Journal of Geomine (2024), 2(1), 21-26
DOI: 10.22077/jgm.2024.8198.1036

Environmental Risk Analysis of Mine Tailings Dam (A Case Study in Iran)

Mohammad Javad Rahimdel[1], Ahmad Aryafar[1]

Recived: 2024 Sep. 27, Revised: 2024 Dec. 02, Online Published: 2024 Dec. 30

ABSTRACT

Mines and mineral industries are vital and strategic resources for every country. However, significant concerns exist regarding the environmental consequences of mining activities, and the severity of these impacts is increasing. The accumulation of mineral tailings, particularly in metal mines during extraction and processing operations, poses a threat to the surrounding land and natural resources. Therefore, it is essential to assess the severity of these hazards and the likelihood of their occurrence in order to develop effective solutions to mitigate adverse consequences. The purpose of this article is to analyze the environmental risks associated with the tailings dam at the Qaleh-Zari Copper Mine using the Failure Mode and Effects Analysis (FMEA) method. To achieve this, first the significant environmental consequences of the tailings dam were identified and then, the severity, probability of occurrence, and probability of detection of these consequences were assessed. Additionally, the importance of each of the aforementioned indicators was determined using the Analytical Hierarchy Process (AHP). Finally, the environmental risks were prioritized. The results indicate that dust dispersion and air pollution, the creation of an unfavorable landscape, and erosion are the most critical environmental consequences of the tailings dam at the Qaleh-Zari Copper Mine.

KEYWORDS

Tailing dam, Environmental risk, FMEA, AHP, Qaleh-Zari Copper Mine

I. INTRODUCTION

Despite the positive contributions of mining—such as increasing national income, fostering economic growth, creating job opportunities, and reducing unemployment and poverty—serious concerns exist regarding the environmental consequences of mining activities. The production and accumulation of substantial amounts of mineral waste during the extraction and processing of minerals pose a significant threat to natural resources. Consequently, tailings dams are constructed near mines to manage, collect, and store waste generated from mineral processing. These tailings dams, which often contain large quantities of tailings, may harbor heavy metals and other hazardous chemicals. The concentration of elements in the tailings frequently exceeds permissible limits set by environmental standards. Such dams represent a major environmental concern associated with mining activities, particularly in cases where the dam's slope is low and a considerable volume of waste material is present (Darban et al., 2018). Sewage from heavy metals contains toxic substances that can infiltrate the surrounding environment, leading to water, soil, and air pollution, ultimately threatening land and natural resources (Hobday, 2003). Therefore, it is essential to assess the risks of environmental damage related to mine tailings dams, prioritize associated hazards, estimate the likelihood of each hazard occurring, and implement operational solutions to prevent the spread of pollution.

In recent years, numerous research studies have been conducted by various researchers to examine the environmental consequences of mine tailings dams. Liu et al. (2015) investigated the risk of pollution to the drinking water sources of Beijing due to the Zhangjiakou tailings dam in China. Their analysis identified a contaminated source and two pools with the highest levels of pollution risk. Additionally, the most significant sources of pollution were determined. Vaezi and Jowdat (2016) explored the potential for pollutant leakage from the tailings dam supports of the Songun copper mine in Iran. This study utilized water sampling, chemical analysis of the samples, and assessments of the permeability of the supporting rock mass and riverbed. The findings indicated that while there is currently no risk of leakage from the dam, increased hydraulic pressure could lead to potential leakage, necessitating the implementation of special measures. Khairkhah and Amiri (2018) assessed the environmental risks associated with the tailings dam at the Songun copper mine using Failure Mode and Effect Analysis (FMEA). They categorized environmental hazards into three groups: physical-chemical, biological, and socio-

---

[1] Department of Mining Engineering, Faculty of Engineering, University of Birjand, Birjand, Iran.
✉ M.J. Rahimdel: rahimdel@birjand.ac.ir

economic. The evaluation of the likelihood of occurrence, intensity, and detectability of each hazard was conducted through field observations and expert judgments. The results highlighted the risk of landscape alteration, seismic activity, and noise pollution as the most critical hazards in the region.

Kaku et al. (2021) investigated the environmental impacts of large-scale gold mining in Ghana. This research utilized the Normalized Difference Vegetation Index (NDVI), along with literature reviews, interviews, and expert opinions. The findings indicated that the area of agricultural land in the studied region decreased by approximately 1%, while the area of fields increased by 21.5% between 2008 and 2015. Additionally, the area's vegetation, land quality, and climate were identified as the most significant threats posed by large-scale gold mining in the studied area. Schafer et al. (2021) investigated the geomechanical risks associated with a tailings dam at a coal mine in Alberta using a generalized Failure Mode and Effects Analysis (FMEA). They presented generalized tables for the four components of the drainage system: the foundation, the body, and the landform of the dam. The aim was to reduce the risk of geomechanical failures that could impact the surrounding environment while focusing on operational and economic solutions. Nišić (2021) assessed the risk of tailings dam failure related to copper and gold mining in western Yugoslavia. This research examined the probability of dam failure based on the safety factor, predicted various states of dam failure and flood flow, and estimated the consequences of dam destruction, including human casualties and the extent of damage. The study also evaluated the effects of such destruction. To assess the risk potential as a function of risk probability and severity, a risk matrix was employed. The findings indicated that nearly 40 individuals are at risk, and the likelihood of dam failure was classified as moderate, representing an acceptable level of risk.

The primary objective of this paper is to analyze the environmental risks associated with the tailings dam at the Qaleh-Zari copper mine in Iran, utilizing the Failure Modes and Effects Analysis (FMEA) method.

The Qaleh-Zari copper mine generates substantial quantities of mineral effluent in the form of slurry on each daily. The slurry produced by the mineral processing facility contains elevated levels of heavy metals, including copper, lead, and zinc. Given that these effluents can impact a broad area, there is a potential for their infiltration into subsurface layers. Consequently, it is essential to evaluate the environmental risks associated with the tailings dam.

FMEA is a systematic approach for identifying potential failure modes within a system and assessing the consequences of those failures. To date, numerous applications of the FMEA method in risk analysis have been documented, including failure risk analysis of LHD machine (Balaraju et al., 2019), risk assessment of belt conveyor system (Burduk et al., 2020), geotechnical risks of tailings dam closure (Schafer et al., 2021), identification of the critical failure modes in mining railcars (Rahimdel and Ghodrati, 2021), and safety risk analysis in coal mining (Wang and Wang, 2022). In the initial step, environmental hazards linked to the tailings dam and their potential consequences are identified. The Risk Priority Number (RPN) for each hazard is determined by evaluating three indicators: the probability of occurrence, severity, and the ability to detect hazards. The significance of each indicator is assessed using the Analytical Hierarchy Process (AHP). AHP is one of the most important multi criteria decision-making tools that has been widely used to determine the importance weights of criteria in decision-making process (Ding et al., 2020). Ultimately, the overall priority of each hazard is calculated based on the Risk Priority Number and its corresponding importance factor.

The structure of this article is organized as follows: In Section 2, the methods of Failure Mode and Effects Analysis (FMEA) and Analytic Hierarchy Process (AHP) are presented. Section 3 discusses the introduction of the Qaleh-Zari copper mine and the significant environmental consequences of its tailings dam. Finally, an environmental risk assessment of the mine's tailings dam is presented and analyzed.

II. RESEARCH METHODOLOGY

In this section, the Failure Modes and Effects Analysis (FMEA) and the Analytic Hierarchy Process (AHP) methods are discussed as research methodology.

A. FMEA method

Failure Modes and Effects Analysis (FMEA) is a structured approach used to identify potential error states within a system and assess the consequences of those errors. This method relies heavily on collaborative teamwork, making it essential to select team members who possess adequate knowledge and experience regarding the system or process being analyzed.

The steps to perform the FMEA method are briefly described below (Chanamool and Naenna, 2016):

- Identification of failure modes
- Identifying the effects of each failure mode.
- Evaluating the ability to detect the severity and occurrence probability of each failure mode.
- Calculating the risk number
- Prioritizing hazards and identifying the most significant consequences

According to the steps outlined above, after identifying each hazard and assessing the probability of occurrence, severity, and ability to detect failure, the risk priority number is calculated. This number indicates the risk associated with each failure. The risk priority number (RPN) is determined using Eq. (1):

$$RPN=O\times S\times D \quad (1)$$

Where, O represents the occurrence of a hazard, S denotes the probability of that occurrence, and D refers to the ability to detect the consequences. The severity of the consequences is defined as the extent of the impact that a potential hazard may have on the environment. It is possible to reduce the severity of these consequences through the implementation of control measures. In this paper, the severity of each consequence is quantified on a scale from 1 to 10, as outlined in Table 1.

To facilitate this assessment, questionnaires have been developed to evaluate the severity, probability of occurrence, and detection capability for each identified risk. Ultimately, the risk number for each outcome is calculated using arithmetic averaging.

B. *AHP method*

Analytic Hierarchy Process (AHP) was first proposed by Saaty (1980). This method is one of the most comprehensive approaches designed for decision-making with multiple criteria. By utilizing this method, it is possible to structure the problem hierarchically. The steps of the AHP method are summarized below (Taherdoost, 2017):

1) *Creating the Problem Hierarchy*

The hierarchy of the problem is a graphical representation of the decision-making process. At the top is the overall goal, followed by the decision criteria and options at the subsequent levels.

2) *Assessing the Significance of Criteria*

The calculation of criteria weights in the AHP occurs in two stages: relative weight and final weight. The relative weight is derived from the pairwise comparison matrix of the decision criteria. The final weight is determined by normalizing these relative weights. Generally, for a decision-making problem with n criteria, the pairwise comparison matrix is represented by Eq. (2).

$$A=\begin{bmatrix} a_{11} & a_{12} & \cdots & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{12} & \cdots & \cdots & a_{nn} \end{bmatrix} \quad (2)$$

Where, a_{ij} is the preference of the ith criterion over the jth criterion.

After creating the pairwise comparison matrix for the decision criteria, the relative weight of each criterion is calculated. In this research, the arithmetic mean method is employed. To achieve this, each column of the pairwise comparison matrix is normalized, and then the weight of each criterion is determined by calculating the average of the elements in each row.

3) *Calculating the Inconsistency Ratio*

In general, the degree of inconsistency in a comparison matrix depends on the decision-making group. Saaty suggests that a consistency ratio (CR) of 0.1 is an acceptable threshold. To assess the inconsistency of the decision, the consistency ratio (CR) is calculated according to Eq. (3).

$$CR=CI/RI \quad (3)$$

Where, CR represents the consistency rate, CI denotes the consistency index, and RI refers to the random index. The consistency index and random consistency index for a pairwise comparison matrix with n criteria are calculated using Eq.s (4) and (5), respectively.

$$CI=((\lambda_{\max}-n))/((n-1)) \quad (4)$$

$$RI=1.98((n-2))/n \quad (5)$$

Where, λ is the eigenvalue of the pairwise comparison matrix.

Table 1. Numerical score for ranking of the severity, probability of occurrence, and detectability of consequences (Ivančan and Lisjak, 2021)

Severity (S)	Occurrence probability (O)	Probability of detection (D)	Numerical score
None	Rarely	Almost certain	10
Very minor	Remote	Very high	9
Minor	Slight	High	8
Very low	Low	Moderately high	7
Low	Moderately low	Moderate	6
Moderate	Moderate	Low	5
High	Moderately high	Very low	4
Very high	High	Remote	3
Hazardous with warning	Very high	Very remote	2
Hazardous without warning	Almost certain	Almost uncertain	1

4) *Modified RPN*

Considering the significance of a hazard's occurrence, the probability of its occurrence, and the ability to detect its consequences, the modified priority number (RPN_M) is calculated using Eq. (6).

$$RPN_M = O^{w_O} \times S^{w_S} \times D^{w_D} \tag{6}$$

Where, the severity of the effect of a hazard, the probability of failure, and the ease of detection are represented by the variables w_O, w_S, and w_D, respectively.

III. RESULTS AND DISCUSSION

In this section, the environmental risks associated with the tailings dam at the Qaleh-Zari copper mine are assessed and discussed. To achieve this, we first present the adverse consequences of the mine's tailings dam, followed by the identification of the most significant environmental hazards using the AHP and FMEA methods.

Qaleh-Zari Copper Mine is located 180 kilometers south of Birjand city in the Southern Khorasan province of Iran, covering an area of approximately 6 square kilometers. The mine employs a shrinkage underground mining method. The copper processing at this site consists of three main stages: crushing, grinding, and flotation. The extracted ore, which is high-quality material, first undergoes crushing operations before being processed as a slurry in the flotation stage. The slurry, combined with chemical compounds, enters the flotation process, where it is separated into light and heavy phases. The heavier part, which settles at the bottom of the slurry flow, is transferred to the mine tailings dam as tailings. The Qaleh-Zari mineral processing plant generates significant amounts of mineral waste in the form of slurry on a daily basis. These slurries contain heavy metals such as copper, lead, and zinc, and are discharged into the surrounding plains near the mineral processing facility. Given that the wastewater produced from mineral processing can affect a wide area, there is a risk of it penetrating the subsurface layers of the earth, potentially contaminating the soil and groundwater in the vicinity of the tailings dam. Therefore, it is essential to investigate the environmental risks associated with this region to identify the adverse consequences of the tailings dam. A view of the wastewater disposal site of the mining processing plant is shown in Fig. 1.

In the initial phase of the research, the most significant environmental hazards associated with mine tailing dams were identified. The primary environmental consequences of these dams include the potential for landslides around the dam, instability of the land slope, increased risk of flooding in the area due to the accumulation of tailings, erosion of the dam, alterations in the direction of surface water flow, changes in the direction of groundwater flow, wind dispersal of dust, air pollution, unpleasant odors emanating from the tailings, sedimentation and settling of tailings, soil contamination surrounding the dam, pollution of surface water, contamination of groundwater, threats to animal life, loss of wildlife habitats, destruction of aquatic ecosystems, noise pollution, adverse effects on agricultural lands, damage to other mining facilities and structures, creation of an unsightly landscape in the region, and risks to the health and safety of local residents.

Fig. 1. A view of the tailing dame of Qaleh-Zari copper mine

To analyze the environmental risks associated with the aforementioned consequences, we evaluated the severity, probability of occurrence, and detectability of these consequences using a questionnaire design. In this approach, we gathered insights from mining experts who are familiar with the environmental conditions of the mining area to complete each questionnaire. Based on their expertise and experience, each expert assigned scores to the parameters of severity, probability of occurrence, and detectability of the environmental consequences. The average numerical values of the scores for these three indicators are presented in Table 2.

To determine the degree of importance for each factor—severity, probability of occurrence, and detectability—a pairwise comparison matrix was constructed based on expert opinions (see Table 2). The degree of importance was then calculated using the AHP method. The results indicated that the weights for severity, probability of occurrence, and detectability were 0.38, 0.33, and 0.29, respectively. To evaluate the consistency of the decisions made, the consistency of the pairwise comparison matrix was assessed. The results showed an inconsistency rate of zero, which is acceptable according to Saaty's criteria (values greater than 0.1 are considered unacceptable).

Table 2. The pairwise comparison matrix

	O	S	D
O	1.00	1.17	1.40
S	0.86	1.00	1.20
D	0.71	0.83	1.00

The average numerical scores for each of the three risk assessment indicators were calculated and are presented in Table 3. In addition, the modified risk preference number is calculated and presented in Fig. 2. According to Table 3, dust dispersion and air pollution exhibit the highest intensity and probability of occurrence, making them easily identifiable. Conversely, changes in the direction of underground water show the lowest values for both intensity and probability of occurrence. Furthermore, it is highly unlikely or nearly impossible to identify this environmental consequence in the mine tailings dam, which has the highest numerical value. As illustrated in Fig. 2, the consequences of wind-induced dust dispersion and air pollution (C7), the creation of an unfavorable landscape in the region (C19), and dam erosion (C4) have the highest risk priority numbers, indicating that they are the most critical environmental consequences. In contrast, the risk of flooding in the region due to the increased volume of tailings, the potential for landslides around the dam, and the instability of the land slope have the lowest risk numbers.

Table 3. The average of numerical scores for the severity, probability of occurrence, and detectability of consequences

Environmental consequence	Severity	Probability	Detectability
Potential for landslides around the dam (C1)	2.86	2.00	2.00
Instability of the ground slope (C2)	2.86	2.14	2.00
An increased risk of flooding in the region due to rising waste volumes (C3)	2.00	2.00	2.14
Dam erosion (C4)	3.14	5.86	5.71
Alterations in the direction of surface water flow (C5)	2.57	2.71	3.14
Changes in groundwater flow (C6)	9.71	2.00	2.00
Wind-induced dust dispersal and air pollution (C7)	2.00	7.86	8.71
Unpleasant odors from the tailings dam (C8)	3.29	5.29	5.86
Sedimentation of tailings (C9)	2.00	6.29	7.00
Soil contamination around the dam (C10)	4.00	4.29	4.71
Pollution of surface water (C11)	3.71	2.86	2.86
Groundwater contamination (C12)	4.14	2.00	2.00
Threats to animal mortality and well-being (C13)	4.86	2.00	2.00
Loss of wildlife habitats (C14)	4.86	2.00	2.00
Destruction of aquatic ecosystems (C15)	4.71	2.00	2.00
Noise pollution (C16)	2.57	4.14	3.57
Contamination and threats to agricultural soils (C17)	4.57	2.86	3.00
Damage to other mining facilities and structures (C18)	3.14	2.29	2.43
An unfavorable visual impact on the area (C19)	2.29	6.86	7.57
Threats to the health and safety of indigenous populations (C20)	2.29	4.57	4.71

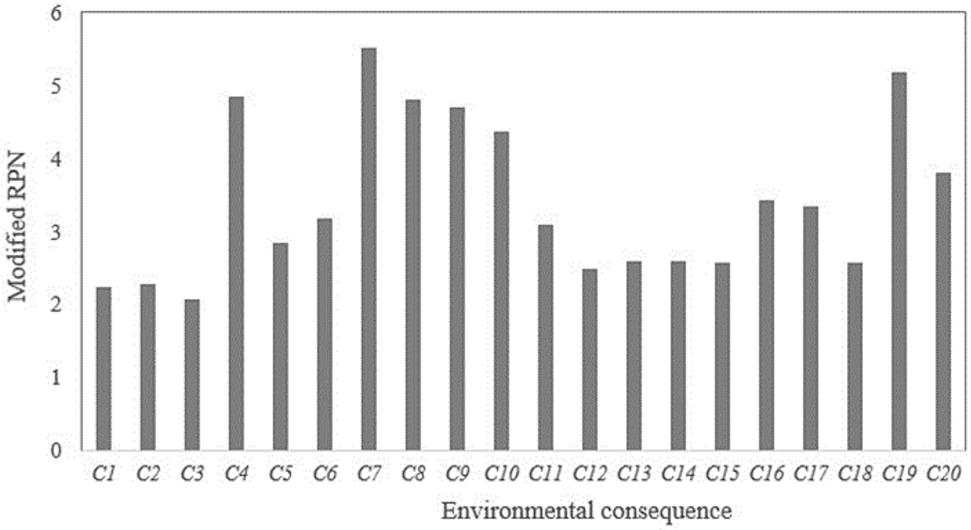

Fig. 2. The modified risk priority number for environmental consequences

IV. CONCLUSIONS

Mines significantly impact the environment, particularly through the accumulation of tailings from mineral processing in tailings dams, which can adversely affect the surrounding ecosystem. The presence of heavy metals in these tailings can lead to numerous negative environmental consequences. This paper investigates the environmental risks associated with the tailings dam of the Qaleh-Zari copper mine in Iran. To achieve this, we first assessed the potential environmental consequences in the study area, followed by an evaluation of the severity, probability of occurrence, and detectability of each consequence. Finally, we determined and discussed the modified risk priority number for these consequences using Failure Mode and Effects Analysis (FMEA) and the Analytic Hierarchy Process (AHP) methods. The results indicate that wind-driven dust dispersion, air pollution, an unfavorable visual impact on the area, and dam erosion pose the highest risks. Therefore, implementing vegetation that is compatible with the local environment can serve as an effective control and corrective measure to mitigate dust spread and prevent erosion of the dam walls.

REFERENCES

Balaraju, J., Raj, M. G., & Murthy, C. S. (2019). Fuzzy-FMEA risk evaluation approach for LHD machine–A case study. Journal of Sustainable Mining, 18(4), 257-268.

Burduk, A., WIĘCEK, D., ZAJAČKO, I., Jurdziak, L., & BŁAŻEJ, R. (2020). Analysis and risk assessment of the supply of copper ore in the belt conveyor system in an underground mine. Acta Montanistica Slovaca, 25(2).

Chanamool, N. and Naenna, T., 2016. Fuzzy FMEA application to improve decision-making process in an emergency department. Applied Soft Computing, 43, 441-453.

Darban, A.K., Webster, R.D., Yarhosseini, H.H., Malekmohammadi, B., & Yavari, A.R. (2018). Environmental Impact Assessment (EIA) of a gold mine tailing through the multi-criteria decision making tool. Journal of Civil Engineering and Environmental Sciences, 4(2), 061-066.

Ding, G., Xin, L., Guo, Q., Wei, Y., Li, M., & Liu, X. (2020). Environmental risk assessment approaches for industry park and their applications. Resources, Conservation and Recycling, 159, 104844.

Hobday, H.B. (2003). Potential for phytoremediation of a metalliferous mine site at Mt. Costigan, NSW, PhD Thesis, Universiy of Technology, Sydney.

Ivančan, J. and Lisjak, D. (2021). New FMEA risks ranking approach utilizing four fuzzy logic systems. Machines, 9(11), p.292.

Kheirkhah, J., & Amiri, M. (2020). Environmental Risk Assessment of Sungun Copper Mine Tailing Dam Using EFMEA Method. Journal of Geography and Environmental Hazards, 8(4), 173-189. doi: 10.22067/geo.v8i4.83225.

Liu, R., Liu, J., Zhang, Z., Borthwick, A., Zhang, K. (2015). Accidental water pollution risk analysis of mine tailings ponds in Guanting reservoir watershed, Zhangjiakou city, China. International journal of environmental research and public health, 12(12), 15269-15284.

Nišić, D. (2021). Preliminary risk assessment of dam failure at the location of the cukaru peki deposit, bor (Serbia). Minerals, 11(10), 1126.

Rahimdel, M. J., & Ghodrati, B. (2021). Risk prioritization for failure modes in mining railcars. Sustainability, 13(11), 6195.

Saaty, T. L. (1980). The analytic hierarchy process. McGraw Hill, New York.

Schafer, H. L., Beier, N. A., & Macciotta, R. (2021). A failure modes and effects analysis framework for assessing geotechnical risks of tailings dam closure. Minerals, 11(11), 1234.

Schafer, H. L., Beier, N. A., & Macciotta, R. (2021). A failure modes and effects analysis framework for assessing geotechnical risks of tailings dam closure. Minerals, 11(11), 1234.

Taherdoost, H. (2017). Decision making using the analytic hierarchy process (AHP); A step by step approach. International Journal of Economics and Management Systems, 2.

Usman Kaku, D., Cao, Y., Al-Masnay, Y. A., & Nizeyimana, J. C. (2021). An integrated approach to assess the environmental impacts of large-scale gold mining: The nzema-gold mines in the ellembelle district of Ghana as a case study. International Journal of Environmental Research and Public Health, 18(13), 7044.

Vaezi, A., & Jowdat Saidabad, Y. (2017). Probably Contamination Seepage Through Abutment of the Tailing Dam of Sungun Cu-Mo Mine Using of Geotechnical Characteristics and Groundwater Hydrogeochemical Evidences. Journal of Civil and Environmental Engineering, 47.3(88), 105-113.

Wang, X., & Wang, H. (2022). Risk assessment of coal mine safety production management activities based on FMEA-BN. Journal of Computational Methods in Sciences and Engineering, 22(1), 123-136.