Risk Analysis of Tailings Dam Failure and Environmental Management Resulting from It

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Abstract

The production of processing waste is increasing due to the increase in global population, the increase in demand and consumption of minerals, the decrease in the grade and quality of minerals, and the improvement of processing technology. The most common method of accumulating waste materials is the tailings dam. The failure of a tailings dam will have severe consequences on the environment and the cost of its cleanup.

In this study, the probability of dam failure and its consequences are predicted by using the risk analysis method. For this purpose, by studying 306 tailings dams that failed between 1914 and 2024, the factors and factors affecting the failure of tailings dams were identified. These factors were categorized into four failure mechanisms and then weighted using the priority voting method. The failure mechanisms and their weights are respectively sloping failure 48.9%, overflow failure 23.7%, gully failure 20.4%, and foundation failure 6.9%. Since the characteristics of the waste materials are effective in slope stability, important characteristics such as the consolidation rate of pore water pressure and shear stress of the waste materials of the Songun copper mine were studied, and the results showed the same range of changes compared to the results of other porphyry copper mines. A new risk analysis model was presented using the concept of risk degree and also using the probability and weight of the failure mechanisms of the tailings dam. The failure probability was calculated using the structural reliability theory of the Monte Carlo simulation method and by the safety factor parameters.

The slope failure safety factor was modified by considering the maximum shear strength of the waste materials. The modified Fulci method was presented to calculate the consequences of failure. Then, the presented methods were used to analyze the failure risk of the tailings dam of the Songun copper mine, in which the probability of slope failure was 67.3, overflow failure, 64, and stirrup failure in the foundation was calculated to be 0%.

Thus, the probability of dam failure due to slope instability or structural failure is within the risk range. Also, in the event of an unexpected heavy rainfall, there is a possibility of overflow failure.

The consequences of dam failure were also assessed as follows: 100% economic consequences, 80% environmental consequences, and 65% social consequences. If the tailings dam of the Songun copper mine fails, severe damage will be caused.
Keywords: processing tailings, prediction of tailings dam failure probability, weighting by priority voting method, structural reliability method, prediction of failure consequences, Fulci method

1. Introduction

Mining is one of the earliest industries in the history of human life and has played a fundamental role in the development of urbanization and technology. Today, products made from minerals still play a significant role in human life. According to studies by the International Association of Mining and Metals, global GDP increased from 1992 to 2014 with the increase in mineral production. These studies also show a significant increase in the rate of urbanization in developed countries such as the United States in line with the increase in GDP. [1]

Studies conducted in 2015 show that children born in developed countries this year will consume 49 kilograms of minerals per person per day, 17,885 kilograms of minerals annually, and with a life expectancy of 80 years, they will consume about 8,430.8 tons of minerals during their lifetime. [2]

Despite reliable statistics on the production and consumption of minerals, there are no accurate statistics on the amount of waste removal and waste production to access ore and produce the final product. In addition, considering the amount of precious metal coal consumption and their average grade, an initial estimate is that the amount of waste removal in the extraction sector and the amount of waste produced in the processing sector was between 15 and 20 billion tons [3].

Given the increase in population, which is expected to exceed 8.5 billion people by 2030 [4] and given the increased consumption of agricultural products for the production of agricultural products, phosphate rock production, potash is required for the production of fertilizers, pharmaceuticals, military, and electronics, the consumption of minerals will be much higher and more waste will be produced.

In other words, the main challenge of mining in the coming years is the large volume of waste produced in the extraction and processing stages. In the production of the final product of the mineral and in order to extract and recover a few grams of metal, a large tonnage of waste is produced in the processing stage, which is called processing waste. Among the various methods of accumulating processing waste, their accumulation in a dam is known as the most common method. Given the numerous reports published every year about the failure of tailings dams and their destructive consequences, especially their effects on the environment, predicting the cause and time of tailings dam failure and managing its consequences has also become more important than ever.

On the other hand, given that easily accessible and moderately high-grade surface minerals are being mined or their extraction has been completed, the challenges facing the future of mining will be increasing deposit depth, low grade, and poor quality of minerals, which will significantly increase the number of tailings produced. Also, with increasing grade and intensity, improved crushing, and advances in processing technology, more tailings will be produced, especially in the processing stage [4]. Therefore, the safe storage of processing tailings is considered the biggest environmental challenge in the mining industry and also one of the most important costs for mining companies.

The need for tailings dams in mineral processing arose many years after the construction of their hydraulic dams. The International Commission on Large Dams, established in 1928, did not pay attention to tailings dams until the establishment of the Registration Committee in 1958. The issue of tailings dams was first raised at the 1976 Congress on Large Dams in Mexico City, and a committee on tailings dams was subsequently established within the International Commission on Large Dams.[5]

Tailings dams are among the largest man-made structures, and a significant area of land surrounding a mine is covered by these dams. Tailings dams are designed and constructed like embankment dams. The cost of constructing tailings dams is high and is considered part of the cost of mineral production. Also, because these dams remain even after mining operations have ended and the mine is closed, and are prepared for rehabilitation and other uses for future generations, their sustainability is of particular importance. So far, more than 300 reports of tailings dam failures have been published, the consequences of which have claimed many lives and caused significant damage to the environment.

Because tailings contain heavy metals and are highly concentrated, the damage caused by tailings flows is much greater than the water flow caused by dam failures. It is difficult to determine how much surface and groundwater is affected by tailings pollution. The costs of cleaning them are also one of the most important concerns of mining companies. Also, considering the increase in population and consumption of minerals and the increase in the production of tailings, and as a result, the increase in the number and volume of tailings dams, it is necessary to examine the factors of tailings dam failure and the probability of its occurrence, as well as the consequences of failure, i.e., analyzing the risk of dams to prevent their failure and manage its consequences, which is the subject of this article.

The failure of embankment dams refers to any erosion and deformation in the dam that causes uncontrolled release of the dam contents, waste materials or water and the resulting damage. To investigate the failure of embankment dams and determine the probability of failure, it is necessary to identify and investigate the mechanisms of the types of failure. In general, failure mechanisms are divided into four categories: slope failure, foundation and footing failure, gully failure, and overflow failure.[6]

Risk analysis is considered as one of the methods for studying the safety of dams, which must be considered and used from the very beginning of the location and design of the dam. Due to the uncertainty in many of the parameters effective in location and especially in the design and construction of dams, as well as the interaction of the parameters effective in failure on each other, risk analysis is considered as a powerful tool in predicting failure.

On the other hand, since, unlike the conventional method of constructing embankment dams, the stages of raising the tailings dam are carried out gradually and simultaneously with the entry of tailings into the dam, and since the mechanical and chemical properties and behavior of the tailings are important factors in the stability of these dams, the analysis of the failure risk of tailings dams has its own complexity that must be considered in studies.

In the dam design instructions and risk analysis, the characteristics and properties of the tailings materials as well as their hydromechanical properties have not been considered, which will be discussed in this article.

Also, the risk of dam failure will not be the same throughout its life cycle. The probability of dam failure is higher in the early years of construction because any mistake in the design of the dam will be obvious in the early years and cause failure.

On the other hand, due to the importance of risk management, it is necessary to predict the maximum probable flow (taking into account the effect of the parameters affecting it). On the other hand, the importance of conducting this research from the perspective of sustainable development is also important.

In 1992, at the Earth Summit at the United Nations headquarters in Rio de Janeiro, Brazil, sustainable development was defined as: "Meeting the needs of the present generation without compromising the ability of future generations to meet their own needs.[7]

2. Research Background

The first studies on dam failures, causes, failure times and consequences were published by the International Committee on Large Dams in 2001, in which the causes and times of failure of 221 tailings dams made of various metallic and non-metallic minerals from 1910 to 2000 were examined.[8]

Information from this source was used in the studies of 306 tailings dams in this article. The World Energy Information Service, Uranium Project Division, has published information on tailings dam failures from 1960 to 2015 on its website, which is frequently updated [9].

Information from this source was used in the studies of 306 tailings dams in this article. In 2015, Booker and Chambers, based on studies by the International Committee on Large Dams and information from the World Energy Information Service, Uranium Project, compiled a list of 270 tailings dam failures between 1915 and 2015, along with an analysis of the cause of failure, failure mechanism, and consequences. [10] They also conducted a study to examine tailings dam failures and compare them with mineral production and calibration, and to predict and predict dam failure rates based on historical data [11].

Information from this source was used in this study of 306 tailings dam failures. It is worth noting that there is overlap between the information from sources [8, 9, 10, and 11].

In 2014 and 2015, Oboni et al. examined the probability of dam failure based on statistical data and also estimated the consequences of tailings dam failures based on cost and safety factors [12, 13].

In 2013, Tarek Hamad used stochastic analytical methods to analyze the stability and design of a dam based on geotechnical factors. In this study, the slope of the dam and the safety factor of the slope stability of the dam were calculated using numerical modeling and limit equilibrium methods. To take into account the uncertainty of geotechnical factors, the Monte Carlo simulator method was used. Also, in this study, two-dimensional modeling in the FLAC2D software environment and the point estimation method were used, and considering the hydraulic parameters and the capability and reliability method were used to calculate the failure probability and the safety factor of the slope stability of the tailings dam [14].

In 2013, Mascoura used static and quasi-static methods of stability analysis and probabilistic methods such as the equilibrium method, limit Monte Carlo simulation, point estimation method, and reliability theory to analyze the stability of rising tailings dams [15].

In 2012, Siayat analyzed the slope stability and seepage in tailings dams by considering and studying geotechnical properties using the finite equilibrium method [16].

In 2011, Zardari investigated the slope stability of tailings dams using numerical modeling. Using PLAXIS software, he investigated the slope stability of rising tailings dams by considering the difference in the process and consolidation rate of tailings materials and also by considering the effect of water pressure [17].

In 2006, Logik evaluated the potential for increasing the fluidity of tailings materials in laboratory conditions for undrained and water-logged tailings materials using elastic wave velocity [18].

Chenxu et al., (2024) attempts to address this gap by developing, and geo-statistically analyzing two comprehensive databases. The findings reveal that (i) Cd, Pb, and Hg are the prominent pollutants across the non-failed TSF sites in China; (ii) lead-zinc and tungsten mine tailings storage sites exhibit the most severe pollution; (iii) Pb, Cd, and Ni present noteworthy non-carcinogenic risks to human health; (iv) >85 % of TSF sites pose carcinogenic risks associated with arsenic; and (v) health risks resulting from dermal absorption surpass ingestion for the majority of heavy metals, with the exception of Pb, where ingestion presents a more pronounced route of exposure. Our study presents a comprehensive evaluation of environmental and human health risks due to TSFs, highlighting the necessity for risk assessment of >14,000 existing TSFs in China [19].

Dinis et al., (2023) proposes a data analysis of failures based on the severity coding system and mining economic growth metric. The reported cases of tailings dam failure in the past have been collected and re-evaluated thoroughly to understand the distribution of the incident better and establish relationships or identify patterns. The analysis focused on the characteristics of the tailings storage facilities, the causes for failure, the type of accident, and the regulatory framework, both in mining and environmental fields [20].

Sousa Figueira et ak., (2024) resorts to a set of upstream tailings dam decommissioning designs to identify key aspects related to risk management of such structures before, during and after decommissioning. The application of the Failure Modes Effects and Criticality Analysis (FMECA) allowed to identify the main risks associated with the decommissioning of the dams and to define preventive and mitigation actions as well as controls to be implemented in order to minimize the risk, consistent with the principles of Global Industry Standard on Tailings Management [21].

3. Proposed Model

3-1 Tailings Dam Failure Risk Analysis Model

As mentioned in the first step, in order to analyze the tailings dam failure risk, it is necessary to calculate the probability of dam failure under failure mechanisms. Considering the failure factors of dams that have failed in the past hundred years and their failure mechanisms, as well as their consequences, and considering the approach to dam risk analysis, in this section, a risk analysis model and calculation of the probability of tailings dam failure under the failure mechanisms of slope failure, dam failure due to overflow, failure due to increased fluidity, internal erosion, leakage and as a result, gully failure, and finally dam foundation failure are presented along with calculating the weight and performance of each of the mechanisms. It is noted that only one factor will not be effective in dam failure and their simultaneous effect will cause failure.

This means that leakage, atmospheric precipitation, destructive loads on the wall and the pier, and other failure mechanisms occur continuously (with a continuous and simultaneous probability distribution function) and that some of the factors affecting failure affect each other and are correlated, and this interaction must be considered in calculating the probability of failure. It is also important to note that the weight and performance of all the parameters affecting failure will not be the same, meaning that only calculating the probability of their occurrence cannot indicate the probability of dam failure, especially since depending on the geographical location and the place where it is built, the performance and weight of these factors will vary from one dam to another. To calculate the probability of failure of the four mechanisms, the concepts and relationships presented in the fault tree model and the Bayesian model of tailings dam failure are used. To apply the performance and weight of the failure mechanism to the risk of tailings dam failure, the concept of risk degree presented by Williams in 1993 [22] is used.

3-2 Proposed fault tree model in tailings dam failure risk analysis

The study mechanism that is used to better understand the causes of tailings dam failure is the failure report and causes and 306 tailings dams that were studied between the years 1914 to 2024 have been broken and examined. After studying and extracting the cause of dam failure, it was determined that in each of the failure mechanisms, a set of factors is involved in order for the failure to occur. Due to the difference in material properties, the internal and external factors of this set will be different, so the set of all these factors is in the form of a fault tree for tailings dam risk analysis, which includes the set of all factors effective in the failure of tailings dams.

According to the figure, the failure mechanisms of tailings dams are shown in four groups. In failure due to overflow, surface erosion, heavy rain and spillway failure are effective, and the improper design of the head and free surface of the dam play an important role in this failure. Factors such as leakage will cause internal erosion and gully failure. Increased pore pressure due to water content of waste materials. Increased fluidity of the gully due to seismic waves. High rate of inflow of waste materials compared to the rate of sedimentation and hardening and during dam elevation. Slope instability and increased shear force due to hardening of the gully are effective factors in slope failure. Leakage and internal erosion cause gully failure. Leakage in the foundation due to high permeability. Low resistance of the foundation against loads (stress and strain of the gully or laser waves) due to selection of inappropriate materials in the foundation, and landslides and settlement are also important factors in foundation failure.

3-3 Proposed Bayesian Network Model

Failure of tailings dams Internal erosion in failure, slope. Increased probability of leakage due to the type of dam wall or foundation materials, or increased pore pressure causes gully failure in the wall or foundation. Heavy rains and improper spillway performance will increase hydraulic pressure, slope instability, and spillway failure. Also, surface erosion of the dam body, as well as the amount of atmospheric precipitation and spillway time management are important factors of spillway failure and act in conjunction with each other. Land subsidence and subsidence, which themselves must be examined in the geological factors of the region, are effective in foundation failure. It is worth noting that the intensity of the earthquake is examined because of its effect on liquefaction potential, and the role of the earthquake and its destructive power in dam stability are other factors that must be examined in examining the forces acting on the dam under earthquake conditions.

3-4 Study Site

3-4-1 Sungun Copper Mine

The Sungun Copper Complex is the second largest porphyry copper mine in Iran, located in East Azerbaijan Province, 130 km from Tabriz, 75 km northwest of Ahar, and 28 km north of Varzaghan. The mine is located at an altitude of approximately 2000 meters above sea level and in part of the Qara Dagh mountain range. The main access route to the mine is via the Tabriz-Varzaghan-Sungun asphalt road. The climate of this region is characterized by cold and icy winters and mild summers. The maximum temperature in the region is recorded as 33°C in summer and -20°C in winter. The annual rainfall is about 350 mm and the annual relative humidity varies between 52 and 85 percent [23].

3-5 Characteristics of the Sungun Copper Mine

In order to analyze the risk of tailings dam failure in the Sungun Copper Mine, due to the importance of the mineral characteristics, as well as the grade, tonnage, and the effect of the processing stages on the produced tailings and their role in tailings dam failure, first the copper mine grade and extractable tonnage, the processing plant, and the materials will be examined, and then the weather conditions, rainfall, geology, seismicity, environment and ecosystem, region, villages and residents of the region, and the status of surface and groundwater will be examined. Then the characteristics and grading of the tailing's materials and finally the tailings dam of this mine will be studied.

3-5-1 Sungun Copper Mine

The total tonnage of Sungun copper ore is estimated to be 604 million tons with an average grade of 0.637% based on the mine technical office data.[24] In 2013, Asanloo and Rahmanpour, in order to assess the environmental impacts of Sungun Copper Mine on the final mine boundary using the Fulci method, after determining the final boundary of Sungun Copper Mine, stated that the definitive copper mine reserve is approximately 740 million tons with a grade of 0.6% and the extractable reserve is 322 million tons with an average grade of 0.62%. They also proposed a possible reserve of nearly 1.7 billion tons for it [24].

The reserve of this mine has an average of 240 ppm molybdenum per ton. The initial capacity of the processing plant in the first phase was 150 thousand tons and was expanded to 300 thousand tons in the second phase. Its third development plan is a capacity of 500 thousand tons of copper concentrate and the ultimate goal is to produce 2 million tons of copper cathode annually [25 and 26]. The Songun copper mine is mined by the open pit method, and the extraction parameters in its final range are as described in Table 1.

Table 1: Results of the final range of the Songun copper mine [26]

Parameter	Amount	Parameter unit
Total ore tonnage	604290896	Metric tons of mineral
Total tailings tonnage	1107726517	Metric tons of tailings
Removal rate	1.833	-
Average mineral grade	0.637	Percentage (%)
Mine life	43	Year

3-6 Tailings Dam of Sungun Copper Mine

The tailings dam is constructed southwest of Sungun Mine, approximately 6 km from the mine, on the upper part of the Ayat Kandi River watershed. The design of the Sungun Copper Mine tailings dam is a rising method with a clay core and is made of rockfill and sand. The consultants for this project were initially Williams Tailings Dam Consulting Company of Australia in 2003. Currently, the Tous Water Consulting Engineering Company is the one whose implementation was assigned to Pars Olang Company since 2004. This dam has had three stages of elevation (with) a volume of 8.5 million cubic meters (soil) and its height is currently 120 meters and the volume of materials inside it (water and tailings) is 41.8 million cubic meters [26].

3-7 Research Method

Regarding the parameters for which a safety factor has been defined, due to the uncertainty of the model input parameters, the Monte Carlo simulator method and their probability distribution function will be used. The probability distribution function of the input parameters is assumed to be normal. The simulation was performed in the Risk@ software environment, version 7.5. The mean and variance of the input parameters for calculation were calculated by the Risk@ software. The Monte Carlo simulator performs the simulation by selecting a random variable and finding its counterpart in the inverse of the cumulative distribution function of the probability distribution function (variable) to the number of times it is instructed to do so. The number of simulations conducted in this research will be 10,000 times. By increasing the number of simulations, the distribution function of the finite state function with the function the calculation of the failure probability will be closer to the normal distribution function and its surface will be more uniform.

In this way, in calculating the failure probability using the structural reliability theory, the reliability is calculated at level three and of the first order.

In this section, it is important to mention that the data obtained from logging and geotechnical studies of the tailings dam are mostly related to the two northern and southern supports of the dam. Therefore, part of the information required for this project has been used from the results of studies by other researchers in calculating the probability of slope failure and the information required for it about the materials used in the dam wall.

To calculate other parameters effective in dam failure whose safety factor is not defined, measured values or their average will be used, in which case the reliability is calculated at levels 1 and 2. Also, the probability distribution function of the data is assumed to be normal.

4. Results

4-1 Analysis of the Risk of Failure of the Tailings Dam of the Songun Copper Mine

As mentioned, it is very difficult and complex to investigate and predict the cause and time of dam failure due to the uncertainty in the effective parameters. The factors affecting the failure of earth dams, especially tailings dams, were investigated. The investigation of the probability of failure of tailings dams using the reliability method of calculating the consequences of dam failure was also studied, and a model based on the probability of consequences and their weight was presented for analyzing the risk of failure.

The characteristics of the tailing's materials of the Songun Copper Mine will be analyzed and investigated based on the studies of geotechnical tests conducted on them. In this study, the grain size, adhesion force, angle of failure, shear force, and the potential for increasing the fluidity degree will be among the characteristics discussed. In addition, in order to investigate the stability of the tailings dam, the characteristics of the dam crown wall and the dam foundation will be studied and investigated.

In this study, studies conducted by the designers of the Songun Tailings Dam, as well as studies related to gravel and tailings dams, have been used. The Monte Carlo simulation method will be used to calculate the probability of failure of the Songun copper mine tailings dam. Then, using the Fulci method, the consequences of the Songun tailings dam failure will be examined with special attention to cost-benefit analysis. Finally, the risk of failure of the Songun copper mine tailings dam will be calculated.

4-2 Calculation of the probability of slope failure

To calculate the failure of the tailings, dam due to slope and dam wall failure, the maximum shear stress of the Songun copper mine tailings materials is calculated.

In this way, Maortail ATA, considering the specific weight of the Songun copper mine tailings materials which is about 27 kN/m3 and the effective failure angle is about 42, the maximum shear stress of the total tailings materials behind the dam wall with a height of 100 meters was calculated to be 2431 kPa.

After entering the data into the Monte Carlo simulation model, the simulation was performed in the RISK@ software environment. The simulation was repeated 10,000 times. After the simulation, the probability of failure of the Songun tailings dam due to slope failure was calculated to be 59 percent. The probability distribution function of the safety factor of failure of the Songun copper mine tailings dam due to slope failure is shown in Figure 1. According to the results, the probability that the safety factor of the dam wall failure is less than 1 is 63.6 percent.

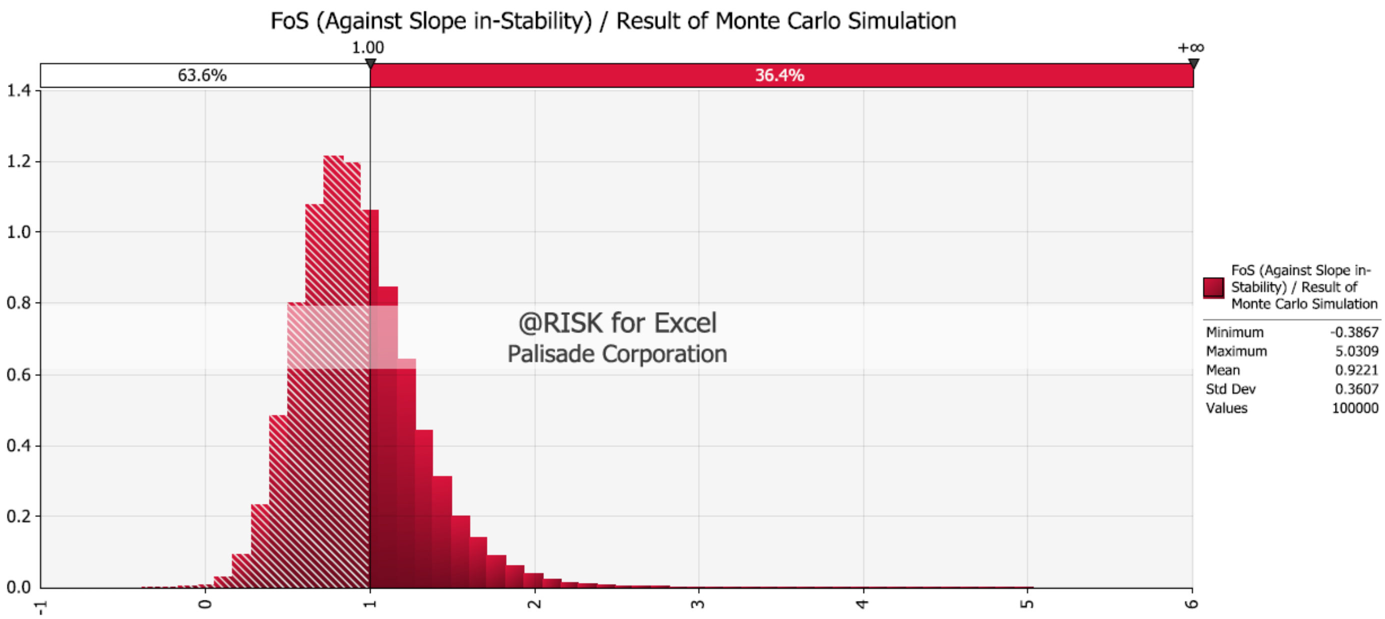

Figure 1: Slope failure safety coefficient probability distribution function

4-3 Calculation of the probability of overflow failure

In calculating the failure of the overflow after rainfall or rising water level in the tailings dam, the difference between the height of the dam wall and the height of the materials, the water void behind the dam wall of 20 meters was considered. Therefore, the calculated pressure due to the water behind the dam wall was calculated to be 0.2 MPa. Other effective parameters in the failure of the overflow slope are.

After entering the data into the model, Monte Carlo simulation was performed in the RISK@ software environment. The simulation was repeated 10,000 times. After the simulation, the probability of failure of the Songun tailings dam due to overflow failure was calculated to be 64 percent. The probability distribution function of the safety coefficient of the Songun copper mine tailings dam failure due to overflow failure is shown in Figure 2. According to the results, the probability that the safety coefficient of the dam wall failure due to overflow is less than one is 65.7 percent.

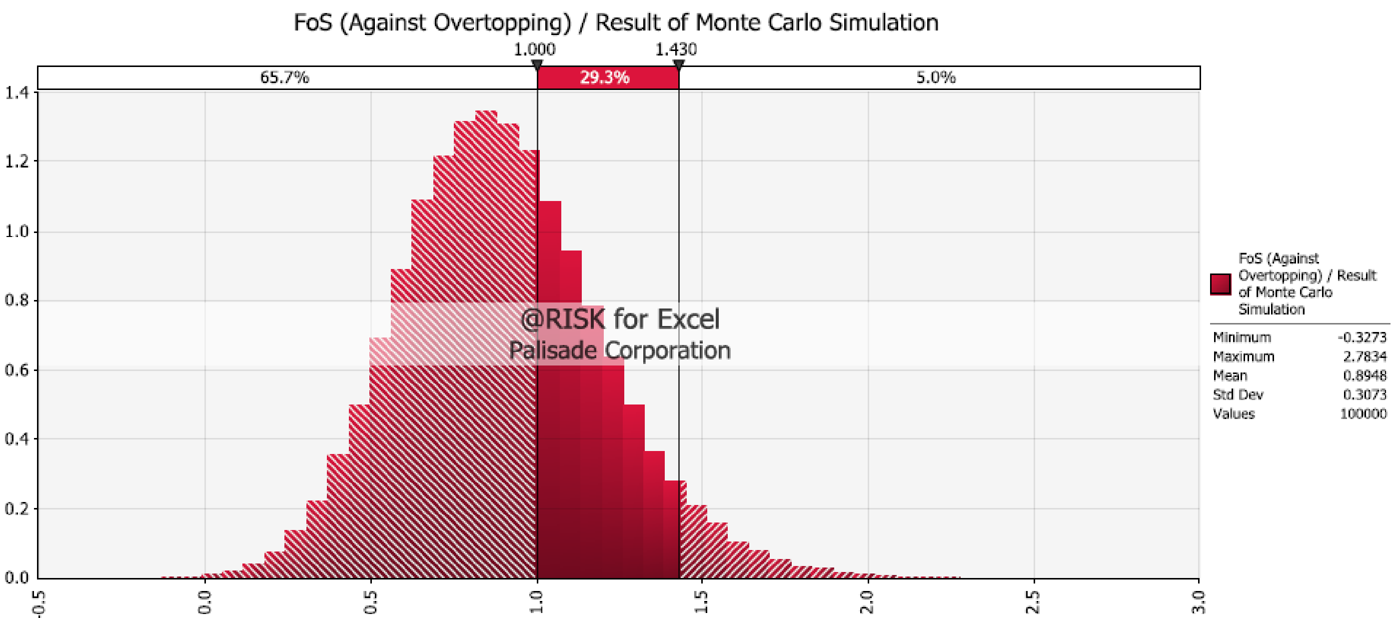

Figure 2: Probability distribution function of safety factor of overflow failure

4-4 Calculation of the probability of gully failure

In this section, the information related to the body of the tailings dam is used to calculate the probability of gully failure in the dam body and foundation to calculate the probability of gully failure in the dam wall. In calculating the pressure due to the water head in the dams of the broken embankments due to gully failure, it was on average equal to 20 meters.

After entering the data into the Monte Carlo simulation model, the simulation was performed in the RISK@ software environment. The simulation was repeated 10,000 times. After the simulation, the probability of failure of the Songun tailings dam due to gully failure was calculated to be 99 percent. The probability distribution function of the safety factor of the Songun copper mine tailings dam failure due to slope failure is shown in Figure 3. According to the results, the probability that the safety factor of the dam wall failure due to gully failure is less than one is 100 percent.

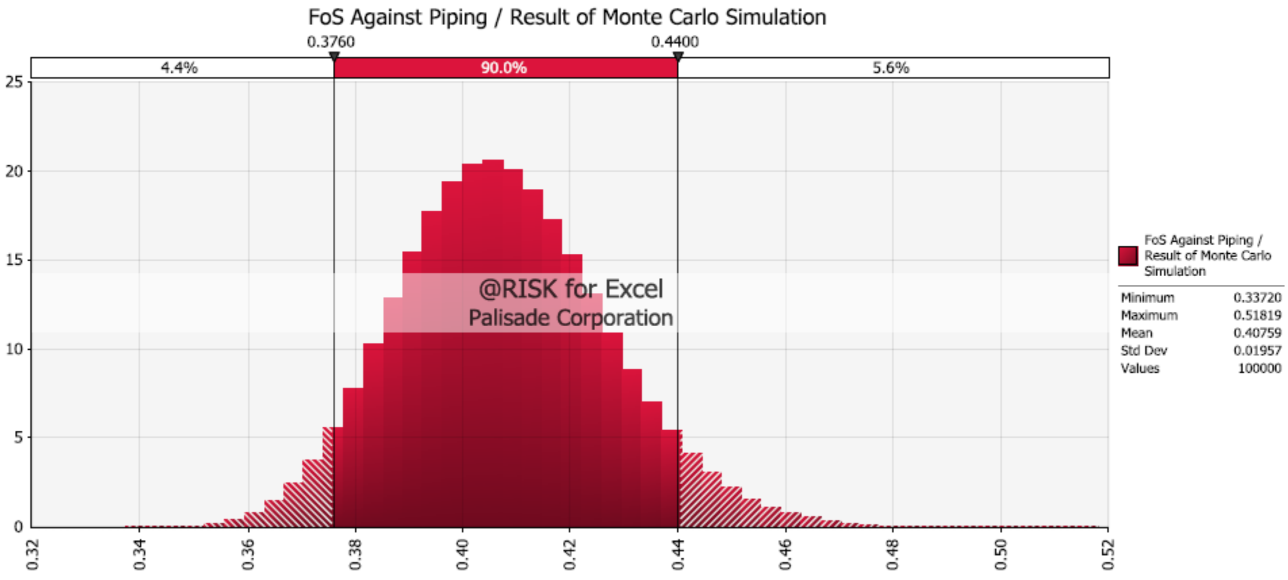

Figure 3: Probability distribution function of the safety factor of the dam foundation failure

4-5 Foundation failure

To calculate the foundation failure, the safety factor of the dam foundation failure and the failure due to landslide are calculated. After entering the data into the Monte Carlo simulation model, the simulation was performed in the RISK@ software environment. The simulation was repeated 10,000 times. After the simulation, the probability of the Songun tailings dam failure due to the failure of the foundation foundation was calculated to be zero percent. The probability distribution function of the safety factor of the Songun copper mine tailings dam failure due to the failure of the foundation foundation foundation is shown in Figure 4. According to the results, the probability that the safety factor of the dam wall failure due to overflow is less than one is zero percent.

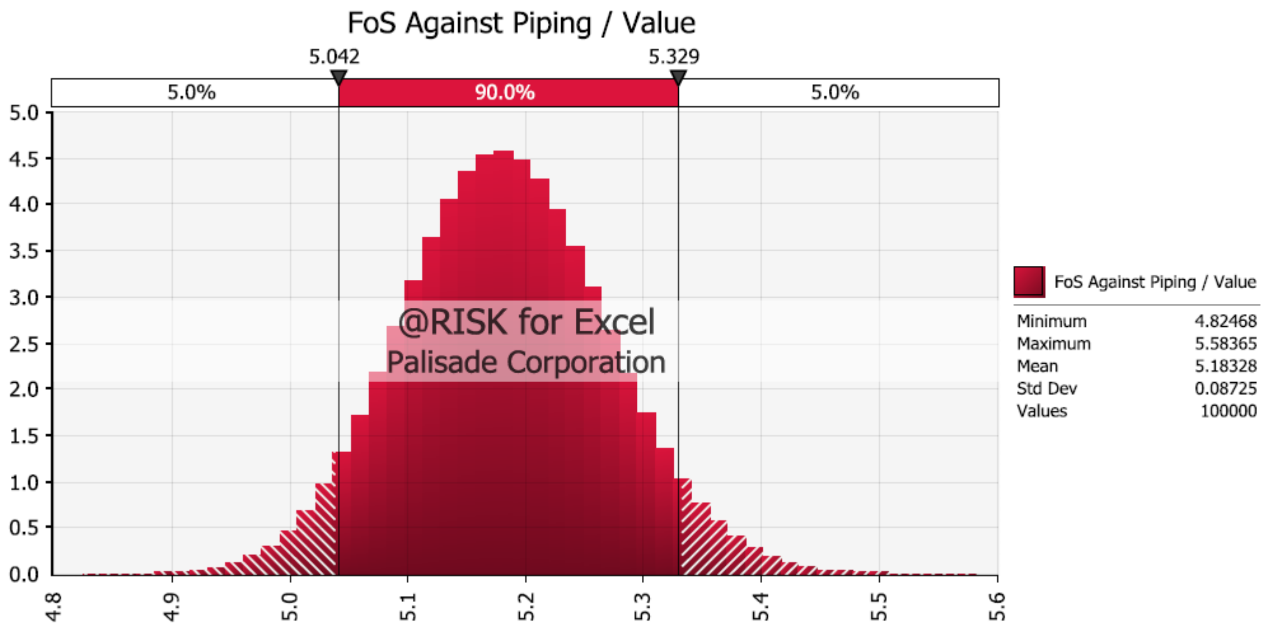

Figure 4: Probability distribution function of the safety factor of dam failure at the base of the dam

4-6 Risk matrix

As mentioned, after calculating the risk degree of tailings dam failure, the risk matrix is used to calculate the probability of failure and its consequences. The final results related to the probability risk degree and its consequences are estimated to be 5396 and 8559 percent to the power of two, respectively, and their summary is shown in Tables 2 and 3. After converting the obtained risk degree in the range of zero to ten, the probability of failure was determined to be 1.4, which is in the range of 2, and the probability and its consequences were determined to be 2.8, which are in the range of consequences. Therefore, in the analysis of the risk of tailings dam failure at the Songun copper mine, 3 was determined and was classified as rare.

Table 2: Final results of the probability of failure of the tailings dam at the Songun copper mine

Failure Mechanism	Probability (P)	Risk Degree (D=WxP)
Slope Failure	67.306	48.9×67.306=3291
Overflow Failure	64	23.7×64=1422

Failure of the Dam Body	99	6.9×99=683
Foundation Failure	0	20.4×0=0
Total	230	5396

Table 3: Final results of the consequences of the failure of the tailings dam of the Songun copper mine

Consequences of Failure	Consequences (C)	Risk Degree (D=WxC)
Environment	65	31x65=2015
Society	80	16.8x80=1344
Economy	100	52.2x100=5200
Total	245	8559

5. Discussion and Conclusion

The tailings dam is designed and built to store the tailings from the mineral processing stage, usually next to mines. Tailings dams are of the type of soil dams and are designed and built similarly to them. These dams, which are called the largest structures built by man, differ from embankment dams in two areas. 1) In tailings dams, unlike embankment dams, the stages of dam elevation are carried out gradually and simultaneously with the entry of tailings. This has caused the failure of tailings dams. 2) In tailings dams, in addition to the effect and pressure exerted on the dam body by water, the force resulting from pore water pressure and the pressure resulting from the shear resistance of the tailings behind the dam, especially after the consolidation of the tailings, must be considered.

Therefore, due to the importance of tailings and their properties on the stability of the dam, the characteristics of the tailings were first examined. The most important characteristics of tailings include their grain size distribution curve, porosity ratio, consolidation rate, pore water pressure behavior, and shear resistance.

Despite numerous studies and engineering efforts in tailings dam design, numerous reports of tailings dam failures are published every year. In a historical review of failed dams, it was concluded that most tailings dams failed due to failure, overflow, slope failure, and foundation failure. Since most of the failed dams were designed in the ascending method, it can be concluded that ascending dams have the highest risk of failure due to the aforementioned mechanisms.

After examining 306 tailings dams that failed between 1914 and 2024, important factors as well as the main mechanisms in tailings dam failure were identified. This study revealed that the factors affecting failure are not independent of each other and each has a performance weight. The fault tree risk analysis method was used to determine how each factor will affect the failure of tailings dams.

According to the presented fault tree model, four main mechanisms in the failure of tailings dams were identified, so that tailings dams under the influence of each of the dam failure factors will ultimately fail through the failure mechanisms, overflow failure, slope failure of the gully (in the dam wall and foundation) and foundation failure.

The erosion factor is influential in gully failure, foundation failure and overflow failure. A Bayesian network model was used to examine the effect of these factors on each other. The fault tree model and the Bayesian network model presented in the failure risk analysis of the tailings dam of the Songun copper mine were used. This model can also be used to analyze the failure risk of other tailings dams in the world. However, since the coefficient of each of the effective factors in the failure of tailings dams can vary from mine to mine, to solve this problem, the weight effect of each of the effective factors in the failure of tailings dams was determined using the hierarchical voting method (PVS).

For this purpose, opinions of domestic and foreign experts were collected through a questionnaire on this matter, and the weight of the effective factors in the failure mechanism and its consequences was calculated by PVS. The weight of the slope failure mechanism was calculated to be 48.9%, the overflow failure was 23.7%, the foundation failure was 20.4%, and the gully failure was 6.9%. As mentioned, the largest number of tailings dam failures occurred due to slope failure and gully failure.

Therefore, the calculated weight for the effective factors in the failure mechanisms is in accordance with the results of historical data on tailings dam failures. The weights obtained were also used in the risk analysis of the tailings dam failure in the Songun copper mine. In addition to the fact that the calculated weights can be used in the risk analysis of all tailing's dams, the voting method presented in determining the weight can also be used to analyze the risk and examine the failure of all tailings dams in the world.

The weight related to the consequences of tailings dam failure is also as follows: The severity of the consequences of dam failure to the environment is 31%, society is 16.8%, and the economy is 52.8%. Therefore, the most economic losses will be caused by the failure of tailings dams. Environmental cleanup costs, infrastructure destruction costs, repair and reconstruction costs, dam costs incurred by mines and mining companies are all classified in the economic consequences class.

Then, the structural reliability method was used to analyze the quantitative risk of tailings dam failure. In this method, the probability of system failure is calculated by determining the limit limit functions. The system is broken when the value of the limit limit function is less than zero. There are several methods for solving the limit function, and in this article, the Monte Carlo simulator method is used.

The Monte Carlo simulator calculates the value of the limit limit function probability distribution function by selecting a random variable and using the probability distribution function.

To analyze the risk of tailings dam failure according to the performance coefficients, the concept of risk degree was used. Then, based on the fault tree model and the presented Bison network, a quantitative model was presented to calculate the probability and consequences of tailings dam failure. In calculating the probability of failure of each of the four mechanisms of tailings dam failure, and using the structural reliability theory, the safety factor of each of the four failure mechanisms was presented. In calculating the failure safety factor, the slope was modified due to the effect of increasing the shear strength of tailings materials on the dam wall, by considering the maximum shear strength of tailings materials as a destructive force, the slope failure safety factor was modified.

In calculating the consequences of tailings dam failure, the Fulci method was used to quantify the effects of dam failure, and by considering the amount of material released from the dam due to the failure, the extent of the tailings flow, the number of people at risk of death, and the economic consequences of the failure, the cost-benefit analysis method was used to calculate the economic consequences of tailings dam failure. In this method, all costs resulting from tailings dam failure are considered as costs resulting from dam failure and the profits from reconstruction operations are considered as profits in the cost-benefit analysis. In order to analyze the risk of tailings dam failure in the Songun copper mine, the copper mine, the mine processing plant, and the environmental conditions of the Ahar-Varzeghan region were first analyzed and examined. Then, due to the importance of dam characteristics in failure risk analysis, the mine tailings dam was examined. The design and geometry characteristics of the dam wall, dam crown, and dam foundation were examined in detail. The characteristics of the tailing's materials in the Songun copper mine were also analyzed and examined in detail. Then, using the presented model, the risk of failure of the tailings dam of the Songun copper mine was investigated and analyzed. After calculating the probability of failure of the tailings dam, the probability of slope failure was estimated at 8.4%. After that, the probability of dam failure due to overflow was estimated at 46.1%. Obviously, this probability will occur when the tailings dam area is exposed to heavy rainstorms and floods. The probability of waterlogging in the dam foundation was calculated to be zero percent. Which is justifiable considering the characteristics of the foundation, which is composed of volcanic rocks without weathering and joints and cracks. However, according to the probability distribution function of the safety factor of waterlogging failure in the dam foundation, there is a risk of waterlogging in the dam foundation. The probability of foundation failure was also calculated to be zero percent for the same reason in the dam foundation. The probability of waterlogging failure in the dam wall was also calculated to be zero percent. In the dam wall, according to the probability distribution function of waterlogging failure, there is a risk of waterlogging in the dam wall. In the study of the consequences of dam failure, the severity of environmental, social and economic consequences was calculated as 65, 80 and 100 percent, respectively. The results show that in the event of failure, severe economic consequences will be imposed on the region. The model presented in the quantitative analysis of tailings failure risk will be applicable in all mines in the world.

5-1 Conclusion

As mentioned, since several factors are effective in the analysis of tailings dam failure risk, and considering that modeling and examining each of the failure mechanisms due to the behavior of soil mechanics, materials, data uncertainty, and errors in predicting unexpected events will be complex, this article attempted to identify and examine all the factors effective in dam failure while conducting a deep and detailed study of the failed dams. After examining these factors, an attempt was made to present a quantitative model to calculate the probability of failure and its consequences. After reviewing historical data on tailings dam failures, weighting the factors affecting failure, and analyzing the quantitative risk of tailings dam failure at the Songun Copper Mine, the following results were obtained. The physical and chemical properties and characteristics of tailings materials are important factors in the stability of tailings dams, the most important of which are their grain size distribution curve, porosity ratio, consolidation rate, pore water pressure behavior, and shear strength. In a study of 306 tailings dams that failed between 1914 and 2024, it was determined that dam failure due to instability, overflow failure slope, and foundation failure are the most important factors in tailings dam failure. Of the dams whose failure times have been reported, 64 percent of the dams occurred between 1961 and 2000. The highest number of dam failures was reported between 1971 and 1975, with 15.7% of dam failures occurring between 2000 and 2024, a higher rate than between 1961 and 2000, due to unprecedented increases in mineral prices in 2000 and increased mining production.

Among the dams whose mineral type was reported, 52 dams (about 17% of 306) were related to copper mines. Among them, 34.6% of these dams failed due to increased fluidity, 23% due to slope failure, and 15.4% due to foundation failure.

In the study of the factors affecting the failure of tailings dams, four main mechanisms were identified: slope failure, overflow failure, gully failure, and foundation failure.

In the study of the factors affecting tailings failure, it was determined that these factors are not independent of each other and each has its own weight and function, which can vary from mine to mine depending on the type of mineral and the location of the dam.

In determining the weight and function of the four mechanisms, the weight of dam failure due to slope instability was calculated to be 48.9%, overflow failure was 23.7%, foundation failure was 20.4%, and gully failure was 6.9%.

The severity of the consequences of tailings dam failure on the pillars of sustainable development was calculated to be 31% for the environment, 16.8% for the community, and 52.2% for the economy.

In the study of the probability of failure The Songun copper mine tailings dam was presented by the model and, using the structural reliability theory method and Monte Carlo simulator, the probability of slope failure was calculated to be 67.3%, the probability of dam failure due to overflow was 64%, the probability of floodwater behind the dam was 0%, and the probability of abutment failure in the dam body was 99%.

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