Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 7895880, 21 pages
https://doi.org/10.1155/2022/7895880

Review Article

Rates and Causes of Tailings Dam Failures

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Received 3 August 2022; Revised 1 November 2022; Accepted 10 November 2022; Published 22 November 2022

Academic Editor: Zhixiong Zeng

This paper analyzes two tailings dam databases and recent failures to assess the local and global failure rates of upstream, downstream, and centerline raised tailings dams. Since 2000, the failure rate for all three raising methods has decreased except in Brazil, which helps explain the recent Brazilian regulations banning upstream raising. However, the failure rates also show that the downstream and centerline raising methods of tailings dams are not immune to failure, so, if mining continues, one of these three raising methods will be used, and all have been involved in prior failures. The paper also presents data on failure mechanisms, showing that slope stability, earthquakes, and overtopping are the three primary causes of tailings dam failures. To continue decreasing the failure rate of tailings dams, the following features and practices should be used in all types of tailings dams: drainage systems, engineering analyses, instrumentation, monitoring, inspection, and qualified external peer review to further reduce the failure rates, especially in Brazil. Finally, a section containing data on release volume as a function of dam height and total storage volume is presented.

1. Introduction

In the last eight years, the following four tailings dam failures have occurred:

(i) Herculano tailings dam failure in Brazil on 11 September 2014

(ii) Fundão tailings dam failure in Brazil on 5 November 2015

(iii) Dam B1 tailings dam failure in Brazil on 25 January 2019

(iv) Jagersfontein dam failure in South Africa on 11 September 2022

In addition to fatalities, these failures caused the significant release of the stored tailings and major environmental damage. For example, the Dam B1 failure caused about 300 fatalities [1], released around 13 million cubic meters of tailings, affected indigenous and nonindigenous populations, negatively impacted an area of more than 250 hectares in a biodiversity hotspot [2], and traveled approximately ten (10) kilometers. Within 10 seconds, the collapse of Dam B1 was complete, and 75% of the tailings flowed out of the dam in less than 5 minutes. Without warning, the sludge instantly killed dozens of workers when it demolished a downslope cafeteria. Likewise, the tailings from the Fundão tailings dam failure killed nineteen people [1] and traveled hundreds of kilometers to the Atlantic Ocean.

After the failure of a tailings dam, the outflow of the stored tailings can result in a fast-moving mudflow, which can devastate downstream areas. Some of the videos following the Fundao [3], https://www.youtube.com/watch?v=O7l7OSFyP2w#action=share, and Dam B1 [4], https://www.youtube.com/watch?v=Adk0AwcISHo, failures illustrate the speed of these mudflows. Using the video of the 2019 Dam B1 failure, the velocity of the resulting flow failure was estimated to be 1.3 to 1.5 km/minute (21.7 to 25 m/s). This potential for rapid inundation of downstream areas makes the design, instrumentation, monitoring, inspection, and external peer review of these structures essential to protecting human life and the environment.

All three of the tailings dam failures in Brazil were raised by the upstream method. The Fundao and Dam B1 failures prompted Brazilian authorities to ban the upstream method in 2019 [5]. The ban was accompanied by a series of additional regulations such as the requirement of installation of automated dam instrumentation and sirens and a prohibition on locating mining facilities downstream of tailings dams [6]. The upstream method had already been banned in other countries prior to Brazil's moratorium. For example, Chile banned the upstream raising method after strong earthquakes between 1960 and 1965, which caused failure of El Cobre dam [7].

To evaluate the validity of banning of the upstream method in response to individual upstream tailings dam failures, this study utilizes two tailings dam databases, both of which will be described in subsequent sections. The first database contains a worldwide inventory of tailings dams and the other a worldwide inventory of tailings dam failures. With this data, local and global failure rates are computed to assess failure rates of upstream, downstream, and centerline raised tailings dams. This comparison leads to an objective evaluation of the performance of all three tailings dam raising methods. More importantly, these computations quantitatively evaluate the performance of upstream, downstream, and centerline tailings dams and reveal the failure rate for all three raising methods that has decreased since 2000 except in Brazil. The objective of these comparisons and evaluations is to determine if the performance of upstream tailings dams differs significantly from that of centerline and downstream raised dams. The paper also presents data on failure mechanisms, showing that slope stability, earthquakes, and overtopping are the three primary causes of tailings dam failures. To continue decreasing the failure rate of tailings dams, the following features and practices should be used in all types of tailings dams drainage systems, analyses, instrumentation, monitoring, inspection, and qualified external peer review to further reduce the failure rates, especially in Brazil. Finally, a section containing data on release volume as a function of dam height and total storage volume is presented.

2. Tailings Dam Construction

Earth impoundment structures are commonly designed and constructed with the possibility of being raised. This is more common for mining structures than water impoundment structures, but both can be designed for subsequent raising. Dam raising is more common in mining applications due to the (1) importance of reducing initial project costs to assess mine viability, (2) generation of fill material during the mining process because total fill volume may not be initially available, and (3) ability to reinvest after generation of some revenue from the mining operation and (4) because retained material is tailings instead of water.

Dam raising occurs by constructing the new embankment upstream, downstream, or above the centerline of the previous embankment. This results in three common embankment raising methods, i.e., upstream, downstream, and centerline. In each method, the new embankment is either shifted towards the tailings storage area (upstream), away from the tailings (downstream), or placed on top of or aligned with the starter embankment (centerline). The upstream method is the most common method for constructing tailings dams [8]. The main advantages of the upstream raising method are time savings, reduced fill material required, decreased space required for dam construction, and avoidance of the need to replace instrumentation installed in the starter dam [9]. Davies and Martin [10] estimate that more than 50% of all tailings dams utilize the upstream raising method. After the 2019 failure of Dam B1, over eighty tailings dams in Brazil alone utilized the upstream raising method [11].

There are also disadvantages associated with the upstream raising method [12]. For example, because subsequent upstream dams are constructed on uncompacted to loose sand tailings, during rapid loading elevated piezometric levels can develop in underlying fine grained tailings, i.e., clay to fine sand. This may not be significant at the beginning when the dam raises over the sandy tailings beach. However, continued upstream raisings can occur over previously placed fine-grained tailings that may eventually develop elevated pore water pressures or bearing problems [13]. The increase in pore water pressure can be calculated by a pore water pressure coefficient [14] times the total normal stress, i.e., unit weight times the height of tailings. Also, the sand tailings can be susceptible to dynamic/earthquake-induced pore water pressures that can further reduce the effective stresses and cause liquefaction [9]. Therefore, drainage systems, instrumentation, monitoring, and inspection should be used to identify, monitor, and mitigate elevated pore water pressures. Some of the design features that can increase the stability of upstream raised dams are given as follows: a subsequent raise should overlap the embankment used in the prior raise to increase the dam volume, the rate of raising should be limited so elevated pore water pressures do not develop, e.g., 1 to 3 m per year depending on site rainfall, tailings placement should be moved away from the dam, raising should be stopped when the raised embankment is no longer over the initial sandy beach, the tailings beach should be extended initially to extend the potential life of the dam [15], and a straight dam axis or an axis cambered upstream should be used so the dam materials are in compression. To maintain dam stability, an underdrainage system should be installed during initial construction and augmented during the service life of the structure to dissipate elevated pore water pressures. Sometimes, a geomembrane on the upstream face of the dam is installed to reduce dam saturation and seepage [16, 17].

Given the upstream method is the most common raising method [10], it is expected that most of the failures would involve upstream raised tailings dams. However, the failure rate for upstream tailings dams is low, i.e., "no more than 5 or 6%" according to Davies and Martin [10] because as of 2000, there were at least 3,500 tailings dams worldwide, of which at least 50% were upstream dams, and there had been fewer than 100 failures of upstream dams. However, the severe consequence of a tailings dam failure shows that a 5% failure rate is still too high. Using data from Lyu et al. [18] on failure distribution by type of tailings dam, the failure rate of centerline and downstream tailings dams is approximately

2% to 3% based on 34 failures and 30 to 40% of the 3,500 dams being centerline and downstream type dams. Thus, constructing a centerline and downstream tailings dam does not guarantee that the dam will be stable. The failure rate for upstream, centerline, and downstream tailings dams is unacceptable because one failure can have tremendous economic/environmental consequences and cause causalities. However, these data show that most of the tailings dams worldwide have not failed and thus have been stable for an extended period.

The Herculano, Fundao [19], and Dam B1 [20] tailings dams mentioned above were all constructed using the upstream raising method and are located in Minas Gerais, Brazil. In response to the Dam B1 failure on 17 February 2019, the Brazilian Agencia Nacional de Mineracao (BANM) [11] banned the use of the upstream raising method for new tailings dams even though most upstream-raised dams in Brazil and around the world have performed well as shown below. This is especially true after the year 2000, except in Brazil, which helps explain the three significant failures in Brazil since 2014. In addition, the BANM showed the requirement that existing upstream dams should be decommissioned or removed by 15 August 2021, because the upstream construction method can "no longer be tolerated" [11]. This new regulation impacts the over eighty upstream-raised tailings dams in Brazil [11] with about fifty of them being located in Minas Gerais.

Brazil is not the only area where the upstream raising method has lost popularity due to a perceived higher risk when compared to other types of dams, such as centerline or downstream [21]. This higher risk perception with upstream raised dams stems from static and earthquake induced failures. These failures occur because the dam is founded on tailings that can have low relative densities, are saturated, and consist of sandy materials [22], which makes them susceptible to the generation of pore water pressures during static and dynamic loadings. For example, construction that proceeds faster than scheduled or designed can result in elevated pore water pressures and reduced effective stresses. Uncompacted tailings can also be contractive under shear induced stresses resulting in elevated pore water pressures.

Existing databases of tailings dams are used below to investigate whether or not this perception of higher risk with upstream raised tailings dams is justified. In particular, the main objective of this paper is to use the available data to compare the performance of tailings dams around the world according to raising type (upstream, centerline, downstream, single-stage, and other) and to assess their performance before and after the year 2000. The year 2000 was selected because there are about 20 years of well documented tailings dam history before 2000 and 20 years after 2000, so it is roughly the midpoint of the use of tailings dams.

The performance of Brazilian tailings dams is reviewed first and then contrasted with information from around the world to evaluate the current situation. Finally, a brief overview of the common failure modes, total storage volume, and heights of failed dams are presented to identify situations where design, analyses, instrumentation, monitoring, inspection, and external peer review are essential to improve tailings dam performance.

3. Databases Used

Two primary databases are used for this study. The first database was created by the Church of England Pensions Board and the Swedish AP Funds Council of Ethics [23] for mining related investors. This study resulted in the Global Tailings Portal being created by Norway based GRID Arendal (GRIDA) [24], which contains data of 1,938 tailings dams worldwide [25]. The database is a compilation of operational and inactive tailings dams. However, only 31% of the 655 companies contacted responded to the survey. Thus, considering that 69% of the companies did not respond and there could be more mining companies that were not contacted in the survey, the total number of tailings dams worldwide is probably greater than 1,938. To get an estimate for the total number of tailings dams, it was assumed the remaining 69% of the mining companies had proportionally the same number of tailings dams as the 31% that responded. This yields a total number of tailings dams worldwide of 6,251, i.e., 1,938/0.31. This total number of tailings dams is higher than the 3,500 tailings dams estimated by Davies and Martin [10].

The second database used is the World Mine Tailings Failures, which lists the world tailings dam failures since 1915. This database includes all of the failures recorded in Bulletin 121 compiled by the International Commission on Large Dams (ICOLD) Committee on tailings dams and waste lagoons between 1915 and 2001, and failures that occurred after 2000 [22]. The primary data used from this database are dam location, dam type, failure mode, and dam height. Even though there are more than 80 listed classifications of tailings dams between the two databases, only five main categories of dams are considered herein: upstream, centerline, downstream, single stage, and other. The single stage dams consist of tailings dams where only a starter dam was built with no future raises. The "other dams" category consists of tailings dams that do not fall in the four previously mentioned categories, i.e., upstream, downstream, centerline, and single stage, and dams where the classification was not reported or reported as unknown.

4. Brazil Tailings Dams and Failure Rates

Brazilian metals and gemstones mining history dates back to the arrival of the Portuguese at the beginning of the 16^{th} century. However, more than two hundred years passed before viable gold deposits were discovered in Minas Gerais [23]. Gradually production rates accelerated, not only in Brazil but globally [24], to the point where tailings and mine waste disposal became a critical issue in the early 20^{th} century. Since then, tailings dams have been constructed to create tailings storage areas, but it was not until the 1960s when engineering technology was applied to these facilities [25]. Six decades later, there is still limited information about tailings dams in Brazil and around the world. However, due to investor concerns some Brazilian mining companies disclosed information on 263 tailings dams to the Global Tailings Portal [24]. In February 2019, the BANM [11] released an updated database with information on more than 750 tailings dams in Brazil [26]. This database is used herein to assess failure rates and causes of tailings dam failures in Brazil.

Figure 1 presents a histogram of the number of tailings dams per dam type in Brazil. The most common dam type (414) is the single stage dam, which consists of only one embankment being constructed and the dam not being subsequently raised. More importantly, Figure 1 shows there are more downstream raised dams than upstream and centerline raised dams combined in Brazil. This downstream raising trend is opposite of the world, where there are more upstream raised tailings dams than centerline and downstream dams combined [25] as shown below. The dams listed as upstream, centerline, and downstream are clearly identified as such in the database and no attempt was to reclassify any of the "unknown" dams to any of these three categories.

Figure 1 also presents the percentage of each type of tailings dam based on a total number of tailings dams in Brazil of 783. Figure 1 shows that 52.9% of the Brazilian tailings dams are single stage, followed by 19.4% downstream, 11.9% upstream, and 5.1% centerline. Therefore, only about 12% of Brazil's dams are upstream raised dams. Given this background, Figure 2 shows the failure rates of these dam types.

The failure rates shown in Figure 2 were calculated by dividing the total number of failures in Brazil found in the World Mine Tailings Failures Database by the total number of that type of tailings dam in Brazil. For example, there are 93 upstream tailings dams in Brazil (see Figure 1) and there have been six (6) failures in Brazil for a percentage of failure of 6.5%, i.e., $6/93 * 100$ (see Figure 2). Figure 2 shows that upstream raised dams have the highest failure percentage, with the centerline being second at 5.0%. No failure of a downstream raised tailings dam in Brazil was found in the database so the failure percentage is zero (0). The data in Figure 2 appears to justify the BANM ban on the upstream raising method for new tailings dams and decommissioning or removing all of the other upstream raised dams by 15 August, 2021 [11].

For completeness, the single stage dams have a failure percentage of 0.7%. This low percentage is probably related to nearly 90% of the single-stage dams having a height of less than 40 meters and approximately 75% of them having a height less than 20 meters [26].

In summary, the performance of Brazilian downstream tailings dams is outstanding because they are the second most common dam type in Brazil and have not experienced a failure. Still, they have an average height of only 24 m with a range of 1 m to 98 m [26]. The upstream and centerline dams in Brazil have average heights of 35 m and 38 m, respectively, so they may be more susceptible to failure than downstream raised dams. In addition, the heights of the upstream and centerline dams in Brazil range from 7 m to 163 m and 3 to 104 m, respectively, compared to 1 to 98 m for downstream raised dams. Also, downstream raised dams

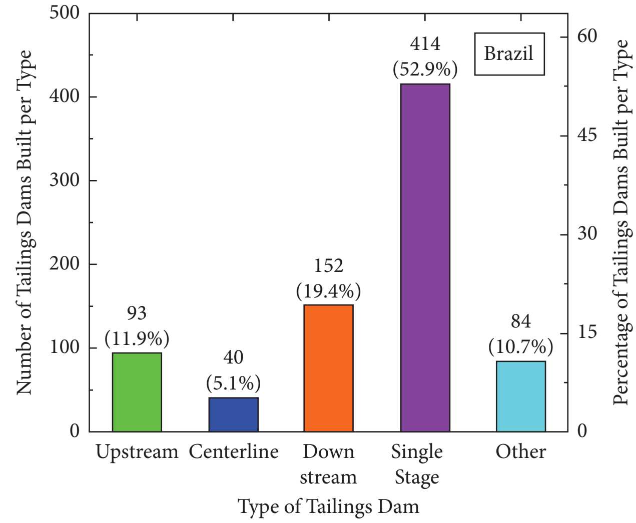

Figure 1: Number and percentage of tailings dams built per type in Brazil (data from Bowker [22] and Agência Nacional de Mineracão [26]).

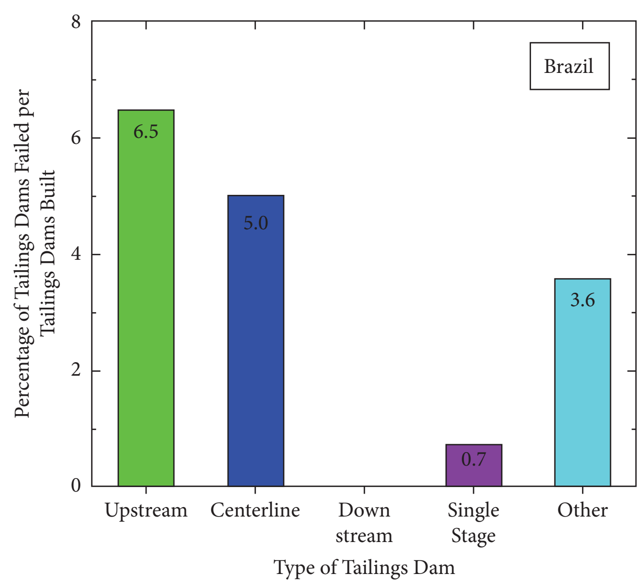

Figure 2: Percentage of tailings dams failed per tailings dams built in Brazil according to dam type (data from Bowker [22] and Agência Nacional de Mineração [26]).

require considerable right of way downstream of the starter dam for construction, which suggests that using a downstream tailings dam may not be suitable for every site, so centerline and upstream raised dams may need to be considered.

If the failures in Figure 2 are divided into two-time frames, i.e., before and after the year 2000, a disturbing trend is observable in Figure 3, which is the failure rate for upstream tailings dams increased after 2000. This finding is alarming because engineering and analysis techniques for evaluating the stability of tailings dams should be improving with time not deteriorating. Before 2000, only 1.1% of upstream raised tailings dams failed over approximately 85

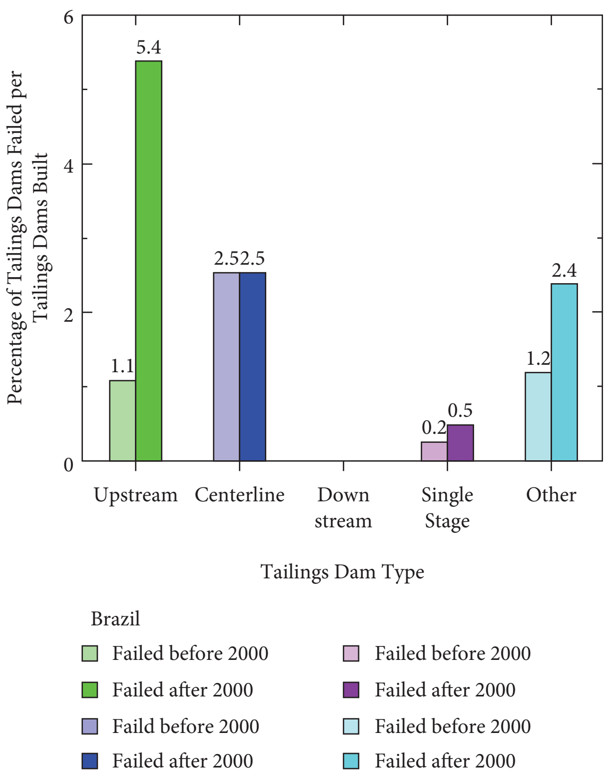

FIGURE 3: Percentage of tailings dams failed per tailings dams built in Brazil, before and after 2000, according to dam type (data from Bowker [22] and Agência Nacional de Mineração [26]).

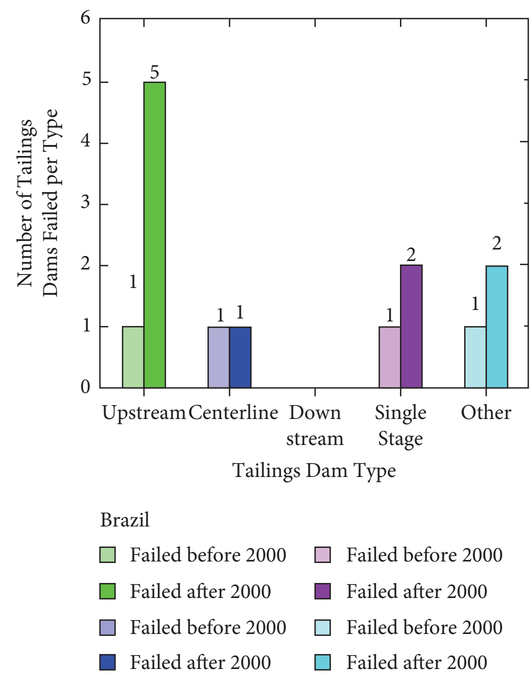

FIGURE 4: Number of tailings dams failed per tailings dams built in Brazil, before and after 2000, according to dam type (data from Bowker [22] and Agência Nacional de Mineração [26]).

years, while after 2000, this percentage increased by a factor of almost five to 6.5%. More significantly, centerline raised dams performed about the same before and after 2000, which also means no improvement from advances in engineering techniques because the failure rate is about 2.5% even though it is over only 20 years instead of 85 years. This data indicates that the engineering associated with design, construction, operation, instrumentation, monitoring, inspection, and external peer review of tailings dams in Brazil, especially in regard to upstream raised dams, needs improvement. This is reflected in the following statement by Professor Norbert Morgenstern of the University of Alberta [27]:

"There is an unwritten covenant in our professional practice with the assumption on the part of an operator that, given reasonable resources, and on the part of the regulator that, given technical guidelines and a modicum of inspection, the engineering team can be relied upon to produce a TSF (tailings storage facility) that will perform as intended. The experience summarized here leads to the conclusion that this covenant is broken."

Figure 4 presents the number of failures as a function of the type of tailings dam and shows five (5) upstream tailings dams have failed since 2000. That is four (4) more failures since 2000 than during the previous 85 years. Of course, the five failures since 2000 include the three recent failures mentioned above, i.e., Herculano (2014), Fundão (2015), and Dam B1 (2019). Figure 4 also shows that one (1) centerline dam failed before and after 2000 for a total of two failures.

5. World Tailings Dams and Failures

This section presents the statistics and failure percentages for tailings dams around the world instead of just Brazil. The paragraphs below describe the procedure adopted to compute estimates of world tailings dams as well as number of tailings dams per type with the results summarized in Tables 1 and 2, respectively.

The Brazilian Agência Nacional de Mineração [26] shows 769 tailings dams in Brazil while only 259 are recorded in the GRIDA database [25]. By dividing the number of tailings dams provided in BANM (n_{BANM}) by that in the GRIDA database ($n_{\mathrm{GRIDA}_{BR}}$), i.e., 769/259, a factor of 2.97 is obtained (see (1)). This factor of 2.97 from Brazil's data (f_{BR}) was used to estimate a total number of tailings dams in the world ($\mathrm{est}_{\mathrm{BANM}}$). In particular, the Brazilian data provides a lower bound by multiplying the original number of tailings dams in the GRIDA database (n_{GRIDA_W}), 1,938, by f_{BR} of 2.97. The result is $\mathrm{est}_{\mathrm{BANM}}$ being 5,754 (see (2)).

$$f_{BR} = \frac{n_{BANM}}{n_{GRIDA_{BR}}} = \frac{769}{259} = 2.97, \quad (1)$$

$$\mathrm{est}_{\mathrm{BANM}} = f_{BR} \times n_{\mathrm{GRIDA}_W} = 2.97 * 1,938 = 5,754. \quad (2)$$

Table 1: Estimation of world tailings dams by the database used.

Database	Scope	Number world	Number Brazil	Number United States	Factor*	Estimated number world**
BANM	Brazil	N/A	769 (n_{BANM})	N/A	2.97	5,754
GRIDA	World	1938 (n_{GRIDA_W})	259 ($n_{\text{GRIDA}_{BR}}$)	263 ($n_{\text{GRIDA}_{US}}$)	3.23	6,251
USACE	United States	N/A	N/A	1,233 (n_{USACE})	4.69	9,085

*Factor refers to **Equation** (1), **Equation** (3), and **Equation** (5), respectively. **Estimated number world refers to **Equation** (2), **Equation** (4), and **Equation** (6), respectively.

Table 2: Estimation of world tailings dams by type.

Type	Number GRIDA	Percentage	Estimated number of world*
Upstream	801	41.3	2,584
Centerline	143	7.4	461
Downstream	494	25.5	1,593
Single stage	140	7.2	452
Other	360	18.6	1,161

*Estimated number world refers to estimates computed using f_W of 3.23 from Table 1.

Similarly, an updated version of the National Inventory of Dams [28] database complied by the U.S. Army Corps of Engineers (USACE), shows 1,233 tailing dams in the United States while only 263 are recorded in the GRIDA [25] database. Dividing the number of tailings dams provided by the USACE (n_{USACE}) by that in the GRIDA database ($n_{\text{GRIDA}_{\text{US}}}$), a factor of 4.69, i.e., 1,233/263, is obtained (see (3)). This factor of 4.69 for the United States (f_{US}) was also used to estimate a total number of tailings dams in the world ($\text{est}_{\text{USACE}}$) by multiplying n_{GRIDA_W}, 1,938, by f_{US} of 4.69. The result is $\text{est}_{\text{USACE}}$ of 9,085 (see (4)) instead of the 5,754 calculated with Equation (2).

$$f_{\text{US}} = \frac{n_{\text{USACE}}}{n_{\text{GRIDA}_{\text{US}}}} = \frac{1,233}{263} = 4.69, \quad (3)$$

$$\text{est}_{\text{USACE}} = f_{\text{US}} * n_{\text{GRIDA}_W} = 4.69 * 1,938 = 9,085. \quad (4)$$

Developing countries tend to have more tailings dams in the GRIDA database than developed countries because developed countries have been more likely to close their problematic mines due to environmental or safety issues [29]. Moreover, few closed mines are recorded in the GRIDA [25] database. Therefore, less data was recorded for developed countries in the GRIDA database because closed mines are not included. The original estimate of total number of tailings dams worldwide from the previous section is 6,251. According to the calculations performed in this section, the potential total number of tailings dams around the world is between 5,754 and 9,085.

Therefore, a total number of 6,251 tailings dams worldwide was used herein to calculate worldwide failure percentages because it is within the estimated range. The number of 6,251 reflects the estimate obtained when assuming the number of tailings dams from the companies that did not respond to the GRIDA survey is proportional to the number of companies that did respond, as explained in the section titled "Databases Used" above. To obtain an estimate of the total number of tailings dams, it was assumed that from all the mining companies contacted ($n_{c_{\text{GRIDA}}}$) the remaining 69% of mining companies that did not respond to the survey had proportionally the same number of tailings dams as the 31% that responded ($n_{r_{\text{GRIDA}}}$). This yields 6,251 tailings dams, i.e., 1,938 ∗ 3.23 (see (5) and (6) below). As a result, the total number of upstream, centerline, downstream, single-stage, and other dams around the world is increased to 2,584, 461, 1,593, 452, and 1,161, respectively, using a total of 6,251 and a factor (f_W) of 3.23, which is the ratio of the companies contacted to the companies that responded to the GRIDA survey (see (6)). These data still show that the upstream raising method is the most popular method of tailings dam raising method with 671 tailings dams, which is more than centerline and downstream combined.

$$f_W = \frac{n_{c_{\text{GRIDA}}}}{n_{r_{\text{GRIDA}}}} = \frac{655}{203} = 3.23, \quad (5)$$

$$\text{est}_{\text{GRIDA}} = f_W * n_{\text{GRIDA}_W} = 3.23 * 1,938 = 6,251. \quad (6)$$

The calculation of the number of tailings dams per type is described in this paragraph and summarized in Table 2. From the number of tailings dams per type originally reported in the GRIDA database [25], namely 801, 143, 494, 140 and 360 for upstream, centerline, downstream, single stage, and other, respectively, the percentage of tailings dams built per type was computed, yielding 41.3, 7.4, 25.5, 7.2, and 18.6% for upstream, centerline, downstream, single stage, and other, respectively. Using $\text{est}_{\text{GRIDA}}$ of 6,251, new estimates of the total number of tailings dams in these five main categories, i.e., upstream, centerline, downstream, single stage, and other, were computed using the percentages above as shown in the following:

(i) Upstream dams (U_W):

$$\begin{aligned} U_W(\%) &= \frac{801}{1,938} \\ &= 41.3\%, \\ \text{est}_{U_W} &= U_W(\%) * \text{est}_{\text{GRIDA}} \\ &= 41.3\% * 6,251 \\ &= 2,584. \end{aligned} \tag{7}$$

(ii) Centerline dams (C_W):

$$\begin{aligned} C_W(\%) &= \frac{143}{1,938} \\ &= 7.4\%, \\ \text{est}_{C_W} &= C_W(\%) * \text{est}_{\text{GRIDA}} \\ &= 7.4\% * 6,251 \\ &= 461. \end{aligned} \tag{8}$$

(iii) Downstream dams (D_W):

$$\begin{aligned} D_W(\%) &= \frac{494}{1,938} \\ &= 25.5\%, \\ \text{est}_{D_W} &= D_W(\%) * \text{est}_{\text{GRIDA}} \\ &= 25.5\% * 6,251 \\ &= 1,593. \end{aligned} \tag{9}$$

(iv) Single stage (SS_W):

$$\begin{aligned} SS_W(\%) &= \frac{140}{1,938} \\ &= 7.2\%, \\ \text{est}_{SS_W} &= SS_W(\%) * \text{est}_{\text{GRIDA}} \\ &= 7.2\% * 6,251 \\ &= 452. \end{aligned} \tag{10}$$

(v) Other (O_W):

$$\begin{aligned} O_W(\%) &= \frac{360}{1,938} \\ &= 18.6\%, \\ \text{est}_{O_W} &= O_W(\%) * \text{est}_{\text{GRIDA}} \\ &= 18.6\% * 6,251 \\ &= 1,161. \end{aligned} \tag{11}$$

Azam and Li [30] conclude that the total number of tailings dams in the world may be greater than the 3,500 reported by Davies and Martin [10] with one estimate reaching 18,000 mines around the world [18]. Other reports suggest that in China alone there could be 12,000 tailings dams [31]. In summary, there is no consensus on the total number of tailings dams worldwide. As a result, the failure percentages presented in this section are probably an upper bound because a smaller total number of tailings dams worldwide was used in the analysis (6,251), which results in a higher failure percentage than using one of the higher estimates of the worldwide total described above.

Since 1915, there have been at least 325 tailings dam failures recorded with 121 corresponding to upstream tailings dams; 15 to centerline; 26 to downstream; 16 to the single stage; and 147 to other dams [22]. The category of “other dams” includes both tailings dams that were not classified and tailings dams that fell into categories other than upstream, centerline, downstream, and single stage. If the worldwide tailings dam failures are also divided into two time frames, i.e., before and after the year 2000, a more positive trend in failure rate with time is observable in Figure 5. For example, the failure rate for upstream tailings dams decreased by 3.1% from 3.9% to 0.7% before and after 2000, respectively. The failure rates for centerline and downstream dams after 2000 also decreased to 0.7% and 0.3%, respectively. As discussed below, similar trends are observed in other active mining regions, e.g., Canada and South Africa. In summary, it appears that better engineering and analysis techniques for evaluating the stability of tailings dams are developing with time but have not been implemented in Brazil.

Many of the upstream tailings dam failures that occurred before 2000 are related to loose sands and weak slimes that were entrapped in the downstream area of the dam [33], which is a factor that also may apply to failures after 2000. Despite their perceived susceptibility to instability, upstream raised tailings dams have experienced the most substantial

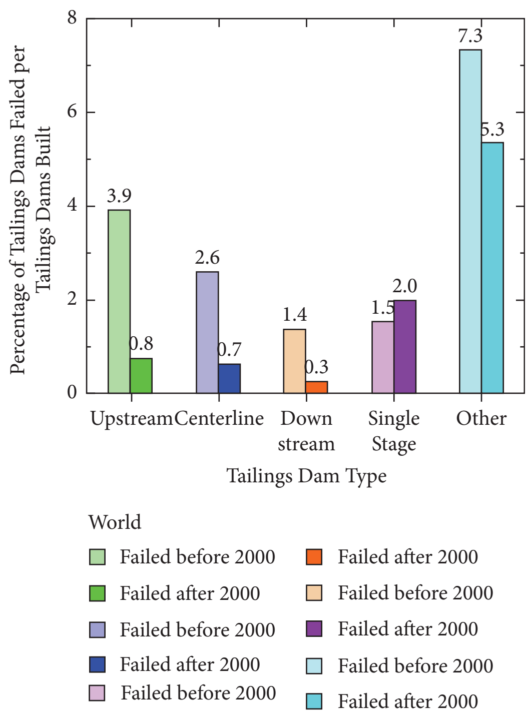

Figure 5: Percentage of tailings dams failed per tailings dams built in the world, before and after 2000, according to dam type (data from GRID-Arendal [25], Bowker [22], and Torrez-Cruz [32]).

improvement in stability because their failure rate dropped 3.1% from 3.9% to 0.8% before and after 2000 versus a decrease of only 1.9% for centerline and 1.1% for downstream dams (see Figure 5).

6. Tailings Dams and Failures in Other Countries and Europe

This section presents the statistics and failure percentages for tailings dams in the United States, Canada, South Africa, Europe, and Australia for comparison with the World and Brazil. These countries were selected because mining is a large industry in these countries and the relevant data is available in the Global Tailings Portal [24] and government sources.

6.1. United States Tailings Dams and Failures. Numerous areas of the United States practice mining, such as lead zinc mining in the Tri State area of Missouri, southeast Kansas, and northeast Oklahoma, while iron is mined in the upper Midwest [34]. As of 2017, more than 1.5 million people have been employed in mining-related activities, generating 98.5 billion dollars of indirect contribution to the annual GDP of the United States [35].

In 2019, mining companies reported over 263 tailings dams in the United States via the Global Tailings Portal [24]. Of these 263 tailings dams, 133, 19, 62, 18, and 31 are upstream, centerline, downstream, single-stage, and other types, respectively [25]. In addition, 97 tailings dam failures have been reported in the United States, which is the largest number of failures among all of the nations in the database [22].

Before the year 2000, the number of tailings dams built in North America is not known due to evolving regulations [36]. This regulatory environment probably contributed to many failures in the "other" type of tailings dams category shown in Figure 6. For example, between 1965 and 1985 seven (7) major tailings dam failures occurred in the United States with the 1972 Buffalo Creek failure causing 125 fatalities. These failures resulted in additional national regulations on tailings dam safety [37]. In 1972 the United States Congress authorized an inventory by the USACE of all dams in the country through the National Dam Inspection Act. Originally there were 45,000 inventoried dams but there are now over 90,000 dams inventoried from which 1,233 correspond to tailings dams [28]. As a result, the percentages of dam type obtained through Global Tailings Portal [24] were extrapolated for a total number of 1,233 instead of 263 American tailings dams. The paragraph below describes the procedure adopted to compute number of United States tailings dams per type and the results are summarized in Table 3.

The extrapolation was performed using the number of each type of tailings dams in the U.S. reported in the GRIDA database [25], namely 133, 62, 19, 18, and 31 for upstream, centerline, downstream, single stage, and other, respectively, and computing the percentage of tailings dams built per type yielding 50.6% (133/263), 7.2% (62/263), 23.6% (19/263), 6.8% (18/263), and 11.8% (31/263) for upstream, centerline, downstream, single stage, and other, respectively. Finally, the 1,233 tailings dams inventoried by the USACE ($n_{\text{USACE}_{US}}$) were divided into the following five categories, i.e., upstream, centerline, downstream, single stage, and other, according to the computed percentages. This resulted in 624, 89, 291, 84, and 145 dams corresponding to upstream, centerline, downstream, single stage, and other categories, respectively, using the following calculations:

(1) Upstream (U_{US}):

$$\begin{aligned} U_{US}(\%) &= \frac{133}{263} \\ &= 50.6\%, \\ \text{est}_{U_{US}} &= U_{US}(\%) * n_{\text{USACE}} \\ &= 50.6\% * 1,233 \\ &= 624. \end{aligned} \tag{12}$$

(2) Centerline (C_{US}):

$$\begin{aligned} C_{US}(\%) &= \frac{19}{263} \\ &= 7.2\%, \\ \text{est}_{C_{US}} &= C_{US}(\%) * n_{\text{USACE}} \\ &= 7.2\% * 1,233 \\ &= 89. \end{aligned} \tag{13}$$

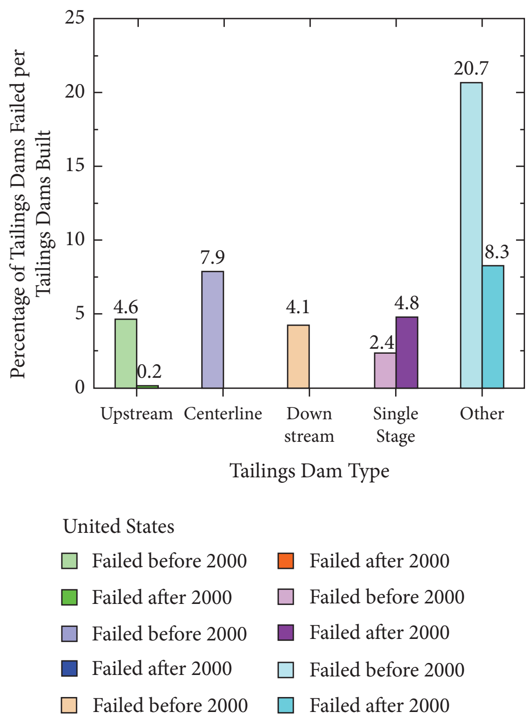

FIGURE 6: Percentage of tailings dams failed per tailings dams built in the United States, before and after 2000, according to dam type (data from GRID-Arendal [25] and Bowker [22]).

TABLE 3: Estimation of United States tailings dams by type.

Type	Number GRIDA	Percentage	Estimated number in United States*
Upstream	133	50.6	624
Centerline	19	7.2	89
Downstream	62	23.6	291
Single stage	18	6.8	84
Other	31	11.8	145

*Estimated number in United States refers to estimates computed using n_{USACE} from Table 1.

(3) Downstream (D_{US}):

$$\begin{aligned} D_{US}(\%) &= \frac{62}{263} \\ &= 23.6\%, \\ \text{est}_{D_{US}} &= D_{US}(\%) * n_{\text{USACE}} \\ &= 23.6\% * 1,233 \\ &= 291. \end{aligned} \tag{14}$$

(4) Single stage (SS_{US}):

$$\begin{aligned} SS_{US}(\%) &= \frac{18}{263} \\ &= 6.8\%, \\ \text{est}_{SS_{US}} &= SS_{US}(\%) * n_{\text{USACE}} \\ &= 6.8\% * 1,233 \\ &= 84. \end{aligned} \tag{15}$$

Table 4: Estimation of Canada tailings number by type.

Type	Number GRIDA	Percentage	Estimated number in Canada*
Upstream	75	32.6	351
Centerline	35	15.2	164
Downstream	67	29.1	314
Single stage	10	4.3	47
Other	43	18.7	202

*Estimated number in Canada refers to estimates computed applying f_{US} from Table 1.

(5) Other (O_{US}):

$$\begin{aligned} O_{US}(\%) &= \frac{31}{263} \\ &= 11.8\%, \\ \text{est}_{U_{US}} &= O_{US}(\%) * n_{\text{USACE}} \\ &= 11.8\% * 1,233 \\ &= 145. \end{aligned} \quad (16)$$

After the total number of failures in the United States was divided into the time frames before and after 2000, Figure 6 shows that tailings dam failures decreased significantly after 2000, which indicates a positive impact of increased regulations and engineering advances. The failure rate of the tailings dams regarding different raising methods decreases significantly in general except for single-stage tailings dam. The failure rate for upstream, centerline, and downstream decreased by 4.4%, 7.9%, and 4.1% to 0.2%, 0%, and 0%, respectively, after 2000. However, the percentage of failure in the single-stage dam before and after 2000 increased by 2.4%.

6.2. Canada Tailings Dams and Failures. Canada started large-scale mineral mining in the 19th century and became a world-leading producer of minerals during the first half of the 20th century. Canada produces both precious and base metals, such as lead, zinc, and copper [38]. According to the Canadian visa immigration website, mining represents about 5% of Canada's annual GDP and employs over 300,000 workers across the nation [39]. According to the GRIDA database [25], 230 tailings dams have been built in Canada, from which 75 were raised by the upstream method; 35 by centerline; 67 by downstream; 10 are single-stage; and 43 are other tailings dams. The paragraph below describes the procedure adopted to compute the number of Canada tailings dams per type and the results are summarized in Table 4.

Global Tailings Portal [24] presents a total of 230 tailings dams in Canada and 263 in the United States. Considering that the countries have similar areas, the factor with which the number of tailings dams in both countries is extrapolated will be assumed to be the same, i.e., 4.69, which is the ratio of number of United States tailings dams according to USACE to the number of United States tailings dams in the GRIDA database. There are 1,233 tailings dams in the United States [28], which is 4.69 times more than what is reported by Global Tailings Portal. Therefore, it will be assumed that in Canada there are 4.69 times more tailings dams than reported in the Global Tailings Portal [24] yielding a total of 1,078 tailings dams or 230 * 4.69 = 1,078 ($n_{\text{USACE},_{\text{CAN}}}$). This results in 351, 164, 314, 47, and 202 tailings dams corresponding to upstream, centerline, downstream, single stage, and other, respectively, after increasing the GRID Arendal [25] by 4.69 times. Therefore, the percentage of Canadian tailings dams built per type is: 32.6% (75/230), 15.2% (35/230), 29.1% (67/230), 4.3% (10/230), and 18.7% (43/230) for upstream, centerline, downstream, single stage, and other, respectively. This calculation was performed in the same way as for United States tailings dams but using the percentages per type corresponding to Canada as follows:

(1) Upstream (U_{CAN}):

$$\begin{aligned} U_{\text{CAN}}(\%) &= \frac{75}{230} \\ &= 32.6\%, \\ \text{est}_{U_{\text{CAN}}} &= U_{\text{CAN}}(\%) * n_{\text{USACE},_{\text{CAN}}} \\ &= 32.6\% * 1,078 \\ &= 351. \end{aligned} \quad (17)$$

(2) Centerline (C_{CAN}):

$$\begin{aligned} C_{\text{CAN}}(\%) &= \frac{35}{230} \\ &= 15.2\%, \\ \text{est}_{C_{\text{CAN}}} &= C_{\text{CAN}}(\%) * n_{\text{USACE},_{\text{CAN}}} \\ &= 15.2\% * 1,078 \\ &= 164. \end{aligned} \quad (18)$$

(3) Downstream (D_{CAN}):

$$\begin{aligned} D_{\text{CAN}}(\%) &= \frac{67}{230} \\ &= 29.1\%, \\ \text{est}_{D_{\text{CAN}}} &= D_{\text{CAN}}(\%) * n_{\text{USACE},_{\text{CAN}}} \\ &= 29.1\% * 1,078 \\ &= 314. \end{aligned} \quad (19)$$

(4) Single Stage (SS_{CAN})

$$SS_{\text{CAN}}(\%) = \frac{10}{230} = 4.3\%,$$
$$\text{est}_{SS_{\text{CAN}}} = SS_{\text{CAN}}(\%) * n_{\text{USACE,CAN}} = 4.3\% * 1,078 = 47. \quad (20)$$

(5) Other (O_{CAN}):

$$O_{\text{CAN}}(\%) = \frac{43}{230} = 18.7\%,$$
$$\text{est}_{O_{\text{CAN}}} = O_{\text{CAN}}(\%) * n_{\text{USACE,CAN}} = 18.7\% * 1,078 = 202. \quad (21)$$

Since 1915, there have been at least 24 tailings dam failures in Canada with 9, 2, 1, 0, and 12 of the failures corresponding to the upstream, centerline, downstream, single stage and other types of tailings dams [22]. The latest tailings dam failure in Canada is the Mount Polley tailings dam failure in British Columbia in 2014. Though no fatalities have been reported from all of these failures, the failures have caused significant environmental impact. For example, when the Coalmont Energy Corporation tailings dam failed in 2013, nearly 30 cubic meters of coal mine tailings flowed into the Tulameen River [40].

Towards the end of the 1990s, the Mining Association of Canada (MAC) published: "A Guide to the Management of Tailings Facilities". The guide responds to the tailings dam failures that had occurred in the country up to that time. This guide provides a framework that covers the life cycle of tailings facilities [41]. Since then, both upstream and centerline raised tailings dams have seen significant safety improvements with a decrease in failure percentages of 1.4% and 1.2%, respectively, after 2000 (see Figure 7). Surprisingly, the failure rate of downstream raised dams increased from zero (0) percent to 0.3% after 2000 in Canada as shown in Figure 7.

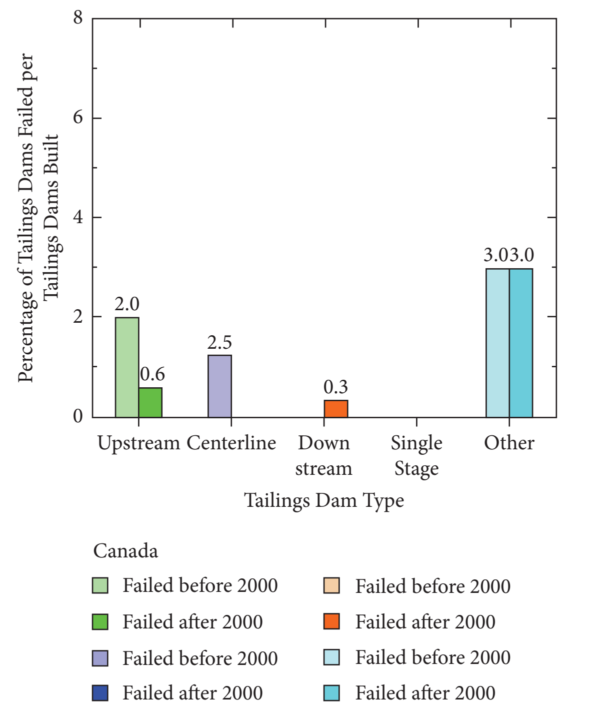

Figure 7: Percentage of tailings dams failed per tailings dams built in Canada, before and after 2000, according to dam type (data from GRID-Arendal [25] and Bowker [22]).

6.3. European Tailings Dams and Failures. The European mining industry also developed early, but now represents a small percentage of the GDP in European countries. However, as of the beginning of the 2000s a significant portion of global mining production came from Europe [42]. For example, in Northern European countries, such as Norway, Sweden, Finland, and Russia, rich mineral deposits are being mined by global mining companies [43].

The Global Tailings Portal [24] only reports 96 tailings dams located across fourteen (14) European countries, in which Kazakhstan and Turkey are included. These 96 tailings dams correspond to 44, 5, 33, 1, and 13 upstream, centerline, downstream, single stage, and other types of tailings dams, respectively [25]. The European tailings dams included in the GRIDA database are limited and few closed mine tailings are reported. However, the databases reviewed herein do show that 90% of the European tailings dam failures occurred in active mines, and only 10% in closed sites [44]. Therefore, closed mine tailings were considered in the total number of mine tailings dams in Europe because mining activities have decreased in Europe. The paragraphs below describe the procedure adopted to compute the number of European tailings dams per type and the results are summarized in Table 5.

The European Commission [29] shows over 3,400 mine waste facilities in Europe with approximately 310 of them being listed as a pond or dam, which is assumed to be a tailings dam. Zibret et al. [45] show about 5,986 waste facilities are present in seven European countries. As a result, it is estimated that there are around 12,000 mine waste storage facilities throughout Europe. Because 310 of the over 3,400 waste facilities correspond to tailings dams, the number of tailings dam is estimated to be about 1,094 in Europe, i.e., 12,000 ∗ (310/3,400). Considering the size and development of the U.S. and Europe, the number of tailings dam in Europe of 1,094 (n_{EUR}) appears reasonable. Moreover, taking into account the number of reported tailings dams in Europe is limited and might not accurately represent the percentages in the entire continent, the distribution of the

Table 5: Estimation of Europe tailings number by type.

Type	Number GRIDA	Percentage*	Estimated number in Europe**
Upstream	44	41.3	452
Centerline	5	7.4	81
Downstream	33	25.5	279
Single stage	1	7.2	79
Other	13	18.6	203

*Percentage refers to because GRIDA tailings dams from Europe are underreported, the percentages per type correspond to the world database are used. ** Estimated number in Europe refers to estimates computed by extrapolating data from the European Commission [29] and Zibret et al. [45].

total number of tailings dams using the upstream, centerline, downstream, single stage, and other raising methods was replicated based on that of the world. This means the 1,094 tailings dams in Europe were divided according to the percentages previously calculated for world-wide tailings dams, namely 41.3, 7.4, 25.5, 7.2, and 18.6%, resulting in 452, 81, 279, 79, and 203 dams corresponding to upstream, centerline, downstream, single-stage, and other, respectively, in Europe using the following calculations:

(1) Upstream (U_{EUR}):

$$\begin{aligned} U_{\text{EUR}}(\%) &= \frac{801}{1,938} \\ &= 41.3\%, \\ \text{est}_{U_{\text{EUR}}} &= U_{\text{EUR}}(\%) * n_{\text{EUR}} \\ &= 41.3\% * 1,094 \\ &= 452. \end{aligned} \tag{22}$$

(2) Centerline (C_{EUR}):

$$\begin{aligned} C_{\text{EUR}}(\%) &= \frac{143}{1,938} \\ &= 7.4\%, \\ \text{est}_{C_{\text{EUR}}} &= C_{\text{EUR}}(\%) * n_{\text{EUR}} \\ &= 7.4\% * 1,094 \\ &= 81. \end{aligned} \tag{23}$$

(3) Downstream (D_{EUR}):

$$\begin{aligned} D_{\text{EUR}}(\%) &= \frac{494}{1,938} \\ &= 25.5\%, \\ \text{est}_{D_{\text{EUR}}} &= D_{\text{EUR}}(\%) * n_{\text{EUR}} \\ &= 25.5\% * 1,094 \\ &= 279. \end{aligned} \tag{24}$$

(4) Single stage (SS_{EUR}):

$$\begin{aligned} SS_{\text{EUR}}(\%) &= \frac{140}{1,938} \\ &= 7.2\%, \\ \text{est}_{SS_{\text{EUR}}} &= SS_{\text{EUR}}(\%) * n_{\text{EUR}} \\ &= 7.2\% * 1,094 \\ &= 79. \end{aligned} \tag{25}$$

(5) Other (O_{EUR}):

$$\begin{aligned} O_{\text{EUR}}(\%) &= \frac{360}{1,938} \\ &= 18.6\%, \\ \text{est}_{O_{\text{EUR}}} &= O_{\text{EUR}}(\%) * n_{\text{EUR}} \\ &= 18.6\% * 1,094 \\ &= 203. \end{aligned} \tag{26}$$

In Europe, a total of 45 tailings dam failures have been reported of which 15 occurred in upstream; 8 in downstream; 7 in single-stage, and 15 in other types of tailings dams. Even though Europe has experienced only 45 reported failures since the start of mining, some of the deadliest tailings dam failures have occurred in this region. The most notable tailings dam failures are in Stava, Italy; Sgorigrad, Bulgaria; and Aberfan, England, where 269, 488, and 144 fatalities occurred, respectively [22]. Nonetheless, it was not until the year 2000 when public concern regarding tailings dam failures generated regulatory changes. In 2000, three (3) significant tailings dam failures occurred with two in Romania and one in Sweden, which contaminated nearby watercourses [44]. Since 2000, upstream raised dams have experienced the most significant decrease in failure rate because they dropped from 3.1% to only 0.2% as shown in Figure 8. Conversely, the failure rate for downstream raised tailings dams decreased by 1.5% after 2000 (see Figure 8). Figure 8 also shows that centerline dams have performed well before and after 2000, with no failures reported.

6.4. South African Tailings Dams and Failures. Moving to South Africa, this economy thrived in the beginning of the 1980s due to gold mining, which contributed one-half to two-thirds of the world gold production. Gold exports represent 40 to 50% of all exports from South Africa [46]. During the late 1980s and early 1990s, the price of gold decreased. This caused a decline in the gold-mining industry that may have contributed to several tailings dam failures prior to the year 2000 due to improper maintenance and/or closure [47].

Currently, there are over 212 reported tailings dams in South Africa of which 139 correspond to upstream; 7 to centerline; 26 to downstream; and 40 to other types of tailings dams. Upstream raised tailings dams are the most common and account for nearly 66% of all tailings dams in South Africa [25]. However, prior to and after 2000 only nine (9) tailings dams failures had been reported in South Africa until the year 2019. Eight of these nine failures occurred before 2000 and only one failure has occurred since 2000 [22], indicating an improvement in design, operation, monitoring, instrumentation, maintenance, and external peer review in the last twenty years.

One of the more notable tailings dams failures in South Africa before 2000 is the 1994 Merriespruit tailings dam failure that caused 17 fatalities and over 2.5 million tons of tailings to flow through the village of Merriespruit. In response to this failure, South Africa created a code of practice that regulates the disposal of tailings and mine wastes using tailings dams. This national regulation prescribes minimum requirements for the handling of tailings and emphasizes the importance of having experienced personnel operating the processes and facilities [48].

Unfortunately, on September 11, 2022, a catastrophic failure of the tailings dam at the Jagersfontein diamond mine occurred [49]. The dam had been closed in 2020 because of high water levels but it reopened in 2021 [50]. Investigators are starting collect post failure information to investigate the breach and preliminary observations suggest that the failure mode was due to overtopping [51]. From aerial photos, the authors have interpreted the Jagersfontein as being raised with the upstream method. Even though upstream raised tailings dams are the most common type in South Africa, this recent failure would be the only recorded since the year 2000 (see Figure 9).

6.5. Australian Tailings Dams and Failures. Finally turning to Australia, where the mining industry has been a major part of the Australian economy since the mid 19th century when alluvial gold was found [52], mining now represents 8% of the Australia's annual GDP [53]. In Australia, there are 311 active and inactive tailings dams with 118 being raised by the upstream method; 26 by centerline; 69 by downstream; 2 are single stage dams; and 96 are other types of tailings dams [25]. Of these 311 dams only seven (7) failures have been reported with four (4) of them occurring in upstream tailings dams and three (3) in "other" types of tailings dams. Fortunately, no fatalities have been reported in any of these failures [22].

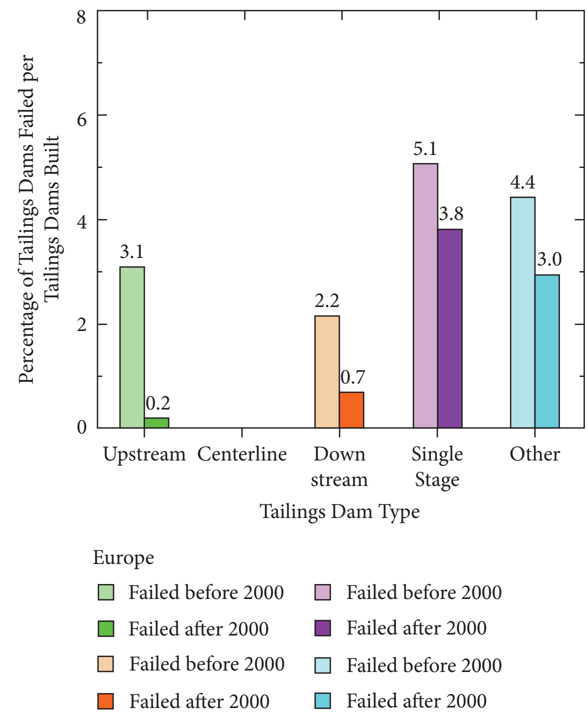

FIGURE 8: Percentage of tailings dams failed per tailings dams built in Europe, before and after 2000, according to dam type (data from GRID-Arendal [25] and Bowker [22]).

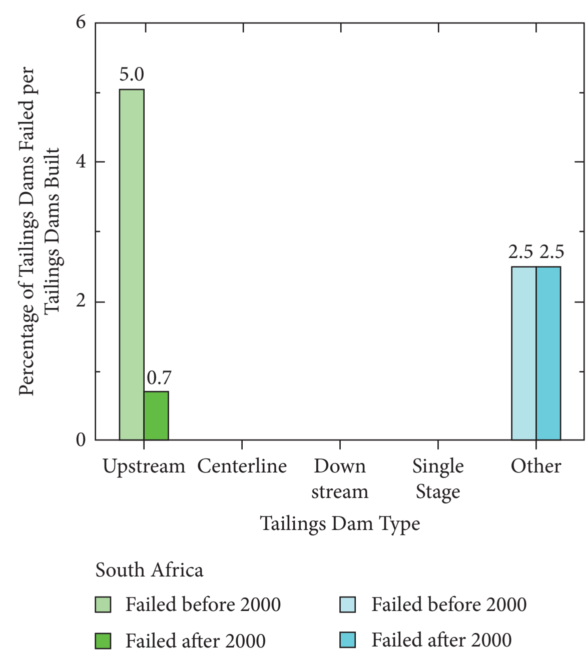

FIGURE 9: Percentage of tailings dams failed per tailings dams built in South Africa, before and after 2000, according to dam type (data from GRID-Arendal [25], Bowker [22], and Torrez-Cruz [32]).

Figure 10 shows the percentage of tailings dams failed per tailings dams built in Australia. The failure rate for upstream raised tailings dams is the same (1.7%) before and after 2000 but the percentage is low compared to other parts of the world. Australia, along with Canada and South Africa,

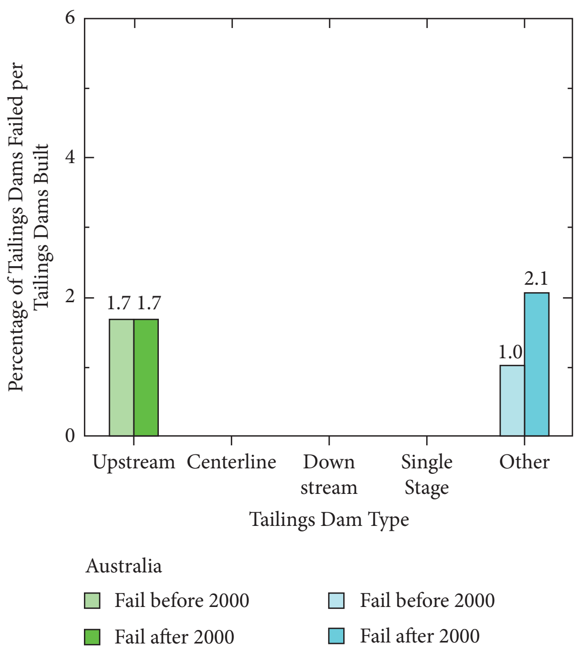

Figure 10: Percentage of tailings dams failed per tailings dams built in Australia, before and after 2000, according to dam type (data from GRID-Arendal [25] and Bowker [22]).

have contributed to development of international tailings management and maintenance protocols. In particular, Australia has published several documents, including Tailings Containment, which has an environmental focus and aims to reduce the long term effects that tailings dams can have on the environment [48].

7. Failure Modes

Bowker [22] reports that the three (3) most common causes of tailings dam failures are earthquakes, overtopping, and slope instability with 53, 54, and 50 failures occurring by these causes, respectively (see Figure 11). Other causes of failure are structural, seepage, foundation, erosion, and mine subsidence resulting in 21, 20, 17, 7, and 3 failures, respectively [22]. Earthquake induced failures usually occur due to liquefaction of the tailings sands that decreases the strength and stiffness of the tailings and make the Earth structure unstable especially for upstream raised dams [54]. Overtopping, on the other hand, generally occurs after heavy rainfalls because of the slow discharge of surface water, which results in overtopping and erosion of the tailings dam [18]. Finally, slope instability can be triggered by a weak foundation and/or erosion if poor drainage conditions are found in or near the bottom of a slope, which prevents water from exiting the dam and/or foundation [55].

The foundation failure mode is important and may become more important with a trend for higher dams because of the higher imposed stresses of the foundation materials. In particular, higher dams can reduce the overconsolidation ratio (OCR) of fine-grained foundation soils to unity (1.0) so these soils are normally consolidated and susceptible to elevated pore-water pressures and low shear strength gain [56]. The fine-grained foundation soils also can undergo strength loss due to: (1) softening from exposure and weathering during excavation/construction, e.g., Cadia slump [57], (2) draining of water from the tailings [58], (3) static shear displacements induced by the applied stresses until a residual strength is mobilized [59], and/or (4) the effects of cyclic loading from dynamic events [60–64].

A good example of a structural failure mode (21 failures in Figure 11) is the collapse of an underdrainage system due to the applied shear stresses from the overlying tailings dam and/or tailings. Another example is a malfunctioning gravity decant system that allows water to pond in the facility.

Examples of well documented tailings dams failures are El Cobre in Chile (1965) due to earthquake shaking; Merriespruit in South Africa (1994) due to overtopping; and Stava in Italy (1985) due to seepage and slope instability [65], which are briefly summarized in the paragraphs below.

On 28 March, 1965, the La Ligua Earthquake ($M = 7.5$) caused the El Cobre tailings dam to fail due to tailings liquefaction during upstream raising. The final inclination of the spilled tailings was about 3.5°, which suggests that the tailings mobilized a liquefied strength [66].

On 22 February, 1994, a heavy thunderstorm triggered the Merriespruit tailings dam failure by overtopping the dam and causing erosion due to an inadequate storm water management system. These heavy rainfalls were frequent in the area, but even so the 50 mm of rain that fell in 30 minutes resulted in overtopping of the tailings dam and erosion failure of the structure [47].

Lastly, on 19 July, 1985, the upstream Stava tailings dam failed due to foundation seepage and slope instability, becoming one of the deadliest tailings dams failure in history. Studies after the failure concluded that the stability was low due to no underdrainage being installed for the upstream construction, and a steep slope in the downstream area that allowed the tailings to flow quickly downslope and overwhelm another tailings dam just downslope. The tailings from both facilities then flow down the mountain and devastated the town of Stava and caused 269 fatalities [67].

If the failures in Figure 11 are divided into the two time frames considered herein, i.e., before and after the year 2000, it can be seen that the number of failures per failure mode has significantly decreased since 2000. However, trends of the most common failure modes, e.g., earthquakes and overtopping, between the two time frames vary. Before the year 2000 the most common failure mode was earthquake-induced failures, followed by slope instability, and overtopping (see Figure 12). After the year 2000, the most common failure mode was overtopping, followed by slope instability and then earthquake-induced failure (see Figure 12).

These failure modes suggest that in earthquake prone locations improved methods for assessing seismic stability and more robust designs have effectively reduced the number of failures caused by earthquake shaking. This significant decrease in earthquake related failures is primarily due to industry changes, that were codified into regulations in Chile after the 1965 El Cobre tailings dam failure due to a 7.4 M earthquake resulting in 200 to 350 fatalities [13]. These

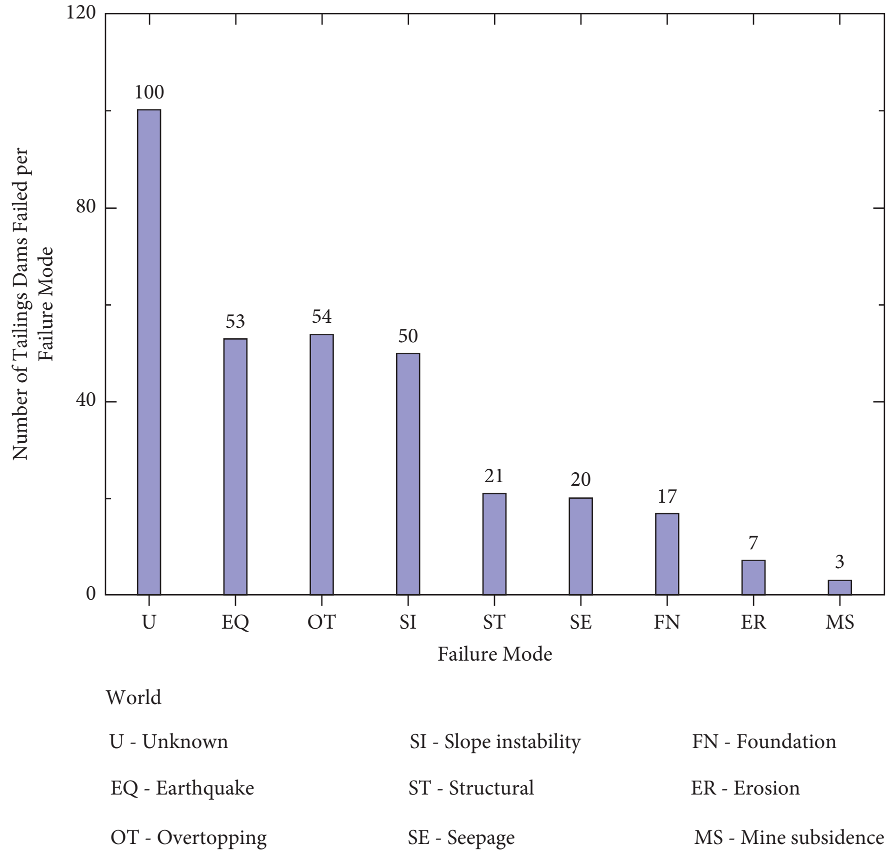

Figure 11: Number of tailings dams failed per failure mode in the world (data from Bowker [22] and Torrez-Cruz [32]).

industry, and eventually regulatory changes, include flattening downstream slopes from 2H : 1 V to 4H : 1 V and compacting the dam fill materials. These regulatory changes were eventually adopted in Peru, which also improved the seismic stability of their tailing dams [13]. This interest in improving the seismic stability of tailings dams has been facilitated by technical advances and development of software that practitioners can utilize to incorporate earthquake effects. For example, the software packages FLAC (https://www.itascacg.com/software/FLAC), RS3 (https://www.rocscience.com/software/rs3), SHAKE2000 (https://shake2000.software.informer.com/5.9/), and PLAXIS (https://www.bentley.com/en/products/brands/plaxis) allow seismic analyses of various Earth structures to be conducted [68].

In addition to enhanced analysis tools, the monitoring of tailings dams through different methodologies is becoming more frequent. For example, satellite and Light Detection and Ranging (LiDAR) data have been used in South Africa to monitor tailings dams [69]. Sweden has been using geophysical methods, such as self-potential and electrical resistivity, to monitor existing tailings dams [70]. A pre alarm system has been proposed by Dong et al. [71] that aims to use cloud computing, Internet of Things, artificial intelligence, and real time data to predict tailings dam behavior and anomalies.

Figure 13 presents the data from Figure 12 such that the dam type from each failure is identified. Figure 13 shows the two most common failure modes for upstream tailings dams are earthquake shaking and slope instability. However, Figure 12 shows that these two failure modes have experienced the greatest decrease in number of failures from 46 to 7 for earthquakes and from 40 to 10 failures for slope instability before and after 2000, respectively. This reduction reflects a better understanding of the failure modes that can affect upstream raised tailings dams and improvements in understanding and technology that allow engineers to better predict the performance of upstream tailings dams. These observations conflict with the Brazilian failures that recently occurred and suggest the lessons learned about upstream raised tailings dams have not been applied worldwide.

8. Released Volume of Tailings

Figure 14 shows the total released volume of tailings caused by a dam failure for each decade since 1920. The disturbing aspect of this data is that within the last decade, i.e., 2010 to 2020, the released volume is four times greater than the total released volume within any other decade. This is alarming because greater released volumes are likely to generate longer runouts that impact broader areas resulting in greater environmental damage and possibly fatalities. The released volume in the last decade is also due to better measuring and reporting procedures so some of the prior decades may have a greater released volume than shown in Figure 14.

The released volume in a tailings dam failure is related to the storage volume. Therefore, it is of interest to understand what percentage of the total volume of tailings stored is

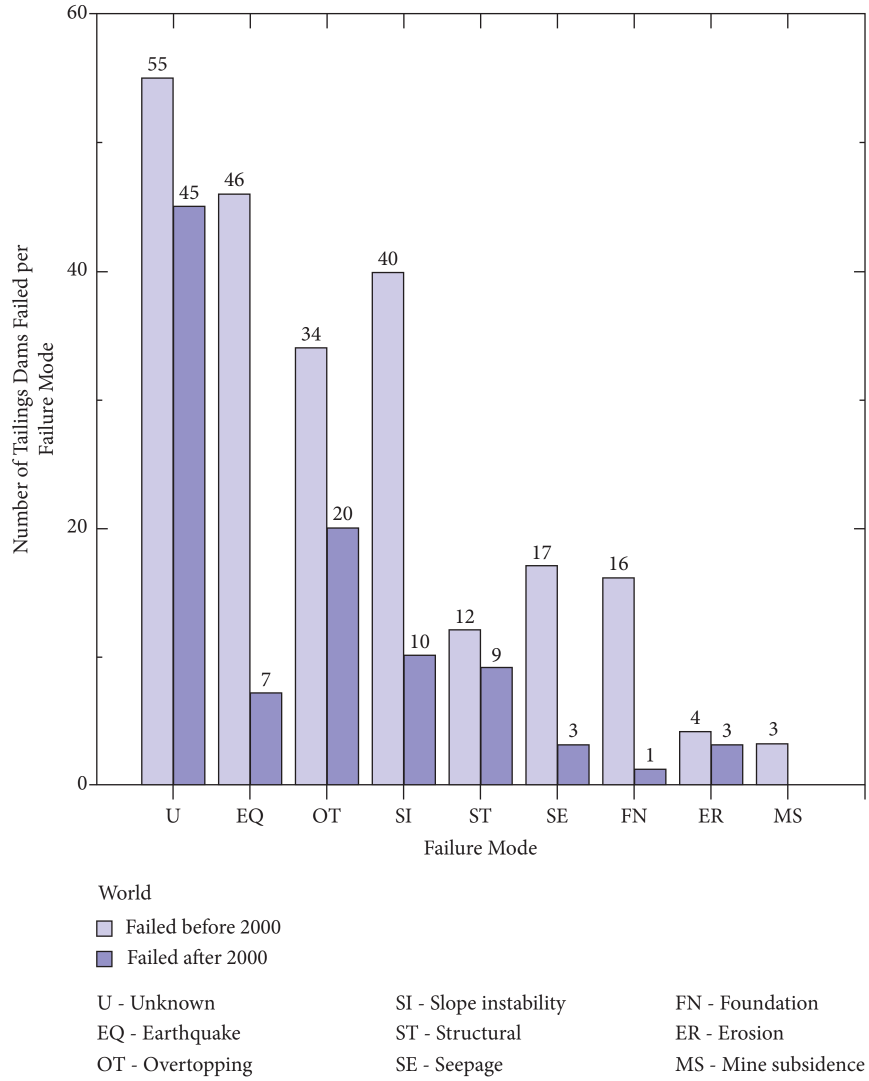

Figure 12: Number of tailings failed per failure mode in the world, before and after 2000 (data from Bowker [22] and Torrez-Cruz [32]).

released by a failure. From the collected data, the released volume can range from 10 to 85% of the total storage volume as shown by the dashed lines in Figure 15.

The released volume in a tailings dam failure is also thought to be related to the height of the dam at the time of failure. However, Figure 16 does not show a clear trend between dam height at failure and released volume. In addition, the B1 dam (86 m) was only about 80% of the height of Fundao (107 m) at the time of failure and it still failed and released less tailings volume. The width of the dam breach also is not a good indicator of the volume of released tailings during a tailings dam failure (see Figure 17).

9. Effect of Tailings Dam Height

The percentage of tailings dams failures per height has decreased before and after 2000 (see Figure 18). The dam height shown in Figure 18 corresponds to the actual or total dam height at the time of failure. The percentage in Figure 18 was calculated by dividing the number of failures by the number of tailings dams in that height range and time period. However, the dam height range of 45 to 60 m has the highest failure rate after 2000 (2.4%), which could suggest a vulnerability in stability for such heights.

Moreover, tailings dams height plays an important role when tailings dams failures occur because higher dams usually can store more tailings, which may influence the released volume, runout distance, and number of fatalities based on statistics in the Bowker [22] database. For instance, the Fundao tailings dam failure released 45 million cubic meters of tailings and produced a runout of about 537 km, which was aided by the Doce River. The B1 tailings dam failure released 12 million cubic meters of tailings and produced a runout of 8 km, which is fairly low when compared to the Fundao tailings dam. In summary, Figure 18 indicates increased stability with increasing dam height, which may be due to additional design, analysis, instrumentation, monitoring, inspection, and external peer review for higher tailings dams.

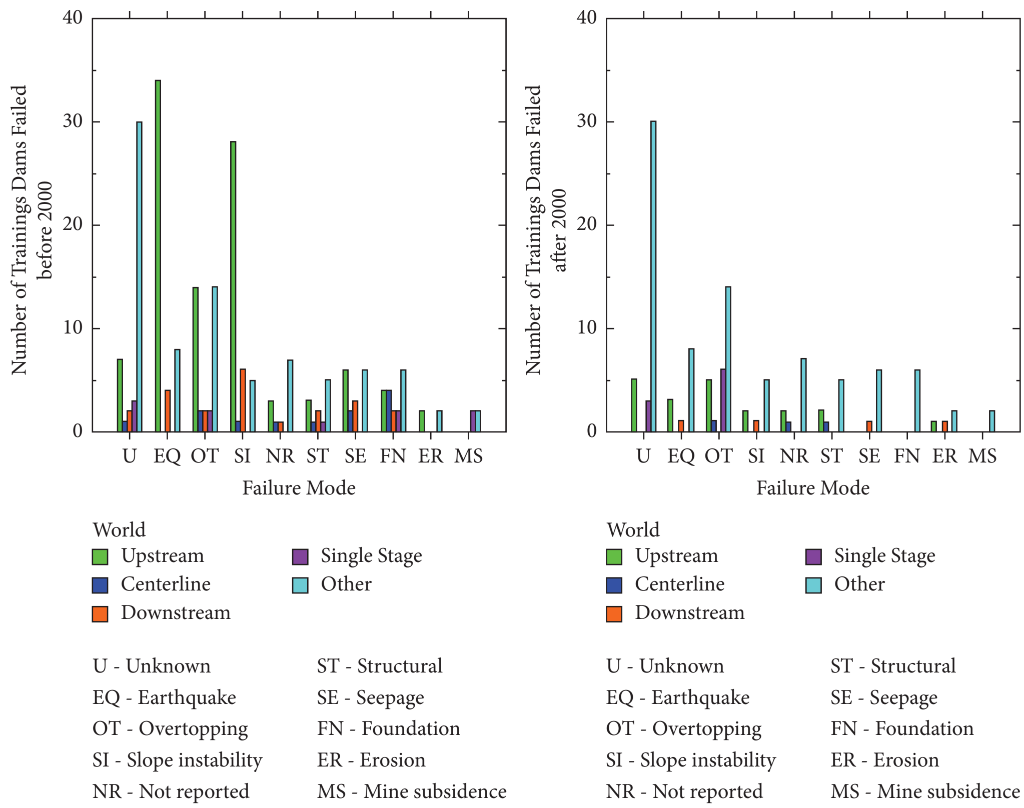

Figure 13: Number of tailings dams failed per failure mode in the world, according to dam type, before and after 2000 (data from Bowker [22] and Torrez-Cruz [32]).

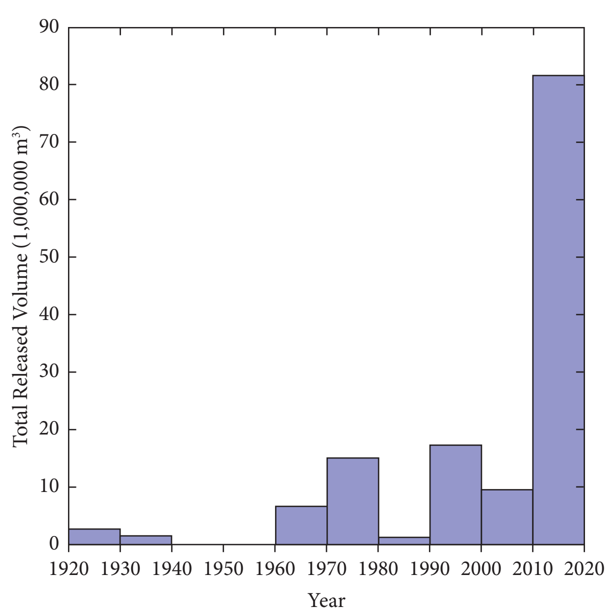

Figure 14: Total released volume of tailings for each decade since 1920 (data from Rana et al. [72]).

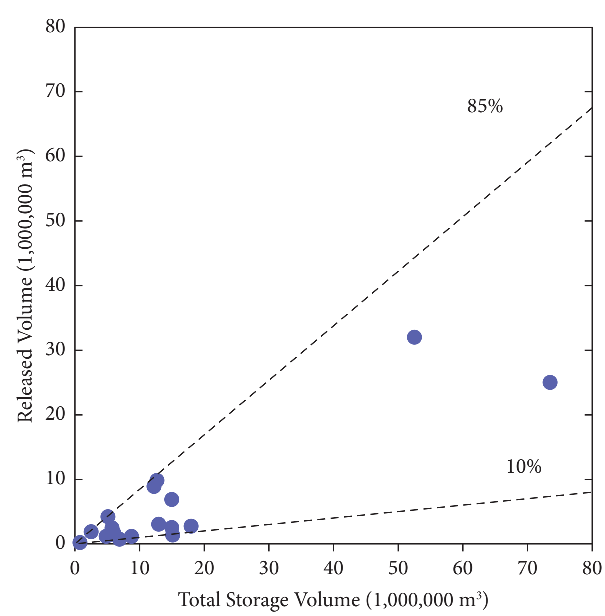

Figure 15: Released volume as a function of total volume of tailings stored (data from Rana et al. [72]).

The number of failures reported for upstream tailings dams does not seem to be influenced by the total height as shown in Figure 19. According to Figure 19, the common height range for upstream tailings dam failures is a height less than 50 meters. The Fundao Tailings Dam in Brazil had a height of 107 meters when it failed, which is more than twice the common failure height of less than 50 meters with a height of only about 25 m accounting for 25.9% of the upstream failures. Only one other upstream dam with a height close to that of the Fundao Dam (107 m) that has

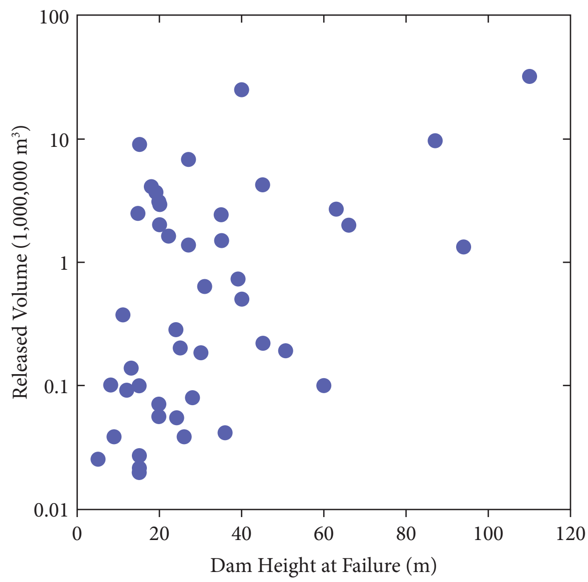

Figure 16: Released volume as a function of dam height at failure (data from Rana et al. [72]).

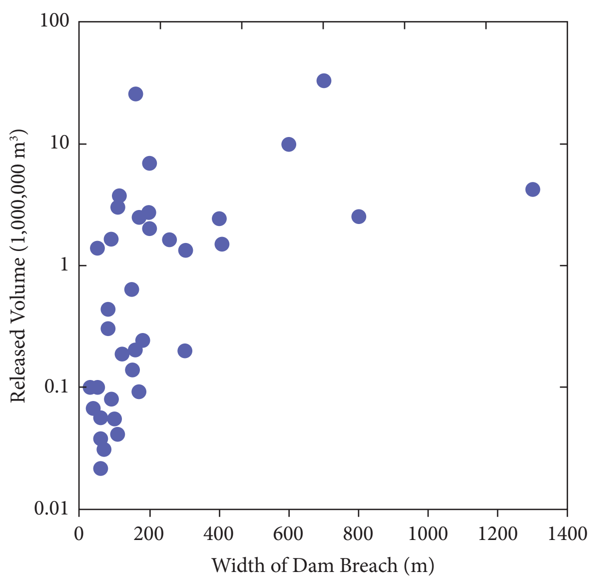

Figure 17: Released volume as a function of width of dam breach (data from Rana et al. [72]).

failed is the B1 Dam (86 m) in 2019. However, the data does suggest that higher dams are being used because the number of tailings dams in height from 80 to 100 m is 59 while the number for heights greater than 100 m is 71. Most of the dams from the latter group, i.e., greater than 100 m in height, were built after 2000.

10. Additional Points and Recommendations

This paper assesses the failure rate of upstream, downstream and centerline raised tailings dams. The failure rates were assessed at a global scale and a local scale in Brazil, United States, Canada, Europe, and South Africa. Since the year

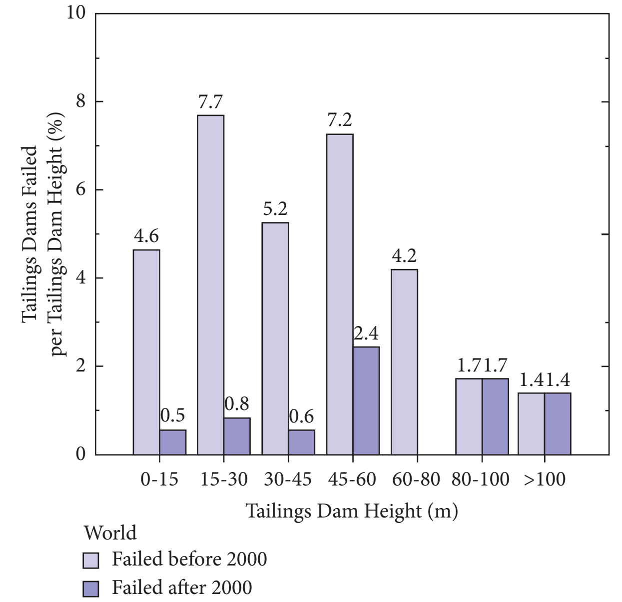

Figure 18: Percentage of tailings dams failed per height in the world, before and after 2000 (data from Bowker [22] and Torrez-Cruz [32]).

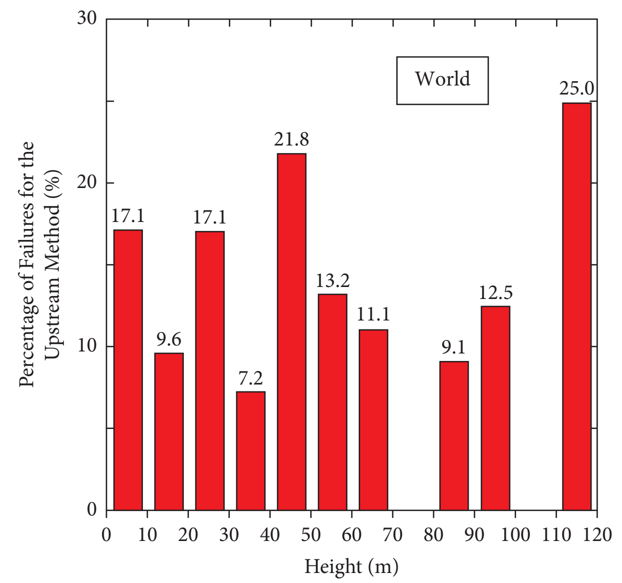

Figure 19: Percentage of upstream raised tailings dams failed per dam height at failure (data from Bowker [22] and Torrez-Cruz [32]).

2000, the failure rate of all three dam raising methods have decreased globally and locally, except in Brazil. In particular, the upstream failure rates decreased more than for the other two raising methods on a global and local scale, except in Brazil where the upstream failure rate has experienced a four fold increase since 2000. The failure rates also show that the downstream and centerline dam raising methods are not immune to failure. Hence if mining continues, one of these raising methods will be used and all have been involved in prior failures. As a result, the following features and practices should be used in all types of tailings dams: drainage systems, engineering analyses, instrumentation, monitoring, inspection, and qualified external peer review to further reduce failure rates, especially in Brazil.

Data Availability

The data that supports the findings of this study is openly available in Global Tailings Portal at https://tailing.grida.no/map/data/ and in the World Mine Tailings Failures upon request at https://worldminetailingsfailures.org/through the contact compiler@worldminetailingsfailures.org.

Disclosure

The contents and views in this paper are those of the authors and do not necessarily reflect those of any of the represented corporations, contractors, agencies, consultants, organizations, National Science Foundation, or any other entity or person involved with tailings dams.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

The first author also appreciates the financial support of the National Science Foundation (NSF Award CMMI-1562010).

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