eliminate, the use of upstream-type dam construction. There is too much risk with upstream-type construction in areas with more than low seismic risk, or in areas with net-precipitation.

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