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Regional Distribution and Causes of Global Mine Tailings Dam Failures

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Abstract: Tailings ponds are one of the three major production facilities in metal mines. The volume of tailings increases year by year, but the storage capacity of existing tailings ponds is limited. Therefore, tailings dams must become more fine-grained and larger. The potential hazard they represent should not be underestimated. This paper reveals the causes and regional distribution patterns of 342 tailings dam failures globally from 1915 to 2021 through statistical analysis. It was found that tailings pond failures occur almost every year, with an average of 4.4 accidents/year (1947–2021). The frequency has been gradually increasing in recent years, and most tailings pond failures are directly related to heavy rainfall or earthquakes. The frequency of tailings pond failures was significantly higher in Asia (21.3%) and the Americas (57.9%), especially in China (n = 43) and the United States (n = 107). Causes of tailings pond failures differed among regions. Most tailings pond failures in Asia and Europe were related to hydroclimate, while those in South America were mainly triggered by earthquakes. This study will provide theoretical data for the pre-design as well as the safe and stable operation of global tailings ponds, which will help to prevent global tailings pond failures.

Keywords: tailings pond; regional distribution; dam break; accident statistics; causation analysis

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1. Introduction

With the continued refinement of tailings particles and the increase in tailings emissions year by year, tailings dams will inevitably become more fine-grained and larger. However, extreme weather events and seismic activity will lead to frequent tailings pond failures.

From 1993 to 2009, the global population grew by 23%, while the global economy grew by 153% [1]. Rapid economic growth and population increase require the supply of more mineral resources. In this context, even low-grade minerals are now being extracted. Mineral extraction harms the environment [2,3] and generates large amounts of byproducts [4,5]. The fine particulate matter produced after beneficiation is called tailings and is usually stored in the form of a slurry in large, man-made dikes, i.e., tailings dams that are intended to protect the natural environment from pollution [6–8]. The global mining industry has produced enormous amounts of tailings, e.g., an estimated 14 billion tons in 2010 alone [4]. Ore grades are showing a decreasing trend, which means that more tailings will have to be stored in tailings impoundments in the future [9–11]. However, once a tailings pond leaks, it will severely damage downstream industrial and agricultural production and the wellbeing of local residents, as well as polluting the environment [12–14]. These negative effects will be exacerbated by pre-existing environmental threats such as land use change (LUC), water pollution, acid mine drainage (AMD) and the loss of biodiversity due to mining activities [15–17]. The failure rate of tailings dams in the last 100 years was reported at about 1.2% [18,19]. However, it should be noted that this figure is not accurate due to information loss, and it is certain that the failure rate of tailings dams is significantly higher than that of water storage dams [20,21].

Since the beginning of the 20th century, the frequency of tailings dam failures has been high worldwide. Dam failures that caused extremely severe damage are as follows [22–44]. On 28 March 1965, 16 tailings ponds in Chile collapsed almost simultaneously due to a 7.25 magnitude earthquake, resulting in 270 deaths. On 26 February 1972, the Buffalo tailings ponds in West Virginia, United States, collapsed due to dam instability, resulting in 125 deaths, destroying 500 homes, and causing more than $65 million of economic damage. On 19 July 1985, the Prealpi Mineraia tailings dam in Stava, Italy, failed due to a frozen drainage system, resulting in 268 fatalities; approximately 180,000 cubic meters of semi-fluid tailings were released, burying the downstream villages of Stava and Tesero. On 22 February 1994, the Merriespruit tailings dam in South Africa failed due to a gap in the dam caused by heavy rainfall, resulting in the loss of 600,000 m^3 of tailings which affected infrastructure up to 4 km downstream and caused 17 fatalities. On 30 January 2000, the Baia Mare tailings pond in Romania collapsed, seriously contaminating water sources; as a result, more than 2 million people had limited access to drinking water. On 8 September 2008, the Xinta mine in Xianfen County, Shanxi Province, collapsed due to illegal construction and local seepage damage, resulting in 277 deaths. On 4 August 2014 at the Mount Polley mine tailings pond in Canada, failure to take into account the ice layer led to the collapse of the glacial lake layer at the base of the dam, resulting in the discharge of about 17 million m^3 of wastewater and 8 million m^3 of tailings into the lake, causing extremely serious pollution to water sources. On 5 November 2015, the Samarco iron ore tailings pond in Brazil collapsed due to a small earthquake that triggered dam liquefaction; about 32 million m^3 of tailings gushed out, flooding 158 houses in downstream villages, killing at least 17 people and polluting 650 km of the river that flows into the Atlantic Ocean. On 25 January 2019, Minas Gerais Cérrego do Feijío Vale's iron ore waste dam in Brazil, that has operated at a high-water level for years, experienced a momentary dam failure due to dam slope instability, leaving 325 people dead or missing and causing 12 million m^3 of tailings to flow out, polluting 650 km of rivers. This final accident is recognized as the most catastrophic mine dam failure of all time. The evolution of this event is shown in Figure 1 [42].

Currently, information on tailings pond dam failures is commonly obtained from the International Commission on Large Dams (ICOLD), the United Nations Environment Programme (UNEP) and the World Energy Information Service (WISE). Kamrul Islam et al. (2021) analyzed the water pollution caused by dam failures including information that is lacking in the aforementioned databases, such as mine location and production data, and using the gray water footprint (WF) as a proxy [43]. Paola Dutto et al. (2017) numerically reproduced a landslide using a pure viscous model with a pure frictional model, taking the Aberfan and gypsum tailings impoundment flow slide as an example [44]. Darve and Laouafa (2002) studied dam damage patterns, referring to the damage pattern of loose sand or normally consolidated clay as "diffuse failure" to distinguish it from the "localised mode". In tailings ponds where tailings are used to build the dam body, "diffuse failure"-type events tend to be more common [45]. Ledesma et al. (2022) proposed a method to assess the damage of tailings dams due to flow liquefaction, and analyzed and validated the Fundão dam to derive three factors that may lead to dam damage: (i) a surface load applied to the crest of the upstream raise; (ii) horizontal deformation at the toe of the setback; and (iii) an increase in the water level within the tailings [46]. Such damage likely imposes a static load impact on the dam, while a dam failure caused by an earthquake is referred to as dynamic ruin. The importance of these databases and the published literature is unquestionable. This study aims to analyze the impact of mine tailings dam failures worldwide over the past 100 years. To this end, we updated the tailings dam failure database, analyzed tailings dam failures from the perspectives of dam height, mine type, and geographic location, summarized the main causal factors (type of failure and regional analyses), and revealed regional distribution patterns of tailings dam failures. It is expected that this study will help to reduce tailings dam failures in the future.

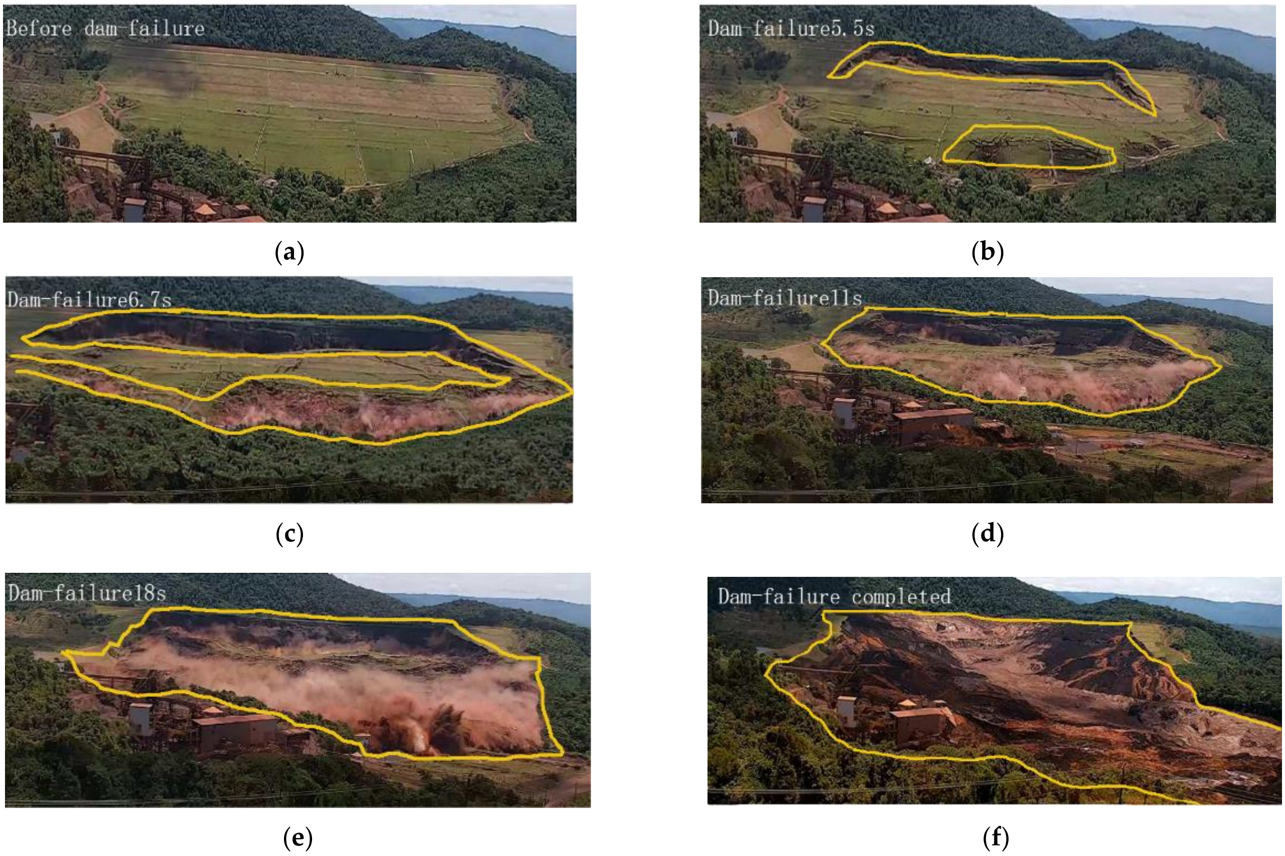

Figure 1. Feijío tailings pond dam failure, Brazil, 2019. (**a**) Before dam-failure; (**b**) Dam-failure 5.5s; (**c**) Dam-failure 6.7s; (**d**) Dam-failure 11s; (**e**) Dam-failure 18s; (**f**) Dam-failure completed.

2. Causal Analysis of Tailings Pond Dam Failures

2.1. Statistics of Tailings Pond Dam Failures

The years 1947–2021 may be divided into three phases (the period of 1915–1946 is excluded due to data loss), with every 25 years being classified as a distinct phase. In the first phase (1947–1971), 73 tailings pond dam failures occurred. In the second phase (1972–1996), 143 tailings pond dam failures took place. During the third phase (1997–2021), 115 tailings pond failures occurred. Figure 2 shows a statistical analysis of the frequency of tailings pond failures; as can be seen, the annual average of global tailings pond failures was at least 4.4 from 1947 to 2021, i.e., 5.7 from 1972 to 1996 (red line), 4.6 from 1997 to 2021 (green line), and 2.9 from 1947 to 1971 (blue line). The frequency of tailings pond failures from 1972 to 1996 was the highest. The probability of tailings pond failures was found to be more than 10 times higher than that of reservoir failures [47]. The yellow spheres in Figure 3 indicate tailings pond failures. When the *Z*-axis value (indicating the number of tailings pond failures) is 0–5, the projection points (green dots) on the XZ surface are the densest, indicating the highest chance of 0–5 dam failure accidents in tailings ponds worldwide each year. As the *Z*-axis value increases, the projection points become more and more sparse. The yellow sphere at the highest point indicates the largest number of tailings pond accidents worldwide in 1965 ($n = 23$), when 18 such events occurred almost simultaneously due to an earthquake in Chile. The projection points (red dots) on the XY surface are the densest ($n = 62$) when the *X*-axis value is 1974–1983, which means that there were more dam failure accidents in tailings ponds during this period. When the *Y*-axis value is 5–10, the number of projection points on the XY surface is the largest.

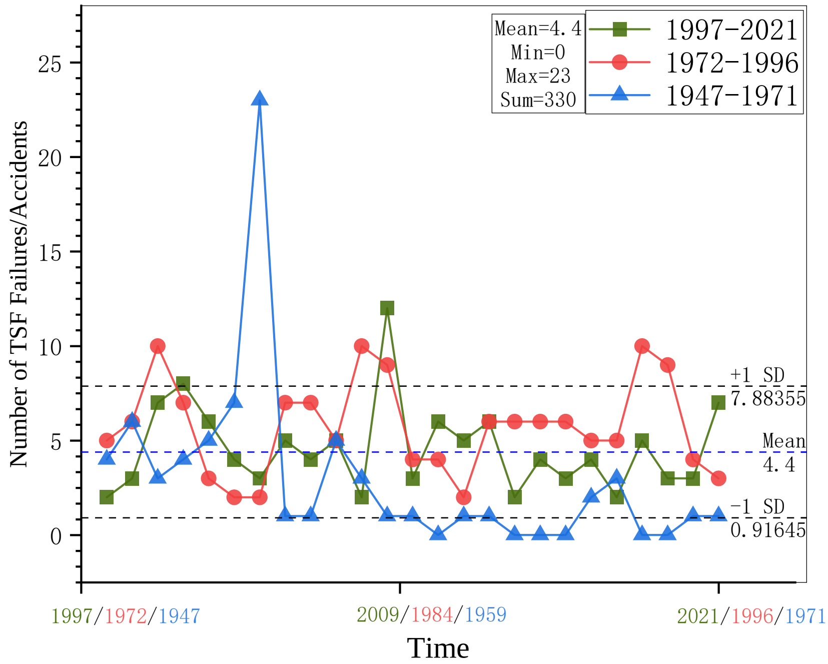

Figure 2. Temporal distribution of tailings pond failures (TSF—Tailings Storage Facility).

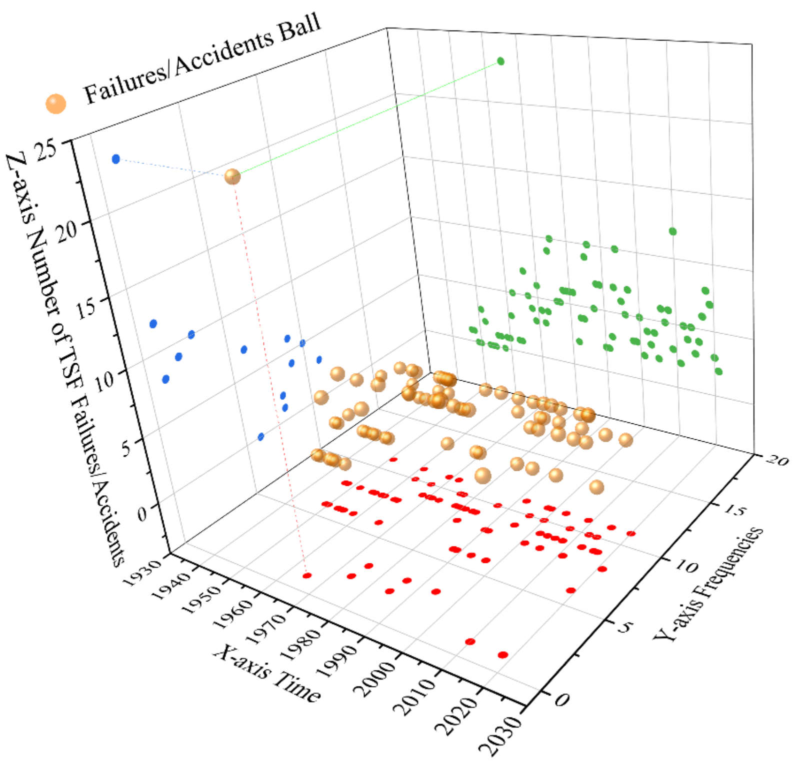

Figure 3. Three-dimensional distribution of tailings pond failures.

The magnitude of tailings pond failures is classified according to the number of human casualties, the degree of pollution to the downstream environment, and the quantity of tailings discharged. The classification is as follows:

1. Very serious tailings dam failures: multiple loss of life (>20) and/or release of 1,000,000 m^3 totals discharge, and/or release travel distance of 20 km or more.
2. Serious tailings dam failures: loss of life and/or release of $\geq$100,000 m^3 semi-solids.
3. Other tailings dam failures: engineering/facility failures other than those classified as very serious or serious, no loss of life.
4. Other tailings-related accidents: accidents are other than those classified as type 1, 2, or 3.

Figure 4 demonstrates the relationship between the severity of tailings pond failures and time. Other failures occupy the largest proportion, followed by serious failures; the number of very serious failures ranks third. In terms of a linear regression analysis, both the red and black lines show an increasing trend, indicating that tailings pond failures are becoming more and more serious, which may be related to the growth of tailings pond dam height.

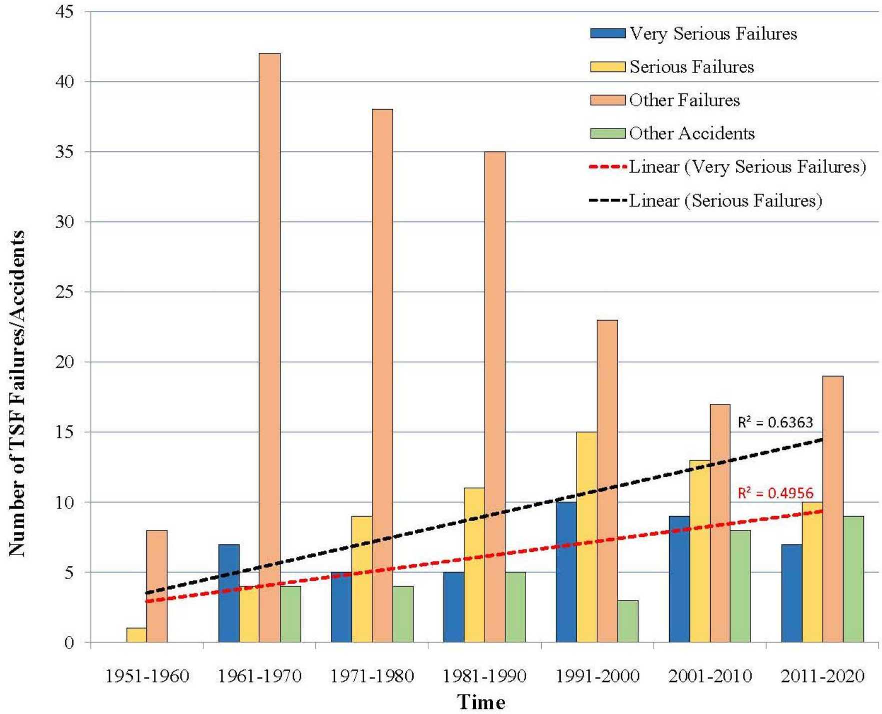

Figure 4. Magnitude of tailings pond failures over time.

From existing dam failure cases, it was found that there are numerous causes of tailings pond failures, and the corresponding patterns and mechanisms are very complex. Tailings pond failures are not brought about by a single factor, but rather, are often the result of multiple factors acting together. In essence, they are due to the influence of the external environment (earthquakes, rainfall, flooding, dam foundation subsidence, etc.), which causes changes in the stress and seepage fields, leading to the destabilization of the structure. The causes of ICOLD tailings pond failures are classified as follows:

- Structure and condition of the dam foundation (FN)

Foundations that have been subjected to great pressure and horizontal thrust may cause damage to the stability of the dam body due to deformation or sliding. The main two causes of this phenomenon are as follows; 1. Low strength of the dam foundation, especially when a karst foundation exists. 2. Poor slip resistance of the dam foundation. Foundation fracture, rock softening, or modifications may cause the foundation slip resistance to decline.

- Earthquakes (EQ)

The mechanisms by which earthquakes cause tailings dam failure are as follows: 1. liquefaction of tailings sand; 2. weakening of tailings dam material; and 3. destabilization of the dam itself. The main factors affecting the seismic liquefaction of the dam are: 1. dynamic load conditions; 2. the physical properties of the tailings conditions; and 3. The burial conditions [48]. Most of the tailings ponds damaged due to earthquakes were upstream-type dams; such ponds have problems, including generally high infiltration lines and poor seismic resistance.

- Mine subsidence (MS)

Generally speaking, the ground cannot withstand the huge pressure of tailings pond settlement or collapse, leading to dam failure. Such tailings ponds are generally built above an underground mine.

- Structural inadequacies, inadequate or failed decants (ST)

Design errors or the failure of a component to function as designed. Failed decants (which drain water from the impoundments) are a common cause.

- External erosion (ER)

At the scale of the structure, erosion by water flow can be divided into two types: if the water erodes the visible part of the structure, it is called external erosion; conversely, if the water erodes an invisible part of the structure or its foundation, it is called internal erosion [49]. On a large scale, rainfall can damage the soil and wash it away by runoff, potentially causing tailings dam failures [50].

- Seepage and internal erosion (SE)

Under the action of the seepage field, tailings sand material may undergo infiltration deformation. For tailings dams, when the infiltration deformation conditions are met, a pipe surge will occur within the dam body, causing cracks and local collapse within the pond and local instability of the dam slope, eventually leading to the failure of the tailings pond.

- Overtopping (OT)

Flood topping triggered-dam failure can be summarized as follows. Excessive wind speed or rainfall, the blockage or destruction of flood discharge and drainage structures, or reduced flood discharge capacity may cause the water to impact the dam or the water level to rise, eventually leading to the destruction of the dam. Flooding in tailings ponds is often the result of multi-factor coupling, with rainfall being the main factor and impermeable dams, aging flood relief facilities, scale blockage, damage, and other phenomena being secondary factors. As such, it can be said that strong rainfall is a necessary condition for flooding dam failure.

- Slope instability (SI)

Dam destabilization refers to damage due to tailing sand extrusion or construction, heavy rainfall, or other factors (non-seepage disturbance). Dam cracks or dam body slip resistance are usually insufficient to cause tailings pond failure. The usual signs of damage are cracking and bulging of the dam face, protrusion of the slope, sinking of the top of the dam, and deformation of the dike edge.

The causes of 258 failures were identified, while those of the remaining 84 failures remain unknown. Among the 258 tailings pond failures with known causes, 10.1% were caused by ST (26), 22.1% by SI (57), 17.1% by EQ (44), 5% by ER (13), 11.2% by SE (29), more than 24.4% by OT (63), 0.4% by MS (1), 9.7% by FN (25). Most tailings pond failures were directly related to heavy rainfall or earthquakes, as shown in Table 1.

Table 1. Statistics on the causes of tailings pond failures.

Reason	Number of Accidents	Region
SI	*n* = 57 (22.1%)	*n* = 1 (Bulgaria, Italy, Ukraine, Russia, Yugoslavia, Romania, Zambia, Spain, Australia, South Africa); *n* = 2 (Brazil); *n* = 3 (South Africa); *n* = 4 (UK); *n* = 5 (Canada); *n* = 11 (China); *n* = 21 (USA)
MS	*n* = 1 (0.4%)	*n* = 1 (China)
SE	*n* = 29 (11.2%)	*n* = 1 (Finland, Hungary, Peru, South Africa, France, UK, Australia); *n* = 3 (Canada); *n* = 4 (China); *n* = 15 (USA)
ST	*n* = 26 (10.1%)	*n* = 1 (UK, Ecuador, India, Canada, Macedonia, Romania, Hungary, Bulgaria Mexico); *n* = 2 (Brazil); *n* = 3 (China, Philippines); *n* = 8 (USA)
FN	*n* = 25 (9.7%)	*n* = 1 (China, Australia, New Zealand, Russia, Spain, China); *n* = 2 (UK); *n* = 3 (Philippines); *n* = 5 (Canada); *n* = 10 (USA)
OT	*n* = 63 (24.4%)	*n* = 1 (Zambia, Portugal, Peru, Zimbabwe, South Africa, Spain, Brazil); *n* = 2 (Mexico, Canada); *n* = 3 (Australia); *n* = 5 (UK); *n* = 6 (Chile, Philippines); *n* = 10 (China); *n* = 14 (USA); *n* = 1 (Region unknown)
EQ	*n* = 44 (17.1%)	*n* = 1 (USA); *n* = 2 (Peru Argentina); *n* = 3 (China); *n* = 5 (Japan); *n* = 29 (Chile)
ER	13 (5%)	*n* = 1 (Philippines, China, Chile, Sweden, Guyana, Montenegro, Bulgaria, Brazil); *n* = 2(Canada, USA).

Figure 5 represents the relationships among damming methods (X), causes of dam failure (Y), and the number of dam failures (Z). Tailings pond damming methods are generally divided into the following types: upstream (US), water retention (WR), downstream (DS), and centerline (CL). It can be seen that the US damming method is the most common, while the CL method is the least widely used. Among tailings ponds using the US method, 30 failed due to EQ and 28 due to SI. Both EQ and SI cause far more dam failures in tailings ponds applying the US method than other factors. It is worth noting that EQ (yellow cone) and SI (dark green cone) also account for a much larger proportion of total dam failures than other factors (FN, MS, ER, ST, SE, OT); MS (cyan cone) causes the fewest failures.

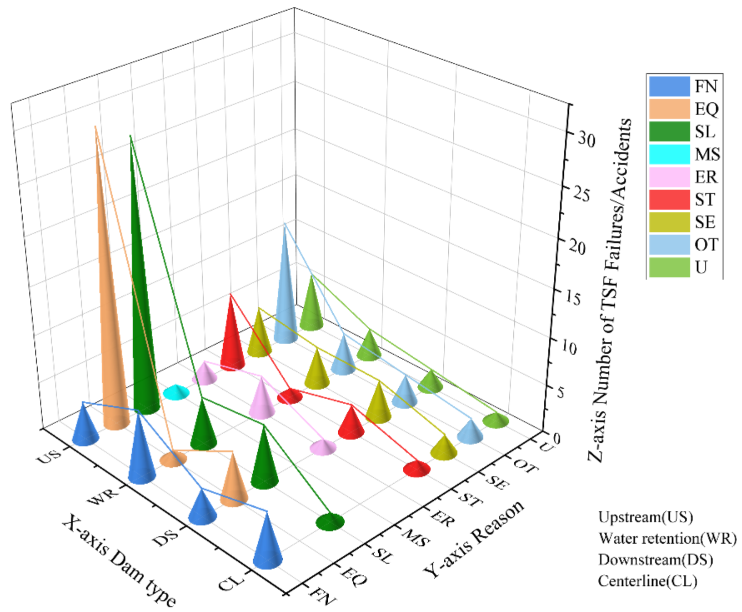

Figure 5. Three-dimensional diagram of the relationship between dam construction method and dam failure causes.

2.2. Analysis of Tailings Pond Dam Failures

Figure 6 shows the global distribution of tailings pond dam failures. The United States (*n* = 107) had the highest number of tailings pond dam failure accidents, followed by China (n = 43). Figure 7 displays the causes of dam failures in seven key regions; it can be seen that the number of dam failures with unknown causes (yellow block, n = 62) is high, which indicates that the information recording system is not perfect. In the United States, 29.9% (n = 32) of tailings pond failures have unknown causes, and most tailings pond failures were caused by SI (19.6%). In China, 25.5% of tailings pond failures were caused by SI and 20.9% by OT. In Chile, 78% of tailings pond failures were caused by EQ, but the 16 accidents in 1965 may result in the true value being less than 78%. In Canada, 19.2% of tailings pond failures were caused by SI (n = 5) and FN (n = 5), while the causes of seven dam failures remain unknown. OT was the main trigger for tailings pond failures in the Philippines (33.3%) and the United Kingdom (33.3%). Among the seven countries, Brazil had the most significant loss of data (46.1%) regarding the cause of dam failures. It is likely that climate and earthquakes were the main causes of these tailings pond failures, as discussed in detail below.

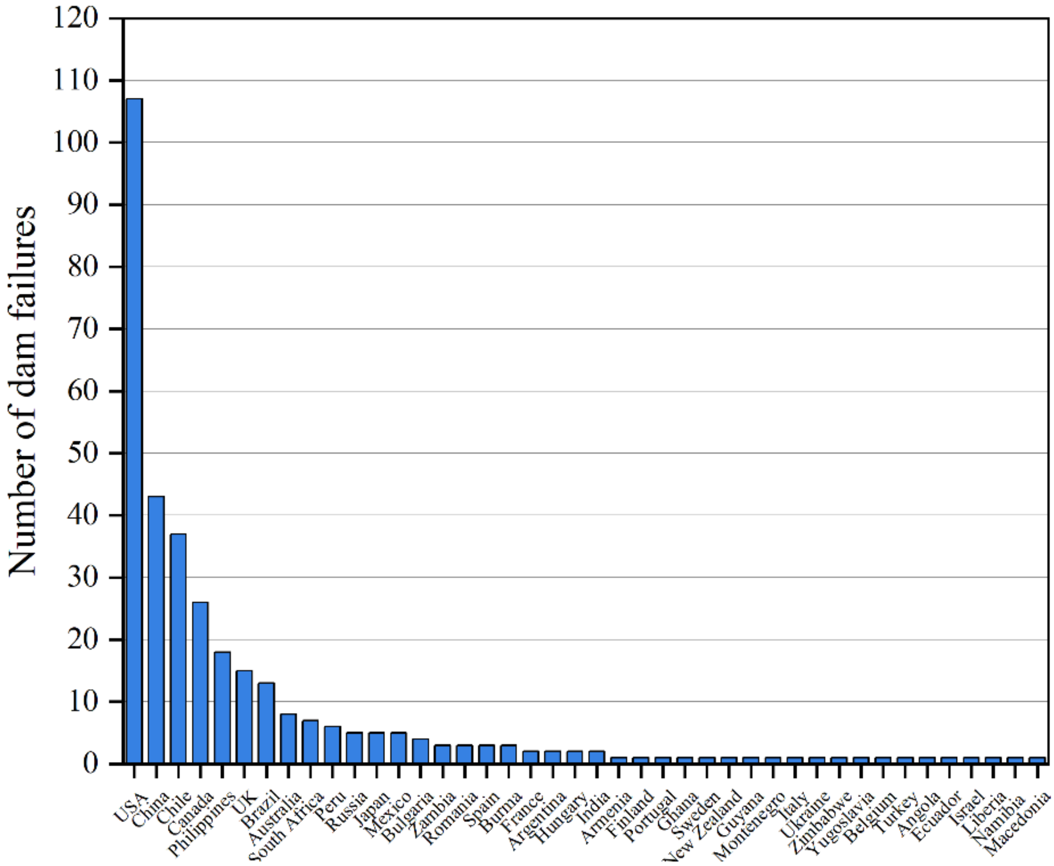

Figure 6. Global distribution of tailings dam events.

Although the causes of 258 mine failures have been determined, the causes of 84 tailings pond failures (24.6%) remain unknown. Figure 8 shows the dam failure causes for different mine types and dam construction methods, where the size of the blue circle is proportional to the number of tailings pond failures. Dam failures in copper mine tailings ponds were mainly caused by EQ and OT, accounting for 24 and 13 cases, respectively. In addition, copper tailings ponds (n = 38) are mainly applied with the US damming method. It is indicated that most US tailings pond failures were triggered by EQ (consistent with the results in Figure 5). Twenty dam failures in Chilean copper mine tailings ponds were caused by earthquakes. The number of gold tailings ponds using the US method was also the highest (n = 13), and ST (n = 9) and OT (n = 11) were the two most common causes of failures. Five (45.5%) gold tailings pond failures in the Philippines were attributed to OT. For the 23 Pb mine tailings pond failures, the main causes were SI (n = 6) and OT (n = 8). In summary, rainfall and extreme weather events are two important factors leading to tailings dam failures.

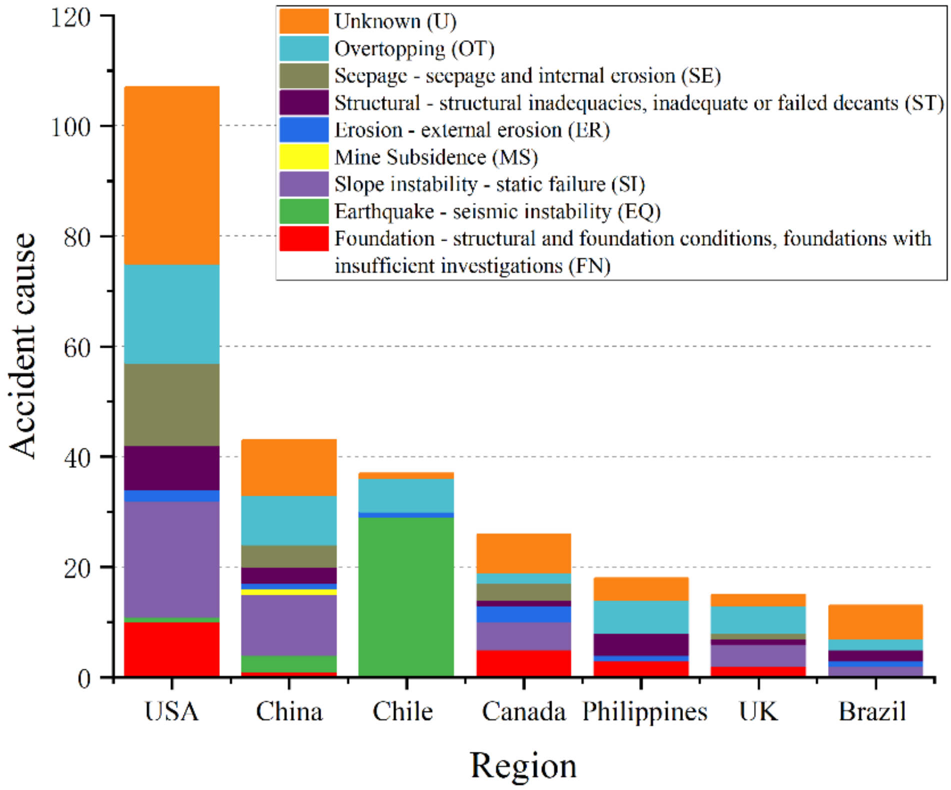

Figure 7. Causes in regions with a high frequency of tailings dam failures.

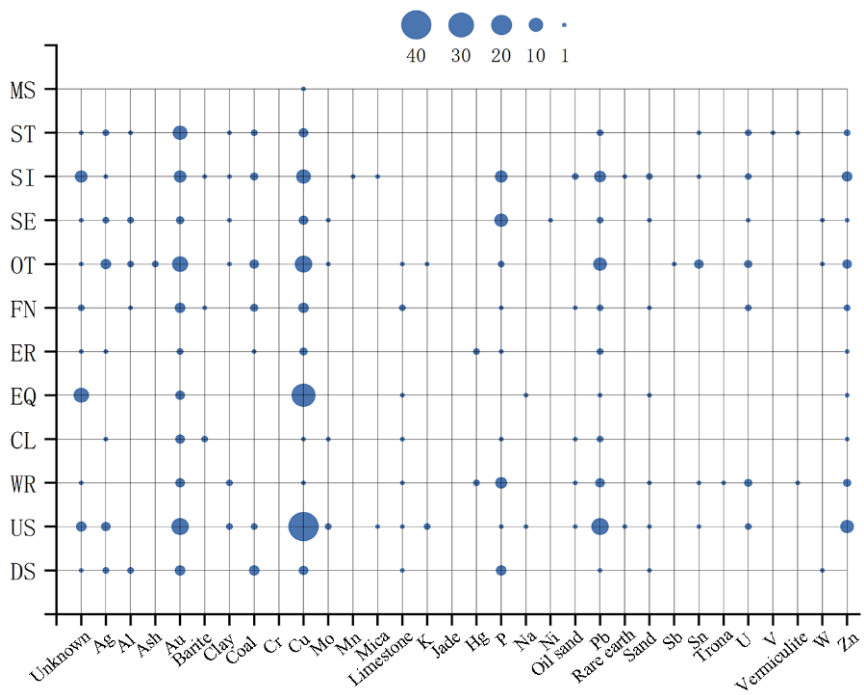

Figure 8. Causes of tailings pond failures in different mines.

The height of a tailings dam is another important factor affecting its safety. The tailings dam failure database contains information, including the dam height, of 159 failure events.

Approximately 89.9% (n = 143) of these events occurred with dam heights between 0 and 50 m; only 8.8% (n = 14) occurred with dam heights between 50 and 100 m, and 1.3% (n = 2) were with dam heights greater than 100 m. However, increasing the height of tailings dams does not prevent dam failures. There is a moderate correlation (r^2 = 0.54) between tailings dam height and mine size (in terms of production). Tailings dam heights between 0 and 100 m correspond to an average production of about 104 million tons, while heights greater than 100 m correspond to an average production of about 643 million tons [43]. The box line in Figure 9 shows the distribution of tailings dam heights in different mines. The blue dots represent the height of the tailings dam and the hollow squares inside the yellow blocks represent the average height of the dam. We found that the chance of dam failure is higher in copper (n = 36), gold (n = 19) and lead (n = 15) mines. As can be seen in Figure 9, the dam heights in instances of copper tailings dam failures were 5–140 m, with the average being 29.8 m and the median being 22.5 m. The dam heights in instances of gold tailings dam failures were 5–94 m, with the average being 24.9 m and the median being 24 m. The dam heights in instances of lead mine tailings pond failures ranged from 5 to 45 m, with the average being 19.2 m and the median being 15 m. Both the average and median height of lead mine tailings pond failures were lower than those of the copper and gold mine pond failures. Figure 10 shows the time distribution relative to the height of tailings dam failures. The linear regression equation (y = (0.28 ± 0.1) x − (528.74 ± 200.94)) indicates that tailings dam heights slowly increased with time.

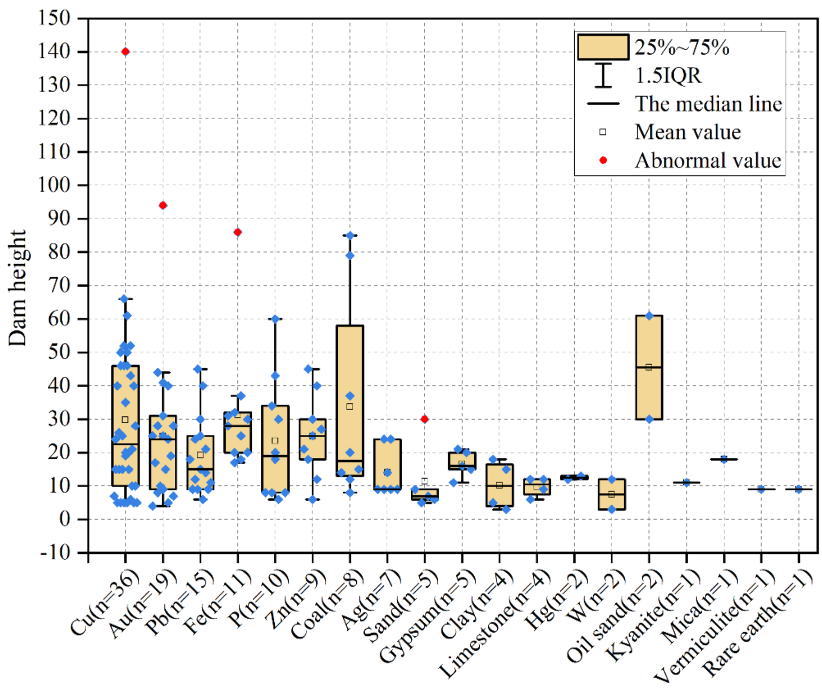

Figure 9. Dam height distributions of tailings dam failures for different mines.

Figure 11 shows the distribution of released tailings (percentage of storage) after a tailings pond break. The black dots represent the proportion of released tailings to the storage volume after the tailings pond break, and the hollow square represents the average height of the tailings dam. The average proportion of sand burst was 0.3455, indicating that after the dam break, the released tailings accounted for 34.6% of the storage volume. The mean and median values of the proportion of released tailings due to FN were 0.561 and 0.463, respectively, i.e., larger than those of the proportion of released tailings caused by other factors. Figure 12 shows the relationship between the proportion of released tailings after a tailings dam failure and the severity of the accident. The mean and median values of the proportion of released tailings after very serious failures were 0.419 and 0.447, respectively, i.e., larger than those after serious failures and other failures.

Figure 13 shows the relationship between the tailings pond storage volume and the tailings release volume after a dam failure. The x-axis of the blue point in Figure 13a represents the tailings storage volume and the y-axis represents the tailings release volume after dam failure. These data are logarithmically transformed in Figure 13b. The linear regression equation in Figure 13b shows a positive correlation between the tailings release volume and the tailings storage volume after dam failure. $y = (0.79 \pm 0.54) + (0.75 \pm 0.08)\,x$, where y is Log (Release volume) (Mm^3), and x is Log (Storage volume) (Mm^3). In general, as the storage volume increases, so does the release of tailings sand.

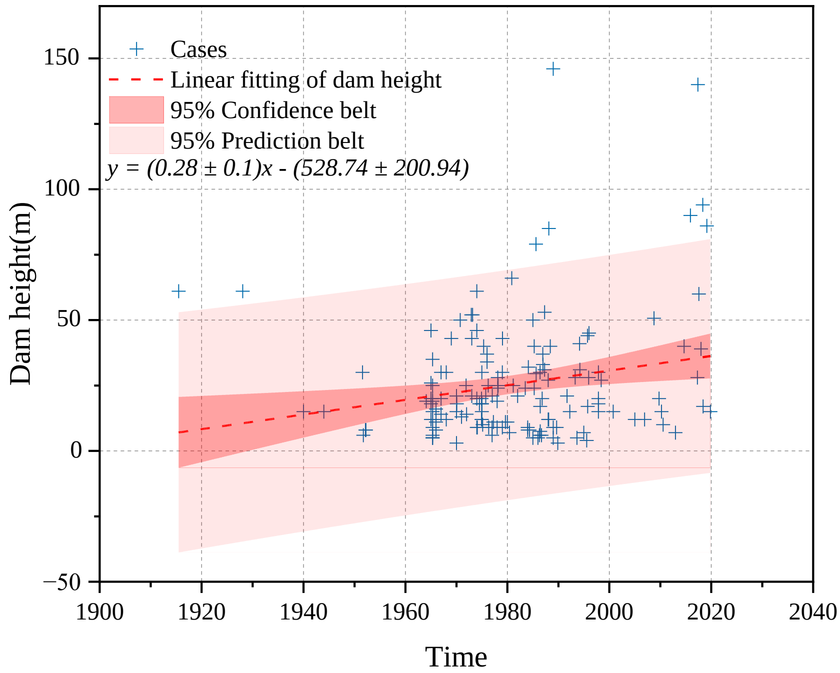

Figure 10. Linear regression analysis of dam height.

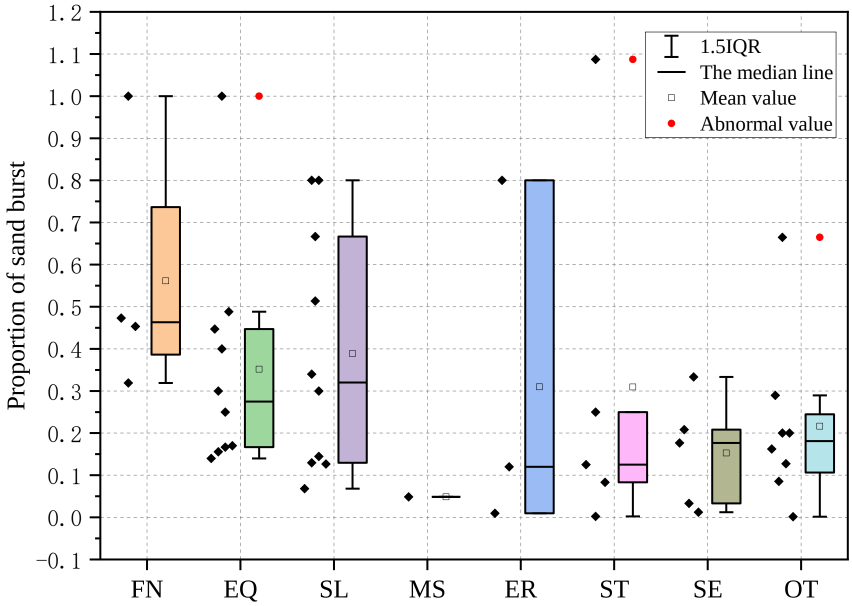

Figure 11. Relationship between the proportion of released tailings and the dam construction method after dam failure.

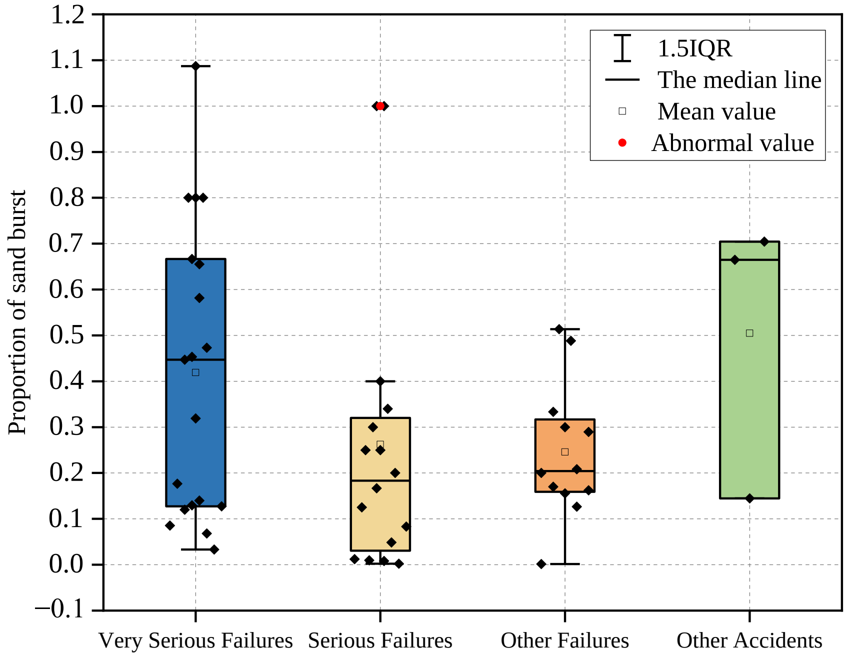

Figure 12. Relationship between the proportion of released tailings and the hazard level after dam failure.

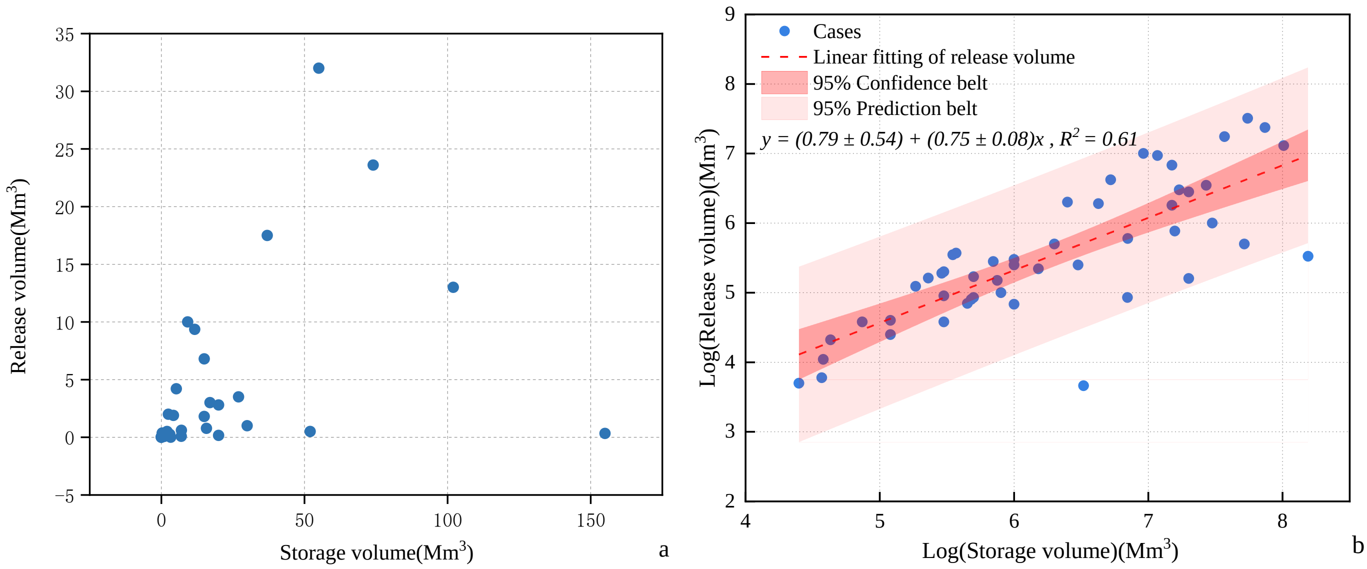

Figure 13. Relationship between tailings storage volume and release volume. (**a**) Before logarithmic transformation; (**b**) after logarithmic transformation.

3. Regional Analysis of Tailings Pond Dam Failure Accidents

Table 2 provides statistics about tailings pond dam failures in different regions. It can be seen that 21.3% of tailings dam failures occurred in Asia, 12.6% in Europe, 57.9% in the Americas, 4.8% in Africa, 2.6% in Oceania, and 0.8% in unknown regions. Figure 14 shows the distribution of tailings pond failures in different regions. The frequency of tailings pond failures in Asia and the Americas, especially in China (n = 43) and the United States (n = 107), was significantly higher than in other regions.

Table 2. Statistics of global tailings dam failures.

Region		Number	Causes of Dam Failure	
Oceania	New Zealand	1	1 FN	9 (3 OT, 1 ER, 1 SI, 2 Unknown, 2 FN)
	Australia	8	3 OT, 1 ER, 1 SI, 2 Unknown, 1 FN	
Asia	Turkey	1	Unknown	73 (4 FN, 8 EQ, 12 SI, 1 MS, 2 ER, 8 ST, 4 SE, 15 OT, 19 Unknown)
	Israel	1	SI	
	India	2	1 ST, 1 Unknown	
	Myanmar	3	3 Unknown	
	Japan	5	5 EQ	
	Philippines	18	6 OT, 4 ST, 3 FN,1 ER, 4 Unknown	
	China	43	1 FN, 3 EQ, 11 SI, 1 MS, 1 ER, 3 ST, 4 SE, 9 OT, 10 Unknown	
Europe	Finland	1	SE	43 (7 OT,4 SE,5 ST,12 SI,4 FN,3 ER, 8 Unknown)
	Portugal	1	OT	
	Swedish	1	ER	
	Montenegro	1	ER	
	Italy	1	SI	
	Ukraine	1	SI	
	Yugoslavia	1	SI	
	Belgium	1	Unknown	
	Macedonia	1	ST	
	French	2	1 SE, 1 Unknown	
	Hungary	2	1 SE, 1 ST	
	Romania	3	1 ST, 1 SI, 1 Unknown	
	Spain	3	1 OT, 1 FN, 1 SI	
	Bulgaria	4	2 SI, 1 ER, 1 ST	
	Russia	5	1 SI, 1 FN, 3 Unknown	
	UK	15	5 OT, 1 SE, 1 ST, 4 SI, 2 FN, 2 Unknown	
Africa	Armenia	1	OT	16 (4 SI, 1 SE, 4 OT, 1 ST, 6 Unknown)
	Ghana	1	Unknown	
	Zimbabwe	1	OT	
	Angola	1	Unknown	
	Liberia	1	ST	
	Namibia	1	Unknown	
	Zambia	3	1 OT, 1 SI, 1 Unknown	
	South Africa	7	3 SI, 1 SE, 1 OT, 2 Unknown	
America	Guyana	1	ER	198 (31 OT, 19 SE, 13 ST, 8 ER, 29 SI, 34 EQ, 15 FN, 49 Unknown)
	Ecuador	1	ST	
	Argentina	2	2 EQ	
	Mexico	5	2 OT, 1 SI, 1 ST, 1 Unknown	
	Peru	6	2 EQ, 1 SE, 1 OT, 2 Unknown	
	Brazil	13	2 OT, 2 ST, 1 ER, 2 SI, 6 Unknown	
	Canada	26	2 OT, 3 SE, 1 ST, 3 ER, 5 SI, 5 FN, 7 Unknown	
	Chile	37	1 ER, 6 OT, 29 EQ, 1 Unknown	
	USA	107	18 OT, 15 SE, 8 ST, 2 ER, 21 SI, 1 EQ, 10 FN, 32 Unknown	
Unknown	Unknown	3	1 OT, 2 EQ	3 (1 OT, 2 EQ)
		Total		342 (61 OT, 27 ST, 28 SE, 44 EQ, 25 FN, 58 SI, 1 MS,14 ER, 84 Unknown)

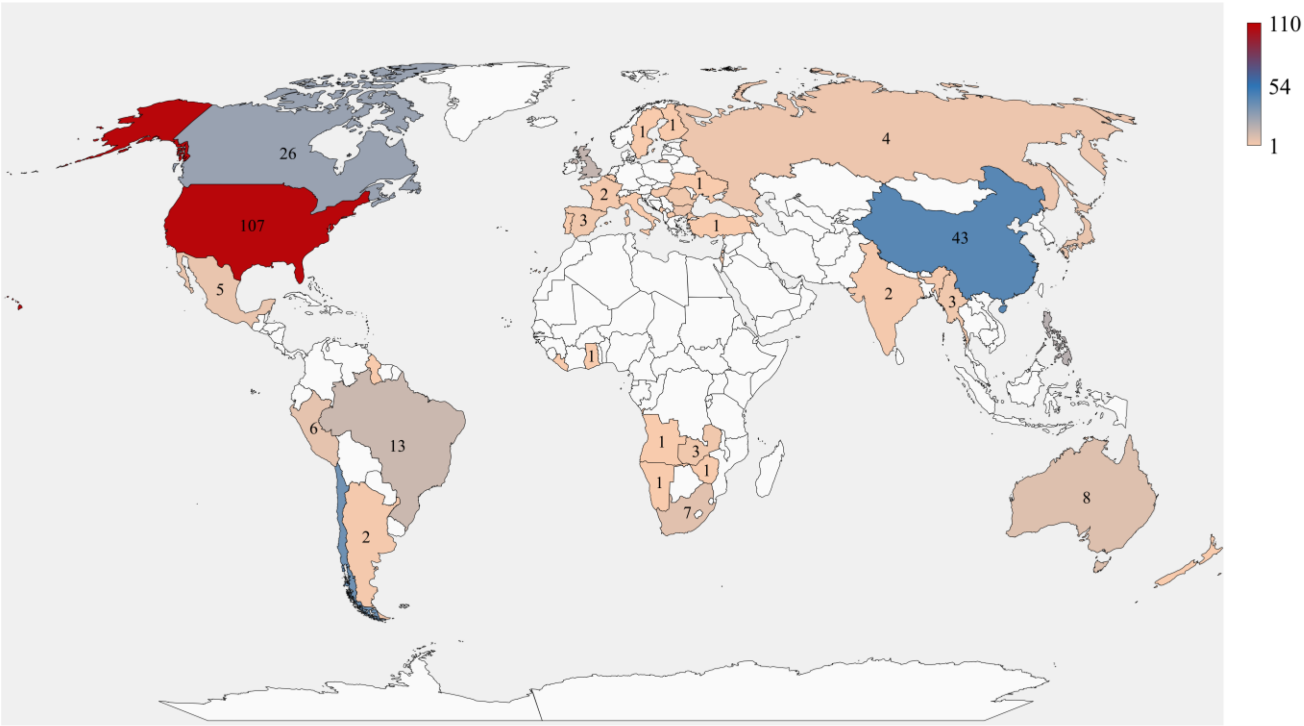

Figure 14. Global geographic distribution of tailings pond dam failures.

Figure 14 illustrates the global distribution of tailings pond failures. Figure 15 shows the locations of some tailings ponds in seismically active zones [43,51]; it can be seen that most of the tailings ponds in South America are located in areas with frequent earthquakes. The Global Seismic Hazard Map depicts the geographic distribution of the Peak Ground Acceleration (PGA) with a 10% probability of being exceeded in 50 years, computed for reference rock conditions (shear wave velocity of 760–800 m/s). Figure 16 shows the distribution of climate types and seismic zones around the world [52–54]. Figure 17 shows the global distribution of rainfall intensity. Seventy-three tailings pond failures occurred in Asia, with 43 in China and 18 in the Philippines. Fifteen of the cases in Asia were caused by OT. As shown in Figure 16, China is located at the intersection of the world's two major seismic zones, i.e., the circum-Pacific seismic belt and the Eurasian seismic belt, and is mainly extruded by the Indian plate in the Cenozoic, resulting in frequent earthquakes in five regions, namely, southwest, northwest, north, Taiwan, and southeast coastal areas [55–57]. However, the tailings ponds in China and seismic zones show a roughly staggered distribution, leading to a small impact of earthquakes on tailings ponds; the number of tailings pond failures triggered by EQ (n = 3) in the study period was much less than that caused by OT (n = 9). It is noteworthy that tailings pond failures in China are mainly concentrated in summer (May, June, July) (n = 13). This pattern is related to climatic characteristics. Summer winds from the Pacific Ocean in the southeast and the Indian Ocean in the southwest are warm and moist, bringing more precipitation. However, the wind in China, especially in the north of the country, is cold and dry because of winter winds from inland Asia [58]. Other tailings pond failures in Asia were also mainly related to the hydroclimate and were concentrated in summer. There were fewer EQ-induced failures in China than in South America. There were 198 tailings dam failures in the Americas, mainly in the United States (n = 107) in North America (n = 138) and in Chile (n = 37) in South America (n = 60); such events were primarily caused by EQ (n = 34) and OT (n = 31), with 29 EQ-induced tailings pond failures in Chile and 18 OT-induced failures in the United States. It is noteworthy that Chile is in a highly seismically active zone and had 17 tailings pond failures due to EQ in 1965, as shown in Figure 16 [59]. The situation in North America is the opposite to that in South America, where 22 tailings pond failures were caused by OT.

In North America, when warm and cold currents meet, heavy rainfall can occur. As such, in North America, the effect of rainfall on the stability of tailings ponds is greater, while the effect of earthquakes is weaker.

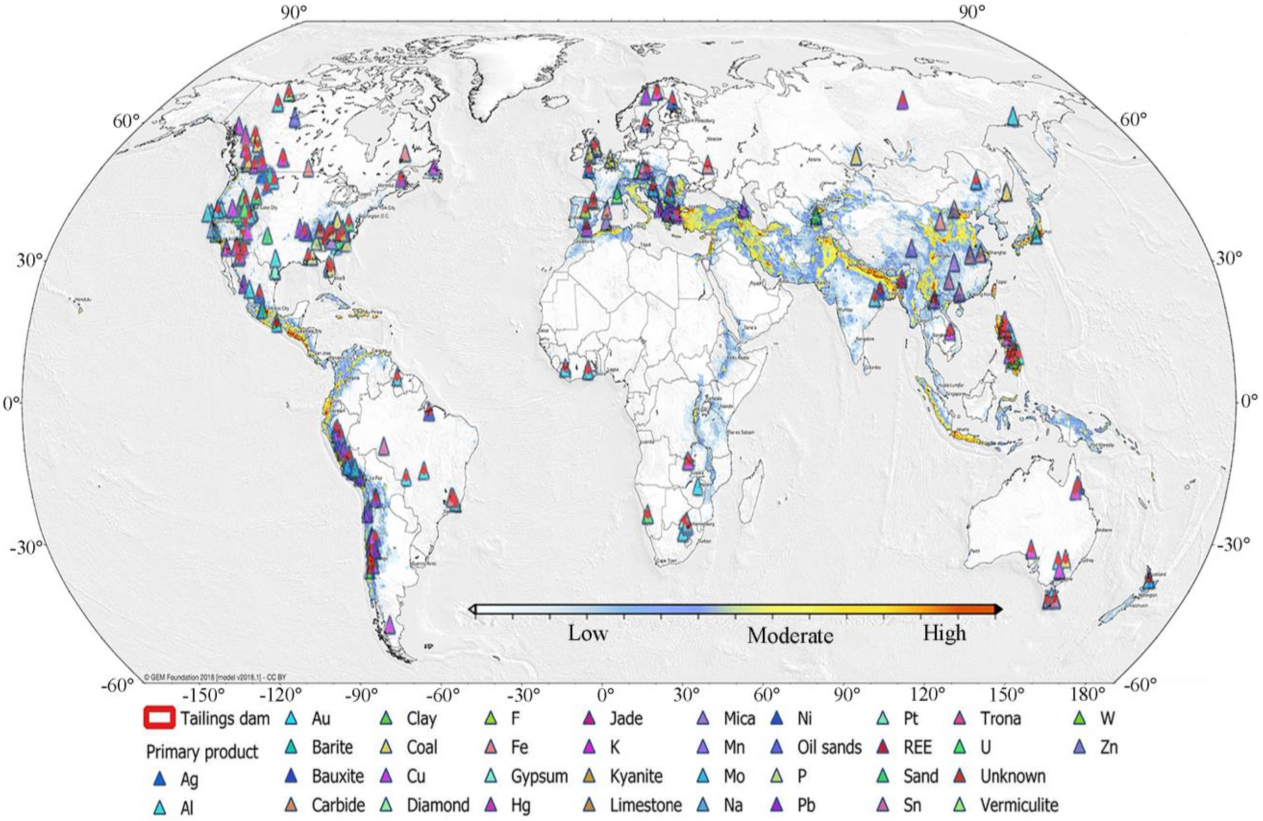

Figure 15. Distribution of global mines in seismic zones.

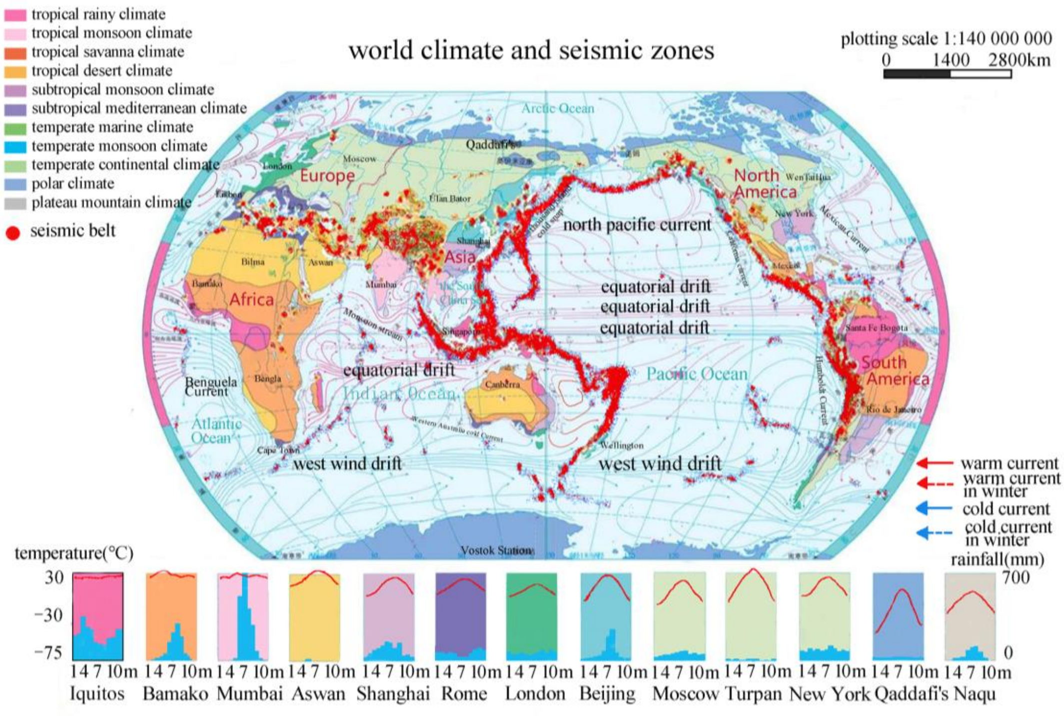

Figure 16. Global climate and seismic zone distribution.

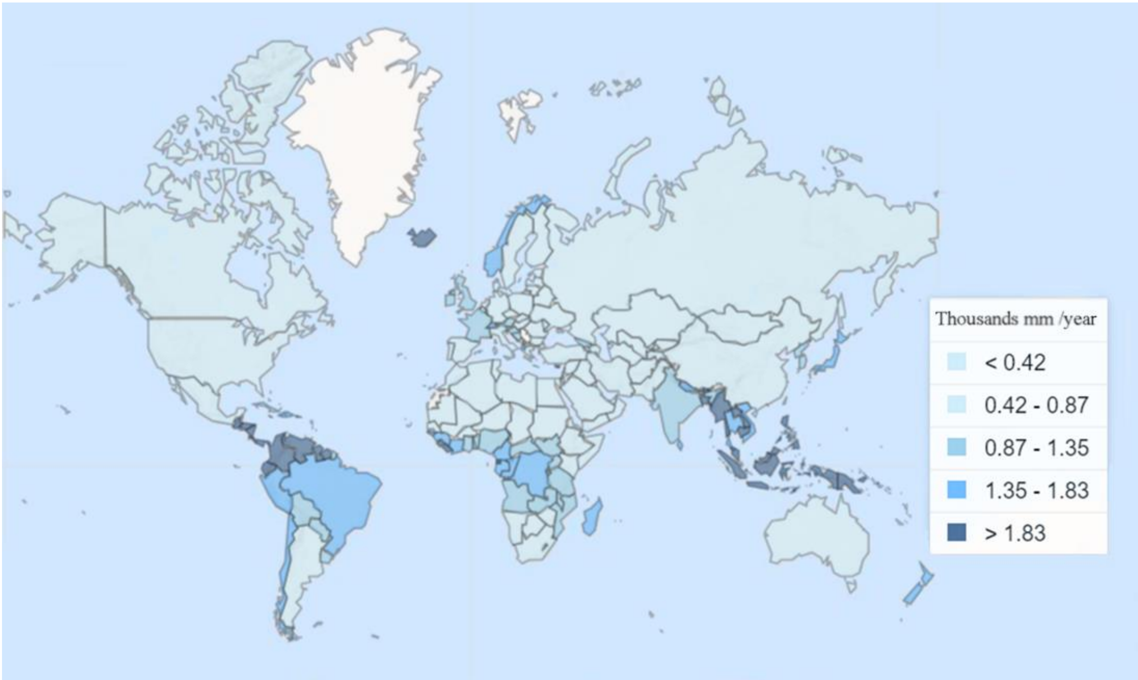

Figure 17. Global average rainfall distribution.

A total of 44 tailings pond failures occurred in Europe, mainly in the United Kingdom (n = 15), which is related to the distribution of seismic zones, as shown in Figure 16. No tailings pond failures due to earthquakes in Europe were found in our statistical analysis. The distribution of failures in Europe is more dispersed than in Asia and America. Tailings pond dam failures in Europe were mainly caused by OT (n = 7) and were concentrated in winter (November, December, January). Stable oxygen (δ18O) and hydrogen (δD) isotopes in Europe show a positive correlation with temperature. They have a negative correlation with precipitation in summer and a positive correlation with precipitation in winter. Both δ18O and δD are significantly heavier in summer and lighter in winter, implying that rainfall in Europe decreases with increasing temperature as well as increasing δ18O and δD [60]. Rainfall in Europe is concentrated in winter, and summers are dry, resulting in a higher incidence of tailings dam failures in the winter. Therefore, factors related to freezing should be considered when damming tailings ponds in Europe [61,62].

Among global tailings pond failures, 4.8% and 2.6% were in Africa and Oceania, respectively. These lower frequencies compared to the other three continents are related to the location of minerals, regional climates and the distribution of seismic zones. Figures 15 and 16 show that earthquakes have little impact on Africa and Oceania, and tailings pond failures in those regions are mainly triggered by OT.

4. Conclusions

A tailings pond failure can cause irrevocable changes in the surrounding ecosystem [63,64], and if the toxic material pollutes the groundwater, the degree of harm will be immense. Following a tailings pond dam break, a tiny number of harmful compounds will be spilled, and these substances will remain in the environment for a long time. In this study, we collected and classified the information on 342 tailings pond failures and used these data to graph tailings pond failures in terms of time and regional distributions, mine type, dam construction methods, etc. Our analysis will provide appropriate data to help future tailings pond researchers. The following conclusions can be drawn:

- We found that the average frequency of tailings pond accidents from 1947 to 2021 was 4.4 per year, and the frequency of tailings pond failures in Asia and the Americas, especially in China (n = 43) and the United States (n = 107), was significantly higher than in other regions. With the increase of large and high tailings ponds, the number of very serious tailings pond accidents is also increasing.

- The causes of 258 failures were identified, while those of 84 failures remain unknown. Among the 258 tailings pond failures with known causes, 10.1% were caused by ST (26), 22.1% by SI (57), 17.1% by EQ (44), 5% by ER (13), 11.2% by SE (29), more than 24.4% by OT (63), 0.4% by MS (1), and 9.7% by FN (25). Most tailings pond failures were directly related to heavy rainfall or earthquakes. Since much of the information regarding tailings pond failures is not disclosed or was undetected, we need to build a better database to capture and document this information.
- Economic development cannot be achieved without the exploitation of mineral resources. We found that the increase in the number of tailings dam failures in developing countries is closely associated with damming methods, climate and earthquakes. The US method is used by most developing countries due to the low construction difficulty and low cost, but tailings dams constructed with the US method have the highest risk of failure. Developing countries need to improve their tailings pond construction, maintenance and monitoring capabilities.

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