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Review Article

A Comprehensive Review on Reasons for Tailings Dam Failures Based on Case History

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On a global scale, the demand for mineral products has increased substantially with economic development. Consequently, the mining of mineral resources results in the production and accumulation of a large number of tailings, causing many problems with respect to mining, the environment, and the economy. In the mining process, tailings must be reasonably treated to prevent them from entering the water cycle through rivers. The storage of tailings under water can effectively hinder the chemical reactions that they undergo. Therefore, it is a critical practice to store these substances in ponds or impoundments behind dams. However, tailings dams frequently fail, resulting in the discharge of significant quantities of tailings into the natural environment, thereby causing grievous casualties and serious economic losses. This paper discusses reasons including seepage, foundation failure, overtopping, and earthquake for tailings dam failures and explores failure mechanisms by referring to the available literature. This research has determined that the failure of tailings dams is closely related to the state of the country's economy. Most of the tailings dam breakages in developed countries occurred decades ago. In recent years, the proportion of tailings dam failures in developing countries has been relatively high. Considering the serious damages caused by tailings dam breakage, it is important to understand the main reasons and mechanisms for their failure. The purpose of this review is to provide a reference for the design and construction to the building of the tailing dams and to reduce the occurrences of their failure.

1. Introduction

The mining industry has a significant impact on modern life, and its products are widely used in computers, airplanes, ships, and jewellery. Mining resources are an important source of income in areas of poverty, and they play a positive role in economic development [1–4]. Furthermore, the mining industry also provides employment for more than 40 million people all over the world [5, 6]. However, with the advancement of science and technology, the rapid growth of mining activities has led to an increase in the number of tailings which are often stored in tailings ponds [7]. Tailings, which are waste products in the beneficiation process, are generally stored in a slurry form [8, 9]. The purpose of establishing a tailings dam is to safely store tailings to protect the natural environment from damage [10–13]. Once a tailings pond leaks, it has a major negative impact on the economy, surrounding properties, and people's lives

[14, 15]. Tailings dams are some of the largest structures built by geotechnical engineers. Nevertheless, on a global scale, incidents of tailings dam failures have occurred often. In addition, relevant departments have an insufficient understanding of the mechanisms associated with tailings dam failure which results in serious environmental pollution and casualties [16–18]. In the reported 18,000 mines around the world, the failure rate in the past 100 years is estimated at 1.2%. The failure rate of the traditional water storage dam is 0.01% [19]. On average, three of the world's 3,500 tailings dams fail every year. The likelihood of tailings dam failure is several times higher than other conventional water-retaining dams [20–22]. Keeping the tailings pond safe and stable is the most challenging task in the entire mining process. The following points are the reasons why tailings dams are more susceptible to damage than other types of water storage structures: (1) embankments constructed with soil, coarse waste, and residual materials from the mining operations; (2) the number of wastewater increases as the height of the tailings dam increases; (3) lack of reasonable regulations on design standards; and (4) the cost of monitoring the tailings dam is high during mine operation and closure [23].

China is experiencing a period of rapid economic development, and the demand for mineral resources is increasing, along with an emphasis on environmental protection [24, 25]. Correspondingly, the number of tailings dams is also increasing. A few decades ago, several tailings dam breakages occurred in China, resulting in economic losses, environmental hazards, and dozens to hundreds of deaths [26]. In the twenty-first century, particular attention is being paid to the stability of tailings dams which is closely related to the population density in China. Yin et al. simulated the construction process of the tailings dam in the laboratory. According to the measured tailings parameters and geological data, a safety and stability analysis was carried out for a tailings dam under different conditions and different heights. The experimental results show that it is necessary to reduce the design height of the tailings dam to ensure safety [27]. The safety and stability of these structures are also a concern for countries all over the world. Therefore, this paper briefly analyses the examples of tailings dam failures in several countries and is based on the current collection of tailings dam data and dam break examples. This article analyses the causes and mechanisms of accidents and offers general conclusions about the safety and stability of tailings dams. The review of global dam failure information is beneficial to the management of tailings storage facilities and can effectively reduce the probability of tailings dam failures. The author considers that these experiences and lessons learned may be useful to researchers and mine operators in other countries.

2. Reasons and Mechanisms for the Current Tailings Dam Failures

On a global scale, there have been many severe accidents related to tailings dams. This paper summarizes the data on more than 300 events that have been collected and categorizes the reasons for tailings dam breakages into four root causes [21, 28–30]. Key examples of tailings dam failures are summarized in Table 1, including basic information about the tailings dam failures including dam height, dam type, and fatalities. Tailings dam can be divided into four categories according to their construction methods [64, 65]. Figure 1 counts the number and types of tailings dam failures in several countries. North America is the largest region in the world for tailings dam accidents. The failure of tailings dams is often caused by multiple factors and, in essence, is due to the influence of the external environment, for example, through increased loading of the tailings dam, earthquakes, rainfall, floods, and dam foundation subsidence [32, 57, 66, 67].

The stress field and the seepage field in tailings reservoir change, leading to the instability of the dam. The following reasons explained for the resulting failure: (1) the seepage field directly induces instability of the tailings dam (seepage and internal erosion); (2) the instability of the tailings dam foundation (poor foundation conditions); (3) flooding that causes the tailings dam slope to becoming unstable (overtopping); (4) an earthquake effect (static and seismic instability); and (5) other reasons (mine subsidence, structural, external erosion, and slope instability).

2.1. Seepage (Seepage Field Directly Induces Instability of Tailings Dam and Leads to Dam Failure). As tailings dams are water permeable, their stability is greatly influenced by the seepage field. The phreatic line of the seepage field is called the "lifeline" of the tailings pond. The determination of the seepage field is the basis for studying the tailings dam failure. At present, the research on the seepage field of tailings impoundments mainly includes a theoretical method, a model test method, and a numerical simulation method. Seepage model, Darcy's law, and groundwater continuity equation are the basis of the theoretical study of the seepage field. Due to the complex geological conditions of the tailings pond and the inaccuracy of the boundary conditions, it is difficult to solve the exact solution of the seepage field in the tailings pond by theoretical study. The model test can also be used to determine the seepage field of the tailings pond. Yin et al. [27] used model tests to study the seepage field characteristics of the tailings pond based on engineering data and verified the results with numerical analysis. However, when the model test is used to study the seepage field of the tailings pond, it will be affected by the scale factor. The test results are greatly affected by the test conditions, and the cost of the model test is high. At present, numerical simulation is the most commonly used method in the study of the seepage field in a tailings pond. Based on the characteristics of tailings distribution in tailings reservoir upstream of the tailings pond, Zhao et al. [68] proposed a generalization method for two-dimensional geological sections and compared the influence of the generalized section on the seepage field. Lu and Cui [69] and Zhang et al. [70] believe that the two-dimensional model cannot fully reflect the complex and variable seepage domain and cannot reflect the true seepage field. Therefore, a new method for the numerical model of

Table 1: Basic information regarding tailings impoundment failures.

Year	Name (location)	Dam height (m)	Dam type	Failure cause (fatalities)
1928	Barahona (Chile) [31]	61	Upstream	Earthquake (54)
1937	Dos Estrellas (Mexico) [32]	UN	Upstream	Seepage (70)
1948	Kimberley (Canada) [33]	UN	Upstream	Seepage (UN)
1962	Huogudu (China) [26]	UN	Upstream	Foundation failure (171)
1965	El Cobre (Chile) [34]	36	Upstream	Earthquake (>300)
1966	Aberfan (UK) [35]	UN	Water retention	Seepage (144)
1966	Mirolubovka (Bulgaria) [36]	45	Upstream	UN (488)
1970	Mufulira (Zambia) [37]	50	Unknown	Mine subsidence (89)
1972	Buffalo Creek (USA) [38]	14–18	Upstream	Seepage (125)
1974	Bafokeng (South Africa) [39]	20	Upstream	Seepage (14)
1974	GCOS (Canada) [40]	61	Upstream	Seepage (UN)
1975	Mike Horse (USA) [37]	18	Upstream	Overtopping (UN)
1976	Dashihe (China) [41]	37	Upstream	Earthquake (UN)
1978	Syncrude (Canada) [42]	UN	Centerline	Foundation failure (UN)
1978	Mochikoshi Nos. 1 and 2 (Japan) [43]	28, 19	Upstream	Earthquake (1)
1978	Arcturus (Zimbabwe) [44]	25	Upstream	Overtopping (1)
1979	Union Carbide (USA) [30]	43	Upstream	Seepage (UN)
1985	Stava (Italy) [45]	29.5	Upstream	Seepage (268)
1985	Chenzhou (China) [46]	UN	Upstream	Overtopping (49)
1985	Cerro Negro No. 4 (Chile) [47]	40	Upstream	Earthquake (UN)
1986	Huangmeishan (China) [32]	UN	Upstream	Seepage (19)
1988	Lixi (China) [48]	40	Upstream	Overtopping (20)
1991	Sullivan (Canada) [49]	21	Upstream	Seepage (UN)
1993	Marsa (Peru) [32]	UN	Upstream	Overtopping (6)
1994	Tapo Canyon (USA) [50]	24	Upstream	Earthquake (UN)
1994	Merriespruit (South Africa) [51]	31	Upstream	Overtopping (17)
1995	Omai (Guyana) [52]	44	Unknown	Seepage (UN)
1995	Surigao (Philippines) [53]	UN	Upstream	Foundation failure (12)
1996	Porco (Bolivia) [6]	UN	Upstream	Overtopping (UN)
1996	Sgurigrad (Bulgaria) [54]	45	Upstream	Seepage (107)
1998	Los Frailes (Spain) [15]	27	Upstream	Foundation failure (UN)
2000	Baia Mare and Baia Borsa (Romania) [55]	7	Downstream	Overtopping (UN)
2002	San Marcelino Zambales (Philippines) [56]	UN	Unknown	Overtopping (UN)
2004	Pinchi Lake (Canada) [57]	12	Water retention	UN (UN)
2009	Karamken tailing plant (Russia) [58]	20	Unknown	UN (1)
2010	Ajka (Hungary) [59]	22	Downstream	Seepage (10)
2011	Kayakari (Japan) [60]	UN	Unknown	Earthquake (UN)
2012	Padcal No. 3 (Philippines) [61]	UN	Upstream	Overtopping (UN)
2014	Mount Polley (Canada) [62]	40	Unknown	Foundation failure (UN)
2015	Fundão (Brazil) [63]	90	Upstream	Seepage (19)

Note: UN = unknown.

the three-dimensional seepage field in the tailings pond is proposed. According to the actual terrain, the main control points of the cross section are connected into a curve, and then the curve forms a synthetic curved surface. A three-dimensional numerical model is a spatial model formed by the surrounding of these surfaces. After comparing with the measured data, it proves that the model has higher accuracy. Hu et al. [71] used a stepwise coupled hydraulic-mechanical model to test the effect of seepage control on the stability of the tailings dam during construction. The numerical results show that the stress-induced variation of tailings permeability can reach 1-2 orders of magnitude. It is important to design the drainage system to reduce the diving surface and protect the tailings from leakage. The main factors affecting the level of the phreatic line include the level of the water in the reservoir (the length of the dry beach), the permeability of the initial dam, and rainfall. According to the relevant literature, the position of the phreatic line affects the stability of the dam slope [51, 72, 73]. The tailings below the phreatic line have a slow consolidation speed, and the nearly saturated tailings increase the weight of the dam, reducing its shear strength and effective stress. In addition, rainstorms, floods, and failure of drainage facilities often cause the phreatic line in the tailings dam to rise which in turn induces seepage damage. For tailings dams, when deformation conditions due to osmosis are met, the piping effect occurs in the tailings dam. The material properties of the tailings change after the occurrence of the piping effect, resulting in enhanced permeability of the tailings and a decrease in shear strength and modulus of deformation—eventually, the tailings pond collapses and the tailings dam breaks. Selected dam breakage events caused by seepage are briefly described and listed in Table 2.

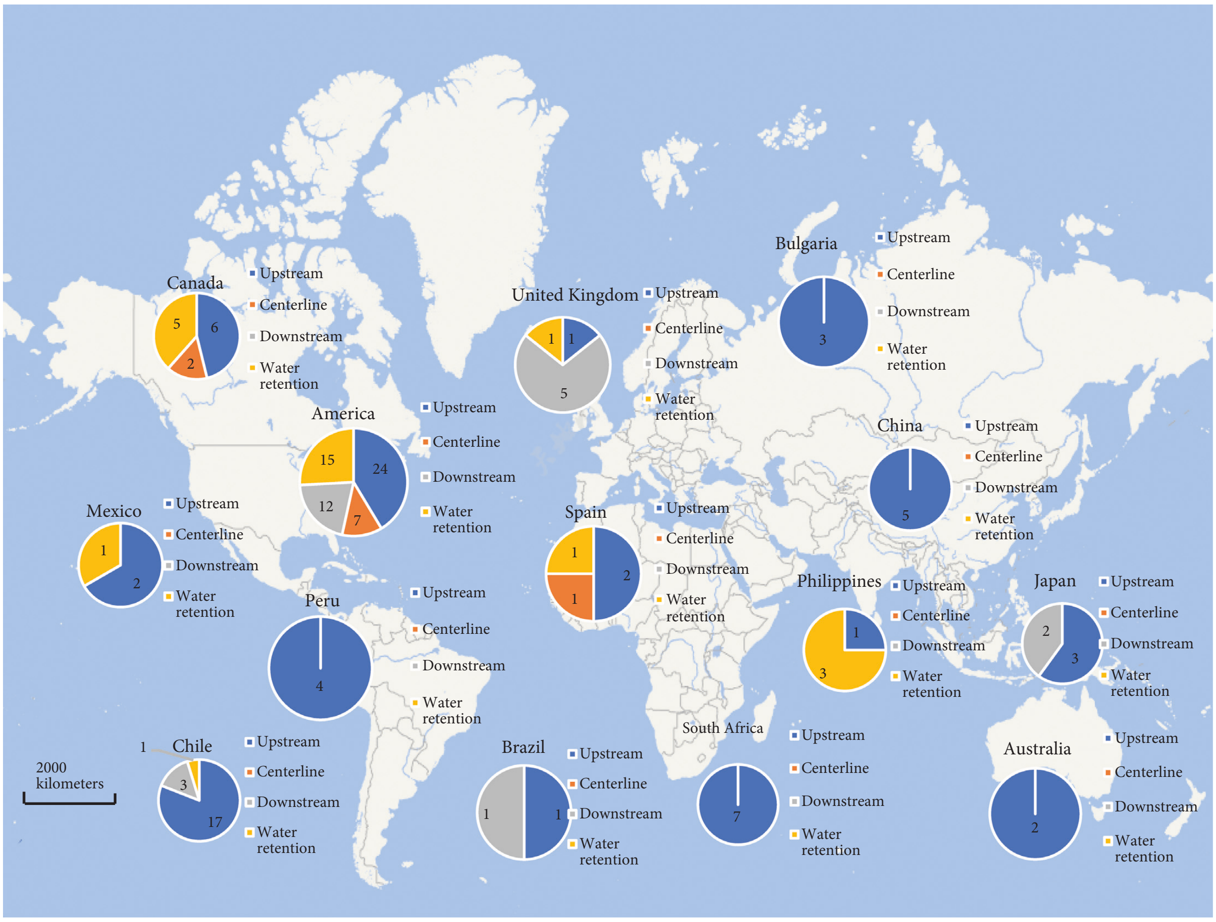

Figure 1: Number and types of tailings dam failures in several countries.

Table 2: Example of tailings dam failure caused by seepage.

Year	Name and location	Ore type	Dam type	Dam height (m)	Release (cu. meters)	Deaths	State
1985	Stava, Peru	Fluorite	US	29.5	200,000	269	Active
1986	Huangmeishan, China	Fe	UN	UN	UN	19	Active
1994	Omai, Guyana	Au	WR	44	4,200,000	UN	Active
2000	Baia Mare and Baia Borsa, Romania	Au, Ag	DS and then US	UN	100,000	0	Active

WR: water retention; UP: upstream; CL: centerline; DS: downstream; UN: unknown.

In 1985, a tailings impoundment near Stava in northern Italy collapsed, killing 268 people and causing significant economic losses. The failure of the two tailings dams resulted in the release of approximately 240,000 m^3 of liquefied tailings [45, 74]. When the tailings dams broke, the upper dam was over 34 m high, and the lower dam was 25 m high. The general reason for this event was the failure of the upper dam which caused the two dams to fail simultaneously [75–77]. Overall, the reasons for the tailings dam failure include the following: (1) due to the rise of the water level, the embankment of the upstream tailings dam was partially damaged; (2) degraded and liquefied sandy silt was the main component of the embankment; (3) silt behind the embankment led to poor drainage and caused the phreatic line of the dam to rise too high and the occurrence of the piping effect; and (4) the upstream dam had an outer slope with a horizontal to vertical ratio between 1.2 and 1.5. There is no doubt that this design did not consider soil mechanics [65, 78]. The Huangmeishan tailings dam failure occurred in 1986. Owing to continuous rainfall for several days, as well as a subdam built out of loose tailings, seepage failure occurred. This led to the failure of the dam, killing 19 people and injuring 95 [32].

In 1994, the Omai tailings dam in Guyana broke down due to internal erosion which resulted in the release of sewage into nearby rivers. This incident caused severe environmental damage, and the report on downstream damages was understated as compared to the actual situation [52, 78, 79]. From the perspective of geotechnical mechanics, this incident was incredible because there was no physical damage to the dam. During the pipeline backfilling process, the pipeline was crushed twice by heavy equipment and failed [52, 80]. Although the pipeline was repaired in time, these incidents adversely affected the safety and stability of the tailings dam. In addition, conventional seepage collars were not added to the pipe. The Omai Dam break event illustrates the fact that if the tailings dam is under construction, there is not enough seepage protection or adequate filter around the pipeline that is being laid. In this case, a dam failure is inevitable. The Omai Dam failure was not caused by complex factors; this event was due to the limited filtration capacity of the pipeline [32, 81], which led to the poor drainage performance of the tailings dam and high phreatic line.

In 2000, the Aurul tailings dam of Baia Mare, Romania, leaked 100,000 m^3 of mud and cyanide-containing tailings water flowed into the surrounding rivers. The reason was that there was a crack in the dam around the tailings pond [5, 82, 83]. Almost a month later, an artificial tailing pond (Novat Rosu) in Baia Borsa caused the reservoir water level to rise rapidly and uncontrollably due to heavy rains and melting snow. Both Baia Borsa and Baia Mare are located in Maramures County, Romania. Heavy snow and snowmelt caused the phreatic line to rise, which in turn, affected the stability of the tailings dam. Eventually, there was a 25 m gap in the dam [84–86]. After detailed investigations conducted by the experts, they concluded that there were two main reasons for the accident including the following: (1) the improper design of the tailings management facilities which the authorities department agreed to use; and (2) upon completing the tailings dam, there was a lack of professionals to monitor its status [55, 87, 88]. The failure of the tailings dam confirms that the storage capacity of the tailings pond during operation must meet requirements; that is, the tailings stored should be based on design criteria.

2.2. Foundation Failure (Dam Foundation of the Tailings Dam Failure Leads to the Dam Failure). Historical data show that foundation failure is a common cause of tailings impoundment failure [6, 23, 65, 89]. It is necessary to analyze the static antisliding stability of the tailings dam. At present, the stability analysis and calculation of the tailings dam body are treated as a complex slope, and it is still analyzed along with the traditional theory of soil mechanics. The typical calculation methods are the limited equilibrium method and the strength reduction method. The finite element limit equilibrium method accurately considers the influence of the overall stress field of the structure through elastoplastic finite element analysis and then combines the optimized search method to determine the position of the most dangerous sliding surface in the stress field and its safety factor [90]. The theoretical system of the limit equilibrium method is strict, there is no need to repeatedly reduce, and the calculation efficiency is high. The method is widely used in engineering [91]. Gens and Alonso [89] analyzed the conditions that led to the failure of the Los Frailes dam. The mechanism of the destruction of the tailings pond is explained by the strength reduction method and the limit equilibrium method. Yu et al. [92] analyzed and compared the difference in a safety factor and the shape and position of the sliding surface between the limit equilibrium method and the strength reduction method under normal, flood, and special working conditions. The limit equilibrium method is used to check the stability of the tailings dam body and make safety evaluation, which provides a reliable basis and technical support for the safe design and construction of the tailings dam. The strength reduction method does not need to assume the shape and position of the sliding surface but requires repeated reduction and trial calculation. At present, the standard for determining the instability of the tailings dam in the process of strength reduction has not been established, and there is no safety judgment for the safety factor obtained by the method. The application of this method in engineering is limited [93].

The permeability of the foundation plays an important role in the stability of the dam structure. Poor permeable base materials cause an increase in pore pressure and shear stress on the foundation [94, 95]. Wang et al. [96] used RFPA-SRM to analyze the instability failure mechanism of surface mines high-steep slopes and provided a basis for formulating reasonable landslide prevention measures. It is a gradual process to obtain the landslide of the slope. During this process, the slope undergoes the generation, expansion, and connection of the fractures and the displacement increases until landslide occurs, the potential sliding surface is combined, and the essential cause of the landslide is the shear stress concentration. Moreover, foundation materials with strong water permeability trigger piping effects in the foundation structure. In addition, during the construction of the dam foundation, greater attention should be paid to areas that are prone to accidents such as slopes and the interface between fine and coarse grain layers. The surrounding hydrology and geological environment should be carefully considered when selecting the dam foundation location [97]. The instability of the tailings dam foundation is usually caused by unclear geological surveys or design errors. Detailed geological data for corresponding ground treatment can effectively prevent dam foundation instability. Various dam breakage events caused by foundation failure are briefly described and listed in Table 3.

In southern Spain, the Los Frailes tailings dam failed in 1998, causing the rockfill dam to slide forward and release 1.3 million m^3 of fine pyrite tailings and 5.5 million·m^3 of tailings water [98, 99]. The deposition of tailings severely polluted the rivers and surrounding residential lands [100–102]. In this event, improper investigation of the geological environment was the primary cause. The Los Frailes tailings dam is located in the Guadalquivir basin which is mainly deposited with carbonate high-plasticity clay, known often as Guadalquivir blue clays. When designing the tailings dam, the thickness and impermeability of the marl were not taken into consideration, and the rate of water flowing out of the marl formation was slow [103]. An expert concluded that the pore pressure of the clay increased and the effective stress decreased, causing its strain to reduce over a period of time. This resulted in a gradual decrease in shear strength along the fracture surface and eventual slide downstream. The expert claimed that the 14 m blue clay layer below the dam moved 60 m laterally [55, 104]. The length of the sliding surface in the foundation was approximately 600 m, and the center position of the dam was 40–55 m away from the sliding location.

Table 3: Example of tailings dam failures caused by foundation failure.

Year	Name and location	Ore type	Dam type	Dam height (m)	Release (cu. meters)	Deaths	State
1998	Los Frailes, Spain	Pb, Zn	WR	27	6,800,000	0	Active
2014	Mount Polley, Canada	Cu, Au	CL	40	23,600,000	7	Active

WR: water retention; UP: upstream; CL: centerline; DS: downstream; UN: unknown.

During the sliding failure process, the dam body essentially did not exhibit substantial deformation, similar to rigid body sliding. A researcher analyzed the dam failure characteristics of the tailings reservoir in detail and explained the mechanism using the strength reduction method and limit equilibrium method. The failure of the Los Frailes tailings dam can provide experience and lessons learned for tailings dams with complex or poor foundations [89, 105].

In 2014, Canada's Mount Polley tailings dam failed, releasing approximately 25 million·m^3 of tailings and tailings water into the lake basin [62, 106, 107]. The impact of this event was extremely serious because the tailings contained large quantities of metal contaminants including nickel, lead, copper, manganese, gold, and arsenic [108–111]. With respect to this incident, the experts raised the following three causes that are described in detail: (1) insufficient analysis of hydrological and geological conditions: the tailings dam is located on a weaker glaciolacustrine layer. The load applied by the dam exceeded the bearing capacity of the dam foundation material, causing shear damage to the dam foundation material. The designer did not account for the fact that the tailings dam would increase the load on the foundation when it was stacked, further causing the weaker glaciolacustrine layer to become unstable. This triggered the tailings water to flow out from the breach. The failure of the Mount Polley dam occurred quickly and without warning [112, 113]. (2) Inadequate design: the design did not consider the local hydrometeorological conditions, and the embankment slope is too steep for 1.3 H: 1 V. The width of the tailings beach was less than 10 m. The designers lacked sufficient knowledge with respect to designing dams and, therefore, did not consider extreme conditions such as floods [114]. (3) Inadequate regulation and regulatory supervision: researchers simulated the damage of the dam flood over the top by two large-scale outdoor dam break tests. The results indicate that the rate of crater development is related to the unit flow rate, the unit flow rate is large, and the rate of crater development is also large [115].

2.3. Overtopping (Flooding Top Makes the Tailings Dam Slope Unstable and the Dam Failure). The majority of tailings ponds are located close to the mountains. During heavy rainfall events, there is a large amount of water flow, and the water level in the reservoir rises in a short period of time. In addition, if the permeability of the dam is poor, rainwater is discharged at an extremely slow rate, resulting in the overtopping phenomenon, which drastically affects the stability of the dam. A tailings dam can be completed all at once, or it can be constructed in stages. Nevertheless, the initially constructed tailings dam should have good permeability. Some major tailings dam breakouts in history have been related to floods.

The tailings dam break process can be divided into three stages in time and space. (1) Tailings dam begins to destabilize under adverse conditions; (2) during the instability of the tailings dam, the tailings sand interacts with the water and formed a debris flow with high energy; and (3) debris flow with high potential energy moves downstream. In the tailings dam break process, the tailings dam may have multiple collapses and instability [116]. This will cause the above three stages to be recurring, and the time crosses each other, making the dam break process more complicated. There is currently no suitable model to simulate the above process during the situation of overtopping, mainly due to flood erosion of the tailings dam until instability. Worldwide, there are few studies on the mechanism of damage to tailings dams in flood situations. However, the research results of earth-rock dams can be used for reference to analyze tailings dams. The erosion mechanism can be attributed to hydraulic erosion and gravity erosion. When the flood top flows through the slope of the tailings dam, the incoming flow intensity is greater than the osmotic strength of the tailings sand, and runoff is formed on the dam surface. The runoff causes the trench on the surface of the tailing dam, resulting in hydraulic erosion. After the overtopping situation occurs, part of the water seeps into the tailings dam, causing the tailings sand to saturate, increasing the dead weight of the tailings dam and causing gravity erosion. At the same time, the tailings sand is saturated to reduce the strength of the tailings sand, further reducing the stability of the tailings dam. Examples of dam break events caused by overtopping are briefly described and listed in Table 4.

In 1994, the Merriespruit tailings dam in South Africa failed, releasing 600,000 m^3 of tailings and 90,000 m^3 of tailings water [81, 117–119]. The tailings dam broke after a few hours of thundershowers [120]. It is worth mentioning that this tailings pond is basically an upstream structure with less freeboard length and less reservoir area. When the flow rate of the overtopping water flow was greater than the starting flow rate of the tailings, the tailings dam continued to cause downward and bilateral erosion [23, 65]. The hydraulic erosion caused the breach of the tailings dam to expand, and the slope became steep, which caused the tailings dam to collapse locally and completely. Wanger et al. [121] presented a hypothetical diagram (Figures 2(a) and 2(b)) of the Merriespruit tailings dam failures, based on information from eyewitnesses [53, 120, 126]. At the early stages of flooding over the dam, the dam break process can be divided into the following 5 steps. They are (1) a small gully appeared on the tailings dam after a rainstorm, (2) erosion of loose tailings in the lower slope, (3) local instability of the lower slope (tailings butter), (4) the water level in the tailings pond is high and the flood erosion

Table 4: Example of tailings dam failure caused by overtopping.

Year	Name and location	Ore type	Dam type	Dam height (m)	Release (cu. meters)	Deaths	State
1994	Merriespruit, South Africa	Au	US	31	600,000	37	Inactive
2010	Zijin, China	Sn	UN	UN	UN	22	Active

WR: water retention; UP: upstream; CL: centerline; DS: downstream; UN: unknown.

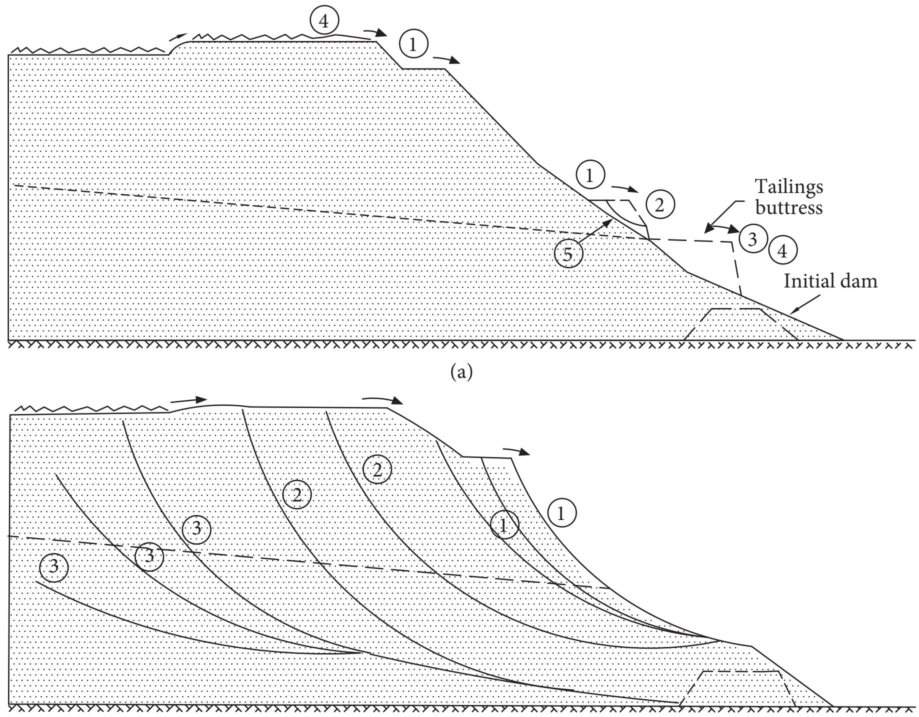

Figure 2: (a) The sequence of retrogressive failures (redrawn after Wanger et al. 1998), the early stages of flooding over the dam. (b) The sequence of retrogressive failures (redrawn after Wanger et al. 1998), the later stages of flooding over the dam.

tailings dam, and (5) local instability on a central slope, the failed material is washed away. At the later stages of flooding over the dam, the dam break process can be divided into the following 3 steps, they are as follows: (1) after the erosion, the tailings dam slope began to be unstable overall, and the tailings sand was taken away by the water, (2) the tailings dam slope continues to be unstable under the domino effect, and the tailings sand is taken away, and (3) a large amount of tailings flow causes the slope to be unstable.

In September 2010, the Zijin tailings pond dam in Guangdong, China, collapsed suddenly. This event caused direct economic losses of approximately 460 million yuan and resulted in the death of 22 people and damage to 6,370 houses. The crop area affected was 72.6 km^2 [122, 123]. The collapse of the tailings pond dam was due to the heavy rains brought on by the Fanapi typhoon and neglectful work of the mining department [124]. The main cause of flooding and tailings reservoir collapse was that the height of the tailings reservoir drainage well entrance did not meet established standards, and the management and operation of the tailings pond were not in compliance with regulations. The indirect cause of the dam collapse was that the hydrogeological parameters of the tailings pond design were not suitable, resulting in low flood control standards for the tailings pond dam. The negligence of the design, supervision, and construction departments also led to the incident [125].

Another reason for the tailings dam breakage was the lack of effective management of the tailings facilities which is a key factor for ensuring the safety and stability of tailings dams [113]. Effective management of mine tailings includes not only controlling environmental impacts but also need to be subject to the legal document [127].

2.4. Earthquake Action Causes the Tailings Reservoir to Break the Dam. The mechanism of earthquake-induced dam breakages in tailings ponds is mainly caused by the liquefaction of the tailings sand which is triggered by earthquakes that weaken the strength of the tailings material, causing large permanent deformation and destabilized the tailings dam [128]. The main factors affecting the liquefaction of tailings are the composition, shape, size, gradation, arrangement, compactness, depth of the wetting line, and seismic intensity. The study on the seismic performance of the tailings dam started late, and the dam structure has more significant anisotropy and heterogeneity, coupled with the shallow groundwater burial in the dam. Compared with similar earth-rock dams, the research and understanding of the seismic response and failure mechanism of tailings dams are low. In order to recognize the possibility of damage to the tailings pond after the earthquake, the analysis of the postearthquake stability of the tailings pond is increasingly incorporated into the design and evaluation process. Seismic performance of tailings dams should include seismic liquefaction analysis, seismic stability analysis, and seismic permanent deformation analysis.

Some research has been done on the study of the dynamic response of tailings dams. Finn et al. developed an effective stress model for liquefaction in 1976 [129]. Xin and Finn analyzed the dynamic response of the damaged Dashihe tailings dam in the Tangshan earthquake and obtained the simulation results consistent with the post-earthquake macroscopic survey results [130]. Psarropoulos and Tsompanakis [131] used the equivalent viscoelastic model to consider the nonlinear characteristics of foundation soil and tailings and simulated the dynamic response of different types of tailings dam under earthquake action. Liu et al. [132] analyzed the dynamic pore water pressure and dynamic shear stress of Baijishan tailings dam using cyclone separator technology and verified the effect of the technology to improve the stability of the dam. Liquefaction is the main cause of damage to high tailings dams; the influence of seismic inertial force on the seismic stability of high dams is secondary. Ferdosi et al. [133] have shown that waste rock inclusions can improve the seismic response of tailings ponds. The effects of different waste rock reinforcement methods on the seismic performance of tailings dams are analyzed under simulated seismic waves with different frequencies. Compared to high-frequency waves, low frequencies tend to produce larger deformations and larger critical displacement volumes of tailings. Ozcan et al. [9] analyzed the static and dynamic stability of the dam slope of the capacity increase project of a tailings mine in Turkey, using the limit equilibrium method and the finite element method, respectively, and verified the feasibility of increasing the capacity. Pépin et al. [134] studied through laboratory tests the dynamic behaviour of tailings caused by cyclic loading on the seismic table. The effects of various factors under different conditions were evaluated, including the density and rigidity of the tailings and the presence of drainage inclusions, and focused on the introduction and discussion of the development of excess pore water pressure. It is concluded that inclusions have a significant effect on the dynamic response of tailings and the occurrence of liquefaction. Yin et al. [135] analyzed the dynamic response and seismic performance of the tailings dam before and after heightening, conducted preliminary exploration on the seismic performance of the tailings dam, characteristics of the dynamic response of tailings dam, and its influencing factors have been understood (e.g.,dam and phreatic line), and drew the following three conclusions: (1) as the height of the tailings dam increases, the seismic performance of the tailings dam will be significantly reduced; (2) acceleration in the tailings dam is not amplified with the increase of the height but is fluctuating, which is different from the earth-rock dam; (3) the permanent deformation increases with dam height and decreases with the immersion line. Moreover, the horizontal deformation is greater than the vertical deformation.

Certain scholars have analyzed the stability mechanism of the tailings dam earthquake loss. It is considered that the stacking material of the tailings dam is relatively loose, and the tailings dam body below the surface is saturated sand. Under the seismic load, the dam body material may be subject to the vibration liquefaction phenomenon [136]. Due to the inhomogeneity of the soil properties and the inconsistent pore pressure development of the entire dam, liquefaction starts from the local areas, and local liquefaction causes stress and deformation, resulting in a rise in non-liquefied soil pore pressure and reduction in strength, ultimately leading to a damaged dam [137]. Before the tailings dam slippage damage, the internal stress of the dam body is diffused by flow slip and a large weak layer may form inside. As the seismic load and liquefaction increase, the weak layer eventually penetrates until the tailings dam losses stability [6, 11, 131]. Under this mechanism, the impact of earthquakes on the stability of tailings dams is mainly manifested in the liquefaction of tailings. When liquefaction begins to appear in the tailings dam, it is easy for a fissure seepage channel to form and cause local collapse. Simultaneously, the earthquake increases the sliding force or torque of the dam, causing it to slip and break [13]. At present, global seismic activity is becoming more and more active, and the distribution of mineral resources has a certain relationship with the distribution of seismic belts. Therefore, how to accurately evaluate the seismic performance of tailings dams is still a challenging problem to be solved. Various dam breakage events caused by earthquakes are briefly described and listed in Table 5.

In 1965, two tailings dams collapsed in the El Cobre Copper Mine in Chile and released 2.3 million·m^3 of tailings water in the downstream valley. More than 200 people died during the destruction of the El Cobre town [6, 31, 33, 34]. This tailings dam failure was mainly caused by earthquake liquefaction and flow failure [138]. The majority of breakage events are related to dams that were built using the upstream method. The following four main factors contributed to the instability of this Chilean tailings dam: (1) the construction method of tailings dam; (2) a low degree of compaction; (3) fine particle size of tailings sand; and (4) high saturation of tailings sand [6, 138]. Another reason was that the designer did not design the dam according to the established criterion. In earthquake-prone areas, downstream or centerline methods should be used to build dams to reduce accidents [139].

In 1994, an earthquake caused a 24 m tailings dam break in the Tapo Canyon, United States of America (USA) [50, 65]. Due to the liquefaction of the tailings and some parts of the dam (saturated tailings usually have low shear strength), the strength and stiffness of the soil were reduced, causing the dam to slide downstream more than 60 m [140]. The most serious damage caused by the earthquake was the failure of the Tapo Canyon tailings dam [141–144]. Although the tailings pond was filled two years prior, the tailings and dam sections were already saturated at the time of the

Table 5: Example of tailings dam failure caused by earthquakes.

Year	Name and location	Ore type	Dam type	Dam height (m)	Release (cu. meters)	Deaths	State
1965	El Cobre, Chile	Cu	US	26	2,300,000	>200	Inactive
1994	Tapo Canyon, USA	UN	UN	UN	UN	UN	UN
2011	Kayakari, Japan	Al	DS	22	1,000,000	10	Active

WR: water retention; UP: upstream; CL: centerline; DS: downstream; UN: unknown.

earthquake. After the tailings pond closed, there was a lack of management which led to the accumulation of large amounts of water in the deep reservoir area and the tailings were kept in a saturated state for a long time. In general, if the water in the reservoir area is discharged in time, the damage of the earthquake to the dam can be minimized [50].

An earthquake occurred in eastern Japan in 2011, and the Kayakari dam at the Ohya mine liquefied because of the tailings material, releasing a large amount of clay and causing damage to the downstream environment [60, 145]. Studies have shown that liquefaction leads to a significant reduction in the safety factors of tailings dams [146]. In addition, the construction method of the dam body, the particle size of the tailings, and the magnitude of the earthquake all affects the stability of the tailings dam during an earthquake [147]. The reasons for the damage of the Kayakari dam during this earthquake were as follows: (1) the accumulation material of the tailings pond itself was inferior in strength and unable to resist the attachment force generated by the earthquake; (2) finer tailings particles had lower plasticity and were easier to liquefy; (3) the contact surface between the mountain body and the dam body was not well protected, and the groundwater seeped into the reservoir area, causing the tailings to remain saturated; (4) the earthquake (the order was 300 Gal at its peak), which lasted for 2 min, caused the tailings to liquefy and the tailings dam to break; and (5) the protection of the smaller tailings pond was ignored [148, 149].

3. Results and Discussion

In fact, the data on the failure of the tailings dam are incomplete. The information collected in this paper forms only part of the actual number of tailings dam accidents in the world as small accidents tend to occur frequently [28, 29, 150, 151]. In addition, many accidents are not reported to the government in time because managers are afraid of taking legal responsibility [81]. This article presents as much of the basic information as possible about selected tailings dam breakages including location, cause, dam construction method, and dam height. The relationship between these data and the safety and stability of tailings dams is also summarized and listed in Table 1 and depicted in Figures 3–8.

Figure 3 demonstrates that tailings dam failure has remained at a relatively high number for decades. From the beginning of the twentieth century to the 1950s, the number of tailings dam breaks was small, and the occurrence was mainly concentrated in the United States, Chile, and other countries. Chile is rich in mineral resources and has been mining mineral resources early. Chile is located at the plate junction, causing frequent earthquakes. In addition, the construction requirements of the tailings dam are low, resulting in the occurrence of the tailings dam failure. In the last sixty years, with the rapid development of industry, the number of tailings dams has gradually increased, but there are poor inspection and maintenance practices in place. The unreasonable disposal of tailings dam has caused about 3-4 large-scale tailings dam collapses every year, causing irreversible damage to the ecological environment and life safety. Tailings dam failure events usually occur in developing countries with rapid economic development (e.g.,Brazil, Chile, and China). In the next few decades, this paper speculates that a high ratio of tailings dam failures will remain. In order to solve this problem, it is necessary for the state to improve the construction specifications of tailings dams and strengthen the safety management of tailings dams. In the process of industrial development, it is also necessary to ensure engineering safety and protect the environment.

Figures 4 and 5 illustrate that accidents in tailings dam breakages occur mostly in North America (43%). In North America, the countries with the most accidents are the United States (37%) and Canada (6%). The proportion of accidents in South America, Asia, and Europe is relatively small, after comparison with North America. But each continent still occupies an average of 15% of tailings dam accidents. In South America, the number of tailings dam accidents in Chile, Brazil, and Peru is high, and the damage is serious. In Asia, China, and Japan are also countries with frequent tailings dam accidents. In Europe, the number of tailings dam breakouts in the United Kingdom is the highest. The situation described above is consistent with its economic development. Most of the tailings dam failures in developed countries occurred before the twenty-first century, which corresponds to the period of rapid economic development, such as in the United States, the United Kingdom, and Canada. Conversely, the majority of the tailings dam failures in developing countries occurred after the twenty-first century. Developing countries, such as Brazil, China, and Chile, need to pay attention to the safety and stability of tailings dams as their economies develop, whilst simultaneously improving the building standards of tailings dams. If necessary, developing countries can learn from the latest building standards of developed countries on tailings dams.

Figure 6 highlights the reasons for the occurrence of tailings dam breakage in the last 100 years. One scholar divided the causes of tailings dam breakage into 11 categories, namely, seepage or piping, foundation failure, overtopping, seismic liquefaction (earthquake), mine subsidence, unusual rain, snowmelt, structural, slope instability, maintenance, and unknown cause. But many accidents are

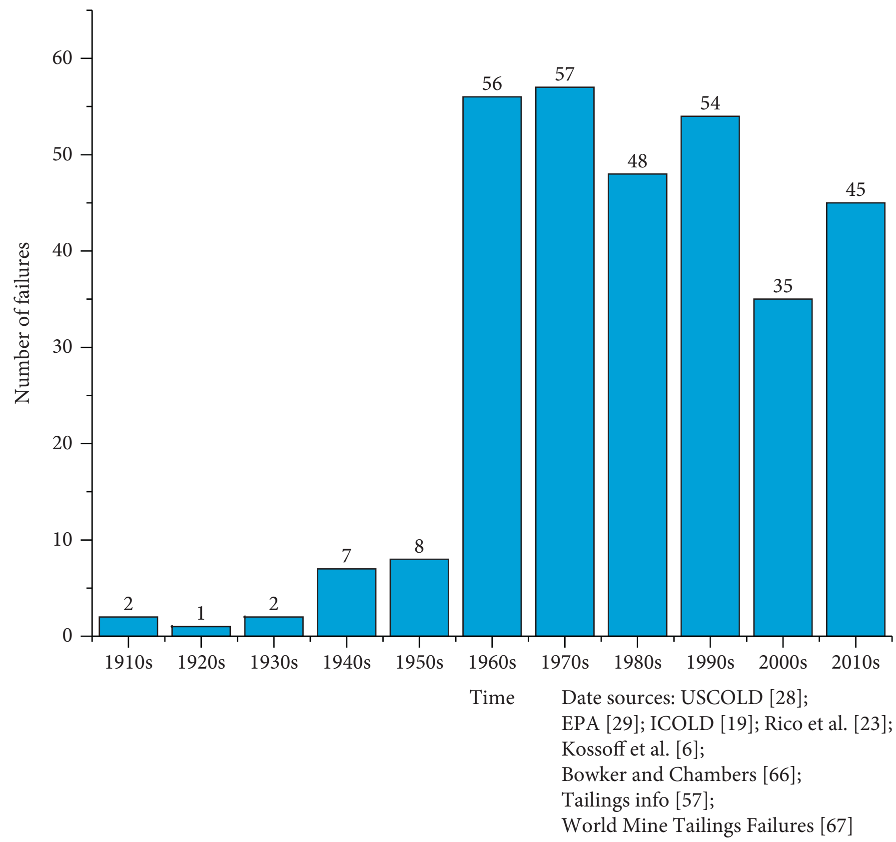

Figure 3: Failure events over time.

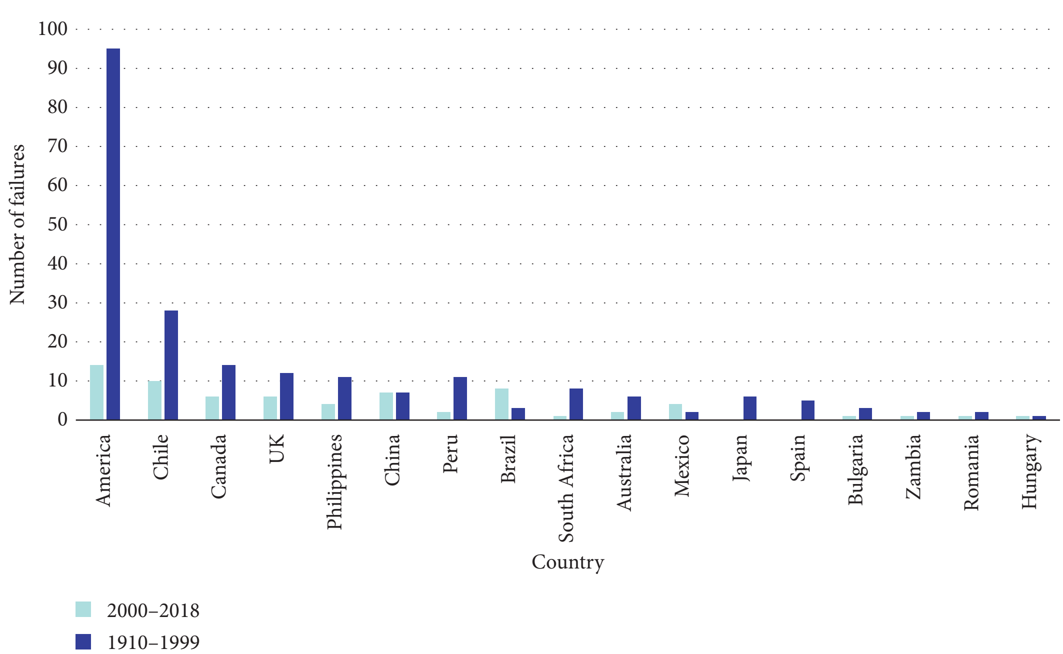

Figure 4: Failure distribution by country.

the result of a combination of multiple causes, and this classification has some overlapping parts, such as unusual rain, snowmelt, and overtopping. According to the main cause of tailings dam failure, the accident percentage of seepage, foundation failure, overtopping, earthquake, and others, are respectively, 21.6%, 17.3%, 20.6%, 17.0%, and 23.5%. It can be seen from the collected data that extreme weather causes serious damage to the safety and stability of

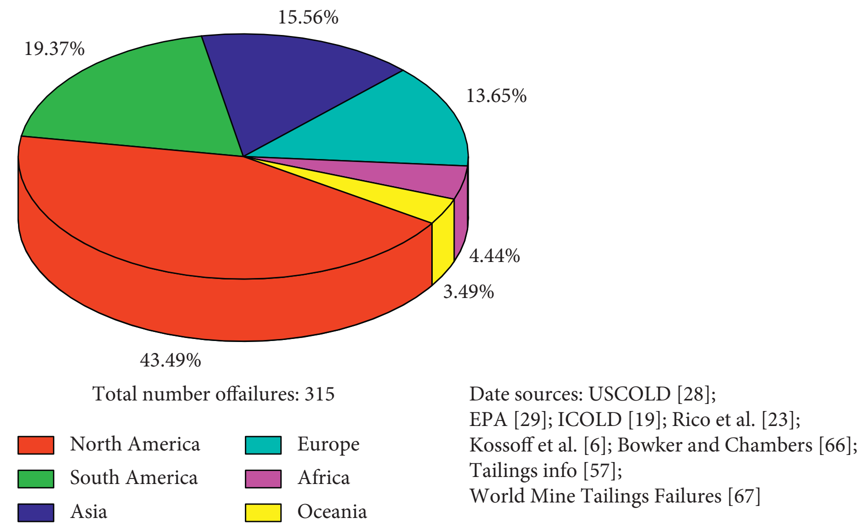

FIGURE 5: Failure distribution by continent.

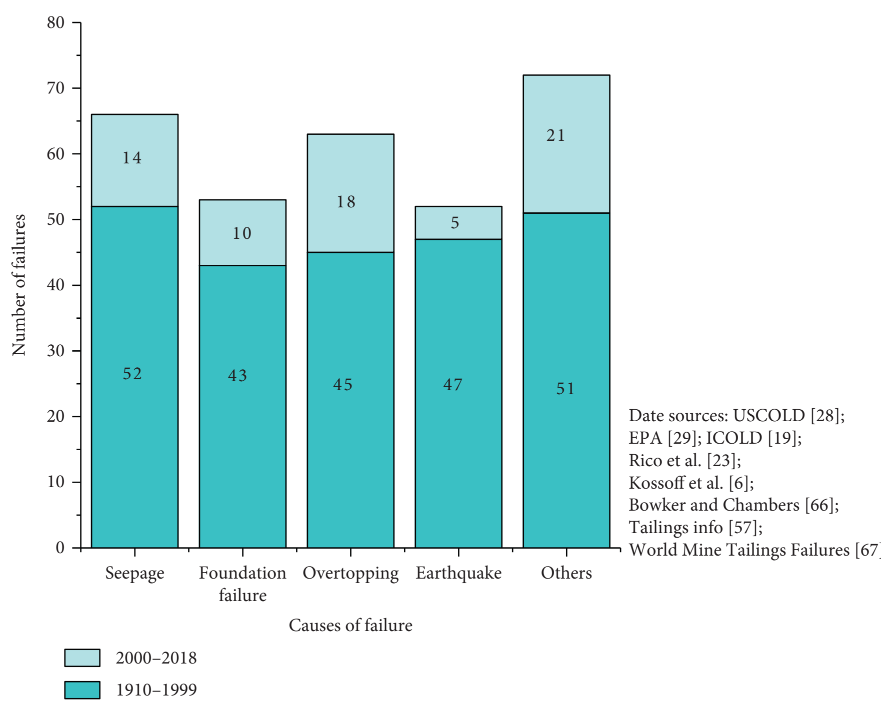

FIGURE 6: Failure distribution by cause.

tailings dams. As human activities cause climate warming, the tailings dam failure ratio caused by extreme weather may gradually increase. It can be seen from the collected data that extreme weather causes serious damage to the safety and stability of tailings dams. As human activities cause climate warming, the tailings dam failure ratio caused by extreme weather may gradually increase.

Figure 7 analyzes the height of the tailings dam accident in the world; it can be concluded 39% of accidents occurred in tailings dams less than 15 meters, 34% of the cases occurred in tailings dams between 15 and 30 m in height, and only 27% of incidents in tailings dams over 30 m. This distribution is generally similar for many countries although there are some differences. The proportion of accidents in high dams over 30 meters in the United States is large. Considering the fast-growing economy of the United States, this phenomenon is reasonable. The graph illustrates that dam breakages occurred mostly with dams less than 45 m. The authorities can improve the specification requirements for tailings dams below 45 m to ensure the safety of small- and medium-sized dams. From the statistical data, we can draw a conclusion that most of these dams were established in the 1960s and 1970s. The dam failures frequently occurred due to the lack of management or disposal of small dams and old dams by managers. The height of the tailings dam can increase the storage of tailings, but it also increases the safety

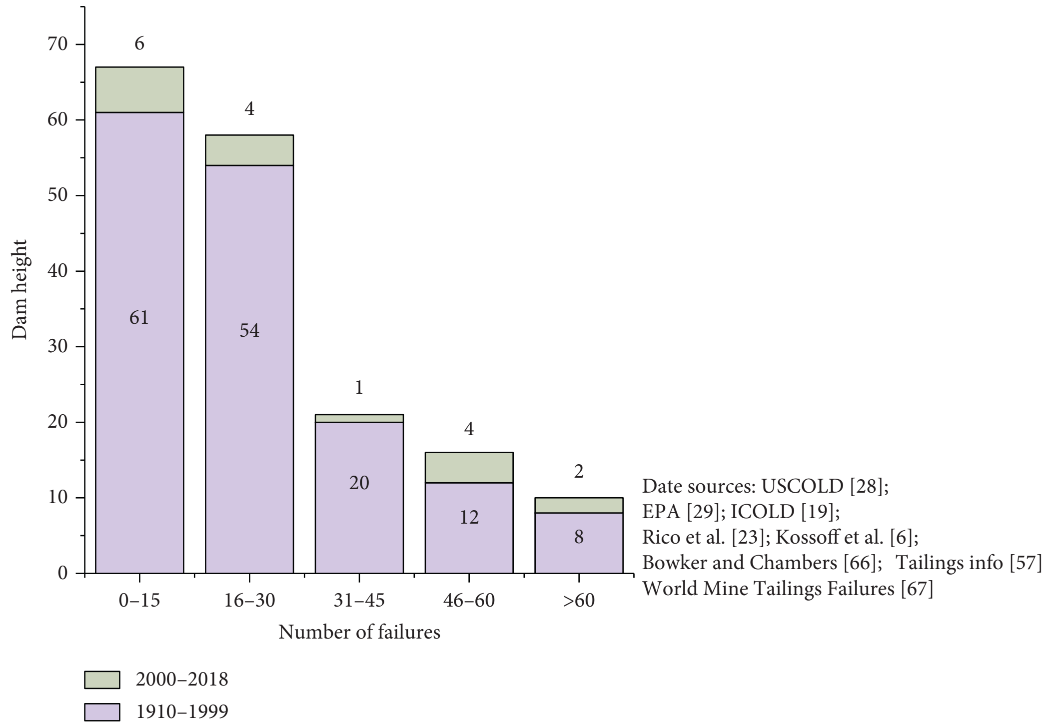

Figure 7: Failure distribution by tailings dam height.

risk. Researchers need to conduct more systematic research, such as phreatic line and slope stability, to contribute to the safety and stability of the tailings dam.

Figure 8 depicts the highest probability (58%) of tailings dam breakages built using the upstream construction method. Water retention dam type accounts for a higher proportion (18%) of tailings dam accidents. The upstream constructed dams require fewer construction materials, but their dams have a high phreatic line and poor stability. Before the establishment of the tailings dam, it is necessary to evaluate the geological conditions and environmental factors comprehensively. A safe method of centerline construction method and downstream construction method is chosen to build a dam, thus reducing the number of dams built by upstream construction methods. In countries such as South Africa and China, tailing dam failures related to abnormal rainfall have occurred. Rain-rich countries should design suitable drainage systems and choose stable central and downstream construction techniques. The reliable flood discharge system is conducive to the treatment of excess water in the reservoir area, thus ensuring safe and stable operation of the tailings dam. In countries with frequent earthquakes, such as Japan and Chile, the dangers caused by earthquakes to tailings dams should be fully considered. The foundation needs to be reinforced to ensure the safe operation of tailings dams.

As in the cases described in this article, although many accidents are related to natural events, such as heavy rain and earthquakes, there are also technical defects, such as overtopping and seepage. However, poorly constructed buildings and human activities near the tailings dam may cause settlement which can be monitored and effectively controlled. Several studies have shown that timely and effective management of tailings storage facilities, monitoring the factors that endanger the safety and stability of tailings dams, and detecting problems and repairing in time can effectively reduce the probability of accidents.

4. Summary and Conclusion

This paper collects newspapers, technical reports, scientific papers, and other electronic data to sort out the database of tailings dam failures in the world and then summarizes the main causes including seepage, foundation failure, overtopping, and earthquakes, as well as mechanisms of the classic examples for tailings dam failures. In order to understand the reason for the failure of the tailings dam, failure height, building type, geographical location, and time distribution, a brief discussion of the collected data was carried out.

On a global scale, the following conclusions are drawn about tailings dam failure:

(i) Based on the main cause of tailings dam failure, the accident percentage of seepage, foundation failure, overtopping, earthquake, and others is, respectively, 21.6%, 17.3%, 20.6%, 17.0%, and 23.5%.

(ii) North America (43%) is the world's largest tailings dam accident area. The accidents are mainly distributed in the United States, Chile, the United Kingdom, and Peru.

(iii) A majority (85%) of tailings dam failures have occurred in dams of less than 45 m high, and most of the dam break over 45 meters occurred in developed

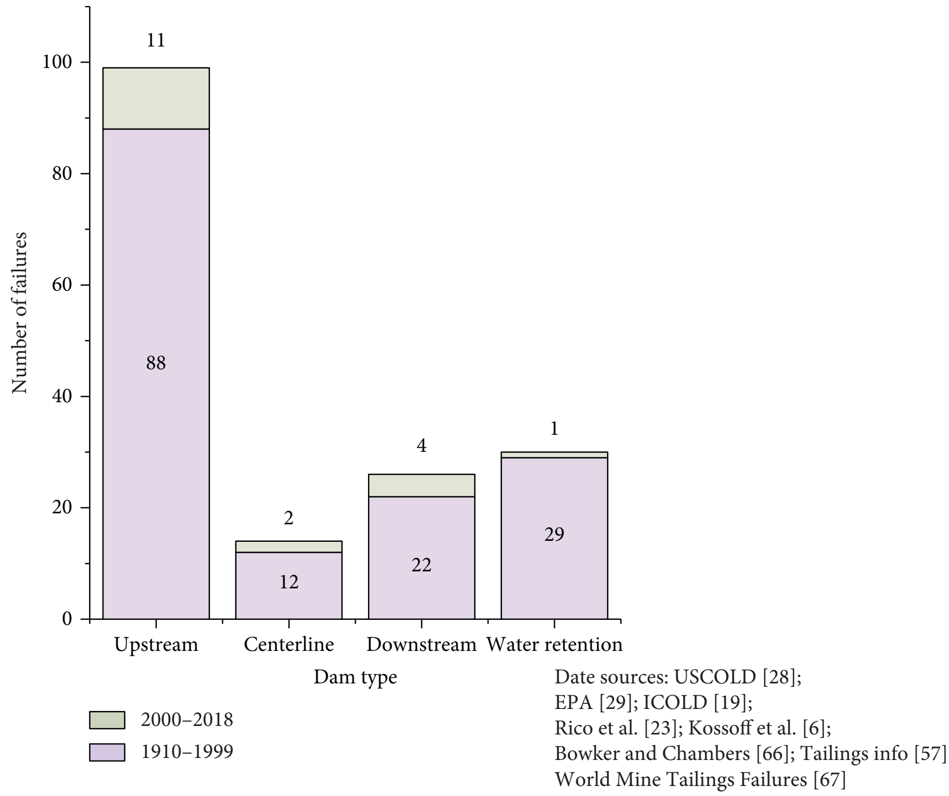

Figure 8: Failure distribution by the tailings dam type.

countries. The government can improve the building codes of small- and medium-sized dams, improve the safety and stability of dams, and reduce the number of dam breaks in future tailings dams. Developing countries should learn from the experience and lessons of developed countries, and they should also try to use centerline or upstream construction methods.

(iv) Upstream dams have a high probability (58%) for damage. Downstream and centerline dams have good stability and less dam failure events. Downstream or centerline dam construction method is recommended to build the tailings dam. For the established upstream tailings dam, it is necessary to give sufficient supervision and management to care about the operation of the tailings dam, thereby reducing the risk of tailings dam breakage and ensuring project safety and property safety.

It is not difficult to infer that each tailing dam failures involve engineering and human factors and that these factors can be avoided. Tailings dam failure is extremely harmful to people's health and living environment. A human being should prevent the occurrence of tailings dam damage events, instead of repairing after the accident. For example, tailings dams should design with special attention given to important factors that have a major impact on the stability of the dam including site conditions (hydrological conditions, geological conditions, and climate), choice of the embankment, and risk prediction (heavy rains and typhoons). In the operation and maintenance stage of the tailings dam, the medium and low tailings dam should be given more attention, and problems should be dealt quickly. Finally, the review of global dam failure information is beneficial to the management of tailings storage facilities and can effectively reduce the probability of tailings dam failures. The safety and stability of tailings dams require the joint effort of the government, design units, construction units, and supervision units.

Data Availability

Previously reported electronic data in figures were used to support this study and are available at https://worldminetailingsfailures.org/. These previous studies (and datasets) are cited at relevant places within the text as reference [67].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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