Propagation Laws of Reclamation Risk in Tailings Ponds Using Complex Network Theory

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Abstract: Accidents have occurred periodically in the tailings ponds where mine solid waste is stored in recent years, and thus their safety has become one of the constraints restricting the sustainable development of the mining industry. Reclamation is an important way to treat tailings ponds, but improper reclamation methods and measures not only cannot reduce the accident risk of tailings ponds, but will further increase the pollution to the surrounding environment. The influencing factors of reclamation accidents in tailings ponds are complex, and the existing models cannot characterize them. In order to study the propagation process of tailings pond reclamation risk, this paper proposes a three-dimensional identification framework for accident hazards based on evidence (TDIFAHE) to identify all potential hazards that may occur during the reclamation stage, and obtain a list of hazards. Based on the complex network theory, this paper uses identified hazards as network nodes and the correlation between hazards as the edges of the network. Based on the identified hazard data, the evolution network of reclamation risk in tailings ponds (ENRRTP) is constructed. By analyzing the statistical characteristics of ENRRTP, it can be found that ENRRTP has small world and scale-free characteristics. The above characteristics show that the reclamation risk of tailings ponds is coupled with multiple factors and the disaster path is short. Giving priority to those hub hazards that have a dominant impact on the reclamation risk can significantly reduce the reclamation risk of the tailings pond.

Keywords: tailings; reclamation risk; hazard identification; complex network; hazard management

1. Introduction

Reclamation of a tailings pond, also known as tailings reclamation, is one of the important methods for comprehensive management and utilization of mine tailings. Tailings reclamation is generally to cover the beach and slopes of the tailings pond after the pond area is closed, while plant crops or cash crops protect the tailings from being carried away by wind and rain under natural conditions [1]. Tailings reclamation would simultaneously promote both economic development and environmental protection [2]. However, if the mining enterprise adopts improper reclamation methods, the result will not only be unable to improve the environment of the pond area, but may even damage the stability of the dam, causing more serious safety accidents and environmental damage. For example, mine workers carried out tailings reclamation in violation of regulations, which may cause damage to drainage pipes. When heavy rainfall occurs in the pond area, the water level rises rapidly because the rainwater cannot be drained in time, which in turn may cause overtopping or dam break accidents. In order to avoid the occurrence of such accidents, it is important to objectively and systematically identify potential accident hazards in the reclamation of tailings ponds, master the propagation laws of reclamation risks, and then take targeted measures to reduce the occurrence of reclamation accidents.

Hazard identification is also known as risk identification, and its purpose is to discover, identify, and describe the risks [3]. Hazard identification is the basis and premise...
of underlying risk management in tailings ponds [4]. Before clarifying the hazards of the tailings pond, rushing to carry out reclamation work may cause serious consequences. Commonly used hazard identification methods include Safety Checklists, Accident Statistics Analyses, Preliminary Hazard Analyses, Failure Models and Effects Analyses, Hazard and OperabilityAnalyses, Cause–Consequence Analyses, Fault Tree Analyses, and Event Tree Analyses [4]. To mitigate tailing-water interactions and support reclamation, Divine et al. inject applied tracers into legacy tailings, and observe the transport behavior of the tracers [5]. Liu et al. used the Root-State Hazard Identification (RSHI) method to identify the hazards in underground coal mine risk management [4]. The above methods provide theoretical support for the identification of hazards, and promote the development of risk management in tailings ponds. However, the composition of the tailings pond reclamation system is very complex, and the entire system is undergoing continuous changes with the progress of reclamation activities, so the existing methods are difficult to meet the needs of hazard identification and risk characterization.

The complex network theory is an appropriate tool for analyzing multidimensional hazards based on holistic thinking and understand the complex interactions among the hazards. The complexity of complex network is mainly reflected in two aspects: (i) the number of nodes in complex network is enough; (ii) the relationships between nodes are complicated and uncertain [6]. Based on the above characteristics, complex networks have been widely used in many fields. The network developed by Lam CY and Tai K. used a topological approach to modeling the causations and characteristics of railway incidents in Japan [7]. To analyze the influence factors of SOC stock, Zhang Z. used the complex network to characterize the complex relationship of SOC stock [6]. Xu W used the Minimum Cumulative Resistance model (MCR) to build a landscape ecological network to identify the important ecological elements, and the complex network method was used to analyze the structure of landscape ecological network [8]. In the field of tailings ponds, Qin et al. applied the complex network theory to the accident risk management of the tailings pond, and found that the influencing factors with larger betweenness centrality have a more important impact on the accident [9]. Zhen et al. used a complex network to characterize the evolution process of tailings dam break risk, and found that the propagation process of dam break risk has the characteristics of a small world and is scale-free [10–18]. Although complex networks have many advantages, no scholar has studied the propagation laws of accident risks during the reclamation of tailings ponds from the perspective of networks.

Based on the shortcomings of the above research, the paper proposes a three-dimensional identification framework for accident hazards based on evidence (TDIFAHE) that can systematically and completely identify the reclamation hazards of tailings pond. After that, this paper uses hazards to represent nodes, and the relationships between hazards represent the edges of complex networks. For the first time, an evolution network of reclamation risk in the tailings pond (ENRRTP) that intuitively characterizes the propagation process of reclamation risks is constructed. Through the analysis of the statistical characteristics of the ENRRTP, the propagation law of reclamation risk is researched from the network perspective. Finally, the method proposed in this paper is applied to a specific tailings pond case, and the network efficiency is used to verify whether the key hazards obtained by the method in this paper are reasonable. The above-mentioned research is helpful to discover the propagation laws of reclamation risk that has not been discovered in the past methods [19–21] from the network perspective, and can improve the safety management during the reclamation of the tailings pond.

2. Research Methods

2.1. Overview

In order to systematically and objectively identify the accident hazards during the tailings pond reclamation period, this paper proposes a three-dimensional identification framework for accident hazards based on evidence (TDIFAHE). After that, this paper uses
the identified hazards as the nodes of the complex network, and the correlation between hazards as the edges of the network, and constructs the ENRRTP which characterizes the propagation process of the tailings pond reclamation risk. Based on the complex network theory, the statistical characteristics of ENRRTP are analyzed, and part of the propagation law of reclamation risk is derived from the network perspective. Finally, the paper adds an application case, and verifies the effectiveness of the method proposed through the index of global network efficiency. The entire research process and main results of this paper are shown in Figure 1.

2. Research Methods

2.1. Overview

In order to systematically and objectively identify the accident hazards during the reclamation period, this paper proposes a three-dimensional identification framework for accident hazards based on evidence (TDIFAHE) to identify the reclamation hazards of tailing pond, as shown in Figure 2 [10,22]. Among them, the Z-axis represents the reclamation process, including five stages: pond area investigation, pond area remediation, reclamation design, reclamation construction and reclamation supervision, highlighting the temporal dynamics of reclamation work. The Y-axis contains eight subsystems of the tailings pond. They are a new division of the tailings pond system after considering the impact of the four influencing factors of personnel, material, environment, and management on the tailings pond reclamation work. In the process of identifying hazards, each subsystem can be further subdivided according to the roles played by each part of the system. The sub-division of the subsystems is not only conducive to detailing all the hazards involved in the reclamation process of the tailings pond, but also helps to

Figure 1. A flow chart of research methods and results.

2.2. Identification Method

2.2.1. The Definition of Hazard

The definition of hazard has many forms. For the purpose of characterizing the evolution process of tailings pond reclamation risk, combined with the structure and accident characteristics of the tailings pond, this paper divides the influencing factors, hidden dangers, accidents and consequences involved in risk propagation into four types of hazards. The first kind is the dormant hazard, which is the initial factor or event that causes the reclamation accident. Other factors or hazards cannot trigger it, and its state is stable. The second kind is the armed hazard, which refers to the intermediate state of hazard evolution [9], and may evolve from the dormant hazard or other armed hazards (armed hazard means the imminent accidents and disasters). The third hazard is the active hazard, which refers to the reclamation accidents that are happening [9]. The reclamation risk of tailings pond includes multiple types of accidents, such as dam break, seepage, overtopping, raise dust in the pond area, and leaks in transmission facilities. The fourth hazard is the consequence hazard, which is the type of disaster caused by the accident, including environment pollution, economic loss, personal injury and reputation loss. This hazard index helps to classify and evaluate the consequences caused by the reclamation accidents.

2.2.2. Hazard Identification and Data Extraction

The structure of the Tailings storage facilities is complex, and the facilities are constantly changing under the influence of the reclamation personnel and the external environment during reclamation process. This has caused many hazards in the reclamation process of the tailings pond, and the relationship and intensity between the hazards are uncertain over time. In order to solve the above problems, this paper proposes a three-dimensional identification framework for accident hazards based on evidence (TDIFAHE) to identify the reclamation hazards of tailing pond, as shown in Figure 2 [10,22]. Among them, the Z-axis represents the reclamation process, including five stages: pond area investigation, pond area remediation, reclamation design, reclamation construction and reclamation supervision, highlighting the temporal dynamics of reclamation work. The Y-axis contains eight subsystems of the tailings pond. They are a new division of the tailings pond system after considering the impact of the four influencing factors of personnel, material, environment, and management on the tailings pond reclamation work. In the process of identifying hazards, each subsystem can be further subdivided according to the roles played by each part of the system. The sub-division of the subsystems is not only conducive to detailing all the hazards involved in the reclamation process of the tailings pond, but also helps to
ensure the independence of each hazard index. The Z-axis represents evidence such as laws and regulations, standards and norms, scientific and technological literature, and accident case. This evidence provides support for the identification of hazards in different subsystems and different stages of reclamation.

![Diagram](image)

**Figure 2.** A three-dimensional identification framework for accident hazards based on evidence.

In Figure 2, the spatial nodes enclosed by three-dimensional coordinates are all initially identified reclamation hazards of tailings pond. Afterwards, by integrating the spatial nodes with the same meaning, such as both Safety Regulations for Tailings Pond (GB GB39496-2020) and Code for Construction of Tailings Facilities (AQ 2001–2018) can provide evidence to support for the hazard 65 (Dam deformation) in the dam subsystem during the reclamation construction stage. However, in Figure 2, the same hazard identified by these two supporting pieces of evidence is shown as two nodes. Therefore, when determining the final hazard index, it needs to be integrated. After identifying and integrating the reclamation hazard of tailings pond, a universal list of reclamation hazard of tailings pond can be obtained to construct a complex network. Therefore, this process can also be called data extraction.

### 2.3. Network Model

#### 2.3.1. Model Building

Based on the identified reclamation hazards and the correlation between hazards of tailings pond, this paper constructs an evolution network of reclamation risk in the tailings pond (ENRRTP) that characterizes the propagation process of tailings pond reclamation risk. In ENRRTP, reclamation hazards represent nodes in a complex network, and the relationships between reclamation hazards represent edges between nodes. The ENRRTP has four hazard nodes (armed hazard, dormant hazard, active hazard/accident, consequence/disaster hazard), and three propagation stages (from armed hazard to dormant hazard, from dormant hazard to active hazard, active hazard to consequence hazard) [10].
2.3.2. Degree

The degree value of a hazard node refers to the number of hazard nodes directly connected to the node, reflecting the direct influence of the hazard [10]. Because the correlation between the reclamation hazards of tailings pond is directional, the ENRRTP is a directed network. The number of relationships from other hazard nodes to a hazard node is called the in-degree of this node, and the number of relationships emitted from a node is called the out-degree of this node. The average value of degree $k_i$ of node $i$ in the ENRRTP is called the average degree of the network, which is denoted as $K$. For any network with $M$ edges and $N$ nodes, its average degree can be expressed as: $K = 2M/N$ [11].

The network density of ENRRTP is an index that characterizes the degree of connection between hazard nodes in the network. The greater the network density means that the relationship between hazards is closer, and the network may have a greater impact on the state or behavior of hazards. For a directed ENRRTP with $N$ nodes and $M$ edges, the theoretical maximum possible value of the total number of edges is $N(N − 1)$, then the density of ENRRTP is [6]:

$$D = \frac{M}{N(N − 1)}. \quad (1)$$

The degree distribution of ENRRTP represents the probability distribution function $P(K)$ of the degree of the hazard node, which refers to the probability that the hazard node has $k$ edges connected. If there are a total of $n$ nodes in ENRRTP, of which there are $n_k$ nodes, and his degree is $k$, then [11]:

$$P(K) = \frac{n_k}{n}. \quad (2)$$

The cumulative degree distribution of ENRRTP is the probability of the occurrence of hazard nodes with degree greater than or equal to $k$ in the network. When the cumulative degree distribution of ENRRTP can be approximated by Equation (3) in double logarithmic coordinates, it indicates that the network is scale-free [12,16,17].

$$Q(k) \sim ax^{-b}. \quad (3)$$

In Equation (3), $a$ and $b$ are constants greater than zero.

2.3.3. Average Path Length and Diameter

The distance of the ENRRTP refers to the step length from one hazard node to another hazard in the network, that is, the distance between hazard nodes $i$ and $j$ in the network, defined as $d_{ij}$, which represents the number of edges connecting these two hazards on the shortest path [23]. The average path length, also known as the characteristic path length, represents the average step length of the hazard node in the network to reach the non-neighboring node. The average path length of ENRRTP reflects the influence relationship between hazards in an average sense. The shorter the path length means the closer the correlation between hazards and the greater the mutual influence. Its mathematical expression is:

$$L = \frac{1}{2N(N − 1)} \sum_{i \geq j} d_{ij}. \quad (4)$$

$N$ is the total number of ENRRTP nodes [11].

The network diameter is also called the maximum path length of the network. The network diameter of ENRRTP represents the number of edges between the two furthest nodes in the network. The network diameter of ENRRTP is closely related to the risk transmission time and the stability of the entire network.
2.3.4. Clustering Coefficient

According to the definition of clustering coefficient, the clustering coefficient of ENRRTP refers to the degree of interconnection of a node with adjacent hazard nodes [23]. Assuming that a hazard node $i$ in ENRRTP has $k_i$ edges to connect it with other hazard nodes, there may be at most $k_i(k_i - 1)/2$ edges between these $k_i$ hazard nodes. Then the ratio of the actual number of edges $E_i$ between these $k_i$ hazard nodes to the total possible number of $k_i(k_i - 1)/2$ is defined as the clustering coefficient of the hazard nodes, namely [24]:

$$C_i = \frac{2E_i}{k_i(k_i - 1)}.$$  \hspace{1cm} (5)

Calculating the average value of the clustering coefficient of all hazard nodes can get the clustering coefficient of the entire ENRRTP, namely [24]:

$$C = \frac{1}{N} \sum_{i=1}^{N} C_i.$$  \hspace{1cm} (6)

2.3.5. Betweenness Centrality

The node betweenness centrality of the ENRRTP reflects the control degree of the hazard node over the surrounding edges and hazards [10]. Specifically, if a hazard node is on the shortest path of many other hazard node pairs, it is said that the hazard node has a high betweenness centrality. Hazard nodes with high betweenness centrality play an intermediary role in the process of the spread of reclamation risks, and aggravate the spread of reclamation risks. The calculation formula of the betweenness centrality is [19]:

$$C_B = \sum_{j<k} \left[ \frac{g_{jk}(i)}{g_{jk}} \right].$$  \hspace{1cm} (7)

The $g_{jk}$ is the number of existing shortest paths between hazard nodes $j$ and $k$, and $g_{jk}(i)$ represents the number of shortest paths passing through hazard node $i$ between hazard node $j$ and hazard node $k$. For the betweenness centrality of the entire ENRRTP, the calculation formula is [24]:

$$C_B = \frac{2 \sum_{i=1}^{n} \sum_{j=1}^{n} CB_{B_{max}}}{(n-1)^2(n-2)}.$$  \hspace{1cm} (8)

3. Results

3.1. Hazard List

Based on the TDIFAHE, this paper has identified 191 potential accident hazards in the reclamation stage of tailings ponds and 1207 relationships among the hazards, as shown in Appendix A [25].

In Table A1, the fourth column is the reclamation hazards of tailings pond after identification and integration. The third column is the number of the hazard in the same row in the fourth column. The numbers in the topology model are conducive to the display of the logical relationship between hazards. The first column and the second column indicate, respectively, that the corresponding hazard belongs to which subsystem of the tailings pond and which element of the subsystem. The last column is the hazards caused by the hazard in the same row in the fourth column confirmed by laws and regulations, documents, accident cases and other evidence. These hazards are characterized by their unique numbers.

3.2. Mode of the ENRRTP

3.2.1. Network Model

Based on the identified reclamation hazards and relationship between hazards in Appendix A, the paper first constructs an adjacency matrix that characterizes the relationship between the reclamation hazards. After that, the adjacency matrix was imported into Pajek.
complex network software to construct the evolution network of reclamation risk in the tailings ponds (ENRRTP). The topological structure of the network is shown as in Figure 3.

![Figure 3. Propagation process of reclamation risk in the tailings ponds.](image)

The ENRRTP systematically characterizes the four states and three transmission stages of the hazards of the tailings pond in the reclamation stage. In Figure 3, the yellow node represents the initial dormant hazard, including 23 hazards, with only out-degrees but no in-degrees; orange nodes reflect armed hazards, involving 127 hazards; red nodes reflect active hazards, involving 37 types of hazards, indicating 37 types of tailings pond reclamation accidents; red nodes reflect the consequence hazards of the accidents, including 4 types, and the in-degree value of these hazards is large, but the out-degree value is small.

3.2.2. Degree and Degree Distribution

The degree value of each node in ENRRTP can be obtained through Pajek complex network software, as shown in Figure 4. The average degree of the ENRRTP is 12.64, and the network density is 0.03, indicating that a hazard node is directly related to 11.81 hazards on average, but the overall density of ENRRTP is not large.

![Figure 4. Node degree in the ENRRTP.](image)
It can be seen from Figure 4 that among the 10 hazards with the largest degree value, hazard 340 (insufficient safety supervision) is the hazard node with the largest degree value in the ENRRTP, which directly affects the 157 reclamation hazards of tailing ponds. These hazards include the accident hazards of all subsystems in the tailings pond reclamation stage, indicating that safety supervision is the key to the safe operation of each subsystem in the reclamation stage of tailings ponds. Hazard 355 (Insufficient experience in personnel or organization qualification problems) is directly related to 90 hazards, which is the second largest hazard in ENRRTP and belongs to the personnel subsystem. The degree value of hazard 345 (Defects in safety production rules and regulations and operating procedures), 344 (Outdated specifications and standards for survey, design, construction and acceptance), 327 (Safety monitoring facilities cannot fully reflect the operating status of the tailings pond) are 85, 81 and 40 respectively. These hazards, and hazard 340, belong to the management subsystem, accounting for 40% of the top 10 hazards, highlighting that management factors play a leading role in the safety management of the reclamation stage of tailings ponds. The degree values of hazard 64 (Dam instability), 65 (Dam deformation), 66 (Dam cracks) and 157 (Filter failure) are 43, 43, 41 and 37, respectively, and these hazards belong to the dam body subsystem. Although the names and numbers of these hazards have appeared in the early stage, the meaning of these hazards has changed greatly during the reclamation stage. Hazard 191 (Fracture of drainage structure) is directly related to 44 types of accident hazards of tailings pond, which belong to the drainage subsystem, indicating that drainage problems are also an important factor affecting the safe operation of tailings ponds in the reclamation stage.

Hazards 340, 355, 345, 344, and 339 are the top five hazards, with an out-degree value of 157, 89, 85, 81, and 34, all of which are dormant hazards. Except for hazard 355, the other four hazards belong to the management subsystem. The above characteristics indicate that the personnel subsystem and the management subsystem are prone to produce hazards that induce the status changes of other hazards. These hazards need to be paid attention to and prevented in advance. In contrast, the five hazards with the largest in-degree are hazard 64 (Dam instability), 191 (Fracture of drainage structure), 65 (Dam deformation), 66 (Dam cracks) and 157 (Filter failure) (41, 39, 38, 37, and 32, respectively), and these hazards are all classified as armed hazards. With the exception of hazard 191, which belongs to the drainage subsystem, all four other hazards belong to the dam subsystem. The above characteristics indicate that the hazards of dams and drainage facilities generally require the use of external forces, and these external influences mainly involve management factors, human factors and environmental factors. The above characteristics indicate that hazards in dams and drainage facilities are generally caused by external forces, and these external influences mainly involve management factors, human factors and environmental factors.

In the double logarithmic coordinates, the cumulative degree distribution of the ENRRTP presents a power-law distribution, which approximates to \( P(k) \sim 4.4265x^{-1.187} \) (\( R^2 = 0.9061 \)), as shown in Figure 5 [12]. As the value of \( k \) gradually increases, the above results deviate from the power-law property, which indicates that the ENRRTP has scale-free characteristics. Therefore, in the process of controlling the reclamation risk, giving priority to those hazards with higher degree values can more effectively reduce the spread of reclamation risks and prevent reclamation accidents from occurring in tailings ponds.

3.2.3. Average Path Length and Diameter of the ENRRTP

After calculation, the average path length of the ENRRTP is 2.91, which represents the average step length of a node to a non-adjacent node; in the average sense, if a hazard wants to affect other hazards, it needs to pass 2.91 network edges in the reclamation stage, or a hazard in the reclamation stage can cause other hazards to change status within 3 steps.
3.2.4. Clustering Coefficient and Small World Property

The network diameter of the ENRRTP is 11, which represents the number of edges between the two furthest nodes in the network. In other words, a hazard can spread to the entire network after 11 steps at most. The pair of nodes with the farthest distance in ENRRTP is node v93 to v142. Compared with some accident networks studied in the past [12–14], the diameter of ENRRTP is larger, and the evolution path of the network is complicated. Therefore, the reclamation hazards of tailings ponds have the characteristics of large workload and rapid risk transmission. To interrupt the transmission path of reclamation risks, it is necessary to find the key hazard nodes that affect risk transmission.

3.2.4. Clustering Coefficient and Small World Property

According to the definition of clustering coefficient, there is no clustering coefficient for nodes with a degree value of 1. Therefore, in the statistical calculation of the clustering coefficient of the ENRRTP, nodes with a degree value of 1 are excluded. The clustering coefficient of nodes in the ENRRTP is between 0 and 0.5, as shown in Figure 6. Among them, hazard 13 (Karst cave or existence of mine shafts) and 182 (Unqualified filter material) are the nodes with the largest clustering coefficient, with a value of 0.5. Hazard 13 is mainly caused by insufficient geological exploration when selecting the site of the tailings pond, which belongs to the pond area system. The hazard 182 belongs to the selection of anti-seepage materials and belongs to the dam subsystem. If an unqualified filter material is selected, it will not only cause seepage accidents but also damage the stability of the dam. In the ENRRTP, the clustering coefficients of most hazard nodes are mainly concentrated in the range of 0.05 to 0.35, which is relatively uniform and does not show clustering characteristics that are too strong.

This paper uses Pajek software to generate a random network with the same number of nodes and the same average degree value as ENRRTP, as shown in Figure 7. After calculation, the average clustering coefficient of the equal-sized random network of the reclamation risk for tailings pond is 0.07, which is smaller than the average clustering coefficient of the ENRRTP (0.1918). A small-world network refers to a network with characteristics of small path length and large clustering coefficient [15]. Therefore, through the above analysis of the two indicators, it can be concluded that the ENRRTP has a small-world effect, which means that the reclamation risk in the tailings pond has the characteristics of specific multi-factor coupling and short disaster path. Therefore, it is extremely important to find the key hazards that affect the spread of accident risk during the reclamation stage of the tailings pond through appropriate methods.

Figure 5. Cumulative degree distribution of the ENRRTP.
Figure 6. Clustering coefficient of the nodes in the ENRRTP.

Figure 7. The equal-sized random network of the ENRRTP.

3.2.5. Betweenness Centrality and Key Hazards

The betweenness centrality of the hazard node in the ENRRTP is shown in Figure 8. The hazard with the largest betweenness centrality is hazard 65 (Dam deformation), with a value of 0.0677, indicating that the ‘dam deformation’ is the most important channel in the process of reclaiming risk transmission. In the ENRRTP, the minimum value of the betweenness centrality of the node is 0, the average value is 0.0021, and the standard deviation is 0.0051. In addition, it can be found that the maximum value of the betweenness centrality of the nodes is 32 times the average value, and the standard deviation is 2.4 times the average value, which proves that the betweenness centrality of the nodes of the ENRRTP is very heterogeneous. Under the effect of this heterogeneity, there are only a small number of hazards with a large betweenness centrality in the network, while most hazards have a small betweenness centrality. There are 25 hazards in the network with a
betweenness centrality of 0; these hazards have only out-degree but no in-degree. They are located at the edge of the network and are the dormant hazards in the reclamation hazards of tailings pond. Heterogeneous networks usually have robustness against random attacks and vulnerability to specific attacks. Random management of hazards is difficult to quickly reduce the spread of reclamation risks. However, if we give priority to the management of those nodes with high betweenness centrality, we can make full use of the vulnerability of the ENRRTP to reduce the reclamation risk of the tailings pond.

![Betweenness centrality of nodes in the ENRRTP.](image)

**4. Application Case**

To better demonstrate the method proposed in the paper, the Gaoxi tailings pond in Yun’an County, Guangdong was selected as an application case [26].

The stacking elevation of the tailings pond is 300–375 m. This area has a subtropical monsoon climate, with the maximum daily rainfall of 144.4 mm. The rainfall is mostly concentrated in April to September, accounting for 70% of the annual rainfall, and the instantaneous maximum wind speed is 23.3 m/s. The tailings of the tailing pond have poor physical structure, poor water and fertilizer retention capacity, and high levels of toxic heavy metals. The reclamation plan of the tailings pond mainly includes the stages of chemical passivation measures, engineering barrier measures and biological measures (establishment of vegetation growth layer or ecological restoration).

Based on the project overview information, management system and personnel qualifications of the Gaoxi tailings ponds during the reclamation, this paper excludes the hazards and the correlation between hazards that did not exist during the reclamation from Appendix A, and constructs the propagation network of reclamation risk for the Gaoxi tailings pond (PNRRGTP), as shown in Figure 9.

Global network efficiency refers to the average value of the reciprocal of the shortest path length between all pairs of hazard nodes in the network, reflecting the propagation speed of the reclamation risk on the network [10]. Therefore, this paper chooses the indicator to measure the spread efficiency of reclamation risks. Before remedying (deleting) the hazards (nodes), R software is used to calculate the global efficiency of the PNRRGTP as 0.1092.

In order to verify whether the hazards obtained based on the degree value and the betweenness centrality of the node are key hazards, the paper randomly deletes 10 nodes in the PNRRGTP and repeats it 10 times, and the average value of the network efficiency is 0.0906. For comparison, the paper first deletes the five hazards with the largest degree value of PNRRGTP (340, 355, 345, 344, and 191), and then deletes the five hazards with the largest betweenness centrality (65, 157, 195, 158, and 192), and the calculated network efficiency is 0.0541.
After comparison, we can find that after the remediation of some hazards, the propagation efficiency of reclamation risks has decreased, but remedying the hazards with the larger degree value and betweenness centrality can more effectively reduce the propagation efficiency of reclamation risks.

Figure 9. Mode of the PNRRGTP.

5. Discussion

The list of reclamation hazards of tailings pond is obtained by the TDIFAHE. The list covers the hazards that may exist during the reclamation of tailing ponds of different types and regions. When using the hazard list to identify the hazards in a specific tailings pond, it is only necessary to eliminate the hazards that do not exist in the hazard list based on the engineering geological information, management and personnel information of the tailings pond. In order to avoid the omission of the hazards and relationship between hazards, this paper analyzes the content one by one in the Code for Design of Tailings Facilities (GB 50863-2013), Code for Construction and Acceptance of Tailings Facilities (GB-T 50864-2013), Geotechnical Engineering Survey Code (GB50021-2009) and Safety Regulations for Tailings Pond (GB GB39496-2020). Because this evidence was compiled by the most experienced experts in the industry for different types of tailings ponds, and after a long period of application and multiple rounds of corrections, essentially cover all the hazards that may occur during the reclamation stage of the tailings ponds. At the same time, this paper also supplements the hazards with literatures, accident cases and other evidence related to the tailings reclamation. After integration, a complete list of hazards can be obtained. Compared with the hazard identification methods used in the reclamation stage of tailings ponds in the past [19,20], the hazards identified by TDIFAHE are more complete and objective.

By using nodes to represent hazards and edges to represent the relationship between hazards, this paper constructs the ENRRTP to characterize the propagation process of reclamation risk for tailings ponds firstly. Using complex network theory to analyze the statistical characteristics of this network, we can find that: (a) the cumulative degree distribution of the ENRRTP presents a power-law distribution, indicating that the ENRRTP is scale-free; (b) the ENRRTP has a larger clustering coefficient and a smaller characteristic path length, which indicates that the network has a small-world characteristic; (c) in the ENRRTP, the distribution of node’s betweenness centrality presents a strong heterogeneity, and a small number of nodes have a large betweenness centrality. The above results
indicate that reclamation risks have many coupling factors and short transmission paths. By applying the above method to the Gaoxi tailings pond, we can find that if nodes with larger degree value and betweenness centrality are prioritized, the propagation efficiency of the accident risk can be greatly reduced, indicating that the hazards with a larger degree value and betweenness centrality plays a dominant role in the spread of reclamation risk.

In order to better analyze the propagation laws of reclamation risk, the paper uses four indicators of degree, path length, clustering coefficient, and betweenness centrality to analyze the statistical characteristics of ENRRTP. These four indicators are relative indicators to measure the reclamation risk, so there is no indicator threshold for dividing high-risk and low-risk. For example, in ENRRTP, although the value range of the degree is 1 to 157, only a few hazards have a larger degree value due to the scale-free nature of the network. From the perspective of the relationship number between hazards, a hazard with a large degree value may have a relatively higher risk than a hazard with a small degree value, but we cannot accurately give a threshold value (when the degree value of a hazard is greater than a certain value, the hazard must enter a high-risk state), because the degree value can only represent one aspect of the strength of the hazard.

The paper successfully uses the complex network to characterize the propagation process the reclamation risk of tailings ponds, and find some important propagation laws and key hazards, but there are still some shortcomings. Due to the lack of real-time monitoring data, the paper simplifies the weights between the continuously changing reclamation hazards to the equal weight during analyzing the network characteristics, which hinders the real-time representation of reclamation risks by the network proposed in the paper. In order to better solve the above problems, the author of the paper next plans to apply the above methods to specific reclamation cases that have secured real-time monitoring equipment, and determine the weights between hazards based on monitoring data, work logs, safety evaluations and other information, so as to improve the practicality of the above methods [23]. Therefore, the authors of the paper will look for a tailing pond with a real-time monitoring system in the reclamation stage for further research.

6. Conclusions

To more systematically and objectively identify the accident hazards in the reclamation stage of tailings ponds, this paper proposes the TDIFAHE method. Based on the method and the integration of the same hazards, this paper obtains a hazard list containing 191 types of reclamation hazards and 1207 relationships between hazards.

This paper uses hazards to represent the nodes of a complex network, and the relationships between hazards represent the edges of the network, and constructs an ENRRTP model that characterizes the propagation of reclamation risks. Through analysis of its statistical characteristics, it is found that the propagation of reclamation risk is small world and scale-free.

Combining the Gaoxi tailings pond, this paper finds that compared with the random hazard remediation, the hazards with larger degree value and betweenness centrality remedied preferentially can reduce the propagation efficiency of reclamation risks more quickly. The above findings are of great significance for preventing accident risks during the reclamation of tailings ponds.

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Appendix A

Table A1. List of reclamation hazards in tailings ponds.

| Tailings Pond Subsystem | Elements of the System | Number (v) | Hazard Name | Number of Hazards Caused |
|-------------------------|------------------------|------------|-------------|-------------------------|
| Pond area system        | Pond environment       | 1          | Environmental pollution | 338, 358, 359 |
|                         |                        | 2          | Flood       | 1, 7, 9, 19, 60, 62, 64–67, 69, 150, 156, 158, 167, 190–193, 195, 273, 325, 358 |
|                         |                        | 3          | Ice and snow | 19, 67, 195 |
|                         |                        | 4          | Strong wind | 1, 7, 19, 66, 142, 325 |
|                         |                        | 5          | Heavy rainfall | 9, 19, 67, 69, 150, 193, 195 |
|                         |                        | 6          | Extreme temperature changes | 19, 62, 65–67, 191, 267, 325, 358 |
|                         |                        | 7          | Surge       | 62, 65–67, 69, 150, 190, 193, 358 |
|                         |                        | 8          | Beyond standard earthquake | 19, 60, 62, 64–66, 70, 136, 150, 191–192, 267, 273, 325, 358 |
|                         |                        | 9          | Mudslide    | 1, 39, 358 |
|                         |                        | 10         | Gravel foundation | 157 |
|                         |                        | 11         | Liquefied soil, soft clay and collapsible loess foundation | 68, 70, 135–136, 157 |
|                         |                        | 12         | Water burst in the tailings pond | 158 |
|                         |                        | 13         | Karst cave or existence of mine shafts | 68, 135–136, 158 |
|                         |                        | 17         | Inadequate research on adverse geological problems and improper handling measures | 19 |
|                         |                        | 19         | Landslides in the tailings pond | 1, 7, 9, 39, 195, 358 |
|                         |                        | 20         | The overburden of the bank slope connected to both ends of the tailings dam is thin | 158 |
|                         |                        | 21         | The rock on the bank slope is broken, joints are developed, or faults pass through | 19, 158 |
|                         |                        | 22         | Animals burrow, camp, and graze illegally | 19, 64, 66, 142, 150, 158 |
|                         |                        | 23         | Private digging in the tailings impoundment | 19, 64, 66, 142, 150 |
|                         |                        | 24         | Illegal soil borrowing behind the dam | 64, 66, 142, 157 |
|                         |                        | 25         | There are mining activities near the site | 19, 62, 64, 66, 142 |
| Tailings Pond Subsystem | Elements of the System | Number (v) | Hazard Name | Number of Hazards Caused |
|-------------------------|------------------------|------------|-------------|-------------------------|
| Selection of pond location | | 27 | Located on the upstream of important facilities and residential areas | 338, 358 |
| | | 28 | Located on the upwind side of the dominant wind in a concentrated residential area | 338, 358 |
| | | 29 | Occupy a lot of arable land and move a large number of residents | 338 |
| | | 30 | Located on a valuable deposit | 338 |
| | | 32 | Insufficient impoundment length (upstream wet tailings impoundment) | 39 |
| | | 34 | Large catchment area | 195 |
| | | 39 | Insufficient storage capacity of tailings pond | 190 |
| | | 40 | The grade of tailings pond does not match the grade of the structures | 338 |
| | | 42 | No antifreeze measures have been taken for tailings facilities | 66, 191 |
| | | 43 | Anti-freezing measures have not been finished before freezing | 66, 191, 338 |
| | | 44 | Blasting construction does not meet the technical specifications | 19, 62, 64–66, 191 |
| | | 45 | Tailings particle size/gradation does not meet the requirements | 47, 51, 66, 68, 70, 61, 142, 234 |
| | | 47 | Excessive tailings unit weight | 51–52, 68, 61 |
| | | 49 | Strongly corrosive tailings | 238 |
| | | 51 | Unqualified dry beach covering materials | 53, 142, 157–158, 195 |
| | | 52 | Unqualified filling materials | 64–68, 70, 73, 135–136, 157 |
| | | 53 | Erodible tailings exposure | 157 |
| | | 54 | Mismatch between tailings pond type and stockpiled waste | 1 |
| Dam body | | 60 | Dam break | 1, 9, 338, 358, 359 |
| | | 62 | Local landslide and collapse of the dam | 1, 9, 60, 63, 338 |
| | | 63 | Decrease of dam elevation | 39, 190, 194 |
| | | 64 | Dam instability | 60, 62 |
| | | 65 | Dam deformation | 62, 64, 157, 267, 273 |
| | | 66 | Dam crack | 62, 64, 73, 158 |
| | | 67 | Dam surface water saturation | 62, 64–66, 70, 73, 157 |
| | | 68 | Uneven settlement of the dam | 62–66, 191–192, 267, 273 |
| | | 69 | Scour the dam | 1, 62, 64–66 |
| | | 70 | Tailings liquefaction | 62, 64, 68, 136, 156–158 |
| | | 73 | Poor stability of tailings dam slope | 62, 64, 70 |
Table A1. Cont.

| Tailings Pond Subsystem | Elements of the System | Number (v) | Hazard Name | Number of Hazards Caused |
|-------------------------|------------------------|------------|-------------|-------------------------|
| 77                      | The tailings dam slope ratio is unreasonable | 62, 64–65, 70, 73, 157 |
| 78                      | Unreasonable width of dam crest | 62, 64–65, 157 |
| 79                      | Improper dam type selection for the initial dam | 39, 64, 157 |
| 80                      | The height of initial dam is unreasonable | 39, 64–65, 73, 81, 194, 228, 338 |
| 81                      | The ratio of the initial dam height to the total dam height of the upstream tailings dam is unreasonable | 64–65, 73 |
| 61                      | Poor control of tailings deposits | 64–65, 68, 77, 142, 152, 157 |
| 85                      | The accumulation dam is too high | 62, 64–65, 81, 338 |
| 86                      | The height of the accumulation dam is lower than the height of tailings accumulation | 39, 65, 190, 194 |
| 89                      | Use the upstream method to build dams on the seismic zone | 60, 62, 70 |
| 90                      | Fine-grained tailings dams using direct method | 64–65, 61 |
| 93                      | No filtration water and sediment storage dams are built in the centerline and downstream tailings dams | 64 |
| 94                      | Unreasonable height of the filtration water and sediment storage dams | 39, 64–65 |
| 110                     | Improper paving | 64–66, 68 |
| 113                     | Improper unloading method | 65–66 |
| 114                     | Filling and slope adjustment are not carried out at the same time | 64, 66, 77 |
| 115                     | Construction machinery and personnel crossing the dam surface in violation of regulations | 65–66 |
| 116                     | Resuming work in violation of regulations | 119 |
| 117                     | The maintenance platform in downstream dam slope is defective | 65–66, 73, 122 |
| 119                     | Construction under environmental indicators exceeding limits | 64, 77–78 |
| 120                     | The subsidence allowance of the dam filling is unreasonable | 358 |
| 122                     | There is a horizontal weld on the slope | 64, 66, 73 |
| 123                     | Improper selection and care of slope protection turf | 73 |
| 124                     | Slope cutting did not follow the design requirements | 19, 64–65 |
| 125                     | Slope protection was not carried out in time | 19, 62, 64–65, 73, 122 |
| Tailings Pond Subsystem | Elements of the System | Number (v) | Hazard Name                                                                 | Number of Hazards Caused                      |
|------------------------|------------------------|------------|------------------------------------------------------------------------------|----------------------------------------------|
|                        |                        | 126        | Unreasonable design of cast-in-place protective surface                      | 19, 62, 64–66, 73, 77, 122, 157              |
|                        |                        | 132        | No effective filter layer is set on the dam foundation                       | 157, 165                                     |
|                        |                        | 135        | Uneven foundation subsidence                                                 | 63–66, 68, 73, 136, 191, 267, 273           |
|                        |                        | 136        | Dam foundation instability                                                   | 64–66, 68, 73                                |
| Dry beach              |                        | 142        | Raise dust in the pond area                                                  | 1, 338, 358–359                              |
|                        |                        | 143        | No watering to reduce dust                                                  | 142                                          |
|                        |                        | 144        | Insufficient dust prevention measures in the tailings accumulation area(dry) |                                               |
|                        |                        | 145        | No coverage measures in the pond area                                        | 53, 142, 157                                 |
|                        |                        | 146        | The main dam has not been reclaimed and greened in time                      | 53, 142                                      |
|                        |                        | 147        | Insufficient soil cover or greening on the dam slope(dry)                    | 53, 142                                      |
|                        |                        | 148        | Weakness of paving has not been reinforced                                   | 158, 142                                     |
|                        |                        | 150        | Natural paving (covering) is destroyed                                       | 158, 142                                     |
|                        |                        | 152        | Poor deposition control for dry beach face                                   | 142, 157                                     |
|                        |                        | 156        | Seepage damage                                                              | 1, 60, 62, 64, 338, 359                      |
|                        |                        | 157        | Filter failure                                                              | 64, 67, 136, 156, 167, 195                   |
|                        |                        | 158        | Leakage channel                                                             | 64, 68, 135–136, 156                         |
|                        | Seepage system         | 163        | The substandard seepage water has not been collected, recovered and treated  | 1                                            |
|                        |                        | 164        | The dam foundation area between the initial dam and sediment storage dam is not equipped with drainage facilities | 157                                          |
|                        |                        | 165        | Defects of dam foundation drainage facilities                                | 157                                          |
|                        |                        | 167        | Seepage line is higher than control seepage line                            | 65–67, 70, 156                               |
|                        |                        | 168        | Improper measures to reduce the seepage line                                 | 167                                          |
|                        |                        | 170        | Insufficient protection measures for seepage prevention facilities           | 158, 165, 183                               |
|                        |                        | 174        | Unqualified geomembrane                                                      | 157, 165                                     |
Table A1. Cont.

| Tailings Pond Subsystem | Elements of the System | Number (v) | Hazard Name | Number of Hazards Caused |
|-------------------------|------------------------|------------|-------------|--------------------------|
| 175                     | No drainage measures under the geomembrane protective layer |           | 157, 165    |                          |
| 176                     | Poor drainage of composite geotechnical drainage network |           | 157, 165    |                          |
| 182                     | Unqualified filter material |           | 183         |                          |
| 183                     | Filter failure | 65, 157, 165 |             |                          |
| 187                     | Geotextile clogged | 165, 183   |             |                          |
| 190                     | Overtopping | 1, 60, 62, 64, 69, 338, 358–359 |             |                          |
| 191                     | Fracture of drainage structure | 66, 69, 158, 192, 200 |             |                          |
| 192                     | Leaking drainage structure | 1, 66–67, 69, 150, 158, 195, 200 |             |                          |
| 193                     | Scour or cavitation drainage structures |           | 191–192     |                          |
| 194                     | Insufficient regulating water storage |           | 39          |                          |
| 195                     | Rapid rise of pond water level | 39, 65, 67, 152, 167, 190, 194 |             |                          |
| 196                     | No drainage facilities | 195, 200   |             |                          |
| 197                     | The foundation pit at the higher groundwater level has no drainage facilities |           | 195, 200    |                          |
| 200                     | Insufficient flood discharge capacity |           | 193, 195    |                          |
| 201                     | Blocking defects of flood drainage facilities |           | 192–193, 195, 200 |             |
| 202                     | Unreasonable temporary flood control plan during construction period |           | 195, 200    |                          |
| 203                     | Improper diversion measures |           | 195, 200    |                          |
| 205                     | The installation location and elevation of drainage facilities do not meet the design requirements |           | 193, 195, 200 |             |
| 206                     | Insufficient elevation of drainage holes in front of the dam |           | 200         |                          |
| 207                     | Flood drainage structures are directly located on the tailings sediment beach |           | 191         |                          |
| 208                     | The foundation of the flood drainage structure is set in the area with poor engineering geology |           | 191         |                          |
| 209                     | Insufficient foundation bearing capacity of underground flood drainage structures |           | 191         |                          |
| 211                     | The dry tailings pond of third–class and above adopts flood interception ditch for flood discharge |           | 200         |                          |
| 212                     | Drainage facilities are not located in front of the blocking dam |           | 193         |                          |
| 213                     | Use mechanical flood drainage |           | 200         |                          |
### Table A1. Cont.

| Tailings Pond Subsystem | Elements of the System | Number (v) | Hazard Name                                                                 | Number of Hazards Caused |
|-------------------------|------------------------|-----------|------------------------------------------------------------------------------|--------------------------|
|                         |                        | 214       | The on–site line setting is inconsistent with the construction drawing       | 77–78, 205, 273          |
|                         |                        | 218       | Improper installation of energy dissipation facilities                      | 191, 193                 |
|                         |                        | 219       | No energy dissipation measures have been taken in the tailings facility     | 191, 193                 |
| Backwater plan          |                        | 221       | The clarified water of the tailings pond is not used for backwater utilization | 195, 338                 |
|                         |                        | 222       | One–sided pursuit of backwater quality                                      | 195                      |
|                         |                        | 223       | Excessive pursuit of backwater in tailings pond                             | 228                      |
|                         |                        | 224       | Low tailings water recovery rate                                            | 195, 338                 |
|                         |                        | 225       | The backwater design of the tailings pond does not utilize the potential energy | 338                      |
|                         |                        | 227       | Insufficient volume of backwater pond                                       | 224                      |
|                         |                        | 228       | Unqualified backwater quality                                               | 1                        |
|                         |                        | 229       | Turbid tailings water                                                       | 1                        |
|                         |                        | 230       | Unexpected discharge or misdischarge water that does not meet the discharge standard | 1, 359                   |
| Conveying facilities    |                        | 234       | Blockage or siltation                                                       | 165, 176, 191, 195, 200  |
|                         |                        | 236       | No flow and pressure detection instrument                                   | 191, 234                 |
|                         |                        | 238       | Serious corrosion of equipment                                              | 191, 228, 231, 325, 338  |
|                         |                        | 240       | No anti–corrosion treatment in tailings facilities                          | 238                      |
|                         |                        | 241       | Unqualified anti–corrosion materials                                        | 193, 238                 |
|                         |                        | 260       | Improper handling of local hydraulic phenomena                              | 234, 238, 267            |
|                         |                        | 267       | Pipes and grooves deformation                                               | 191, 193, 234,           |
|                         |                        | 268       | Defects of the interception ring in pipe body                               | 69, 192–193              |
|                         |                        | 269       | The pipe body is in direct contact with the big rocks                       | 191, 267                 |
|                         |                        | 270       | The outer wall of the pipe is not protected                                 | 191, 267                 |
|                         |                        | 271       | The dimensions of pipes, grooves, tunnels, etc. do not meet the requirements | 191, 193, 234, 267       |
|                         |                        | 272       | Pipes and grooves material unqualified                                      | 191, 193, 267            |
| Other transportation facilities |                  |           |                                                                              |                          |
| Tailings Pond Subsystem | Elements of the System | Number (v) | Hazard Name                                                                 | Number of Hazards Caused |
|-------------------------|------------------------|-----------|------------------------------------------------------------------------------|--------------------------|
|                         |                        | 273       | Subsidence or deformation of supporting facilities such as pipes, trenches and tunnels | 191, 267                 |
|                         |                        | 275       | Excessive slope deviation for laying pipes, trenches, tunnels, etc.           | 191, 193, 234, 267       |
|                         |                        | 281       | Poor quality of fill around the pipeline                                      | 191, 267                 |
|                         |                        | 285       | No settlement joints between pipe and well                                    | 191, 267                 |
|                         |                        | 286       | The joint length of the drain pipe is unreasonable                            | 191–192, 267             |
|                         |                        | 287       | Deformation joints are not provided at both ends of the drain pipe according to the design requirements | 191, 267                 |
|                         |                        | 289       | Improper excavation (pipes, trenches, tunnels, etc.)                         | 65–66, 117, 120, 191     |
| Pump                    |                        | 291       | Poor construction ventilation                                                | 358                      |
|                         |                        | 296       | Poor pump quality                                                            | 192–193, 234, 307        |
|                         |                        | 307       | Pump failure                                                                 | 61, 192, 195, 200, 228, 338 |
|                         |                        | 373       | No liquid can be discharged from the sand pump                               | 307                      |
|                         |                        | 374       | Insufficient liquid output from sand pump                                    | 307                      |
|                         |                        | 375       | Pump consumes too much power                                                 | 307                      |
|                         |                        | 376       | Pump bearing heat                                                            | 307                      |
|                         |                        | 377       | Deformed or broken pump shaft                                                | 307                      |
|                         |                        | 310       | The surrounding environment improvement does not meet the requirements       | 1, 9, 19, 142             |
|                         |                        | 312       | Dam body renovation does not meet the requirements                           | 62–70, 73, 135–136, 142, 148, 157–158, 167, 183 |
|                         |                        | 313       | The improvement of flood discharge system does not meet the requirements     | 191–192, 195, 228, 234, 267, 273, 307 |
|                         |                        | 315       | Unreasonable reclamation plan                                                | 1, 19, 310, 312–313      |
| Monitoring System       |                        | 324       | Improper selection of monitoring instruments and equipment                   | 327, 338, 343            |
|                         |                        | 325       | Monitoring instrument failure, work interruption                            | 327, 338, 343            |
|                         |                        | 326       | The third-class and above tailings ponds are not equipped with monitoring facilities that combine manual and automatic monitoring | 1, 19, 22–24, 142, 327   |
|                         |                        | 327       | Safety monitoring facilities cannot fully reflect the operating status of the tailings pond | 1, 7, 9, 19, 22–24, 37, 45, 47, 49, 54, 65–69, 135–136, 163, 191–192, 200, 228–230, 267, 343 |
| Tailings Pond Subsystem | Elements of the System | Number (v) | Hazard Name                                                                 | Number of Hazards Caused |
|-------------------------|------------------------|------------|-------------------------------------------------------------------------------|--------------------------|
|                         |                        | 328        | No monitoring points are arranged outside the dam toe                         | 9, 19, 22–23, 142, 144, 310, 327 |
|                         |                        | 329        | No additional monitoring facilities are installed at the dam abutment, bedrock faults, and buried pipes in the dam | 65–69, 135–136, 191–192, 267, 327 |
|                         |                        | 331        | No external drainage and composition monitoring                               | 1, 163, 200, 228–230, 327 |
|                         |                        | 332        | No monitoring of groundwater and surrounding water bodies                     | 1, 230, 327               |
|                         |                        | 334        | The number of water quality monitoring wells around the tailings pond is insufficient | 1, 230, 327               |
| Management system       |                        | 338        | Economic losses                                                               | 359                      |
|                         |                        | 339        | Insufficient capital investment                                               | 7, 9, 17, 19, 22–24, 40, 42, 43–45, 47, 49, 51–52, 54, 60, 62–70, 73, 77–81, 85–86, 89–90, 93–94, 110,113–117, 119–120, 122–126, 130, 132, 135–136, 142–150, 152, 156–158, 163–168, 170, 174–176, 182–183, 187, 190–197, 200–203, 205–209, 211–214, 218–219, 221–225, 227–230, 234, 236, 238, 240–241, 260, 267–273, 275, 281, 285–287, 289, 291, 296, 307, 310, 312–313, 315, 324–329, 331–332, 334, 346, 348, 351–352, 354–355, 358 |
|                         |                        | 340        | Insufficient safety supervision                                               | 17, 23–24, 27–30, 32, 40, 42–43, 61, 73, 77–81, 85–86, 89–90, 93–94, 110, 115–116, 120, 123–124, 130, 145, 157–158, 164, 168, 170, 174, 191–192, 194, 196–197, 200, 207–208, 211–212, 214, 221, 225, 227, 238, 240, 268–271, 275, 281, 285–287, 289, 296, 310, 312–313, 315, 324–326, 329, 331–332, 334, 343, 346, 351, 354, 358 |
|                         |                        | 343        | Inadequate safety evaluation                                                  | 1, 19, 60, 142, 156, 190, 200, 224, 228, 327, 358–359 |
|                         |                        | 344        | Outdated specifications and standards for survey, design, construction, and acceptance | 17, 23–24, 27–30, 32, 40, 42–43, 61, 73, 77–81, 85–86, 89–90, 93–94, 110, 115–116, 120, 123–124, 130, 145, 157–158, 164, 168, 170, 174, 191–192, 194, 196–197, 200, 207–208, 211–212, 214, 221, 225, 227, 238, 240, 268–271, 275, 281, 285–287, 289, 296, 310, 312–313, 315, 324–326, 329, 331–332, 334, 343, 346, 351, 354, 358 |
|                         |                        | 345        | Defects in safety production rules and regulations and operating procedures    | 23–24, 39, 42–43, 54, 80, 85–86, 90, 93–94, 110, 113–115, 119–120, 122–125, 130, 132, 142–148, 150, 157–158, 163–165, 167–168, 170, 174–175, 183, 191–193, 201, 203, 205–208, 213–214, 218–219, 221–224, 229–230, 234, 236, 238, 240, 260, 267–268, 270, 275, 281, 285–289, 291, 307, 310, 312–313, 325, 343, 352, 358 |
### Table A1. Cont.

| Tailings Pond Subsystem | Elements of the System | Number (v) | Hazard Name                                                                 | Number of Hazards Caused                                                                 |
|-------------------------|------------------------|------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
|                         |                        | 346        | Improper data management                                                      | 17, 42–43, 79, 197, 205, 207–208, 225, 315, 324, 327, 343, 352                           |
|                         |                        | 347        | Insufficient or wrong hydrological and geological data                         | 17, 42–43, 79, 197, 205, 207–208, 225, 309, 315, 324, 327, 343, 352                   |
|                         |                        | 348        | Improper quality acceptance                                                   | 19, 60, 62–70, 135–136, 142, 156–158, 167, 183, 190–193, 200, 234, 238, 267, 307, 310, 312–313 |
|                         |                        | 351        | Improper maintenance                                                          | 60, 62, 64–70, 142, 156–158, 167, 183, 190–193, 234, 238–239, 254, 267, 307, 325    |
|                         |                        | 352        | Design defects of emergency plan                                               | 1, 19, 60, 62, 142, 156, 190–191, 195, 338, 358                                       |
|                         |                        | 354        | Insufficient emergency plan drills                                             | 1, 19, 60, 62, 142, 156, 190–191, 195, 338, 358                                       |
| Personnel system        |                        | 355        | Insufficient experience in personnel or organization qualification problems   | 17, 23–24, 44, 54, 61, 79, 110, 113–116, 119, 123–126, 130, 132, 143–149, 163–164, 168, 170, 174–176, 187, 196–197, 201–203, 205–209, 211–214, 218–219, 221–225, 230, 240, 260, 268–272, 275, 281, 285–289, 291, 310, 312–315, 324, 326, 328–332, 334, 343, 346–348, 351–352, 354 |
|                         |                        | 358        | Personal injury                                                               | 338, 359                                                                             |
|                         |                        | 359        | Loss of reputation                                                            | 338                                                                                  |

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