



Tailings Dam Failures: A Historical Analysis of the Risk

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Abstract The number of great magnitude tailings dam collapses has made society increasingly aware of the need to better understand the risk associated with tailings dams' collapse. Also, the analysis and studies of prior disasters should define the risk profiles and lead to the adoption of more adequate and successful policies and measures to reduce hazards. For this, we evaluated the material post-failure behavior, the construction methods, the failure causes and the geographical distribution of tailings dams' failures worldwide. The post-failure behavior was evaluated by the occurrence or absence of flow sliding recorded after the collapse. The historical risks were analyzed by the F–N curve. It was thus possible to better understand these structures' safety historically, as well as to analyze their relationship with the material's behavior. The statistics indicate the correlation between flow behavior and the event consequences. A correlation was also observed deriving from upstream failures, certain materials, some causes of failure and flow sliding. The F–N charts analysis remarks that the unsafety of tailings dams is due to

upstream dams since other construction methods present risks under acceptable ranges.

Keywords Tailings dam failure · Risk analysis · Historical risk · Flow sliding

Introduction

Tailings dams are structures particularly susceptible to failures [1], with causes broadly discussed in the geotechnical community [1–6]. Dam collapses are the most devastating types of failures and often result in mudslides [7], with the release of the material with high potential energy [8].

The impact of a tailings dam failure, therefore, depends on travel distance and path, as well as its surrounding exposure and vulnerability [9]. Therefore, it is necessary to evaluate the mechanical properties of the material, the flow behavior and the potential velocities and runout [10]. Flow slide of tailings is a phenomenon related to many devastating tailings dam failures [11]; nonetheless, few studies analyze the dam break process and the possibility of the flow of tailings.

Case histories might assist in the identification of the most frequent causes of failure [12]. Also, it may be used to comprehend the historical risk associated with these structure failure probabilities and losses. However, it has been observed a limited effort from the industry and the scientific community to incorporate the material behavior post-failure in the risk assessment [13]. A simple way is to incorporate it in the fault tree analysis (FTA)—a logic method to identify possible outcomes and their respective probabilities after a failure event [14].

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This paper studies the historical failure of tailings dams by using various methods [15–18] and from multiple perspectives to increase the understanding of the risk associated with these structures. Both the probabilities of failure and the losses were closely analyzed. It was observed the close relationship between the type of failure and geometry to the presence of flow of liquefied tailings dams and also was observed the close relationship between the flow collapse and event consequences. Finally, a simplified fault tree analysis was built based on historical tailings dams’ failures and considering post-failure behavior, to assist risk assessment studies.

Analysis on Historical Tailings Dam Failures

The Bowker and Chambers Database [19–21] for tailings dam failures as of June 2020 and the WISE database as of December 2020 [22] were adapted and used in this research. The tailings dam accidents are analyzed from two different perspectives to facilitate the fault tree analysis: the total number of accidents and the accidents in which a flow sliding behavior was observed. The historical data from 1940 to June 2020 are summarized in Fig. 1 to understand the risk. Similar trends can be observed in both failures (total and with flow sliding), with the number of accidents increasing in the 1950s and remaining roughly constant from the 1970s to the 2000s. After the 2000s, however, there was a decrease in the number of reported accidents, following an increase in the 2010s as also highlighted by Bowker and Chambers [20]. The years with the highest number of tailings dam failures observed were 1965 due to the Valparaíso earthquake in Chile [23] and 2018 with no clear cause. In total, there were 356 tailings

dam failures, with 82 resulting in liquefied tailings post-failure flow.

Figure 2 presents the geographical distribution of tailings dam failures. The country with the most tailings dam failures reported was the USA (32%), followed by Chile (11%) and Canada (9%). Figure 3 illustrates the geographical distribution of flow sliding accidents. Most of the events with liquefied flow failures occurred in Chile (21%), more than 42% of its failures, due to the country’s seismic liquefaction history. The USA had 13% of flowing events and Peru, 10%. Brazil showed 6% of the recorded flow slides, but 46% of accidents in the country flowed even without seismic instability.

Figure 4 shows that copper tailings dams are the most common to fail and 30% of these presented flow liquefaction collapse. This connection between minerals and flow failures is often higher than 30%, with only uranium and phosphate having very low flow liquefaction rates. However, there is still a risk of casualties due to failure. Consequently, the tailings material is not considered a good enough parameter for the fault tree analysis.

Figure 5 displays the tailings construction method associated with failure. For the dam geometry involved in the total number of failures, the highest number of incidents occurred in upstream (US) dams (58%)—a decrease when compared with the 76% observed by Rico et al. [24]. Upstream structures have a high risk of flow sliding failures (88%) and more than 40% of the US failures presented flow behavior.

The main cause of tailings dam failures as reported in the literature is indicated in Fig. 6. The three most known causes of failures are slope instability (24%), overtopping (23%) and earthquakes (19%), but most of the failures have unknown causes. This distribution of causes is in

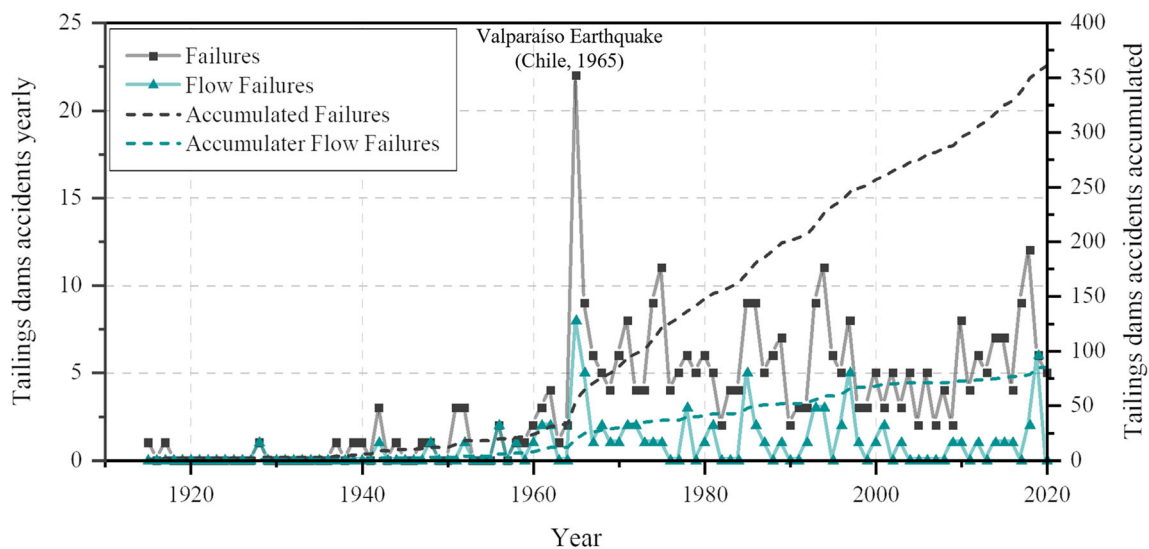


Fig. 1 Tailings dam failures recorded yearly from 1940 to June 2020

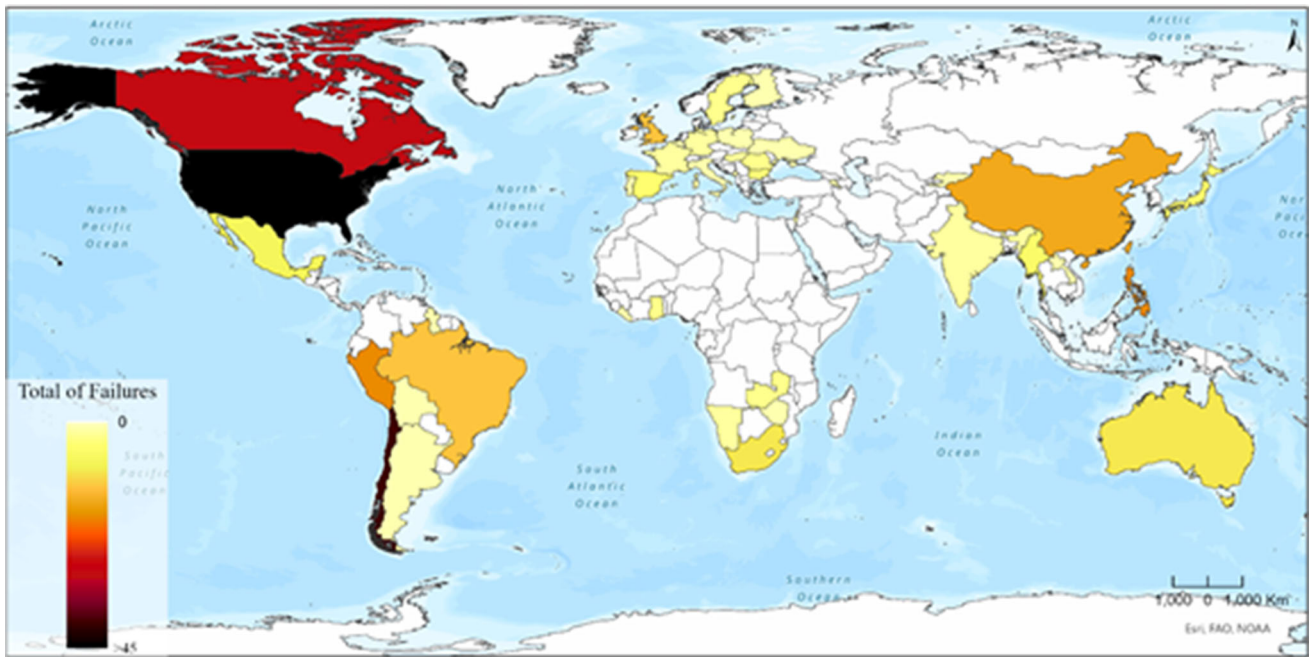


Fig. 2 Geographical distribution of the historical tailings dam failures events

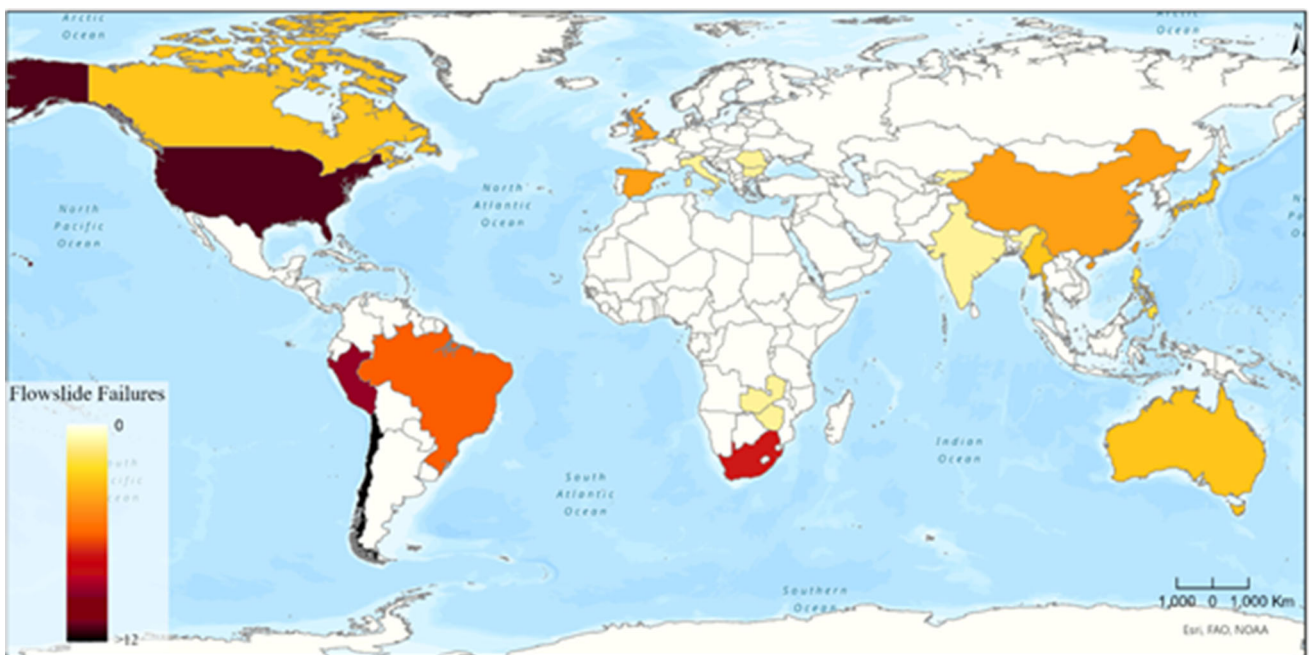


Fig. 3 Geographical distribution of the historical tailings dam failures associated with flow of liquefied tailings

accordance with the ones presented by Rico et al. [24]. The main cause of flow sliding failures is earthquake-induced failures (41%), followed by slope instability (29%) and overtopping (13%). There is a strong correlation between flow sliding and earthquakes (> 50%) and slope instability (> 35%). In turn, failures due to structural problems presented fewer records of flow sliding.

Risk Analysis Methodologies

In this paper, the risk of tailings dam failures was analysed based on the base sub-model proposed by Shen and Hwang [25] and the probability and consequence of failure according to the accepted risks defined by the literature [15, 17, 18]. The loss parameters were defined as the

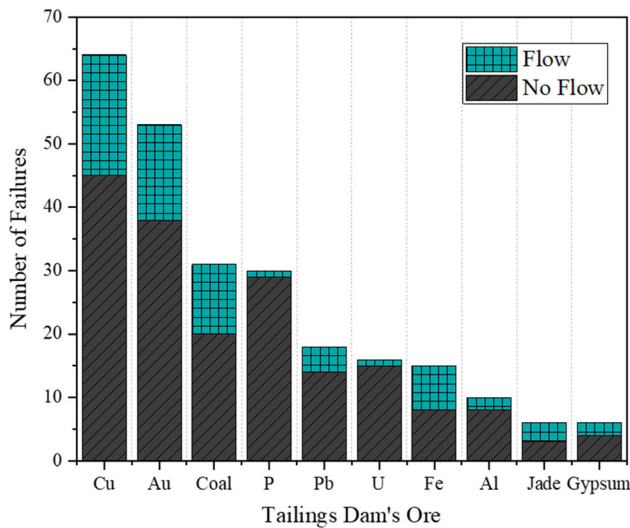


Fig. 4 Tailings dam failure distribution according to ore and records of flow slide; following the periodic table Cu = copper, Au = gold, P = phosphate, Pb = lead, U = uranium, Fe = iron, Al = aluminum

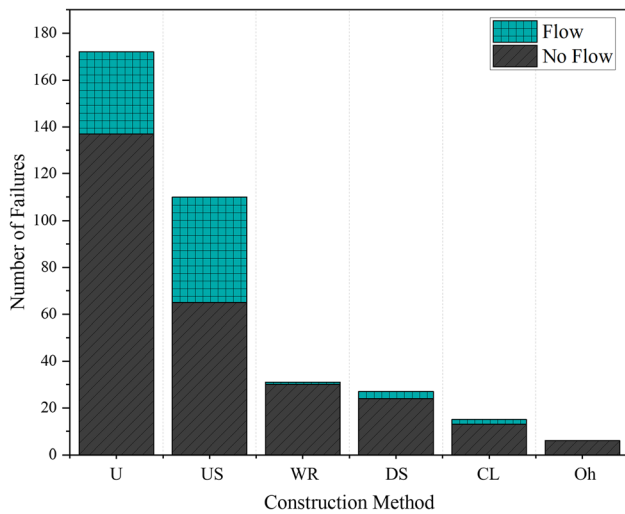


Fig. 5 Tailings dam failure distribution according to construction method and records of flow slide, where U = unknown, US = upstream, WR = water retention, DS = downstream, CL = centerline, Oh = others

number of dead and missing people, since data for economic losses is limited.

Risk Assessment of Tailings Dam Failures

The tolerability, or F–N curves, summarizes the relationship between frequencies of failure and the human or monetary costs and is a good way to compare the risk associated with different structures [15–18, 26]. The losses caused by tailings dam failures were then compared to the annual probability of failures, taking into consideration

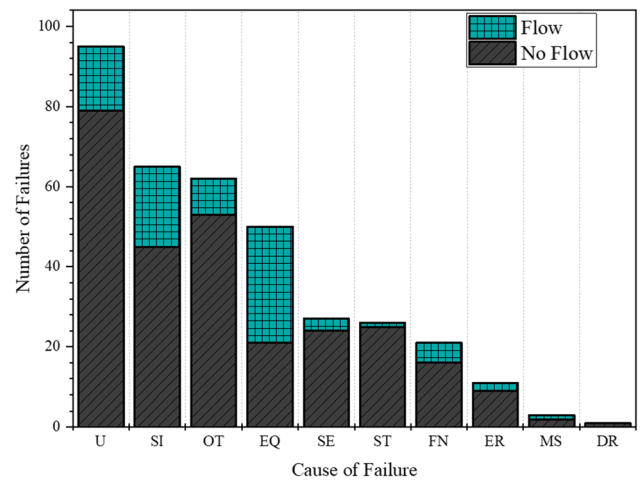


Fig. 6 Tailings dam failure distribution according to the cause of failure and records of flow slide, where U = unknown, SI = slope instability, OT = overtopping, EQ = earthquake, SE = seepage, ST = structural, FN = foundation, ER = erosion, MS = mine subsidence and DR = drainage

three different factors of analysis: the country, the mined material and the dam construction methods.

For the country analysis, the probability of failure was calculated by dividing the failures recorded in the database chosen for this study and the estimated number of tailings dams according to a national inventory or the literature. The context for Brazil, the USA and Chile was also estimated since there are readily available state databases with inventories of the tailings dams by their respective agencies [27–30]. In China, the number of 8,000 dams was found in news reports [31] while Yin et al [32] estimated 12,000. In Australia, due to the paucity of data, the number of dams was roughly estimated by doubling the 350 dams accounted for Western Australia, as this province corresponds to approximately half of the country’s tailings dams [11, 33]. Due to the absence of information on the number of tailings dams in Myanmar, its annual probability of failure was not analyzed.

Different values are found in the literature as for the number of tailings dams in the world [34–36]. It is not possible to determine an exact number of tailings dams worldwide; thus, to better contemplate the data from national records, the value of 18,400 as proposed by Azam and Li [34] was used in this research. To detail the TSF characteristics, however, the Franks et al. [35] tailings facilities database was used. According to the database, the ores with the most recorded tailings dams are gold (27%), copper (13%), coal (9%), zinc (8%) and iron ore (7%). The construction methods more common are upstream (43%), downstream (27%) and centerline (9%), and those that diverge from these were labeled as others (21%). This database was used as a representative sample of the total of

tailings dams as its calculated sampling errors of 10% [35] were considered negligible in probability studies defined by order of magnitude.

The annual probability of failure was firstly estimated for the total number of accidents since 1950—the last 70 years. For the last 70 years of historical data used in the first three analyses, however, calculations were needed to determine a better approximation. According to reports from Reuters [31] and Franks et al [35], the construction of new tailings dams gained momentum around the 1950s and, after that, has increased yearly. Therefore, in order to calculate the number of existing tailings dams used in the annual probability of failure, the number of yearly built tailings dams was supposed to increase at a linear rate starting in 1950. Thus, the average number of tailings dams in the 70 years was determined by the average of the total of tailings dam parabolic curve, approximated by dividing the number of existing tailings dams by three. Due to evolving engineering development and population characteristics, the tailings dam risks from the 2010s were also calculated. For the 2010s case, the total of existing dams was used as an adequate approximation.

Adaptation of the Base Sub-Model

The base sub-model is used to describe the distribution of disasters by type, for each country described in the database [25]. It was used here to evaluate the distribution of the tailings dam failures per country ($k = 0, 1, 2, \dots$, in alphabetical order), according to the cause of failure ($i = 1, 2, \dots, m$). The cause of failure is defined by $i = 1$ for overtopping, $i = 2$ for slope instability, $i = 3$ for earthquake, $i = 4$ for seepage, $i = 5$ for foundation, $i = 6$ for structural inadequacy, $i = 7$ for erosion, $i = 8$ for mine subsidence, $i = 9$ for drainage and $i = 10$ for unknown. This method was used to study the tailings dam flow failures relating their causes. Also, t_i^k is the number of tailings dam failures of cause i in country k . The probability distribution P_i^k of cause i in country k , therefore, is defined as the division of this number by the total number of failures by each country, as in Eq 1.

$$P_i^k = \frac{t_i^k}{\sum_{i=1}^m t_j^k} \tag{Eq 1}$$

The total of death and missing people is defined as the accident loss, l_j^k , of cause j in country k and can be calculated by summing the individual losses of each individual accident ($j = 1, 2, \dots, n$) of cause i in country k , r_{ij}^k , as in Eq 2. For each country, therefore, there will be an expected loss, R_{BM}^k , that is equal to the average of the various causes of failure in tailings dams by their probability of occurrence previously calculated, as presented in Eq 3.

$$l_i^k = \sum_{j=1}^n r_{ij}^k \tag{Eq 2}$$

$$R_{BM}^k = \sum_{i=1}^m P_i^k l_i^k \tag{Eq 3}$$

Results

Risk Analysis of Historical Events

Figure 7 presents the number of casualties of the ten countries with the highest number of deaths and missing people recorded. Most of the events with severe consequences in the literature registered flow sliding. Also, the guidelines by ANCOLD [16], FERC [17] and Whitman [18] were used as societal risk criteria.

Table 1 summarizes the probability calculations for the six materials studied: iron, gold, zinc, coal, copper and lead. The materials selected were associated with the highest losses and were limited to a total of six for clarity purposes. The probability of failure for all the different tailings is of about the same order of 10^{-4} . However, we can still see the relation of higher consequences in failures due to flow behavior, which is around five times higher than the total of failures to five of the six materials, with iron tailings dams exceptionally presenting the same risks. Events without flow slides present average casualties lower than 10, and events with flow slide present casualties averaging from 10 to 100. For the structures analyzed, the risks of tailings dams for the total of events are higher than the more recent tolerability curves presented by FERC [17] and ANCOLD [15] and only tolerable to outdated risk perceptions [18].

Table 2 summarizes the probability calculations for the four construction methods analyzed: upstream, downstream, centerline and others, as well as the accidents of

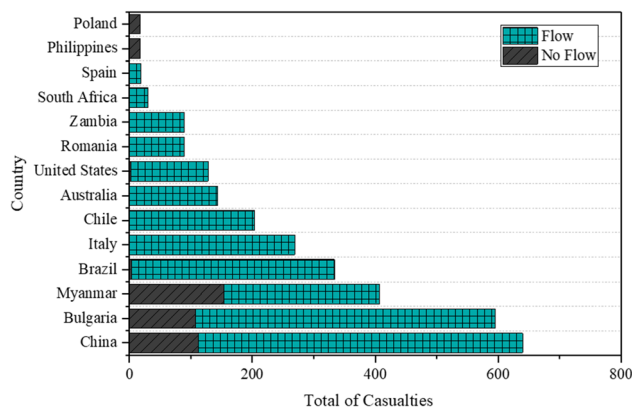


Fig. 7 Number of casualties recorded to the ten countries with the most risks

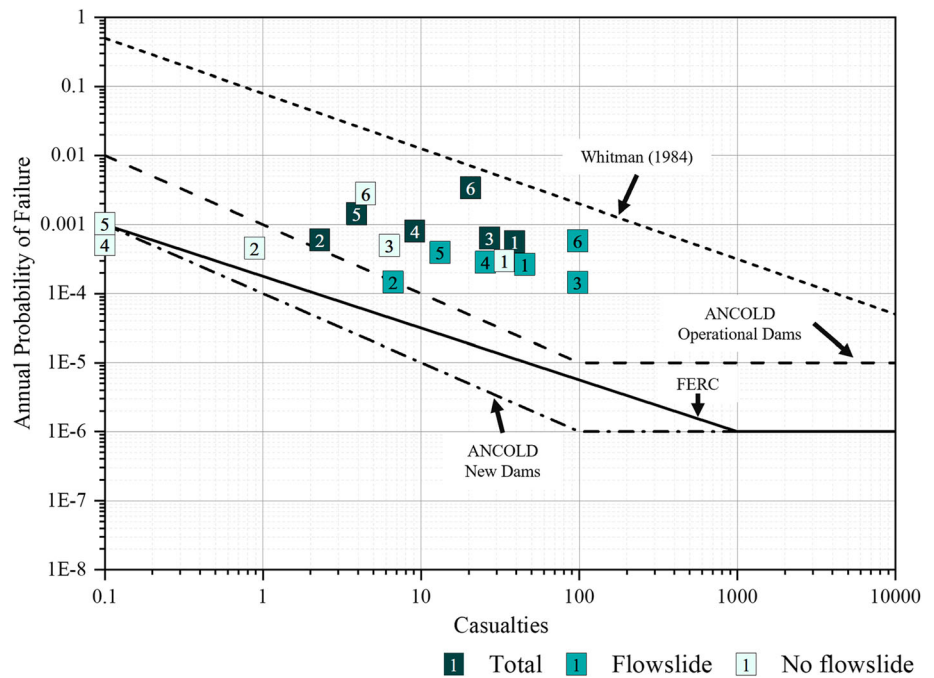
Table 1 Summary of risk calculations for the main ore tailings for the last 70 years

Ore	Percentage of dams (%)	Total of dams by ore	Casualties	Number of failures	Percentage of failures (%)	Average casualties	Annual probability of failure
<i>Total of failures</i>							
Iron	7	1288	664	17	4.8	39	5.66E–04
Gold	27	4968	160	70	19.7	2	6.04E–04
Zinc	8	1472	596	22	6.2	27	6.41E–04
Coal	9	1656	283	31	8.7	9	8.02E–04
Copper	13	2392	313	80	22.5	4	1.43E–03
Lead	2	368	596	29	8.1	21	3.38E–03
<i>Flow failures</i>							
Iron	7	1288	362	8	2.2	45	2.66E–04
Gold	27	4968	113	17	4.8	7	1.47E–04
Zinc	8	1472	489	5	1.4	98	1.46E–04
Coal	9	1656	281	11	3.1	26	2.85E–04
Copper	13	2392	290	22	6.2	13	3.94E–04
Lead	2	368	489	5	1.4	98	5.82E–04
<i>Failures without flow behavior</i>							
Iron	7	1288	302	9	2.5	34	2.99E–04
Gold	27	4968	47	53	14.9	1	4.57E–04
Zinc	8	1472	107	17	4.8	6	4.95E–04
Coal	9	1656	2	20	5.6	0	5.18E–04
Copper	13	2392	23	58	16.3	0	1.04E–03
Lead	2	368	107	24	6.7	4	2.80E–03

Table 2 Summary of risk calculations for tailings dams’ construction methods for the last 70 years

Construction method	Percentage of dams (%)	Total of dams by method	Casualties	Number of failures	Percentage of failures (%)	Average casualties	Annual probability of failure
<i>Total of Failures</i>							
Upstream	43	7,926	1709	113	31.7	15	6.11E–04
Downstream	27	5,031	10	27	7.6	0	2.30E–04
Centerline	9	1,583	0	15	4.2	0	4.06E–04
Other	21	3,860	0	34	9.6	0	3.77E–04
Unknown	100	18,400	1205	168	47.2	7	3.91E–04
<i>Flow failures</i>							
Upstream	43	7,926	1271	44	12.4	29	2.38E–04
Downstream	27	5,031	0	3	0.8	0	2.56E–05
Centerline	9	1,583	0	2	0.6	0	5.41E–05
Other	21	3,860	0	1	0.3		1.11E–05
Unknown	100	18,400	798	34	9.6	23	7.92E–05
<i>Failures without flow behavior</i>							
Upstream	43	7,926	438	69	19.4	6	3.73E–04
Downstream	27	5,031	10	24	6.7	0	2.04E–04
Centerline	9	1,583	0	13	3.7	0	3.52E–04
Other	21	3,860	0	33	9.3	0	3.66E–04
Unknown	100	18,400	407	134	37.6	3	3.12E–04

Fig. 8 Evaluation of the risk of tailings dams according to tailings main ore since the 1950s. Ores are labeled as: 1 = iron; 2 = gold; 3 = zinc; 4 = coal; 5 = copper; 6 = lead



unknown geometry. Figure 8 illustrates the FN charts for the probability of tailings dam failure according to the tailings main ore. The total probability of failure of all the construction methods is observed to be of the same order, of 10^{-4} , but the probability of flow sliding is 10 times higher for the upstream method. The average casualties of upstream dams are two to three orders higher than the downstream method, second in the order, while the average casualties due to flow sliding for both upstream and unknown dams are around 2 times higher than the total of events and 5 times higher than the ones without flow sliding.

Figure 9 presents the FN charts for the probability of total failures, and discriminates those with and without flow sliding. From the structures with the construction method described, only upstream dams (1) have risks higher than the tolerable ones. The risk of tailings dams constructed by acknowledged safer methods, such as downstream (2) and centerline (3), or others (4), is tolerable.

Table 3 shows the summary for the annual probability of failure for each of the six countries analyzed, as well as the world's total. The worldwide probability of failure of 8.3×10^{-4} is in accordance with the failure of 1.2% of the total of tailings dams before the 2010s (an annual probability of 6×10^{-4}) observed by Azam and Li [34]. The probability of failure follows in the number of failures for all the countries, with the country with the highest probability being the US followed by Chile and Australia in the total of failures, and the highest for flow failures being

Chile, followed by the USA and Brazil. For the average losses per accident, Italy is the leading country—primarily due to the occurrence of only one high magnitude accident—followed by China, Brazil and Australia. These four countries presented an average loss higher than the global events. Also, flow sliding failures have average losses more than 5 times higher than the total events, indicating greater consequences of tailings dams with post-collapse flow behavior.

Figure 10 illustrates the correlation between these results and the tolerability curves. Remarkably, the historical risk associated with tailings dams is not within recent acceptable ranges. For the past 70 years, the risk of tailings dams' failures presents an approximate constant individual risk of 10^{-2} p.a., or in the cases analyzed, there was a probability of 1% of an annual casualty due to tailings dam collapse. For the 2010s decade, however, a constant individual risk could not be observed.

The risks of tailings dam flow sliding seem to be very closely related to flow failures, with a similar number of casualties despite the decreasing trend in the number of accidents. Therefore, the average loss for post-failure flow behavior is higher than for the total failures. The risks involved with these types of accidents are still not in the engineering current risk acceptable range.

The risks of tailings dams were compared to the ones observed by Whitman [18] to related civil engineering structures and highlighted in red in Fig. 10. Tailings dams present a frequency of failure like the one for water dams recorded before 1984. Also, other geotechnical structures,

Fig. 9 Evaluation of the risk of tailings dams according to their construction method since the 1960s. Construction method labeled as: 1 = upstream; 2 = downstream; 3 = centerline; 4 = other; 5 = unknown

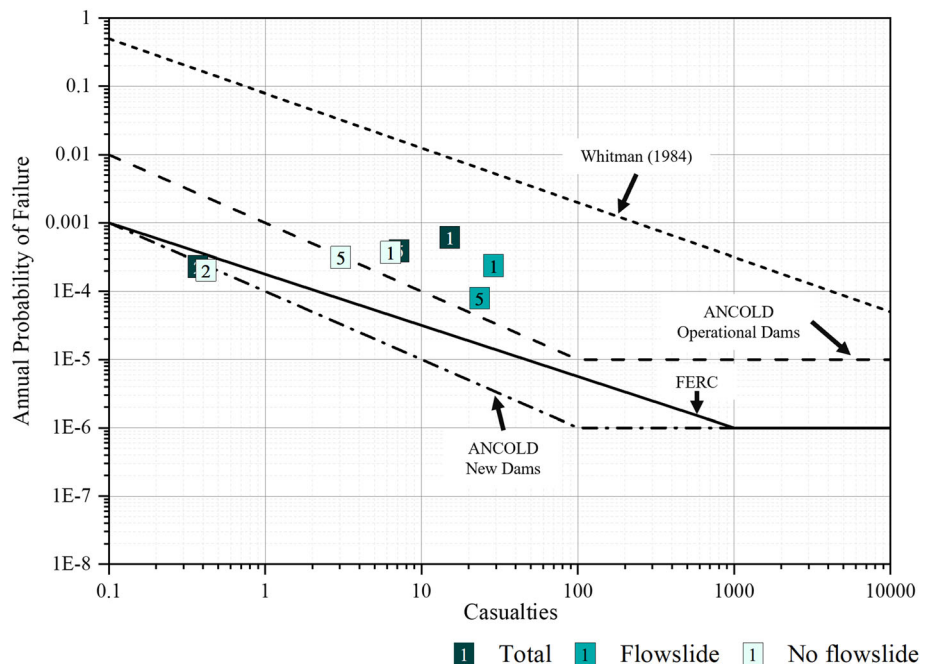


Table 3 Summary of risk calculations for the historical data of 70 years

Country	Tailings Dams	Source	Casualties	Number of Failures	Percentage of failures (%)	Average Casualties	Annual probability of failure
<i>Total of failures</i>							
Australia	700	*	144	14	3.9	10	8.57E-04
Brazil	762	ANM	322	13	3.7	25	7.31E-04
Chile	693	SERNAGEOMIN	204	40	11.2	5	2.47E-03
China	8000	Reuters	640	15	4.2	43	8.04E-05
Italy	650	ISPRA	269	1	0.3	269	6.59E-05
USA	1218	NID	128	114	32.0	1	4.01E-03
World	18400	Azam and Li [34]	2313	356	100.0	6	8.29E-04
<i>Flow failures</i>							
Australia	700	*	144	3	0.8	48	1.84E-04
Brazil	762	ANM	319	5	1.4	64	2.81E-04
Chile	693	SERNAGEOMIN	204	17	4.8	12	1.05E-03
China	8000	Reuters	251	4	1.1	63	2.14E-05
Italy	650	ISPRA	269	1	0.3	269	6.59E-05
USA	1218	NID	126	11	3.1	11	3.87E-04
World	18400	Azam and Li [34]	1727	82	23.0	21	1.91E-04
<i>Failures without flow behavior</i>							
Australia	700	*	0	11	3.1	0	6.73E-04
Brazil	762	ANM	3	8	2.2	0	4.50E-04
Chile	693	SERNAGEOMIN	0	23	6.5	0	1.42E-03
China	8000	Reuters	389	11	3.1	35	5.89E-05
Italy	650	ISPRA	0	0	0.0		0.00E+00
USA	1218	NID	2	103	28.9	0	3.62E-03
World	18400	Azam and Li [34]	586	274	77.0	2	6.38E-04

*Rough estimate based on Davies 2002

Fig. 10 Evaluation of the risk of tailings dams since the 1950s. Countries labeled in alphabetical order: 1 = Australia; 2 = Brazil; 3 = Chile; 4 = China; 5 = Italy; 6 = USA; 7 = world.

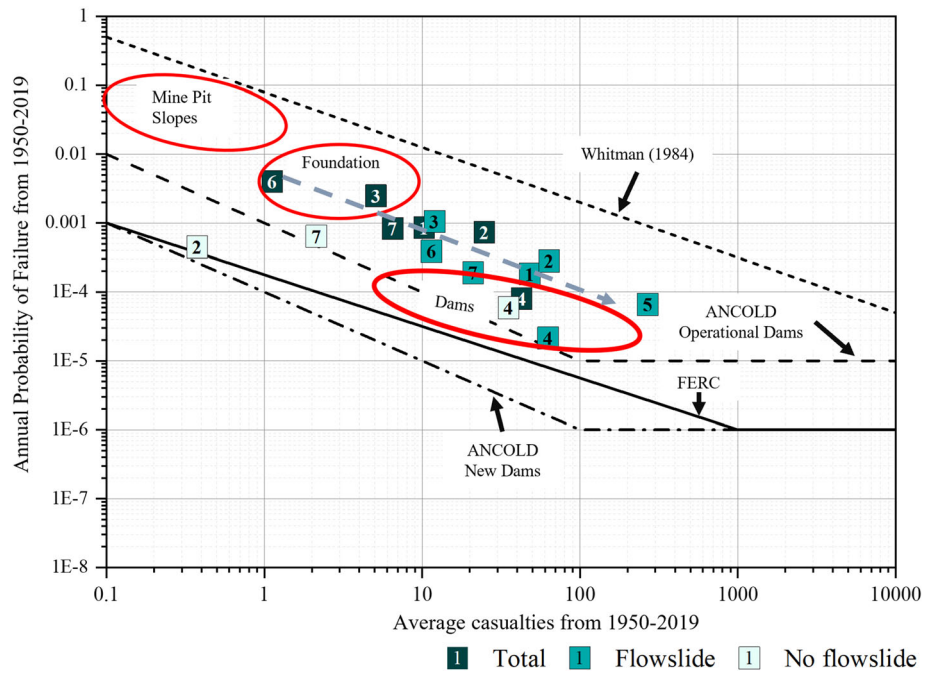


Table 4 Summary of risk calculations for the historical data of tailings dam failures for the 2010s

Country	Tailings dams	Source	Casualties	Number of failures	Percentage of failures (%)	Average casualties	Annual probability of failure
<i>Total of failures</i>							
Australia	700	*	0.01	4	5.9	0	5.71E-04
Brazil	762	ANM	304	6	8.8	51	7.87E-04
Chile	693	SERNAGEOMIN	4	6	8.8	1	8.66E-04
China	8000	Reuters	25	4	5.9	6	5.00E-05
Italy	650	ISPRA	0	0	0.0	0	1.54E-06
USA	1218	NID	1	10	14.7	0	8.21E-04
World	18400	Azam and Li [34]	600	68	100.0	9	3.70E-04
<i>Flow failures</i>							
Australia	700	*	1	0	0.0	100	1.43E-06
Brazil	762	ANM	301	3	4.4	100	3.94E-04
Chile	693	SERNAGEOMIN	4	1	1.5	4	1.44E-04
China	8000	Reuters	0	1	1.5	0	1.25E-05
Italy	650	ISPRA	0	0	0.0	0	0.00E+00
USA	1218	NID	0	0	0.0	0	8.21E-07
World	18400	Azam and Li [34]	401	12	17.6	33	6.52E-05
<i>Failures without flow behavior</i>							
Australia	700	*	0	4	5.9	0	5.70E-04
Brazil	762	ANM	3	3	4.4	1	3.94E-04
Chile	693	SERNAGEOMIN	0	5	7.4	0	7.22E-04
China	8000	Reuters	25	3	4.4	8	3.75E-05
Italy	650	ISPRA	0	0	0.0	0	1.54E-06
USA	1218	NID	1	10	14.7	0	8.20E-04
World	18400	Azam and Li [34]	199	56	82.4	4	3.04E-04

*Rough estimate based on Davies 2002

such as mine slopes and foundations, present higher probabilities of failure, but average casualties are two to three orders smaller.

The risk of failure of tailings dams updated for the 2010s is presented in Table 4 and Fig. 11, along with the tolerability curves. The yearly probabilities of failure have noticeably decreased in all the countries analyzed and in the world. The average losses have also decreased for all the studied countries except for Brazil. Worldwide, the average losses of tailings dams were higher in the last decade than the overall loss, in the last 70 years, whereas the annual probability has remained very similar. Again, the losses for flow sliding are higher than for total failures.

According to the F–N chart, the risk associated with tailings dam failures has decreased considerably for most of the studied countries. Currently, they are mostly within the range of acceptability for existing dams in the ANCOLD [15], except for Brazil. However, in Brazil and overall, according to the world’s statistics, the risk is currently higher than in previous decades. The previous apparent correlation is also not currently seen, as the annual probability of failure by country is no longer inversely correlated to the casualties. This indicates a shift in the risk of tailings dams from the countries that were historically more affected by these accidents. Apart from Brazil, Myanmar’s recent events also demonstrate an increase in associated risk, with a total of five events with more than 227 casualties—a number probably underestimated by far [37]—mostly in the same area of Hpakant. It is also highlighted that engineering risks associated with different structures have probably changed and decreased

in the last decades, as observed for tailings dams, and thus, the comparison of data from 1984 would be inappropriate.

Assessment Of Losses Involving Tailings Dam Failures

By using the base sub-model methodology, the consequences of tailings dam failure in each country are determined as the average of accidents. Figure 12 presents a distribution of the tailings dam failure risks calculated by the base sub-model for the totality of events as well as for flow failures, per country. Italy has the highest historical risk, with an average of 269 casualties per accident (21%),

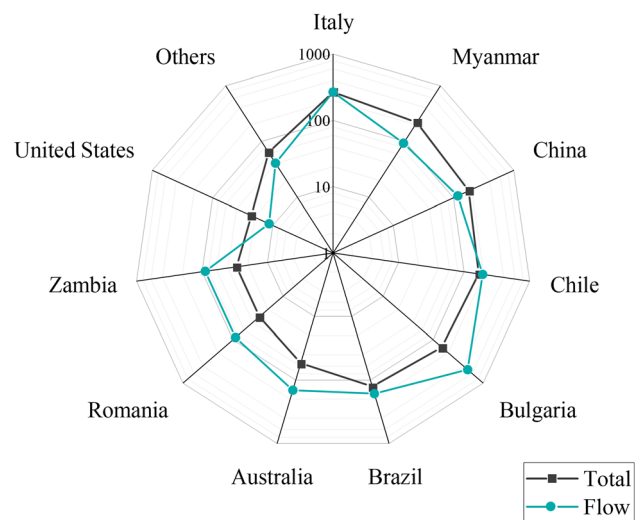
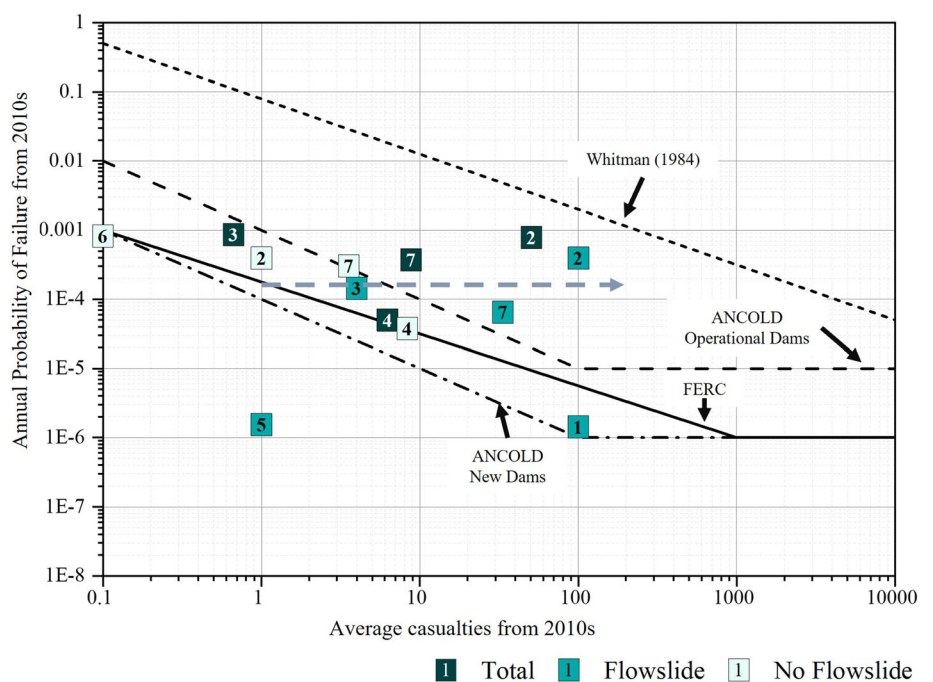


Fig. 12 Distribution of the risk associated with tailings dam failures calculated by the base sub-model

Fig. 11 Evaluation of the risk of tailings dams for the 2010s decade. Countries labeled in alphabetical order: 1 = Australia; 2 = Brazil; 3 = Chile; 4 = China; 5 = Italy; 6 = United States; 7 = world



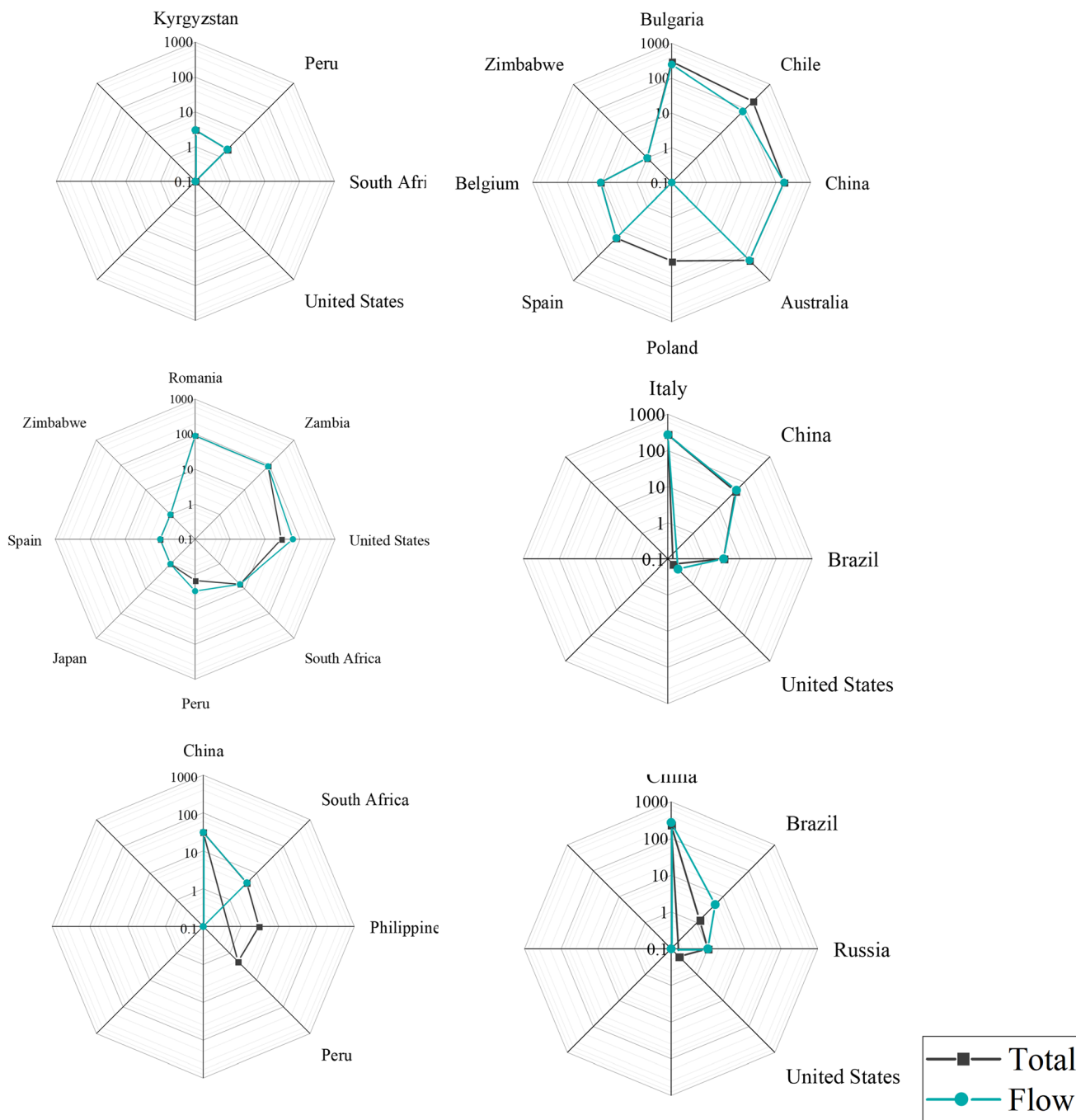


Fig. 13 Distribution of the risk calculated by the base sub-model by decade, from the 1950s to the 2000s

followed by Myanmar with 219 (17%). Nonetheless, China, Chile, Bulgaria and Brazil attract attention for their average losses related to tailings dam incidents, respectively, with 179 (14%), 166 (13%), 149 (11%) and 126 (10%) casualties. Note that, despite being the country with the highest number of accidents, the USA presented a lower rate of losses, only 23 casualties (2%).

Regarding the tailings dam flow risk, it can be observed that the country with the highest risks per accident is

Bulgaria, with 488 casualties in the Mir Mine accident in 1966 [21, 22] which corresponds to 29% of the global risk. Since Italy has only one recorded accident, Stava, with 269 casualties [38], the risk remained the same as the total accidents. However, the overall risks in the accidents involving tailings dams increase when considering only the post-failure flow behavior, for instance, in Bulgaria, by more than 220%. This trend is observed in most countries to a smaller extent, with Chile having an average of 191 (+

15%), Brazil with 163 (+ 29%), Australia with 144 (167%), Romania with 89 (+ 200%) and Zambia also with 89 (200%) casualties. Conversely, in countries where the number of documented tailings flow is smaller, the risk decreased. China showed a risk reduction of almost 34% (to 118) and Myanmar, a decrease of 58% (to 93). Concerning flow sliding, countries with a high occurrence of seismic liquefaction, as Chile, present 11% of the tailings flow sliding risk worldwide. Static liquefaction, though, is shown to be a concern. Brazil presents 14% of flow sliding risks with no earthquakes, similarly to other high magnitude failures in Italy and Bulgaria.

Analysis of the Evolution of Risk in the Worldwide Context

The risks have historically changed in the 100 years of recorded tailings dam failures, and these structures should be analyzed as smaller ranges of time. Therefore, the temporal evolution of risks is evaluated. Figure 13 shows the evolution of the casualty risk of tailings dams worldwide between the 1950s and 2000s, as calculated by the risk sub-model.

Firstly, low risk was verified in the 1950s, possibly due to the lower number of tailings dams and their smaller size. In the 1960s, however, there were several major accidents in Bulgaria, Chile, China and Australia, making it the decade with the most casualties due to tailings dam failures. At that time, the geotechnical design of these structures was mostly nonexistent [39]. Chile presented an enormous amount of liquefaction and flow failure due to the occurrence of a major earthquake in March 1965 [23], yet despite the higher number of flow events, it appears as having a lower average risk by accident if compared to the other countries.

For the 1970s, a decrease in the number of accidents is observed, but casualties are still abundant. The 1980s showed a decrease in failures in the worldwide context, except for the Stava disaster [40]. After that, the number of accidents in Europe and their related risk decreased substantially, and a change of hot spot for less developed countries is verified in the 1990s, with a decrease in casualties overall. For the 2000s, there was again a decrease in the number of failures with casualties, but a high magnitude event in Linfeng city, and other smaller ones with casualties, in China [22].

For the 2010s, there was an increase in the number of failures overall, with more accidents reported in more countries, as shown in Fig. 14. There was also an increase in the consequences of the failures, with the average risks of casualties calculated being the highest since 1960. In recent decades, the losses associated with tailings dam failures indicate two hot spots: Brazil and Myanmar. This

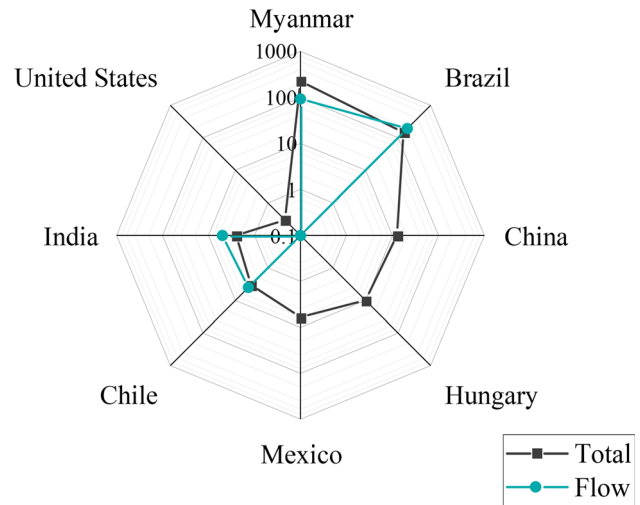


Fig. 14 Distribution of the risk calculated by the base sub-model for the 2010s

trend appears to continue to the 2020s. In July 2020, at least 168 were killed in the collapse of one mine [22].

Simplified Fault Tree Analysis of Tailings Dam Failures

Based on the data collected from the tailings dam failures, a very simplified fault tree analysis is proposed to assist in the decision process of dam break analysis of tailings dams. Table 5 analyses the probability of a failure event to evolve into a flow failure, based on the tailing’s construction method (upstream, downstream or centerline) and the cause of failure. The occurrence of flow failure was considered of main interest, as are related to most losses, and indicates the need to perform dam break analysis. As the influence of the tailing’s material was considered inconclusive, it was not analyzed, and it should be considered that all tailings have an equal possibility of becoming a flow failure. Also, geographical information is not considered a factor, although legislation and engineering practices might influence indirectly. Due to the scarcity of reported data from these failures, the failure modes were simplified by their main cause, and an actual event tree was not possible.

Table 5 may be used as a decision-making tool in the development of dam break analysis of tailings dams. Firstly, the downstream construction method does not represent as much risk for flow failures, and upstream dams are the more common to failure. Also, the dam break analysis should be developed considering an immediate failure with static liquefaction, as it is related to most historical events. Contrarily to water dams, slower failures due to drainage and overtopping are not very common. The response to tailings dam collapse should always be

Table 5 Summary of the failure probabilities of tailings dams according to construction method and cause of failure

	Tailings Dams	Upstream		Centreline		Downstream	
	18400	43%		9%		27%	
	Total	Total	Flow Failure	Total	Flow Failure	Total	Flow Failure
Total	2.86%	1.42%	0.55%	0.91%	0.14%	0.54%	0.05%
Earthquake	0.62%	0.505%	0.305%	0.000%	0.000%	0.113%	0.023%
Slope Instability	0.63%	0.420%	0.125%	0.070%	0.000%	0.136%	0.023%
Overtopping	0.52%	0.266%	0.069%	0.209%	0.000%	0.045%	0.000%
Drainage	0.36%	0.112%	0.042%	0.139%	0.000%	0.113%	0.000%
Foundation	0.47%	0.056%	0.000%	0.348%	0.139%	0.068%	0.000%
Others	0.26%	0.056%	0.014%	0.139%	0.000%	0.068%	0.000%

prepared to the dams' immediate collapse by liquefaction, which can take less than 5 min.

Conclusions

This paper collected several technical reports and scientific papers, in addition to the Bowker and Chambers [20] database, updated in July 2020, to better understand the risk associated with tailings dams. Since there is a correlation between the consequences of failures and the occurrence of flow post-failure behavior [9, 11, 41, 42], these were divided into two sub-categories: accidents with and without flow sliding.

The post-failure behavior of the material in the dam is of great importance to the consequences of the failures, as most of the recorded casualties were caused by flow sliding. Also, the upstream method is not only related to most of the events but also presents major importance to the occurrence of flow sliding, since 40% of these accidents evolved into the release of liquefied tailings, and 88% of the flow failures with the building method described were upstream dams. These statistics highlight the correlation between flow failures and upstream dams. Concerning the tolerability of risks by construction method, the high risk associated with tailings dams is mostly associated with the unsafety of upstream tailings dams, as other construction methods have risks under acceptable ranges.

None of the six countries analyzed, Australia, Brazil, Chile, China, Italy and the USA, or the world, agree with the acceptability range of recent guidelines, with average risk higher for flow sliding events, since there was an approximate constant individual risk of 10-2 p.a. However, the 2010s a reduction, in risks, because of a decrease in casualties per event for most of the world, except Brazil and Myanmar.

To assist in the risk assessment studies for dam break analysis, focused on the flow behavior post-collapse, a simplified fault tree analysis was proposed. It can be used as a decision-making tool in the development of dam break analysis.

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