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Research Article

Exploration and Research on the Propagation Law of Seepage Risk Network in Tailings Storage Facility

Zhixin Zhen[1], **Xuewei Ma**[2], **and Bo Ma**[1]

[1]*School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing, China*
[2]*School of Finance and Taxation, Inner Mongolia University of Finance and Economics, Hohhot, China*

Correspondence should be addressed to Zhixin Zhen; b20160029@xs.ustb.edu.cn

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The seepage accident of a tailings pond poses a serious threat to the stability of tailings dams and the surrounding environment. To reduce the occurrence of seepage accidents, this paper studies the identification of seepage hazards, the propagation law of seepage risk, the importance of hazards, and the priority of hazard treatment. To overcome the subjectivity and omission of hazard identification, according to the complexity and dynamics of tailings seepage, this paper proposes the evidence-based identification method of three-dimensional seepage hazards (EIMTSH) to identify the hazards of the tailings seepage system and the relationship between hazards. Then, on the basis of identifying the hazards of the tailings seepage system, the propagation network of seepage risk in tailing ponds (PNSRTP) is constructed based on the complex network theory. By analyzing the characteristics of the PNSRTP, it can be found that the propagation of seepage risk is scale-free and small-world. Through the node deletion method, this paper finds that the nodes with a higher degree value can reduce the network efficiency more quickly and should be governed first. By giving priority to the treatment of hazards with higher degree, the propagation of seepage risk can be reduced more quickly and the risk management level of tailings ponds can be improved, which is helpful to realize the sustainable development of mining production.

1. Introduction

Tailings pond is a kind of geotechnical facility used for storing mine waste, which is called tailings in the mining industry. The composition of tailings is very complex, which may show strong corrosive, volatile, acidic, and other characteristics affected by the types of minerals mined. If the tailings cannot be managed effectively, the tailings may leak under the action of seepage, mainly in the form of flowing soil, piping, contact erosion,contact flowing soil, etc., which is called tailings seepage [1]. Seepage accident of tailings pond is one of the typical accident types of tailings pond, which not only directly pollutes the surrounding environment but also destroys the stability of the tailings dams. In serious cases, it will lead to dam breaks, causing greater accidents and ecological disasters [2, 3].

Seepage refers to the flow of fluid in porous media. The material which is composed of granular or fragmentary material and contains many pores or fissures is called the porous medium. Seepage is widely used in many fields. Tong Shujiao et al. used the two-dimensional seepage accident consequence analysis software to analyze the temporal and spatial variation law of leakage poison concentration [4]. In order to improve the design, management, and follow-up restoration of the landfill site, Shu et al. proposed a new simplified method to calculate breakthrough time of municipal solid waste landfill liners [5]. He et al. studied the biological damage to Sprague-Dawley rats by contaminated groundwater from rare earth metals tailings pond seepage at the individual, organ, tissue, and cell level [6]. CA López-Morales and Lilia conducted research on seepage in wastewater treatment and reuse processes [7].

In order to correctly analyze the change law of seepage field and stress field caused by tailings storage and rainfall, we should attach great importance to the identification of seepage hazards. Hazard identification, also known as risk identification, is an important basis for risk management [8]. To achieve the sustainable development goals, Li used the official data of the Belt and Road Initiative (BRI) countries from year 2000 to year 2015 to identify socioeconomic vulnerability to natural hazards of Belt and Road Initiative countries [9]. Makowski and Niedbalski used the geomechanical method to identify rock burst hazards in underground mining, which helped to predict rock burst accidents before mining operations [10]. Ibrahim used the national data of fire anomalies to analyze the risk of wastefires in Sweden and found that controlling upstream hazards in waste management chain helped to reduce the risk of fire [11]. Ferreira et al. proposed a hazard classification system based on the use of the CFs of the virtual substances as a hazardous reference to help perform a preliminary screening, which can be integrated with other criteria to facilitate the identification of PBT chemicals [12]. Wu Deng et al. improved the safety level of complex systems by optimizing complex systems [13–15].

For the seepage problem of the dam body, there are dozens of common identification methods for hazards, such as fault type and impact analysis, prehazard analysis, checklist method, hazard and operability research, fault tree analysis, and event tree analysis [16]. In addition, some new methods are also applied to the identification of dam hazard. Gao Shipei et al. combined the detection of levee engineering with numerical simulation analysis, so as to determine the location, outline, and size of levee hazard [17]. Based on the distributed optical fiber temperature measurement technology, Wang monitored the leakage volume of homogeneous earth dam and the damage degree of optical fiber geomembrane, so as to realize a more comprehensive monitoring of the hazard of seepage field [18]. Ma et al. have conducted treatment and research on the leakage hazard of Yuecheng dam in combination with the engineering practice [19].

The cause of seepage accident in tailings pond is complex, and many influencing factors are coupled with each other. At the same time, the seepage system is constantly changing with the construction of tailings pond, which creates a big problem for the characterization of seepage risk propagation process in tailings pond. Complex network has the characteristics of node diversity and connection diversity, which can better represent the internal relationship between research objects (nodes) [20]. In order to promote the sustainable use of rare earths (RE), Xibo Wang built an embodied RE network by combining both input-output analysis and complex network theory [21]. Jiujie Shi used thw complex network analysis method to analyze the historical evolution of the international plastic wastes trade and showed that China's management policies are the main driving forces for the expansion and shrinkage of the global plastic wastes trade network [22]. Guo S took the Chinese construction industry as an example and conducted research and exploration on the accident behavior risk chain network based on the accident causality theory [23]. Mohmand and Wang studied the structural properties of the Pakistan railway network (PRN) [24]. After the construction of the complex network which represents the relationship between nodes, scholars began to try to use the characteristics of the complex network to find the key nodes that dominate the operation of the network. Yu et al. converted the critical node identification problem in complex networks into a regression problem and presented it to identify critical nodes with the best spreading ability [25]. Because it is difficult to distinguish the importance of nodes with the same degree, an average shortest path centrality to rank the spreaders was proposed [26]. Zhen et al. initially tried to apply the important nodes of complex network identified by the network centrality index to the prevention of tailing pond accidents [27].

2. Research Overview

In order to explore and study the propagation law of seepage risk in tailings storage facility, this paper studies this problem in three steps. Firstly, based on the constitution and function of the seepage system of tailings ponds, the hazards in different life cycle stages of the tailings pond are identified objectively and systematically by using laws and regulations, literature, and accident cases, and the list of seepage hazards and propagation paths of seepage risk are determined after the same hazards are integrated. Secondly, based on the list of seepage hazards, this paper uses the Pajek software to construct the propagation network of seepage risk in tailing ponds (PNSRTP) for the first time; Finally, this paper analyzes the characteristics of this PNSRTP with the help of some analysis methods in the complex network theory and tries to find the key hazards that dominate the propagation of seepage risk from the perspective of reducing the network efficiency. The entire research process of this paper is shown in Figure 1.

3. Identification of Seepage Hazard in Tailings Pond

3.1. Identification Method. A hazard may cause loss of life, injury, or other health impacts, property damage, social and economic disruption, or environmental degradation [28]. In this paper, according to the characteristics of the tailing pond seepage system with the dynamic change of tailing pond life cycle, combined with industry laws and regulations and technical specifications, the seepage hazards of tailing ponds are divided into three modes or three states from the perspective of safety production. The first state is the dormant hazard, which is the initial factor or event to cause the seepage. It is an indirect factor and cannot be triggered by other factors or events. Its state is basically stable. The second is the armed hazard, which refers to the intermediate state of hazard evolution. It may evolve from the dormant hazard, or other armed hazards may cause it [29]. The third is the active hazard, which mainly refers to the seepage events that are happening [29].

The causes of seepage accidents in tailings pond are complex, and the seepage system changes continuously with the life cycle of tailings pond. These characteristics make it difficult to identify the seepage hazards in tailings ponds. Although some scholars have proposed a series of hazard

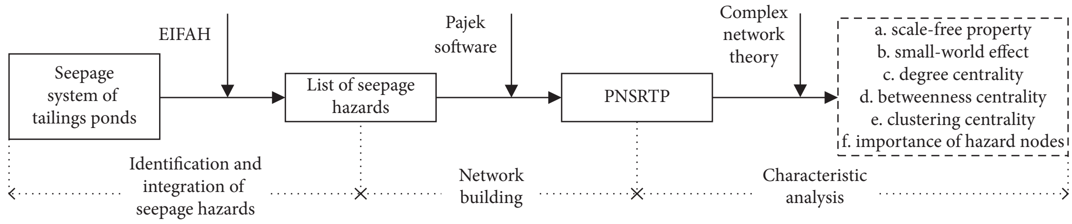

Figure 1: The flow chart of research methods and results.

identification methods for such dynamic complex systems, these methods are mainly based on the experience and subjective judgment of the identification personnel. The result is that some key hazards may be missed [30]. In order to overcome the above shortcomings, this paper proposes a method to identify the seepage hazards of tailings pond, which is called the evidence-based identification method of three-dimensional seepage hazards (EIMTSH), as shown in Figure 2.

It can be seen from Figure 2 that the EIMTSH includes three dimensions and each point in the space specifically represents the seepage hazards and influencing factors at each life cycle stage of tailings ponds under different supporting evidence. The Y-axis is composed of eight subsystems of the tailings pond seepage system, mainly including pond area subsystem, personnel subsystem, conveyor subsystem, drainage subsystem, monitoring subsystem, dam subsystem, material subsystem, and management subsystem. Each subsystem can be divided into different modules according to its function and structural characteristics. The Z-axis is the life cycle stage of tailings pond, which mainly includes construction stage, operation stage, closing stage, and reclamation stage or recovery stage. The division method of Z-axis and Y-axis is used to divide all the objects that need to be identified at different time periods and in different subsystems [29]. The X-axis is the supporting evidence used to identify the potential seepage hazards of tailings ponds, mainly including the relevant technical specifications and laws and regulations, seepage accident cases, literature, news media information, etc., as shown in Appendix A, B, and C [29].

In order to find out all the seepage hazards, the paper analyzes the Code for Design of Tailings Facilities (GB 50863-2013), Code for Construction and Acceptance of Tailings Facilities (GB-T 50864-2013), and other evidence in Appendix A and then extract the hazards and the influence mechanism between hazards in each content one by one [29]. At the same time, referring to the content in Appendix B and Appendix C, we can get all the hazards of the seepage system in tailings ponds that has not been integrated, that is, all the spatial nodes in Figure 2. After integrating these identified hazards, all hazards of the seepage system in tailings ponds can be obtained, as shown in Table 1.

3.2. Identification Result. Based on the EIMTSH, the seepage hazards of tailings pond are systematically identified. In this paper, 313 seepage hazards of tailings ponds are identified and 1912 relationships among them are shown in Table 1 [31]. In the first column of Table 1, the names of eight subsystems of seepage system of tailings pond are listed. The fourth column is the hazard identified by the EIMTSH, which is given as the number in the third column. The second column indicates the specific category of the seepage subsystem of tailings ponds to which the fourth column of hazards belongs. The fifth column indicates that the hazard in the fourth column of the same row is identified by the supporting evidence, and the type and location of the evidence are marked. The details of the evidence are shown in Appendix. The last column is the hazard number, which indicates the hazard or event directly caused by the hazard in the fourth column of the same row.

Take hazard 77 (The tailings dam slope ratio is unreasonable) as an example, the number of this hazard is 77, which belongs to the dam body class of the dam system. Based on the evidence F1-4.5, W4, and W7, we can confirm the existence of hazard 77 and find that hazard 77 can directly cause hazards 62, 64, 65, 73, and 157. Evidence F represents laws, standards, and norms, and W represents the scientific literature and accurate case. F1-4.1 indicates that the evidence is located in the first section of Chapter IV of 'Code for Design of Tailings Facilities (GB 50863–2013)'. More detailed supporting evidence information is provided in appendix A, B, and C.

4. Propagation Network of Seepage Risk in Tailings Pond

4.1. Model Construction. In order to apply the complex network model to characterize the seepage risk evolution process of tailings pond, this paper uses the seepage hazard to represent the network node and the relationship between hazards represents the network edge. At the same time, according to the three states of seepage hazards mentioned above, the PNSRTP is divided into three-layer nodes (dormant hazard, threat hazard, and activity hazard/accident) and two stages (from dormant hazard to threat hazard and from threat hazard to activity hazard). In this paper, with the help of complex network software Pajek, the hazard and the relationship between hazards in Table 1 are constructed as the PNSRTP, as shown in Figure 3.

In Figure 3, the first layer of nodes constitutes dormant hazards, represented by yellow nodes, with a total of 31. Dormant hazards are the initial hazards that cause other hazards, which cannot be caused by others. Earthquakes, floods, strong winds, etc., are all dormant hazards. The second layer of nodes includes armed hazards, represented

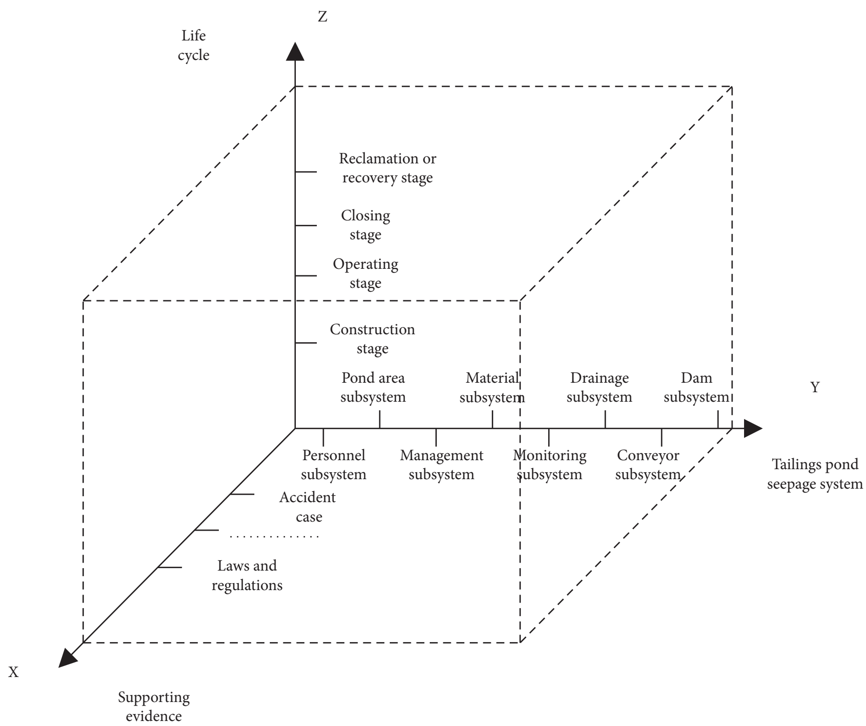

Figure 2: The evidence-based identification method of three-dimensional seepage hazards.

Table 1: List of seepage hazards in tailings pond.

Tailings dam subsystem	Modules of the subsystem	Number (v)	Hazard name	Evidence	Number of hazards caused
		2	Flood	W1-1.2.1, W6, W7, W8, W9	7, 19, 60, 62, 64, 65, 66, 67, 69, 150, 151, 156, 158, 167, 190, 191, 192, 193, 195, 273, 325
		3	Ice and snow	F2-3.4, W7	19, 67, 112, 181, 195
		4	Strong wind	W5, W1-3.4.4	7, 19, 66, 325
		5	Heavy rainfall	W5, W9, W4, W6, W7, W8, F4, C2, C11, C13	19, 67, 69, 150, 151, 193, 195
		6	Extreme temperature changes	W1-3.4.4, W7	19, 62, 65–67, 191, 232, 267, 325
		7	Surge	W6, W1-3.4.4, F1-4.2, W6, C3, C11	62, 65–67, 69, 150, 151, 190, 193
		8	Beyond standard earthquake	W5, W2-3, W9, W11, W12, W4, W6, F4	19, 60, 62, 64–66, 70, 136, 150, 151, 191, 192, 232, 267, 273, 325
		9	Mudslide	W2-2, W10, W8	39
		10	Gravel foundation	F1-4.1, W2-3, F3	157
		11	Liquefied soil, soft clay, and collapsible loess foundation	F1-4.1, W2-3, F3, C2	68, 70, 135, 136, 157
		12	Water burst in the tailings pond	F1-5.7, W2-3, F3	127, 158
		13	Karst cave or existence of mine shafts	F1-4.1, W2-3, F3	68, 135, 136, 158
	Pond environment	14	Insufficient geological exploration	W1-3.4.4, W6, F4, F3	89, 121
		15	Failure to do engineering geological weaving and surveying during excavation and tunneling	W1-3.4.4, F5, F4, F3	347
		16	Failure to predict and forecast engineering geological problems that may occur during construction	W1-3.4.4, F5, F4, F3	121
		17	Inadequate research on adverse geological problems and improper handling measures	W1-3.4.4, F4, F3	19, 121
		18	No engineering geological and hydrogeological surveys were carried out when the tailings dam reached the corresponding height	W1-3.4.4, F5, F3	19, 121, 347
Pond area subsystem		19	Landslides in the tailings pond	F6, W1-3.4.4, W9, W10, W6	7, 39, 195
		20	The overburden of the bank slope connected to both ends of the tailings dam is thin	W1-3.4.4, F3	158
		21	The rock on the bank slope is broken, joints are developed, or faults pass through	W1-3.4.4, W8, F3	19, 158
		22	Animals burrow, camp, and graze illegally	W1-3.4.3, W1-3.4.4	19, 64, 66, 150, 151, 158
		23	Private digging in the tailings impoundment	W1-3.4.4, W2-3, W6	19, 64, 66, 150, 151
		24	Illegal soil borrowing behind the dam	W1-3.4.4, W2-3, W6	64, 66, 157
		25	There are mining activities near the site	F1-3.1, W2-3, W6	19, 62, 64, 66
		26	Inappropriate selection of pond location	F1-3.1, W11, F3	10–13, 20, 21, 25, 32–34, 52, 208
		31	Open pits and depressions reserve tailings without special safety demonstration	F1-3.1	135
		32	Insufficient impoundment length (upstream wet tailings impoundment)	W1-1.1.1	39
	Selection of pond location	33	The dam site is not conducive to the layout of drainage structures	F1-6.1, C8	200
		34	Large catchment area	W2-2, W2-3, W8	195
		35	Unreasonable multidatabase phased construction plan	F1-1	39, 194
		36	No operation plan for the joint impoundment	F1-1	39, 194
		37	Overdue service of tailings pond	F1-7, W9, W11, W5, W8	39, 65-66, 70, 73, 183, 191–193, 232–234
	Tailings pond construction	38	Inaccurate storage capacity calculation	F1-3.2	39, 194
		39	Insufficient storage capacity of tailings pond	F1-3.2, W9	190
		42	No antifreeze measures have been taken for tailings facilities	F1-10, F1-11	66, 112, 191, 232, 244
		43	Antifreezing measures have not been finished before freezing	F1-10	66, 112, 191, 232, 244
		44	Blasting construction does not meet the technical specifications	F2-4.2, W6	19, 62, 64–66, 191
		45	Tailings particle size/gradation does not meet the requirements	W1-3.5.2, W9, F3	47, 48, 50, 51, 66, 68, 61, 234
		46	Excessive flow of tailings slurry	F1-11, W1-3.5.2	50, 61, 233, 234, 267
		47	Excessive tailings unit weight	W1-3.5.2, C2	51, 52, 68, 61, 233
		48	Concentration and consistency of tailings slurry do not meet the requirements	F1-11, W1-3.5.2	50, 51, 68, 61, 233, 234
Material subsystem		49	Strongly corrosive tailings	F1-11, W1-3.5.2, W12, C3, C9	233, 238
		50	Tailings are highly abrasive	F1-11, W1-3.5.2	233
		51	Unqualified dry beach-covering materials	W1-3.4.4	53, 157, 158, 195
		52	Unqualified filling materials	F2-3.3	64–68, 70, 73, 135, 136, 157
		53	Erodible tailings exposure	W1-3.4.4, C3, C5, C6	157

Table 1: Continued.

Tailings dam subsystem	Modules of the subsystem	Number (v)	Hazard name	Evidence	Number of hazards caused
		63	Decrease of dam elevation	W6, W11, W6, C2	39, 190, 194
		65	Dam deformation	W1-3.4.5, W8, C2	62, 64, 157, 267, 273
		66	Dam crack	F6, W1-3.6.6, W6, W7, C8, C11–C13	62, 64, 73, 158
		67	Dam surface water saturation	W2-3, W3, W6	62, 64–66, 73, 157
		68	Uneven settlement of the dam	W1-3.6.6, W6, C9	62–66, 191, 192, 267, 273
		69	Scouring of the dam	W6, W2-3, W6, W7, C11, C13	62, 64–66
		70	Tailings liquefaction	F1-4.4, W1-1.1.4, W8, W9	62, 64, 68, 136, 156–158
		71	Defects in seismic calculation of tailing pond	F1-4.4	72
		72	Improper seismic design	F1-4.4, W8	62, 64, 66, 70, 73, 135, 136
		75	Improper calculation method of tailings dam stability	F1-4.4, W4	64, 73, 77–81, 89, 90, 92–94
		77	The tailings dam slope ratio is unreasonable	F1-4.5, W4, W7	62, 64, 65, 73, 157
		78	Unreasonable width of dam crest	F1-4.5, W4	62, 64, 65, 157
		79	Improper dam type selection for the initial dam	W1-1.1.2	39, 64, 157
		80	The height of initial dam is unreasonable	F1-4.1, W9	39, 64, 65, 73, 81, 88, 194
	Dam body	81	The ratio of the initial dam height to the total dam height of the upstream tailings dam is unreasonable	F1-4.1, W9	64, 65, 73
		82	The dam layout is unreasonable (the location of subdam and primary dam)	F1-4.1, C2	32, 39, 69, 73, 135
		61	Poor control of tailings deposits	W1-1.1.3	64, 65, 68, 77, 152, 154, 155, 157
		83	The rising speed of tailings between dam downstream and upstream is unbalanced	W1-1.1.3	61
		84	The rising speed of the dam does not meet the requirements of the rising speed of the sedimentary beach	W1-1.1.3	80, 61, 85, 86
		85	The accumulation dam is too high	F1-4.1, F5	62, 64, 65, 81
		86	The height of the accumulation dam is lower than the height of tailings accumulation	F1-4.1, F5	39, 65, 88, 190, 194
		87	Defects in the layout of maintenance passages of the primary dam	F1-4.5, F5	65, 66, 82
		88	The requirements for discharge under ice cannot be met in frozen areas	F1-4.1	112
		89	The upstream method is used to build dams on the seismic zone	F1-4.1	60, 62, 70
		90	Fine-grained tailings dams using the direct method	F1-4.1	64, 65, 61
		91	Unreasonable setting of tailings dam berm	F1-4.5	65, 66, 82
		92	The tailings dam is not equipped with antiscouring measures	F1-4.6, F5	69, 82
		93	No filtration water and sediment storage dams are built in the centerline and downstream tailings dams	F1-4.6	64, 82
		94	Unreasonable height of the filtration water and sediment storage dams	F1-4.6	39, 64, 65
		95	Defects of step arrangement on the outer slope of accumulation dam	F1-3.4	65, 66, 82
		96	Use of only one tailings discharge point for a long time	F1-3.4, W2-3	61, 86, 152
		97	Long time no replacement of tailings discharge point	F1-3.4, W2-3	61, 86, 152
		98	The tailings discharge method does not match the direction of advancement	F1-3.4, W2-3	61, 152
		99	The branch pipes that discharge tailings are opened too little	F1-3.4, W2-3	61, 152, 234
		100	Failure to evenly discharge tailings	F1-3.4, W2-3	61, 86, 152
		101	Unreasonable layout of ore branch pipe	F1-3.4	61, 86, 88, 152, 234
		102	Layered filling and layered compaction are not carried out	F2-3.4, F5	64–66, 68, 77
		103	Improper method of sectionalized filling and rolling	F2-3.4, F5	64–66, 68, 77, 122
		104	Unreasonable slope of the top surface of layered rolling	F2-3.4, F5	64–66, 68
		105	The tailings discharged into the pond are not leveled and rolled	F2-3.4, F5	86
		106	Improper selection of tailings leveling and compaction equipment	F2-3.4, F5	77, 104, 122
		107	Rolling is perpendicular to the dam axis	F2-3.4, F5	65, 66, 104
		108	Laying the upper layer of new materials before the dam body is qualified	F2-3.4, F5	65, 66, 68, 104, 122, 158
		109	The filling and rolling of the cohesive tailings dam is not continuous	F2-3.4, F5	65, 66, 68, 104, 122
		110	Improper paving	F2-3.4, F5	64–66, 68, 104
		111	Downhill paving when the ground is uneven	F2-3.4, F5	64–66, 68, 104
	Dam filling	112	The dam is filled with ice, snow, or other debris	F2-3.4, F5	64–66, 68, 158
		113	Improper unloading method	F2-3.4, F5	65, 66
		114	Filling and slope adjustment are not carried out at the same time	F2-3.4, F5	64, 66, 77
		115	Construction machinery and personnel crossing the dam surface in violation of regulations	F2-3.4, F5	65, 66
		116	Resuming work in violation of regulations	F2-3.4, F5	112
		117	The maintenance platform in downstream dam slope is defective	F2-3.4	65, 66, 73, 122
		118	Unreasonable determination and modification of dam construction indicators	F2-3.4	64, 77, 78
		120	The subsidence allowance of the dam filling is unreasonable	F2-3.4	65, 66, 158
		121	Improper handling of dam-bank junction	W1-3.4.4	65, 66, 73, 158
		122	There is a horizontal weld on the slope	F2-3.6	64, 66, 73
		124	Slope cutting did not follow the design requirements	F2-3.6, F5	19, 64, 65
		125	Slope protection was not carried out in time	F2-3.6, F5	19, 62, 64, 65, 73, 122
		126	Unreasonable design of cast-in-place protective surface	F2-3.6	19, 62, 64–66, 73, 77, 122, 157
		127	When the dry storage method is adopted, the accumulated water in the pond area is not discharged in time	F1-5	64, 67
		128	Mixing dry and wet tailings when using dry storage	F1-5	64, 65, 68
		129	Tailings pond of insufficient depth and water resources chooses wet storage	F1-5	39
		131	Poor construction quality of vertical antiseepage facilities	F2-3.2	66, 157, 165
		132	No effective filter layer is set on the dam foundation	W1-3.4.4	131, 157, 165
		133	The concrete cutoff wall is not on the fresh bedrock	F2-3.2	131, 157, 165
		134	Inadequate protection measures after dam foundation excavation	F2-3.2	66, 131, 135, 136
		135	Uneven foundation subsidence	W1-1.4, W9	63–66, 68, 73, 136, 191, 267, 273
Dam subsystem	Dam foundation	136	Dam foundation instability	F4, F6, W1-1.4, W11, W12, W8, W9	64–66, 68, 73
		137	The protective layer reserved has not been removed before filling when the natural clay is used as the dam foundation	F2-3.2, F5	131, 133, 135, 136, 158
		138	No measurement and set-up before clearing dam foundation	F2-3.2, F5	131, 133, 135, 136, 165
		139	Untreated strong weathered layer and broken zone of rock foundation	F2-3.2, F5	131, 133, 135, 136, 158
		140	Improper handling of the alluvium above the bedrock	F2-3.2, F5	131, 133, 135, 136, 158
		141	Irregular grouting work for dam foundation treatment	F2-3.2, F5	131, 135, 136, 157
		145	No coverage measures in the pond area	W1-3.4.4	53, 157
		146	The main dam has not been reclaimed and greened in time	F1-5.7	53
		147	Insufficient soil cover or greening on the dam slope (dry)	W1-3.4.4, F1-5.7	53
		148	Weakness of paving has not been reinforced	W1-3.4.4, F5	158
		130	Poor construction quality of horizontal paving	W1-3.4.4	157
	Dry beach	149	The length or thickness of the horizontal paving in front of the dam is insufficient	W1-3.4.4	157
		150	Natural paving (covering) is destroyed	W1-3.4.4	158
		151	The protective layer (cover) of the dry beach is destroyed	W1-3.4.4	53, 158
		152	Poor deposition control for dry beach face	W1-3.4.4, F4	154, 155, 157
		154	The minimum dry beach length does not meet the requirements	F1-4.2, W8	64, 167
		155	The minimum free height does not meet the requirements	F1-4.2, W8	64, 167
		156	Leakage damage	F6, W1-3.4.4, W2-3, W8, W9, W11, W12, C1-C13	60, 62, 64
		157	Filter failure	W1-3.4.4, W8	64, 67, 136, 156, 167, 195
		158	Leakage channel	W1-3.4.4, W8, C1, C5, C9-C10, C12-C13	64, 68, 135-136, 156
		159	No special seepage simulation experiments were done for the 1st and 2nd level tailings dams according to the terrain conditions	F1-4.3	93, 162, 167
		160	The seepage calculation of the dam body was not carried out in the preliminary design stage	F1-4.3	93, 162, 167
		161	The expanded or heightened tailings pond did not carry out the dam seepage calculation	F1-4.3	162, 167
		162	Unreasonable antiseepage design	W1-3.4.4	67, 156-157
		164	The dam foundation area between the initial dam and sediment storage dam is not equipped with drainage facilities	W1-3.4.4	157
		165	Defects of dam foundation drainage facilities	W1-3.4.4	157
		166	Inaccurate confirmation of critical and control seepage lines	F1-4.3	167
		167	Seepage line is higher than control seepage line	F1-4.3, W11, W3, F4, C1	65–67, 154–156
		168	Improper measures to reduce the seepage line	F1-4.3	167
		169	Improper construction connection of impermeable geosynthetics	F2-4.3	157, 165, 184
		170	Insufficient protection measures for seepage prevention facilities	F2-11	158, 165, 183
		171	Improper selection of soil for the soil cushion	F2-11	157, 165, 184
		172	Unqualified soil pad compaction	F2-11	157, 165, 184
		173	Improper laying of geomembrane	F2-11, F4	157, 165, 184
		365	The HDPE geomembrane did not conduct visual inspection and physical performance index testing before laying	F5-11.3	173
		366	The laying amount of HDPE geomembrane exceeds the amount of welding that can be completed in one working day	F5-11.3	173
		367	When laying the HDPE geomembrane, unfold first and then drag	F5-11.3	173
	Seepage	368	Improper windproof measures of HDPE geomembrane	F5-11.3	173
		369	After the HDPE geomembrane was laid, no welding was carried out within the specified time	F5-11.3	173
		370	Welding seam and welding inspection and quality control are not carried out in the HDPE geomembrane laying	F5-11.3	173
		371	The vehicle is rolled directly on the HDPE geomembrane and the HDPE geomembrane is damaged	F5-11.3	173
		372	The laying of HDPE geomembrane does not allow for expansion and contraction of the material	F5-11.3	173
		174	Unqualified geomembrane	F2-11	157, 165, 184
		175	No drainage measures under the geomembrane protective layer	F2-11	157, 165, 184
		176	Poor drainage of composite geotechnical drainage network	F2-11	157, 165
		177	Improper installation of composite geotechnical drainage network	F2-11	157, 165, 176, 183
		178	Improper construction of sodium bentonite mat	F2-11	157, 165, 184
		360	The sodium bentonite pad appears wrinkled and suspended	F5-11.5	178
		361	Personnel and vehicles rolled on on the sodium bentonite pad	F5-11.5	178
		362	Improper repair materials and scope for damaged parts of sodium bentonite pad	F5-11.5	178
		363	Construction of sodium bentonite pad under rain and snow	F5-11.5	178
		364	The construction of sodium bentonite mat shows a cross	F5-11.5	178
		179	The materials are poured down from the top of the slope	F2-3.5	184
		180	People walking, rolling stones, and handling other materials on the paved filter layer	F2-3.5	183
		181	Ice and snow and debris are mixed in the filter material	F2-3.5	182
		182	Unqualified filter material	F2-3.5	183
		183	Filter failure	F2-3.5, W2-3, W3, F4	65, 157, 165
		184	Unqualified filter layer paving	F2-3.5, F4	66, 183
		186	Improper laying of geotextile	F2-3.5	165, 184
		187	Geotextile clogged	F2-3.5	165, 183
		188	The geotextile is exposed to the sun for a long time	F2-3.5	165, 183
		189	Unreasonable geotextile design	F2-3.5	165, 183

Table 1: Continued.

Tailings dam subsystem	Modules of the subsystem	Number (v)	Hazard name	Evidence	Number of hazards caused
		190	Overtopping	F6, W2-3, W9, W12, W11, F4, C1, C3, C11	60, 62, 64, 69
		191	Fracture of drainage structure	W1-3.4.4, F4	66, 69, 127, 158, 192, 200
		192	Leaking drainage structure	W1-3.4.4, F4, C7	66, 67, 69, 127, 150, 151, 158, 195, 200
		193	Scour or cavitation drainage structures	W1-3.4.4, F4	191, 192
		194	Insufficient regulating water storage	W1-3.4.4	39
		195	Rapid rise of pond water level	W1-3.4.4, W2-3, C2, C1	39, 65, 67, 152, 154, 155, 167, 190, 194
		196	No drainage facilities	F1-6.1	127, 195, 200
		197	The foundation pit at the higher groundwater level has no drainage facilities	F1-6.1	195, 200
		198	The flood drainage system does not match the dam construction method	F1-6.3, F4	191, 200
		199	The determination of the flood control standard of the tailing pond is not accurate	F1-6.1	127, 190, 194, 200
		200	Insufficient flood discharge capacity	F1-6.2, F6, W9	127, 193, 195
		201	Blocking defects of flood drainage facilities	F1-6.3	192, 193, 195, 200
		202	Unreasonable temporary flood control plan during construction period	W1-3.4.4	195, 200
		203	Improper diversion measures	W1-3.4.4	195, 200
	Drainage plan	205	The installation location and elevation of drainage facilities do not meet the design requirements	F1-6.1, F4	193, 195, 200
		206	Insufficient elevation of drainage holes in front of the dam	F1-6.1	200
Drainage subsystem		207	Flood drainage structures are directly located on the tailings sediment beach	F1-6.1, F4	191
		208	The foundation of the flood drainage structure is set in the area with poor engineering geology	F1-6.1	191
		209	Insufficient foundation bearing capacity of underground flood drainage structures	F1-6.1	191
		210	Improper installation of flood interception and drainage facilities	F1-6.1, F4	191, 200
		211	The dry tailings pond of third-class and above adopts flood interception ditch for flood discharge	F1-6.1, F4	200
		212	Drainage facilities are not located in front of the blocking dam	F1-5.6	193
		213	Use of mechanical flood drainage	F1-6.2	200
		214	The on-site line setting is inconsistent with the construction drawing	F2-3.1	77, 78, 205, 210, 237, 273, 274
		215	Confluence calculation is not accurate	F1-6.2, F4	195, 200
		216	Use of unproven non-24-hour rainfall duration	F1-6.2	215
		218	Improper installation of energy dissipation facilities	F1-6.3	191, 193
		219	No energy dissipation measures have been taken in the tailings facility	F1-6.3	191, 193
		220	The maximum flow rate of flood is greater than the allowable flow rate of the building materials	F1-6.2	191, 193
		221	The clarified water of the tailings pond is not used for backwater utilization	F1-9, F4	195
	Backwater plan	222	One-sided pursuit of backwater quality	W1-3.4.3, W8, F4	195
		224	Low tailings water recovery rate	F1-9	195
		227	Insufficient volume of backwater pond	F1-9	224
		231	Leaks in transmission facilities	F6, W1-3.4.4, W8, C4	69, 61, 150–152
		232	Broken conveying facilities	W1-3.4.4, W12	69, 100, 231, 253
		233	Scour or cavitation transportation facilities	W1-3.4.4	232, 238-239
		234	Blockage or siltation	W1-3.5.2	100, 165, 176, 191, 195, 200, 232, 253
		235	No overload alarm signal and protection device	F1-10	46, 191, 233-234, 239
		236	No flow and pressure detection instrument	F1-10	46, 191, 233-234, 239
		237	The installation location and elevation of the transportation facilities do not meet the design requirements	F2-10	234
		238	Serious corrosion of equipment	W1-3.4.4, W11, W12	191, 231-232, 253, 325
		239	Serious wear and tear of conveying facilities	W1-3.4.4	231-232, 253
		240	No anticorrosion treatment in tailings facilities	F1-6.3, F2-5.3, W9	233, 238, 244
		241	Unqualified anticorrosion materials	F2-5.3	193, 233, 238, 244
		242	Improper anticorrosion construction	F2-5.3, W11	193, 233, 238, 244
		244	Incident pool defect	W1-3.5.5	231
		245	Improper installation of the instrument of the thickener	F1-10, F4	46–48, 233, 238, 239
		246	Unreasonable area of thickening tank	W1-3.5.5, F2-10, F4	250
	Conveying facilities	247	The height of the thickening tank is unreasonable	W1-3.5.5, F2-10, F4	231, 250
		248	Improper selection of thickening tank	W1-3.5.5, F2-10	231, 250
		249	Improper selection of the inclined plate and inclined pipe	W1-3.5.5	231-232, 238-239, 250
		250	Insufficient production capacity of the thickener	W1-3.5.5	234
		251	The pipelines and valves of the conveying equipment are not connected tightly	F2-10, F4	231, 238, 239, 253
		252	Flocculant preparation and addition do not meet the requirements	F1-10	47-48, 234, 253
		253	Concentration equipment failure	F2-10	47-48, 231, 234, 250
		258	Waste mixed into tailings slurry	W1-3.5.2	47–50, 65, 112, 233-234, 238-239, 253, 267
		260	Improper handling of local hydraulic phenomena	W1-3.5.2	233-234, 238-239, 267
		261	Unreasonable selection of classification equipment	W1-3.5.5	45, 254, 264
		262	No spare grading equipment	W1-3.5.5	264
		263	The pressure of the cyclone to feed the tailings is unstable	W1-3.5.5	45, 233, 239
		254	Damaged grading equipment	W1-3.5.5	45, 231, 234, 263, 264
		264	Insufficient cyclone production capacity	W1-3.5.5	234
		265	Damaged dredger	W1-3.5.5	234
		266	Insufficient production capacity of dredger	W1-3.5.5	234
		267	Pipes and grooves deformation	F2-5.3	191, 193, 232, 234, 239
		268	Defects of the interception ring in the pipe body	F2-5.3	69, 192, 193
		269	The pipe body is in direct contact with the big rocks	F2-5.3	191, 232, 267
		270	The outer wall of the pipe is not protected	F2-5.3	191, 232, 267
		271	The dimensions of pipes, grooves, tunnels, etc. do not meet the requirements	F1-6.3, W1-3.5.2	191, 193, 234, 267
		272	Pipes and grooves material unqualified	F1-11, F4	191, 193, 232, 267
		273	Subsidence or deformation of supporting facilities such as pipes, trenches, and tunnels	F1-11, F2-4.3	191, 232, 267
		274	Improper installation of supporting facilities	F1-11,F2-4.3	191, 232, 267, 273
		275	Excessive slope deviation for laying pipes, trenches, tunnels, etc.	F1-11, W1-3.5.2	191, 193, 233, 234, 239, 267
Conveyor subsystem		276	Improper design of corners of pipes, grooves, tunnels, etc.	F1-11	191, 193, 233, 234, 239, 267
	Other transportation facilities	277	Improper subgrade design of pipes and grooves	F1-11	193, 233, 234, 239
		278	Improper design of slope ratio of pipe trench and embankment	F1-11, F4	193, 239
		279	The pipe opening was not closed when the pipeline installation and laying were suspended	F1-11	192
		280	Pipes and grooves failed the pressure test	F1-11, F2-8.4	191, 232, 267
		281	Poor quality of fill around the pipeline	F1-11	191, 267
		282	The axial filling height of the pipe in the dam body is different	W1-3.4.4	191, 267
		283	Improper rolling of the backfill on the top of the facility	W1-3.4.4	191, 267
		284	Improper pipe welding	F1-6.3	191, 192, 233, 251, 267
		285	No settlement joints between pipe and well	F1-6.3	191, 233, 267
		286	The joint length of the drain pipe is unreasonable	F1-6.3	191, 192, 233, 267
		287	Deformation joints are not provided at both ends of the drain pipe according to the design requirements	F1-6.3	191, 233, 267
		288	Lax masonry of pipe walls	F2-5.2	192, 232, 233, 251
		289	Improper excavation (pipes, trenches, tunnels, etc.)	F2-4.2, F2-5.2	65, 66, 87, 91, 95, 117, 120, 131, 133, 191
		293	Pump selection does not meet the requirements	F1-12, W1-4.4	46, 195, 200, 232, 234, 307
		294	Insufficient capacity of pumping station design	F1-9, F1-12	195, 200
		296	Poor pump quality	F1-12, W1-4.4	192, 193, 233, 234, 239, 307
		297	Unreasonable valve selection in pumping station	F1-12, W1-4.4	192, 234, 251, 307
		298	Improper pump station configuration	F1-12, W1-4.4	46, 192, 195, 234, 307
		378	There are no flow and pressure detection instruments in the pumping station	W1-4.4	298
		379	Defect of buffer device in pump	W1-4.4	298
		380	Defects of the slurry pipeline in the pumping station	W1-4.4	298
		299	Improper installation of pumps	F1-11, W1-4.4	192, 195, 200, 233, 234, 307
		307	Pump failure	F1-11, W1-4.4	61, 100, 127, 192, 195, 200, 231
		373	No liquid can be discharged from the sand pump	W1-4.4	307
		374	Insufficient liquid output from sand pump	W1-4.4	307
		375	Pump consumes too much power	W1-4.4	307
	Pump	376	Pump bearing heat	W1-4.4	307
		377	Deformed or broken pump shaft	W1-4.4	307
		308	Closure design not in accordance with regulations	F1-6.3, W5, F4	19, 37, 62–70, 73, 135, 136, 148, 157, 158, 167, 183, 191, 192, 232, 234, 238, 254, 265, 267, 273, 307, 314
		309	The tailings pond are closed without understanding the hidden dangers and risks	F1-7, W5, F4, F3	66, 310, 312, 313
		310	The surrounding environment improvement does not meet the requirements	F1-7, W5	19
		312	Dam body renovation does not meet the requirements	F1-7, W5	62–70, 73, 135, 136, 148, 157, 158, 167, 183,
		313	The improvement of flood discharge system does not meet the requirements	F1-7, W5	191, 192, 195, 234, 267, 273, 307
		314	No plans for reclamation and ecological restoration after closure design	F1-7, W5, F4	19
		315	Unreasonable reclamation plan	W2-5, W8, F4	19, 310, 312, 313
		316	Simultaneous mining and discharge of tailings in a tailings pond	F1-8, F4	65, 66, 68, 61, 151, 152, 157, 158, 191, 232
		317	The upstream wet-stacking tailings pond adopts the recovery method advancing from the embankment to the pond	F1-8	64–66
		318	Mechanical excavation of tailings near drainage facilities	F1-8	191, 192, 267, 273
		320	Unreasonable tailings recovery plan	F1-8, F4	64, 151, 157, 158, 191, 192
		321	Stability analysis and safety measures of the tailings dam and the slope is insufficient	F1-8	19, 64, 73

Table 1: Continued.

Tailings dam subsystem	Modules of the subsystem	Number (v)	Hazard name	Evidence	Number of hazards caused
Monitoring subsystem		324	Improper selection of monitoring instruments and equipment	F1-3.4, W8, F4, C2	235, 327, 343
		325	Monitoring instrument failure and work interruption	F1-3.4, W8, C2	327, 343
		326	The third-class and above tailings ponds are not equipped with monitoring facilities that combine manual and automatic monitoring	F1-3.4	19, 22–24, 154, 155, 231, 327
		327	Safety monitoring facilities cannot fully reflect the operating status of the tailings pond	F1-3.4, C2	7, 19, 22–24, 37, 45–50, 65–69, 135, 136, 191, 192, 200, 267, 343
		328	No monitoring points are arranged outside the dam toe	W1-3.4.5	19, 22, 23, 231, 310, 327
		329	No additional monitoring facilities are installed at the dam abutment, bedrock faults, and buried pipes in the dam	W1-3.4.5	65–69, 135, 136, 191, 192, 267, 327
		330	No monitoring of the amount and composition of tailings entering the pond	F1-3.4	45–50, 327
		331	No external drainage and composition monitoring	F1-3.4	200, 327
		332	No monitoring of groundwater and surrounding water bodies	F1-3.4	327
		334	The number of water quality monitoring wells around the tailings pond is insufficient	F1-3.4	327
		336	The setting of monitoring facilities is not included in the construction plan	F2-3.7	325, 327
		337	Improper safety monitoring during tunnel excavation	F2-6.1	214, 271, 273–276, 289, 327
Management subsystem		339	Insufficient capital investment	W2-3, W3	14–18, 24, 31, 37, 42, 52, 89, 90, 92, 93, 132, 134, 145–148, 159–161, 164, 196, 197, 221, 235, 236, 240, 268, 293, 294, 308, 310, 312, 324, 326, 328–334, 351,
		340	Insufficient safety supervision	W2-3, W11, W12, W5, C4	7, 14–19, 22–24, 26, 31, 36, 37, 42–52, 60, 62–70, 73, 74, 76–173, 174–178, 179–214, 218–298, 299, 307, 308–337, 346, 348, 351–355
		343	Inadequate safety evaluation	W2-3, W3, W5	19, 31, 60, 156, 190, 200, 224, 231, 327
		344	Outdated specifications and standards for survey, design, construction, and acceptance	W2-3, W3	14–18, 23, 24, 26–33, 35, 36, 42, 43, 73–82, 85–87, 89–94, 101, 103, 104, 107, 108, 110, 111, 115, 116, 118, 120, 123, 124, 128, 131, 141, 145, 130, 157–164, 168, 170, 172–174, 177, 178, 184, 191, 192, 194, 196–200, 207, 208, 210–212, 214, 221, 227, 238–240, 242, 244, 246, 247, 261, 262, 268–271, 274–279, 281–298, 299, 308–315, 320, 324, 326, 337, 343, 346, 351, 354
		345	Defects in safety production rules and regulations and operating procedures	W2-3, W3	15, 16, 18, 23, 24, 37, 39, 42, 43, 46, 80, 82, 84–87, 90–94, 96–100, 102–105, 107–115, 120–125, 128, 131–134, 137–148, 130, 150, 151, 157, 158, 164, 165, 167–170, 172–175, 177, 178–184, 189, 191–193, 201, 203, 205–208, 213, 214, 216–224, 232–236, 238–240, 242, 245–247, 251–253, 258, 260, 254, 265, 267, 268, 270, 274, 275, 279, 281–289, 307, 310, 312, 313, 316–318, 321, 325, 337, 343, 352
		346	Improper data management	F2-1, F2-3.7	16, 17, 26, 38, 42, 43, 71, 72, 79, 118, 162, 197, 199, 205, 207, 208, 215, 216, 237, 274, 299, 309, 315, 320, 321, 324, 327, 343, 352
		347	Insufficient or wrong hydrological and geological data	F2-1	16, 17, 26, 38, 42, 43, 71, 72, 79, 118, 162, 197, 199, 205, 207, 208, 215, 216, 237, 274, 299, 309, 315, 320, 321, 324, 327, 343, 352
		348	Improper quality acceptance	F2-3.4, F2-1	19, 60, 62–70, 135, 136, 156–158, 167, 183, 190–193, 200, 231, 232, 234, 238, 239, 253, 267, 307, 310, 312, 313
		351	Improper maintenance	W2-5, W11	60, 62, 64–70, 156–158, 167, 183, 190–193, 231–234, 238, 239, 253, 254, 265, 267, 307, 325
		352	Design defects of emergency plan	W2-5, W8	19, 60, 62, 156, 190, 191, 195, 231, 232
		354	Insufficient emergency plan drills	W2-5, W8	19, 60, 62, 156, 190, 191, 195, 231, 232
Personnel subsystem		355	Insufficient experience in personnel or organization qualification problems	F2-1, W8, W11, W2-3	14–18, 23, 24, 26, 31, 35, 36, 38, 44, 71, 72, 74–76, 79, 82, 61, 96–116, 121, 123–134, 137–149, 159–164, 166, 168–173, 174–178, 179–180, 184–189, 196–199, 201–224, 235–237, 240, 242, 245–252, 260–263, 268–272, 274–279, 281–294, 297–298, 299, 308–324, 326, 328–337, 343, 346–354

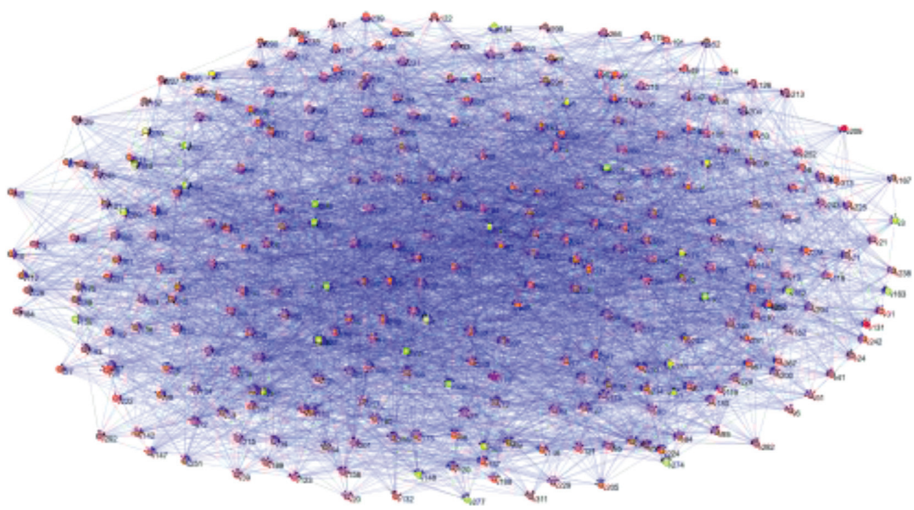

Figure 3: Model of the PNSRTP.

by orange, with a total of 279. The second-layer node can be formed by the evolution of the initial dormant hazard and can also be caused by other armed hazards. The evolution relationship between hazards is complex, such as slope ratio, rapid rise of pond water level, and high phreatic line. The third-layer nodes are active hazards, which are indicated by red nodes, indicating that the accidents are happening or have happened. The seepage system of the tailings pond mainly includes three types of accidents: overtopping, leaks in transmission facilities, and seepage damage.

4.2. Analysis of Network Statistical Characteristics

4.2.1. Degree Values and Degree Distribution. The degree values of each node in the PNSRTP are shown in Figure 4. The degree value of the seepage hazard node is an important index to reflect the influence of hazards. According to the different directions of the relationship between hazards, it can be divided into out degree and in degree. Through the calculation using Pajek software, the average degree of the PNSRTP is found to be 12.22 and the network density is 0.02. It shows that a node with potential seepage hazard is directly related to 12.22 hazards on average, but the overall density of the PNSRTP is not large.

As can be seen from Figure 4, the node with the largest degree is 340 (insufficient safety supervision), which can directly affect 261 kinds of hazards. 355 (lack of qualification and experience of personnel and institutions) belongs to the personnel system, which is the second largest hazard (182). The degree values of 345 (defects of safety production rules and regulations and operation procedures) and 344 (outdated specifications and standards for survey, design, construction, and acceptance) are 145 and 136, respectively. The degree values of 65 (dam deformation), 66 (dam crack), and 191 (drainage structure fracture) are all 59, of which 65 and 66 belong to the dam system and 191 belongs to the drainage system. 157 (filter water failure) also belongs to the dam system, for which the degree value is 49. The degree value of 339 (insufficient capital input) is 45, which belongs to the

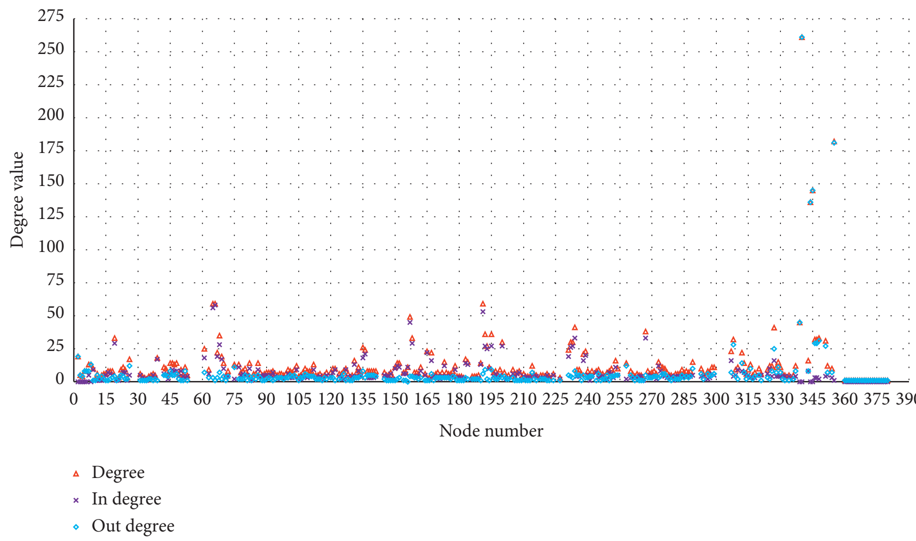

FIGURE 4: Node degree in the PNSRTP.

management system with hazards 340, 344, and 345, which highlights that the management factor plays a vital role in the safety management of the tailings seepage system. The degree value of 234 (blockage or siltation) is 41, which is the smallest hazard in the top ten hazards and also the only hazard belonging to the conveying system. It shows that the conveying system also has a certain impact on the seepage of tailings pond.

From the perspective of out degree, 340 (lack of safety supervision), 355 (lack of qualification and experience of personnel and institutions), 345 (defects in safety production rules and regulations and operating procedures), 344 (outdated specifications and standards for survey, design, construction, and acceptance), and 339 (insufficient capital investment) are the five biggest hazards, which are 261, 181, 145, 136, and 45, respectively. These hazards can easily trigger other hazards, which are important causes of seepage risk transmission. 65 (dam deformation), 66 (dam crack), 191 (drainage structure fracture), 157 (filter water failure), and 234 (blockage or siltation) are the five biggest hazards of in-degree value, which have degree values 58, 56, 53, 45, and 33 respectively. Because these are easily caused by other hazards, these hazards should be monitored and paid attention to in the prevention of seepage accidents.

The cumulative degree distribution of the PNSRTP is shown in Figure 5. The cumulative degree distribution presents a power-law distribution that has the approximate fit $P(k) = 3.8428x^{-1.192}$ ($R^2 = 0.9468$) [23]. The above result deviates from the power-law nature for lager k, which indicates that the PNSRTP has scale-free property [23]. The scale-free property shows that a few nodes have high degree values in the PNSRTP, which is consistent with the distribution of degree values in Figure 4. These nodes make the PNSRTP robust to random attacks. This is reflected in the fact that although the world's major economies have invested a lot of resources in the safety management of the seepage system of tailings pond in the past, the seepage accidents of tailings pond often occur due to the inability to

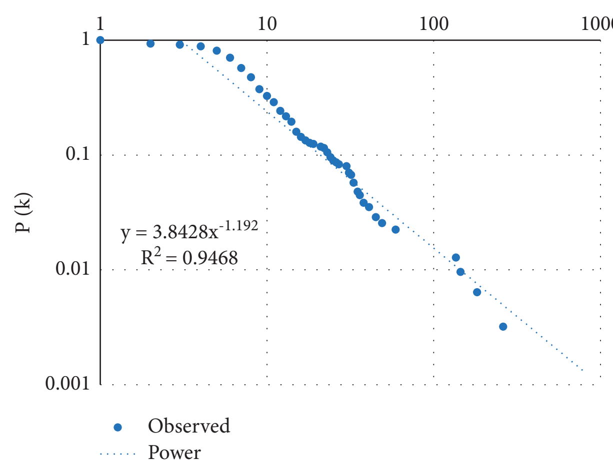

FIGURE 5: Cumulative degree distribution of the PNSRTP.

find out the key hazards (determine the importance of the hazards). At the same time, these high degree value nodes show vulnerability to specific attacks. If we can apply this characteristic to the treatment of seepage risk of tailings pond, determine the optimal treatment sequence of hazards, and block the correlation between hazards, the occurrence of seepage accidents will be greatly reduced.

4.2.2. Average Path Length and Network Diameter. According to Pajek calculation, the diameter of the PNSRT network is 13, which represents the longest distance between two hazard nodes in the network. The distance between node 9 (mudslide) and 224 (low tailings water recovery rate) or node 8 (beyond standard earthquake) and 207 (flood drainage structures are directly located on the tailings sediment beach) is 13. They are the node pairs with the farthest risk propagation distance in the network.

The average path length of the PNSRTP is 4.90, which means that the seepage risk propagates from one hazard node to other hazard nodes in the network with an average of no more than 5 nodes. The PNSRTP has more than 300 hazard nodes and nearly 2000 hazard relationships, but the average distance between the two hazard nodes is very short. The above characteristics show that the cause of seepage risk is complex and the propagation speed is fast. When the seepage risk is formed, if effective measures are not taken to control and manage it in time, the seepage accident of tailings pond may be caused.

4.2.3. Clustering Coefficient and Small-World Property. According to the definition of clustering coefficient, the node with degree value of 1 has no agglomeration. Therefore, when calculating the clustering coefficient of each node in the PNSRTP, the node with degree value of 1 is excluded. The clustering coefficient of each point in the PNSRTP is shown in Figure 6. It can be seen from Figure 6 that the clustering coefficient of nodes is between 0 and 0.5. The clustering efficiency of hazards 83 (the rising speed of tailings between dam downstream and upstream is unbalanced) and 266 (insufficient production capacity of dryer) is 0.5. The clustering of other most nodes is between 0.05 and 0.35, and the distribution is more uniform. This reflects the aggregation of the PNSRTP around hazards 83 and 266.

In order to determine whether the PNSRTP has the small-world property, this paper uses Pajek complex network software to generate a random network with the same number of nodes and average degree value as the PNSRTP, as shown in Figure 7. After calculation, the average clustering coefficient of this random network is 0.04, which is far less than that of the PNSRTP (0.19). Combined with the fact that the average path length of the PNSRTP is less than 5, it can be concluded that the PNSRTP has the small-world property [32].

5. Importance and Treatment Sequence of Hazard Nodes

The global network efficiency of seepage network refers to the average value of the reciprocal sum of the shortest path lengths between pairs of hazard nodes, which reflects the propagation speed of seepage risk in the PNSRTP [33,34]. According to the above definition, this paper takes the global network efficiency as an index to measure the management effect of seepage risk after the treatment of seepage hazard.

The betweenness centrality and the degree value and the node clustering coefficient mentioned above are the indicators to measure the importance of nodes. In the process of seepage risk propagation, the node with larger betweenness centrality is the main channel of risk propagation. Therefore, in the treatment of tailings dam seepage risk, we should focus on the nodes with larger betweenness centrality. After calculation, the overall betweenness centralization of the PNSRTP is 0.0643 and the betweenness centrality of each node is shown in Figure 8. It can be seen from Figure 8 that the distribution of the betweenness centrality of the nodes presents serious heterogeneity and the betweenness centrality among the nodes has serious uneven distribution. The betweenness centrality of hazards 65 (dam deformation), 267 (pipes and grooves deformation), and 253 (concentration equipment failure) is 0.0669, 0.0647, and 0.0577, respectively, which are significantly larger than those of other nodes, indicating that timely treatment of these hazards is helpful to reduce the spread of seepage risk of tailings dam.

In order to verify which one of the three indicators can reduce the global efficiency of the network more quickly and effectively, that is, to reduce the spread of seepage risk, according to the order (size) of the index value, the hazard nodes are treated (deleted) in turn in this paper and then the global efficiency of the network after treatment is calculated. In the management of hazard nodes, the hazard node with the largest index value is treated for the first time and then 5 hazards are treated at a time according to the order of index values, until all hazards are treated. The decline of the network efficiency of the PNSRTP under the three hazard remediation methods is shown in Figure 9.

As can be seen from Figure 9, after the hazard of high clustering coefficient is treated, the network efficiency cannot decline rapidly. Even when the node deletion ratio is less than about 70%, the network efficiency shows an increasing trend. Therefore, the nodes with a large clustering coefficient are not suitable for priority governance. Both betweenness centrality and degree centrality can quickly reduce the network efficiency of the PNSRTP, but obviously, the effect of degree centrality is better. When the ratio of hazard treatment is less than 5%, the two indexes have the same effect on the reduction of seepage risk and even the betweenness centrality is slightly dominant. However, with the increase in remediation proportion, the gap between the two began to increase. When the governance ratio reaches about 30%, the network efficiency of the PNSRTP is quickly reduced to around 0 under the degree centrality, while the network efficiency is maintained between 0.1 and 0.15 under the betweenness centrality. Therefore, in the prevention and control of tailings pond seepage risk, we should select degree centrality as the index to measure the importance of nodes and give priority to the nodes with large degree value.

6. Discussion

The cause of seepage accident in tailings pond is complex, and the seepage hazards changes with the life cycle of tailings ponds, which makes it very difficult to identify the seepage hazard completely and accurately. At the same time, the existing methods of hazard identification are mainly based on the subjective judgment of researchers and these methods lack objective supporting evidence. In order to solve these problems, this paper divides the seepage system of tailings pond into eight subsystems according to its functions and composition characteristics and identifies the seepage hazards in different life cycles according to laws and regulations, accident cases, and other evidence. The evidence is collectively compiled by the most experienced and knowledgeable experts in the industry. At the completion of the compilation, it has undergone decades of practical application verification. After multiple rounds of updates and improvements, the evidence can fully meet the goal of

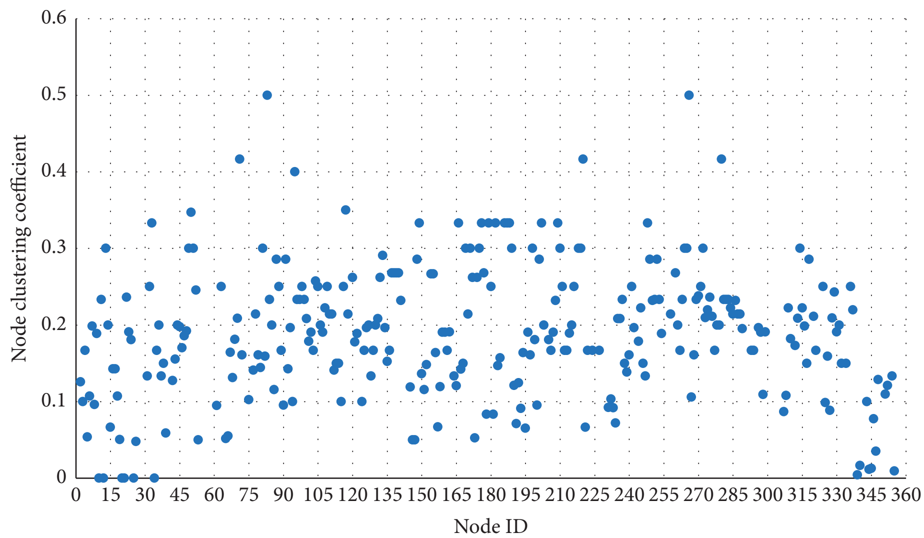

Figure 6: Clustering coefficient of nodes in PNSRTP.

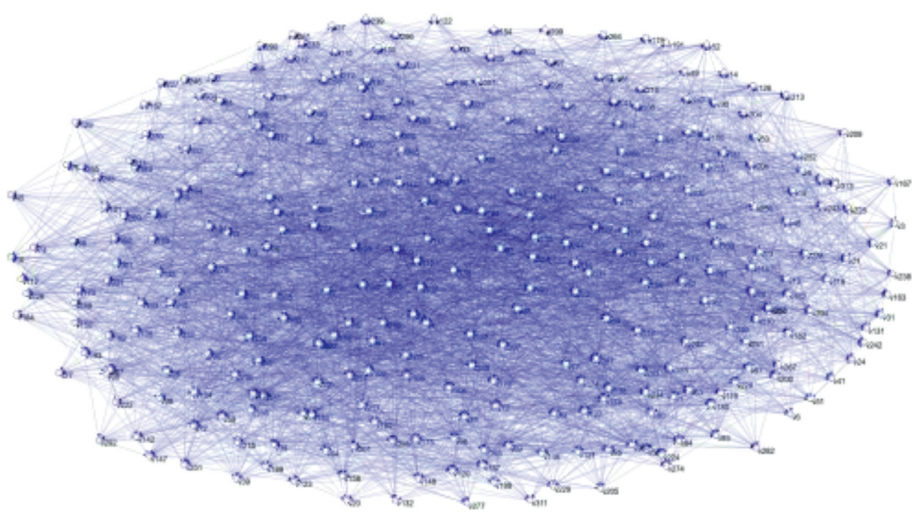

Figure 7: Equal-sized seepage risk random network.

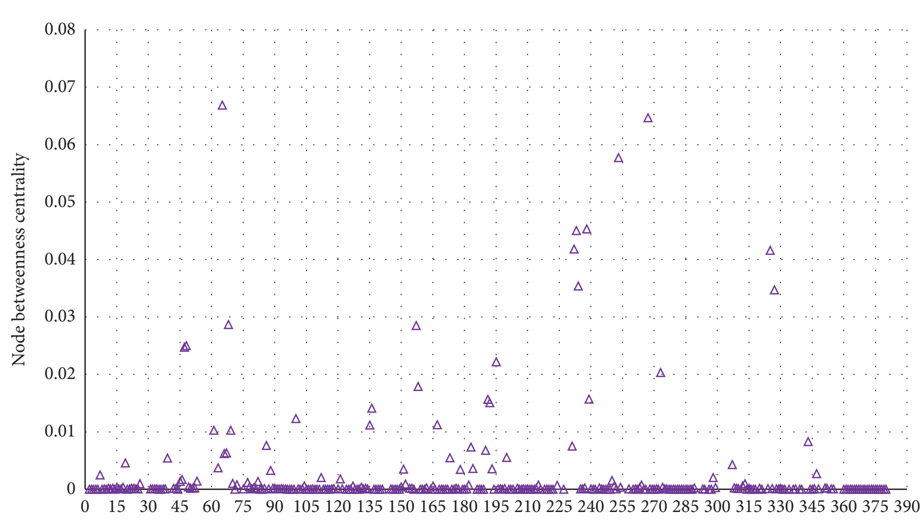

Figure 8: Betweenness centrality of nodes in the PNSRTP.

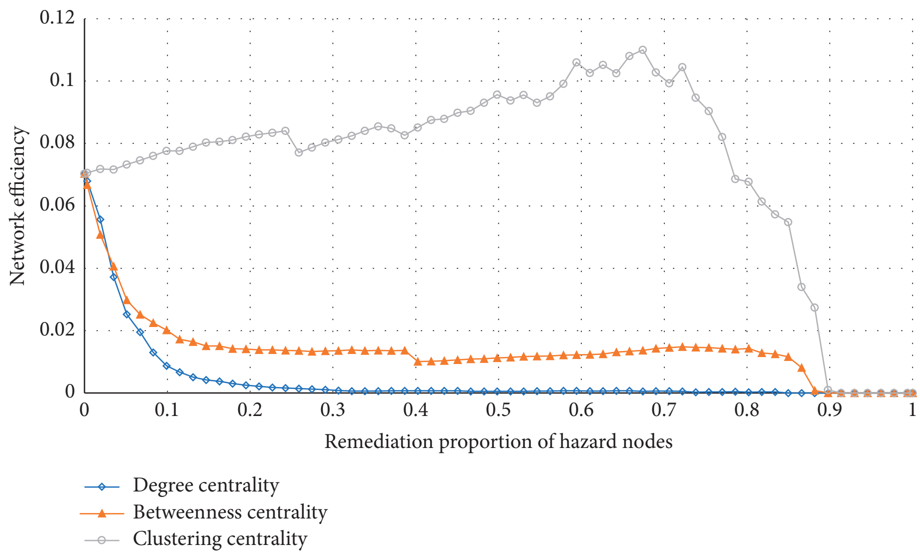

Figure 9: The change of the network efficiency of the PNSRTP.

identifying all the hazards of the seepage system [29]. In a sense, the EIMTSH is a separation of the causal model, which divides the complex system and various influencing factors into small modules to reduce the difficulty of hazard identification.

The nodes and edges of the complex network can better represent the operation process of the complex system. Therefore, this paper takes the seepage hazards as the nodes and the relationship between hazards as the edges to represent the propagation process of seepage risk of tailings pond and constructs the PNSRTP. By analyzing the network characteristics of the PNSRTP with universal applicability, we can get the following: (a) The cumulative degree distribution of the PNSRTP presents a power-law distribution, which shows that the PNSRTP presents the scale-free property. (b) The PNSRTP has a larger clustering coefficient and smaller characteristic path length, which indicates that the network is a small-world network. Compared with the nodes with high betweenness centrality and high clustering coefficient, the nodes with higher degree value can reduce the network efficiency more quickly, which indicates that the nodes with higher degree value have greater importance in the propagation of seepage risk and belong to the hazard nodes with priority governance. It should be noted that the conclusion here is drawn from the perspective of the PNSRTP as a whole. Since the hazards of the tailings ponds and the relationship between hazards are constantly changing in a real tailings pond, it is necessary to use the safety inspection data, work logs, and safety evaluations of the tailings ponds to determine them.

The advantage of the EIMTSH is that it provides support for the complete identification of hazards and the relationship between hazards. However, these support evidence pieces are simplified to have the same reliability without considering the strength of the relationship between hazards, which is obviously different from the actual propagation process of seepage risk. In addition, we analyzed the PNSRTP as a universal network, which contains all the hazards and their relationship of different types and different life cycles of tailings ponds, but the actual operating tailings pond only has some of these hazards and their relationship. This may lead to that some properties and conclusions obtained by analyzing the universal PNSRTP are not applicable to the actual seepage system of tailings ponds.

In order to solve the above problems, the authors will consider the classification of supporting evidence in the future and divide the relationship weight between hazards by combining with AHP, triangular fuzzy, and other methods. At the same time, a number of specific cases are selected to use the above methods for application analysis and research, the nature differences between the PNSRTP and the case networks are observed, and then the above methods are modified and improved, so as to build a more practical research system for the seepage risk of tailings ponds.

7. Conclusion

This paper uses the proposed EIMTSH to identify the hazards of the tailings pond seepage system and obtains a hazard list supported by evidence. This list includes a total of 313 hazards and 1912 relationships among hazards. This list will help decision makers and scientists to actively participate in the evidence-based risk assessment process for tailing pond seepage.

Based on the identified list of seepage hazards in tailings ponds, the PNSRTP with nodes of three layers and two stages is constructed based on the complex network theory, which realizes the characterization of the seepage risk propagation process of tailings pond. Through the analysis of the characteristics of the PNSRTP, we can find that the PNSRTP has the scale-free property and small-world property.

In this paper, the network efficiency is selected as the criterion of seepage risk propagation ability. By comparing the effects of degree centrality, node betweenness centrality, and clustering coefficient in reducing the network efficiency of the PNSRTP, it is concluded that nodes with higher degree values play a more important role in the process of seepage risk propagation. Through giving priority to the treatment of nodes with a high degree value, the seepage risk can be reduced more quickly and the occurrence of seepage accidents can be avoided, which is conducive to the sustainable development of the mining industry.

Appendix

A. Laws, Standards, and Norms of Supporting Evidence

Code	Name
F1	Code for Design of Tailings Facilities (GB 50863-2013)
F2	Code for Construction and Acceptance of Tailings Facilities (GB-T 50864-2013)
F3	Geotechnical Engineering Survey Code (GB 50021-2009)
F4	Safety Regulations for Tailings Pond (GB GB39496-2020)
F5	Code for Construction of Tailings Facilities (AQ 2001–2018)
F6	Determination of Hidden Dangers of Major Production Safety Accidents in Metal And Non-Metal Mines Standards (trial) (safety supervisor no. 1 [2017] no. 98)

B. Scientific Literature Supporting Evidence

Code	Literature
W1	Wang Yishui, Peng Zeng, Xiao Chuibin. Selections of Mine Geology. Volume Seven, Technical Manual of Tailings Pond Design, Construction, Management and Development and Utilization of Tailings Resources. Central South University Press, 2015.
W2	Zhao Yiqing. Representation theory and model of hazards and risks of tailings ponds[M]. Metallurgical Industry Press, 2016.
W3	Qin Xuan, Li Zhongxue, Zhao Yiqing. Complex network model of tailing pond risk evolution and analysis of key hazards[J]. Systems Engineering Theory and Practice, 2017(6).
W4	Zhao Yiqing, Qin Xuan, Li Zhongxue, et al. System dynamics simulation and simulation of hazards and risk evolution of tailings ponds[J]. Journal of University of Science and Technology Beijing, 2014(9):1158-1165.
W5	Zhao Yiqing, Tang Liangyong, Li Zhongxue, et al. Recognition of hazards of tailing pond accidents based on process-cause grid method[J]. China Work Safety Science and Technology, 2013, 9(004):91-98.
W6	Li Quanming, Wang Yunhai, Zhang Xingkai, et al. Analysis of dam-break disaster factors of tailing pond and research on risk index system[J]. China Work Safety Science and Technology, 2008(03):50-53.
W7	Liu Haiming, Cao Jing, Yang Chunhe. Analysis of disaster-causing factors of tailing dam accidents at home and abroad[J]. Metal Mine, 2013, 42(2):126-129.

Table : Continued.

Code	Literature
W8	Chai Jianshe, Wang Shu, Men Yongsheng. Case analysis and accident prediction of tailing pond accidents[M]. Chemical Industry Press, 2011.
W9	M. Rico, Benito G , Salgueiro A R , et al. Reported tailings dam failures: A review of the European incidents in the worldwide context[J]. Journal of Hazardous Materials, 2008.
W10	Hatje V , Pedreira R M A , De Rezende C E , et al. The environmental impacts of one of the largest tailing dam failures worldwide[J]. entific Reports, 2017, 7(1):10706.
W11	RISKGATE ; http://www.riskgate.org/topic/18; RISKGATE is an Australian coal industry initiative driven by The University of Queensland, ACARP, and industry partners ;
W12	Assessing Risks of Mine Tailing Dam Failures, Paulina Concha Larrauri, August, 2017

C. Accident Case Supporting Evidence

Code	Date	Location	Type of incident	Impacts
C1	2020, Mar. 28	Tieli, Yichun City, Heilongjiang Province, China	Seepage or leakage	Water and tailings flowed through surrounding area, reaching Yijimi River after 3 km, threatening the drinking water resource of 68,000 people in Tieli City; by Apr. 4, the pollution reached 208 km downstream
C2	2019, Jan. 25	Córrego de Feijão Mine, Brazil	Tailings dam failure and seepage	259 people were killed, and 11 are reported missing
C3	2017, June 30	Mishor Rotem, Israel	Tailings dam failure, overtopping, and seepage	The toxic wastewater surged through the dry Ashalim riverbed and left a wake of ecological destruction more than 20 km long
C4	2016, Oct. 27	Antamok Mine (inactive), Itogon, Benguet Province, Philippines	Seepage or leakage	The leaked tailings flowed into Liang River, then Ambalanga River before reaching Agno River
C5	2016, Aug. 27	New Wales Plant, Mulberry, Polk County, Florida, USA	Seepage or leakage	Thee leaked tailings flowed into Liang River, then Ambalanga River before reaching Agno River

Table : Continued.

Code	Date	Location	Type of incident	Impacts
C6	2012, Nov. 4	Sotkamo, Kainuu Province, Finland	Seepage or leakage	Nickel and zinc concentrations in nearby snow river exceeded the values that are harmful to organisms tenfold or even a hundredfold, uranium concentrations more than tenfold
C7	2004, May 22	Partizansk, Primorski Krai, Russia	Seepage or leakage	The ash flowed through a drainage canal into a tributary to the Partizanskaya River which empties in to Nahodka Bay in Primorski Krai (east of Vladivostok)
C8	1996, Mar. 24	Marcopper, Marinduque Island, Philippines	Seepage or leakage	Evacuation of 1200 residents, 18 km of river channel filled with tailings, US$ 80 million damage
C9	1994, June	Sinkhole Opens in Phosphogypsum Stake	Seepage or leakage	Release of gypsum and water into groundwater
C10	1994, Feb. 14	Olympic Dam, Roxby Downs, South Australia	Seepage or leakage	Leakage of tailings dam during 2 years or more
C11	1993	Marsa, Peru	Dam failure, overtopping, and seepage	6 people killed
C12	1986	Huangmeishan, China	Dam failure and seepage	19 people killed
C13	1966, May 1	Mir mine, Sgorigrad, Bulgaria	Dam failure and seepage	Dam failure from rising pond level after heavy rains and/or failure of diversion channel

Data Availability

The data that support the findings of this study are included within the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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