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Historical Cases of Tailings Dam Failures in Peru: An Analysis of The Triggering Factors

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Abstract

The research focused on determining the main causes of failures in Peruvian mining tailings dams, covering a historical analysis from 1952 to 2023. To this end, an exhaustive review of literature and documents provided by the Geological, Mining and Metallurgical Institute was carried out. (INGEMMET), as well as supervision reports from the General Directorate of Mining (DGM), the Environmental Assessment and Supervision Body (OEFA) and the Supervisory Body for Investment in Energy and Mining (OSINERGMIN), complemented with international data from the CSP2 and WISE Uranium Project bases; and using Google Earth Pro (GEP) to verify the location of the tailing's deposits. The results identified 20 failures in tailings dams in Peru, with 65% of incidents related to seismic activity, where 35% of the cases were directly caused by earthquakes and 30% attributable to short-term induced failures; Likewise, deficiencies in design (25%), construction (20%), and operational or management (10%) were highlighted, while 5% of the failures were caused by problems in auxiliary structures and another 5% remained unidentified. . The main conclusion highlights the need to improve design and construction practices of these structures, especially considering seismic risks, to prevent future disasters in the mining industry. This research contributes significantly to knowledge, providing a basis to improve regulations and practices in the construction and maintenance of tailings dams in Peru.

Keywords: *Participatory Budget, Public Investment Projects, Citizen Participation, Municipal Management, Transparency, Efficiency, Correlation*

INTRODUCTION

Mining is one of the most important and oldest economic activities in the world, playing a crucial role in industrial and technological development (Hancock & Coulthard, 2022). This industry is dedicated to the extraction of valuable minerals from the earth, which are essential for the manufacture of products in sectors such as construction, technology, energy and manufacturing. The extracted minerals, such as copper, gold, silver and iron, are essential to produce electrical cables, electronic devices, batteries and metal structures, among others. However, mining also generates a large number of byproducts and waste, known as tailings, which are the remains of the process of separating valuable minerals from the extracted material. (Islam & Murakami, 2021). These tailings, composed of crushed rock, small amounts of valuable minerals, chemicals and processed water, must be handled with great care to avoid any type of disaster. (Lyu et al., 2019). Improper tailings management can lead to tailings dam failures, releasing toxic material and causing serious environmental and social impacts (Palmer, 2019). Therefore, the correct management of this waste is essential

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not only to minimize the environmental and social impact, but also to guarantee the safety of mining operations and avoid potential risks. Tailings management safety is an ongoing challenge that requires cooperation from industry, regulators and local communities to ensure mining operations can continue safely and sustainably (Rana et al., 2021).

The failure of tailings dams is a catastrophic phenomenon that has occurred worldwide, causing significant human, environmental and economic losses. These critical structures in the mining industry are designed to store waste generated during the mineral extraction process (Islam & Murakami, 2021). Given their essential role, it is essential that these dams are built and maintained to the highest safety standards. For this, various construction methods are used, the most common being the upstream, downstream and centerline method. Each of these methods has advantages and disadvantages, and their choice can significantly influence the stability and safety of the dam over time (Lin et al., 2022).

The upstream tailings dam construction method is one of the most used due to its lower cost and material requirements. In this method, the initial dam is built with compacted borrow materials, and subsequent lifts are carried out using the deposited tailings themselves, advancing in an upstream direction. This method is efficient in terms of costs and materials, but has a greater susceptibility to failure, especially in seismic zones. Worldwide, numerous cases of tailings dam failures with this construction method have been recorded, highlighting the need for proper design, construction and operation. One of the most notorious failures was that of the Bento Rodrigues tailings dam in Brazil in 2015, which resulted in the release of millions of cubic meters of mining waste, causing the death of 19 people and seriously affecting the environment, it is a tragic example of the risks associated with this method, where the combination of insufficient design and seismic activity resulted in a catastrophic collapse (Mei et al., 2022).

The downstream construction method involves construction of the initial dam with compacted borrow materials, followed by successive lifts also downstream. This method requires more material and is more expensive compared to the upstream method, but offers better structural stability, especially under seismic conditions. The dam expands outward, providing a wider, more solid base. However, this method is not without risks. The failure of the Mount Polley tailings dam in Canada, partially built using the downstream method, demonstrated that inadequate management and lack of continuous monitoring can lead to catastrophic failures like the one in 2014, which released approximately 24 million cubic meters of tailings in surrounding rivers and lakes, generating a severe environmental impact. These events have highlighted the importance of implementing better practices and stricter regulations in tailings management.

The centerline construction method is an intermediate approach that combines features of the upstream and downstream methods. The initial dam is constructed from borrowed materials, and successive surveys are performed in such a way that the elevation line remains approximately in the center of the original base. This method offers moderate stability and an intermediate cost between the other two methods. Failures in dams built with the centerline method are less frequent but can occur due to design and management problems. The failure of the Huaybillo tailings facility in Peru, partially built using this method, underscores the need for careful design and constant monitoring to prevent disasters.

In Latin America, the situation is equally worrying. The region is home to some of the largest mines in the world, and with them, many tailings' dams. In 2019, the failure of the tailings dam in Brumadinho, Brazil, was one of the most devastating mining disasters in recent history, resulting in 270 fatalities and irreparable environmental damage. This event highlighted deficiencies in the supervision and control of tailings containment structures, as well as the urgent need for reforms in tailings management policies in the region. Other countries such as Chile and Peru have also experienced significant failures, which have led to growing recognition of the importance of tailings dam stability in environmental protection and community safety (Mei et al., 2022).

In Peru, the mining industry is one of the most important for the national economy, but it has also witnessed several incidents of tailings dam failures. Which are reasons for this study, since, despite advances in technology and the implementation of best practices, tailings management remains a critical challenge.

Deficiencies in the design, construction and operation of tailings dams have been recurring factors in these events.

Because tailings deposits are built to store the greatest volume in the smallest possible area, they are built up as high as their stability and national regulations allow, causing a failure event to produce catastrophic consequences due to the great accumulated potential energy (Lin et al., 2022).

In this research, we will adjust the choice of failure causes to the definition of (Rana et al., 2022), however, not only the variables that act as triggers will be considered in the failure cause list, but also the variables that act with failure conditions.

To address this study, an exhaustive background review was carried out. In this sense (Rana et al., 2022) indicates that worldwide the annual rate of construction of tailings deposits is increasing and at the same time the impact on the facilities, bodies of water and communities located downstream of the tailings deposit. This is due to the increasing global rate of stored volumes.

Tailings dam failures cause not only many victims and material losses, but also great damage to the environment, because the tailings contain a large amount of heavy metals (Punia, 2021). On the other hand, (Clarkson & Williams, 2021) state that retrospective analysis of failure events is invaluable in improving understanding and the ability to anticipate future events. Due to the, it is essential to carry out relevant research on disasters due to failures in tailings dams (Wu et al., 2023).

In the research presented by, (Rana et al., 2022) who conducted a review of existing databases and published research, then adopted multiple estimation and extrapolation approaches to illustrate the range of uncertainty in their results. Furthermore, they indicate that the annual number of tailings pond failures remained relatively constant, while the annual rate of tailings pond construction tripled, therefore, it follows that the cumulative failure rate decreased over time. As a result of the investigation, it was determined that the cumulative failure rate of tailings deposits is between 1.5% and 4.4% at the end of 2020. However, the impact of tailings deposit failures has increased on average throughout the world, especially since 2014, this due to the large volumes stored which is proportional to the increasing global rate of tailings production since 1990. Finally, the authors concluded that heavy rains and intensification of precipitation patterns are statistically causal important of the failures, for this reason they recommend considering the conditions of climate change for the design of the storage capacity and drainage of the facilities.

In research, carried out in China by (Lin et al., 2022) aimed to reveal the causes and regional distribution patterns of 342 tailings dam failures worldwide from 1915 to 2021, through statistical analysis. They obtained information on tailings dam failures from the International Commission on Large Dams (ICOLD), the United Nations Environment Program (UNEP) and the World Energy Information Service (WISE), in addition, they added information related to the type of mine, height of the dam, regrowth method, etc. Tailings pond failures were found to occur with an average of 4.4 accidents/year between 1947–2021. The researchers concluded that the frequency has been gradually increasing in recent years, and that most tailings pond failures are directly related to strong rainfall or earthquakes. They also indicate that most of the failures of tailings deposits in Asia and Europe were related to hydroclimate, while in South America they were caused mainly by earthquakes.

In research conducted in Tokyo, Japan by (Islam & Murakami, 2021) They aimed to update the existing tailings dam failure database developed by the International Commission on Large Dams and the World Energy Information Service. In addition, they analyzed the impacts of dam failure in the last hundred years from a global perspective. To identify the mines, they used GEP, key publications and government reports. The result obtained was a failure rate of 3.45 per year during the period 1915-2020. Finally, the authors concluded that the number of failures is increasing once again, with a much higher incidence for developing countries. Furthermore, they suggested that rainfall and extreme weather events are crucial factors to consider in future research.

At the national level, there is no updated official information on tailings dam failure events throughout the history of Peruvian mining. For this reason, the importance of this work is that the location, date of the event and possible causes of failures in tailings dams in Peru will be identified; Consequently, the door is opened to future research that will allow us to learn about the failure mechanisms, geotechnical parameters, risk factors, monitoring of the identified dams, among other related topics; which is pertinent since Peru does not have regulations for the construction and expansion of tailings dams.

The Current Study

The central objective of this research is to analyze in depth the historical failures of tailings dams in Peru, from 1952 to 2023, with the purpose of identifying and understanding the critical factors that have contributed to these disasters. By using a combination of historical data, literature reviews, technical reports and international databases, it is intended to offer a comprehensive view of the underlying causes that have led to the failure of these structures, paying special attention to seismic events, deficiencies in design, construction and operational management. This study not only seeks to document and analyze these incidents, but also to propose improvements in current regulations and practices for the design and construction of tailings dams, considering seismic risks and other critical geotechnical factors. The results of this work aim to provide a solid foundation for the creation of more effective policies and the implementation of strategies that improve the safety and sustainability of mining operations, thereby minimizing the risk of future disasters and protecting both local communities and to the environment.

METHODS

Participants

Since this study focuses on a historical and technical analysis of tailings dam failures in Peru, no direct human participants are involved in the research process. Instead, a methodology based on the exhaustive review and synthesis of a wide range of previous research, technical reports, and historical data collected over several decades is employed. These sources include empirical and theoretical studies conducted by geotechnical engineers, mining experts, and regulatory agencies, whose work has been instrumental in understanding the dynamics that lead to tailings dam failures. Key reports and case studies were selected, such as the works of ICOLD (2001), WISE Uranium (2008), and the detailed analysis of seismic events related to tailings faults by authors such as Vick (1990) and Blight (2010). In addition, data obtained from supervision and inspection reports carried out by entities such as the Geological, Mining and Metallurgical Institute (INGEMMET), the Environmental Assessment and Supervision Body (OEFA), and the Energy Investment Supervisory Body were incorporated into the review. and Mining (OSINERGMIN). These data include records of documented failures, geotechnical analyses, and physical stability studies of tailings dams. The combination of these sources and data allows the development of a robust analysis framework that integrates both the geotechnical and seismic conditions as well as the operational factors that have influenced historical dam failures in Peru. This approach provides a comprehensive perspective that not only allows us to better understand the causes of these failures, but also propose improvements in the design, construction and operation practices of these critical structures in the mining industry.

Instruments

To carry out this investigation, various instruments and technical tools were used that allowed an exhaustive analysis of the failures in the tailing's dams in Peru. One of the key instruments used was Google Earth Pro (GEP), which allowed the verification and precise mapping of the location of the tailing's dams, as well as the observation of changes in their structure over time using historical satellite images. This software was crucial to visually confirm failure events and to obtain exact geographic coordinates, which were essential for the identification and analysis of documented cases.

Additionally, international databases were used, such as those provided by the International Commission on Large Dams (ICOLD) and the WISE Uranium Project, which were essential to contrast and verify the information collected at the local level. These databases contain detailed records of dam failures worldwide and provided useful comparative context for the research.

The technical and supervision reports obtained from Peruvian institutions such as the Geological, Mining and Metallurgical Institute (INGEMMET), the Environmental Evaluation and Supervision Agency (OEFA), and the Supervisory Agency for Investment in Energy and Mining (OSINERGMIN) were other instruments. crucial. These reports included details on the construction, operation, and monitoring of the dams, and were used to identify possible deficiencies in the design and management of the tailing's dams.

In addition, a systematic recording format was used for data collection and analysis as shown in Table 1, which allowed the information on each failure case to be organized and evaluated in a structured manner. This format included sections for review of design engineering, construction quality control, operational parameters, and potential causes of failure. The combination of these tools and instruments provided a solid basis for detailed analysis and allowed the development of informed conclusions about the causes and possible mitigation measures for tailings dam failures in Peru.

Procedure

The procedure of this investigation was carried out in several stages, each one designed to address different aspects of failure analysis in tailings dams in Peru. Each of them is detailed below:

Search for information

Data collection began with a search for the list of failures in tailings dams in Peru published on the websites of INGEMMET, MINEM, OEFA and OSINERGMIN. Then, INGEMMET conference proceedings, theses and articles with information related to failures in tailings dams in Peru were obtained. In addition, a request for information was sent to the relevant public institution. Through this requirement, public entities provided us with inspection reports on tailings dams with failure events. List of reports in Table 1.

Table 1. Inspection reports obtained through requests for access to public information

Report name	*Fountain*	*Year*
Information on the tailing's fields of Minera Aurifera Retamas S.A. – MARSA - REPORT N°310-96-EM-DGM/DPDM	DGM	1996
Special Supervision Report on Mining Safety and Hygiene to the tailing's deposits and the Escala Riverbed, in the UEA Huachocolpa one, of CÍA Minera Caudalosa S.A. - Report No. 003 - 2010- MINEC/ESP	OSINERGMIN	2010
Special Supervision Report - File No. 201600043411	OSINERGMIN	2016
Special Supervision Report - File No. 201700185865	OSINERGMIN	2017
Special Supervision Report - File No. 201800037488	OSINERGMIN	2018
Special Supervision Report - File No. 201800209550	OSINERGMIN	2018
Special Supervision Report - File No. 201900115438	OSINERGMIN	2019
Unscheduled Inspection Report - File No. 202200014319	OSINERGMIN	2022
Supervision Report No. 431-2018-OEFA/DSEM-CMIN	OEFA	2018
Supervision Report No. 157-2019-OEFA/DSEM-CMIN	OEFA	2019

Likewise, international databases were used to cross-check and verify the information provided by the public institutions on failure cases. It should be noted that information on tailings dams belonging to small and artisanal mining was omitted because they were outside the scope of this investigation.

Mapping and listing of Dams

With the information collected, the first list of tailings dams was obtained, which included 23 incidents. After the respective analysis of the sources, 3 cases were discarded. The cases discarded were Cuajone 2001, because it did not correspond to a tailings dam; Chungar 1971, because the incident was due to the flooding and discharge of a lagoon and not a tailings deposit; and Ananea 2021, because belonging to small mining would be outside the scope of this research. In this sense, for visual confirmation of the dams, determining the exact location and date of failure, use was made of the GEP satellite image explorer, specifically the historical images function. It should be noted that it was not possible to map some of the tailings dams due to the low quality of certain images, the time intervals without images or the information limitations of the cases before 2000; For these cases, it was decided to use as reference the names of the affected rivers, roads or population centers that were mentioned in the limited information, in this way the region, province and district of all the tailings deposits on the list were obtained. Finally, the list of the 20 tailings dams that failed until 2023 was made. Figure 1 shows an example of the use of historical GEP images for visual confirmation of the failure event.

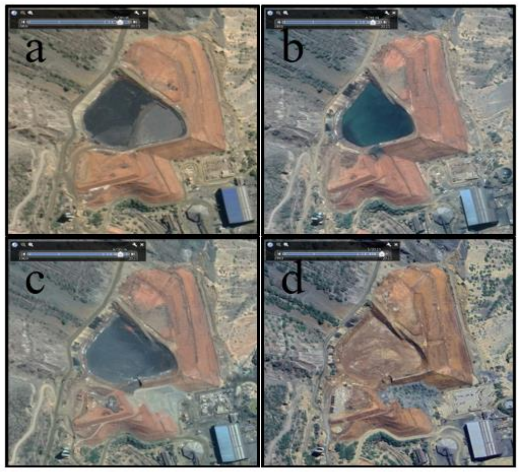

Figure 1. Plan images of the North Area tailings deposit condition on four (04) different dates, close to the failure.

Note. [a] June 30, 2018. [b] June 12, 2019. [c] August 1, 2019. [d] May 31, 2023. Source. GEP.

The list will include the name of the tailings deposit, the location of the deposit (Region, district, province) and the date of failure.

Engineering review for construction, operation and Closure

For this stage, a registration format was used, which included in its first section the general information of the failure cases, in this section the name of the deposit, mining unit, mining owner, benefit concession and a Checklist of all were detailed. the documents collected for each failure case. The Checklist verified whether there was an incident inspection report by the competent authority, design engineering, construction quality report, operations manual, operational parameters, geotechnical monitoring report, physical stability study and topographic plans. Based on this information, it was reviewed whether engineering was available for the construction, operation and closure of the identified tailings deposits.

Description of the event and characteristics of the Tailing's Dams

For this stage, a record format was used, which included in its second, third and fourth sections, the location of the tank, the description of the failure event and the operating parameters of the tank during the failure. With this information, a description of the failure event and the characteristics of the tailings deposits was made, indicating their operating parameters, location, date of failure, type of tailings stored, type of regrowth, operating status, among others.

Identification of possible causes of Failure

Having the list of the tailing's deposits and the registration forms with the pertinent information, the possible causes of failure in each of the cases were analyzed. First, the context in which the failure occurred was studied, first verifying unusual precipitation or earthquakes. Secondly, the design criteria were studied, verifying that principles 4 and 5 indicated by the ICMM are met, which refer to plans and design criteria in the tailing's facility, and to the development of a solid design that minimizes the risks of failure during all phases of the tailing's facility life cycle, respectively. Thirdly, the construction quality reports, and the photographic panel of the inspection reports were studied, verifying that principle 6 oriented towards construction, indicated by the ICMM, which refers to the importance of managing quality, is complied with. and adequacy of construction processes, and the presence of qualified personnel. Fourthly, the operational parameters and the operations manual were studied, verifying those principles 6 and 8 oriented to the operation, indicated by the ICMM, are met, which refer to operating the tailings facility to manage the risk in all phases of their life cycle and establish policies, systems and accountability to support the safety and integrity of tailings facilities, respectively. Finally, the available inspection reports were reviewed in search of less frequent causes of failure such as mine subsidence, melted snow or failure of auxiliary structures.

Analytic Plan

The analysis plan for this research was designed to deeply and rigorously explore how the The analysis plan for this research was structured in several phases in order to comprehensively examine the causes and consequences of failures in tailings dams in Peru, covering a study period extending from 1952 to 2023. The first phase of the analysis consisted of the classification and organization of the collected data, which included both historical failure records and technical reports from various sources. These data were categorized according to key variables such as dam type, construction method, geographic location, date of failure, and identified triggering factors.

In the second phase, descriptive statistical analysis was used to identify patterns and trends in the data. This included the geographic distribution of failures, the timing of events, and the relationship between construction methods and failure incidence. Graphs and tables were generated that illustrated the frequency of failures according to different categories, allowing for clear visualization of the data and identification of critical risk areas.

The third phase of the analysis focused on identifying correlations between the triggering factors and the observed failures. To this end, correlation analyzes were performed to examine the relationship between seismic activity, unusual rainfall, and deficiencies in the design and construction of tailings dams. This analysis made it possible to establish connections between environmental and operational factors with the probability of dam failure

In the fourth phase, a comparative analysis of documented failure cases was carried out, contrasting the results obtained with international standards and best practices recommended by organizations such as the International Commission on Large Dams (ICOLD) and the International Council on Mining. and Metals (ICMM). This comparative analysis helped identify gaps in current practices and provided a basis for recommendations for improvement.

Finally, the fifth phase of the analytical plan consisted of a synthesis and evaluation of the results, in which all the findings were integrated into a theoretical framework that explained the multifactorial causes of failures in tailings dams. Conceptual models were developed that illustrated how interactions between geotechnical, seismic, and operational factors contribute to dam instability. This theoretical framework served as a basis for the formulation of strategies and policies aimed at improving the safety and management of tailings dams in Peru.

RESULTS

Listing Results of Tailings Dams with Failure Events

By visually confirming the location of the tailing's dams using GEP's historical images function, images of most failure cases were obtained. Figure 2 presents some of the most recent cases.

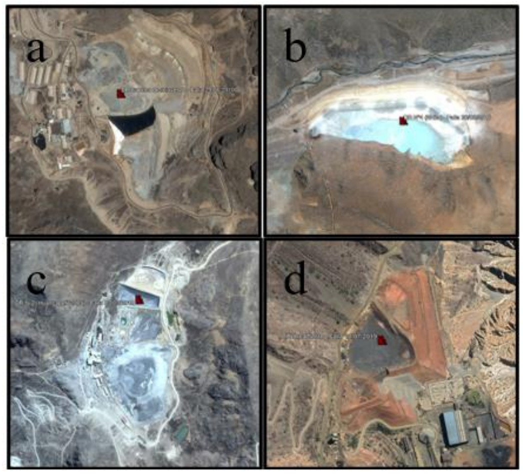

Figure 2. Plan images of four (04) tailings deposits with failure events.

Note. [a] Cancha A tailings deposit with failure date of 06/25/2010. [b] Tailings deposit No. 4 with failure date of 03/26/2016. [c] Tailings deposit No. 2 with failure date of 03/03/2018. [d] North Area tailings deposit with failure date of 07/10/2019. Fountain. GEP.

From the review described in the previous section, a total of 20 cases of failure in tailings dams were obtained. The name of the tailings deposit, the location and the date of the failure were extracted from the articles, theses, databases and institutional information. It is necessary to mention that there were limitations when collecting information before 2007, because there are no publications related to these failures and the public institutions that have information related to tailings dams such as OSINERGMIN and OEFA were created on year 2007 and 2008, respectively. Table 2 summarizes the 20 failure cases studied.

Table 2. Cases of failure of tailings dams in Peru: 1952-2023

Tailings deposit	***Location (Region, province, district)***	***Failure date***
Huaybillo	*Puno, Lampa, Paratía*	*24/01/2022*
North Area	*Huancavelica, Churcapampa, San Pedro de Coris*	*10/07/2019*
TSF	*Cajamarca, Hualgayoc, Hualgayoc*	*16/12/2018*
No. 2	*Áncash, Aija, Aija*	*03/03/2018*
Filtered Yuracyacu	*La libertad, Pataz, Parcoy*	*29/10/2017*
No. 4	*Arequipa, Castilla, Chachas*	*26/03/2016*
Tailings field A	*Huancavelica, Huancavelica, Huachocolpa*	*25/06/2010*
*amethyst **	*Arequipa, Caravelí, Acarí*	*12/11/1996*
*Caravelí **	*Arequipa, Caravelí, Huanuhuanu*	*12/11/1996*
Tailings fields 3A and 3B	*La libertad, Pataz, Parcoy*	*31/03/1993*
*Saint Nicholas **	*Cajamarca, Hualgayoc, Bambamarca*	*12/06/1980*
Tailings field No. 2 (Ticapampa)	*Ancash, Recuay, Ticapampa*	*27/11/1971*
*Atacocha**	*Pasco, Pasco, San Francisco de Asís de Yarusyacán ó Yanacancha*	*1971*
Almivirca (Event 2)	*La libertad, Santiago de Chuco, Quiruvilca*	*31/05/1970*
recovered	*Huancavelica, Huancavelica, Huachocolpa*	*1969*
Yauliyacu	*Lima, Huarochirí, Chicla*	*28/09/1968*
Almivirca (Event 1)	*La libertad, Santiago de Chuco, Quiruvilca*	*18/04/1962*
Tailings field No. 3 (Milpo)	*Pasco, Pasco, San Francisco de Asís de Yarusyacán ó Yanacancha*	*29/10/1956*
Casapalca (Event 2)	*Lima, Huarochirí, Chicla*	*1952*
Casapalca (Event 1)	*Lima, Huarochirí, Chicla*	*1952*

Note. *Referential name found in old books or conference minutes.

Review of documents relevant to the Investigation

To evaluate the causes of failures, the available historical information has been reviewed, see Table 3. In this sense, the definition and evaluation of the causes of failure were conceptualized based on the elements:

ANT (Background: Theses, conference proceedings, scientific articles, ICOLD bulletins and/or international databases)
IF (Inspection reports obtained through a request for access to public information to the MINEM, the OSINERGMIN or the OEFA)

ING (Design engineering: Geotechnics, hydrology, civil-hydraulic design)
CQA/CQC (Construction Quality Control or Construction Quality Assurance)
MO (operations manual or deposit risk management)

Table 3. Information collected and evaluated from tailings dam failure cases

Tailings deposit	*ANT*	*IF*	*ING*	*CQA/CQC*	*MO*
Huaybillo	*No*	*Yaeh*	*Yaeh*	*No*	*Yaeh*
North Area	*Yaeh*	*Yaeh*	*Yaeh*	*No*	*Yaeh*
TSF	*No*	*Yaeh*	*Yaeh*	*No*	*Yaeh*
No. 2	*Yaeh*	*Yaeh*	*Yaeh*	*Si*	*No*
Filtered Yuracyacu	*No*	*Yaeh*	*Yaeh*	*No*	*Yaeh*
No. 4	*No*	*Yaeh*	*Yaeh*	*No*	*No*
Tailings field A	*Yaeh*	*Yaeh*	*No*	*No*	*No*
*amethyst **	*Yaeh*	*No*	*No*	*No*	*No*
*Caravelí **	*Yaeh*	*No*	*No*	*No*	*No*
Tailings fields 3A and 3B	*Yaeh*	*Yaeh*	*No*	*No*	*No*
*Saint Nicholas **	*Yaeh*	*No*	*No*	*No*	*No*
Tailings field No. 2 (Ticapampa)	*Yaeh*	*No*	*No*	*No*	*No*
*Atacocha**	*Yaeh*	*No*	*No*	*No*	*No*
Almivirca (Event 2)	*Yaeh*	*No*	*No*	*No*	*No*
recovered	*Yaeh*	*No*	*No*	*No*	*No*
Yauliyacu	*Yaeh*	*No*	*No*	*No*	*No*
Almivirca (Event 1)	*Yaeh*	*No*	*No*	*No*	*No*
Tailings field No. 3 (Milpo)	*Yaeh*	*No*	*No*	*No*	*No*
Casapalca (Event 2)	*Yaeh*	*No*	*No*	*No*	*No*
Casapalca (Event 1)	*Yaeh*	*No*	*No*	*No*	*No*

Description of failure events and possible causes

Failure of the Huaybillo tailings deposit – El Cofre

On January 24, 2022, at 5:00 p.m., the spill of course and fine tailings from the Huaybillo tailings deposit occurred, as a result of the slide of the main dam and part of the basin, in a volume estimated by the owner of 1,106.26 m3. in an area of 2,714.41 m2. The Huaybillo tailings deposit is in the Paratía district, Lampa province, Puno region; In UTM projection and WGS 84 datum its coordinates are E: 328366, N: 8291595, zone 19 South. Figure 3 shows the condition of the dam 3 days after failure.

Figure 3. Gap covered with geomembrane after carrying out temporary repair on the main slope - northern area of the Huaybillo tailings deposit.

Note. Adapted from the Unscheduled inspection report, carried out from January 26 to 28, 2022 (p. 65) [Photograph], by OSINERGMIN

Tailings Dam Characteristics

The starting dam was built with thick cyclone tailings and by the centerline swell method. The tailings pond stored a tailings volume of 879,483.23 m3 of the conventional type, the tailings pond basin had an area of 13.18 ha, and approximately 60% of the basin was covered with geomembrane. In addition, 1.31 ha of basin area was occupied by a sludge zone. The slopes of the main dam and perimeter of the Huaybillo tailings deposit were covered with non-woven geotextile and 1.5 mm thick LLDPE Geomembrane. It should be noted that the tailings deposit was undergoing closure work.

Possible causes of the Event

Consecutive rainfall on January 16, 17, 18, 19, 20, 21, 22, 23 and 24, 2022 in a range of 2 to 7.5 hours.

Unfinished closure activities, such as the installation of 1.5mm LLDPE geomembrane with anchor trenches in the crown of the main dam and semi-open perimeter dam awaiting geocells.

In the detailed engineering for closure of the tailings deposit, rainfall was not considered during closure and post-closure activities.

Not updating the operations manual and Contingency Plan for the conditions of the Huaybillo tailings deposit.

Failure of the North Area tailings deposit - Cobriza

On July 10, 2019, a spill of water and tailings from the North Area tailings deposit occurred, because of the failure of its lateral dam. The water and tailings were channeled towards the electrical substation of the processing plant, damming in an old maintenance workshop, breaking the 1.0 m high safety berm into two sectors and finally reaching the downstream slope of the stream until reaching the Mantaro River. The North Area tailings deposit is in the San Pedro de Coris district, Churcampa province, Huancavelica region; In UTM projection and WGS 84 datum its coordinates are E: 567903, N: 8608358, zone 18 South. Figure 4 shows the condition of the dam 02 days after the failure.

Figure 4. View of the breach in the dam 2 days after the failure in the North Area tailings deposit.

Note. Adapted from the Special Supervision Report carried out from July 12 to 14, 2019 (p. 83) [Photograph], by OSINERGMIN

Tailings Dam Characteristics

The North Area tailings deposit was made up of the dam, the basin, the drainage system and the subdrainage system. The dam is the main structure for retaining the deposited tailings, it is located to the east of the tailings deposit, it was built in an "L" shape with loan material compacted by the upstream swell method and for greater detail of the Geometric parameters of the dam This was divided into two areas called frontal dam and lateral dam. On the other hand, the tailings tank basin was waterproofed with a 2.0 mm thick HDPE geomembrane.

On the upstream slope of the Frontal and Lateral dams of the North Area tailings deposit, a drainage system composed of steel settling quenas has been installed. The infiltration waters from the North Area tailings deposit are captured through a subdrain structure made up of a set of main drains composed of perforated HDPE pipes of 6.00 inches in diameter and secondary drains composed of perforated HDPE pipes of 4.00 inches in diameter. diameter that connects to the main drains forming a herringbone-type collection network.

Possible causes of the event

Disposition of the tailings from the southwest sector adjacent to the hill and opposite end to the front dam, which caused the water mirror to be in contact with the slope upstream of the front dam and side dam. See Figure 5.

The reflecting pool occupied an area of 33,500.00 m2, which represents 79.85% of the total area of the basin of the North Area tailings deposit, which would have had an impact on the stability of the deposit.

The design did not consider the need to move the water body further away from the dam. Likewise, in the last physical stability study, the contact of the slope upstream of the dam with the water body was not considered.

Figure 5. View of the water mirror in contact with the dam in the North Area tailings deposit.

Note. Adapted from the Operational Supervision Report carried out from May 18 to 22, 2019 (p. 123 and 124) [Photograph], by OSINERGMIN

Failure of the TSF tailings deposit – Carolina N°1

On December 16, 2018, water containing tailings was spilled from the TSF tailings deposit into the La Grass ravine, from a drainage pipe due to possible tailings filtration. It should be noted that the tailings dam maintained its conditions. of stability despite said event. The TSF tailings deposit is in the Hualgayoc district, Hualgayoc province, Cajamarca region; In UTM projection and WGS 84 datum its coordinates are E: 760632, N: 9251709, zone 17 South.

Tailings Dam Characteristics

The TSF tailings deposit is made up of the Las Gordas, Las Águilas, and Las Hierbas dams, three containment layers UCB, Rhyolite RCB and Sur SCBS in the dam and a drainage system. The 3 dams of the TSF tailings deposit were built with borrow material (quarry material and mine waste) formed by compaction and the regrowth method was centerline. The Las Gordas, Las Águilas and Las Hiervas dams had a length of 375.0 m, 295.0 m and 759.00 m respectively, forming a single dam of 1,429.00 m in length at crown level. The water collected from the seepage flows of the drainage system of the TSF tailings deposit dam is transported to the blanket drains installed at the base of the Las Gordas, Las Águilas and Las Hierbas dams, conducting the flow to the pools. LVU Las Gordas and Las Águilas.

Possible causes of the event

The elevation of the TSF reservoir to a level of 3,778.0 meters above sea level, caused the tailings with water to connect with the water table (vertical flow) through a fracture; and then with the Las Tomas Remnant Water Diversion System, which is buried and, on its way, passes under the TSF tailings deposit, which led to the occurrence of the incident. More details of the possible conditions that caused the spill in Figure 6.

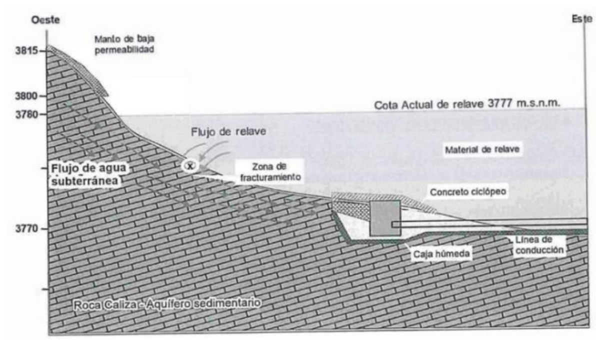

Figure 6. Descriptive profile of the possible conditions that caused the TSF tailings deposit spill.

Note. Adapted from the Special Supervision Report carried out on December 17, 2018 (p. 29).

Failure of tailings deposit No. 2 – Huancapetí 2009

On March 3, 2018, a tailings spill occurred from tailings deposit No. 2, because of the sliding of the frontal dam from the progressive 0+539.20 m to the progressive 0+566.20 m (length of 27.04 m). Tailings deposit No. 2 is in the district of Aija, province of Aija, Ancash region; In UTM projection and WGS 84 datum its coordinates are E: 222578, N: 8921378, zone 18 South.

Tailings dam characteristics

Tailings deposit No. 2 is made up of two (02) dams called lateral and frontal with lengths of 301.30 m and 264.90 m respectively, which are joined in an L shape. See Figure 7. The lateral dam was built with quarry material, and the front dam, called overlift with thick cyclone tailings, was built in two (02) phases with two types of materials. In phase I, the frontal dam was built with loan material formed by compaction and was called the start dam, which was built up to the level of 4,508.77 meters above sea level; and phase II was built with compacted coarse tailings material for the build-up of the starting dam, also called raising with cyclone coarse tailings, for which they used the downstream build-up system. The slope upstream of the lateral and frontal dam was waterproofed with 1.5 mm thick HDPE geomembrane.

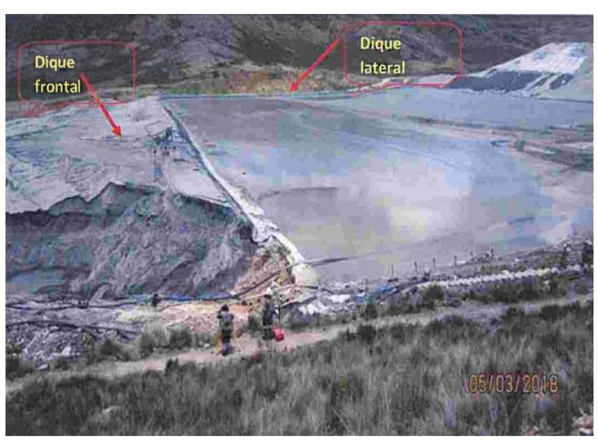

Figure 7. View of the front and side dams of tailings deposit No. 2 joined in an L shape after failure.

Note. Adapted from the special supervision report carried out on March 4, 2018 (p. 70) [Photograph], by OSINERGMIN

The foot of the dam is built with compacted borrow material. The filtration waters from the tailings deposit No. 2 are captured through a herringbone-type subdrainage structure, then they are conveyed to two (02) subdrainage water collection ponds of 150 m3 each. The East crown canal has a length of 1,232 m, with a trapezoidal section of 0.60 x 0.60 m. Likewise, the West crown canal has a length of 1,200.0 m, with a trapezoidal section of 0.50 x 0.50 m. Both channels are waterproofed with 1.5 mm thick HDPE geomembrane.

Possible causes of the Event

The reflecting pool was close to the frontal dam, when the minimum distance from the beach was 40.0 m according to the recommendation of the last physical stability study.

The free edge was 0.97 m before the collapse, when according to the authorized design it should have been 1.00 m.

Lack of anchoring of the 1.5 mm HDPE geomembrane on the left abutment in the contact area of the dam with the hillside, in addition to the lack of evidence of welding at the junction of the geomembrane of the dam's rise. (elevation 4,512 masl) with the geomembrane from the previous stage (starting dam crown elevation 4,508 masl).

Failure of the Yuracyacu tailings deposit - Parcoy Accumulation N°1

On October 29, 2017, at 09:00 a.m., the tailings spill occurred from the Yuracyacu filtered tailings deposit, because of the clogging of the area adjacent to the slope upstream of the dam with fine tailings and its subsequent overflow, the tailings Overflowed, they moved by gravity towards the fruit tree plantations located downstream of the West side containment dam and a sector of the Yuracyacu annex. The Yuracyacu filtered tailings deposit is in the Parcoy district, Pataz province, La Libertad region; In UTM projection and WGS 84 datum its coordinates are E: 223195, N: 9122204, zone 18 South.

Tailings dam characteristics

The Yuracyacu filtered tailings deposit is made up of a containment dam and the tailings deposit basin. The containment dam, in its first stage, was built with compacted borrow material, the slope upstream of the containment dam has a screen drain with a thickness of one meter, made up of gravel, confined with biaxial geogrid and non-woven geotextile with installation of 6-inch HDPE perforated pipes at the base to capture the infiltrated waters and convey them to the drainage pond located downstream of the West side containment dam. The owner does not dispose of filtered tailings in the tank basin when there is rainfall; in this case the filtered tailings are stored in the drying yard of the filtering plant.

Possible causes of the event

Poor supervision of the Yuracyacu filtered tailings deposit, since at the beginning of work on the day of the incident the tailings dam supervisor did not inspect the basin and the crown of the dam, only the area of the subdrainage pond. According to the Operations Manual and Contingency Plan, the visual check of the tailing's disposal levels should have been carried out on a daily basis.

Lack of control of runoff water on the natural slope on the north side, between the crown channel and the tailings deposit. Consequently, the circulation of runoff waters occurred through the embankment slopes formed by the filtered tailings. See Figure 8.

Having exceeded the number of fines in the filtered tailings that make up the embankments arranged in the tailings deposit, with respect to the standard established in the operations manual, facilitating the erosion and circulation of the fine tailings.

The fine tailings that circulated with the water from the rainfall covered the drainage screen built on the slope upstream of the containment dam, not allowing drainage through this medium.

Figure 8. View of the distance between the crown channel and the Yuracyacu filtered tailings deposit, with drainage of uncontrolled runoff water in said section.

Note. Adapted from the Report of the special supervision carried out on November 3, 2017 (p. 82) [Photograph], by OSINERGMIN.

Failure of tailings deposit No. 4 - Shila

On March 26, 2016, at 06:30 a.m., the tailings stored in tailings deposit No. 4 were discharged, because of the movement of the containment dam downstream, corresponding to the section: progressive 0+013.80 - progressive 0+030.60. The saturated tailings from the basin and dam reached the Collpamayo River and sectors adjacent to tailings deposit No. 4. The opening of the tailings dam and the cavity of the basin were left with almost vertical slopes, due to the presence of silt and the consolidation process of the tailings. See Figure 9. Tailings deposit No. 4 is in the district of Chachas, province of Castilla, Arequipa region; In UTM projection and WGS 84 datum its coordinates are E: 810945, N: 8301593, zone 18 South.

Figure 9. View of the breach of the tailings deposit No. 4 dam, with an almost vertical slope.

Note. Adapted from the special supervision report carried out on March 28, 2016 (p. 62) [Photograph], by OSINERGMIN

Tailings dam characteristics

Tailings deposit No. 4 had a dam built with thick cyclone tailings and a stabilization buttress built with compacted borrow material, made up of three benches with heights between 5.00 m to 7.00 m, with a total height of 17.00 m, The deposit had been without tailings disposal since June 2013.

Possible causes of the event

Not presenting compaction controls related to the construction of the dam.

The percentage of water surface area indicated in the design was exceeded.

Cuts were observed in geomembranes and sprinkler pipes. These cuts allowed water to enter the southwest sector of the basin, so it is presumed that the event was due to the intervention of third parties.

Failure of tailings deposit A - Huachocolpa Uno

On June 25, 2010, at 6:00 p.m., a water leak suddenly occurred along the slope of the southern side of tailings deposit A, approximately 1.00 m below the crown of the dam. This fact caused the erosion and slide of the slope, causing a gap with an opening of 41.50 m and the spillage of the tailings into the basin of the new tailings deposit C, being filled. See Figure 10. The overflow discharged into the bed of the Escalera River, running along the cause in a stretch of approximately 3.50 km. The impacted area consists of terraces located on both banks of the river. Tailings deposit A is in the Huachocolpa district, Huancavelica province, Huancavelica region; In UTM projection and WGS 84 datum its coordinates are E: 501255, N: 8556021, zone 18 South.

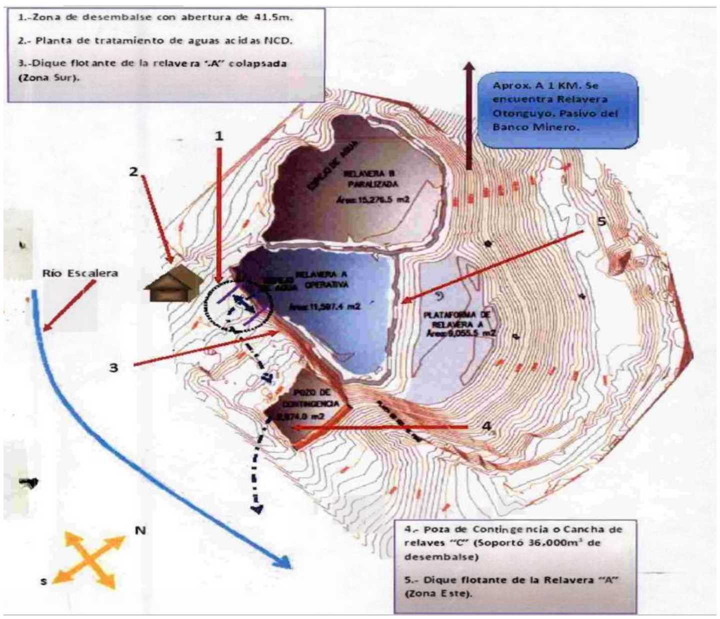

Figure 10. Sketch with the location of the relevant areas of the failure event.

Note. Adapted from the Report on special supervision of mining safety and hygiene to the tailing's deposits and bed of the Escalera River, carried out on June 30, 2010 (p. 179) [Croquis], by OSINERGMIN

Tailings dam characteristics

Tailings deposit A was located between tailings deposit B and the new tailings deposit C. For operational reasons, the regrowth of the dam of tailings deposit A and tailings deposit B was carried out alternately. The growth of tailings dam A is made up of a triangular configuration of dam sections: East side dam (main), North dam (adjacent to tailings dam B) and South Floating Dam (adjacent to tailings dam C). Likewise, the location of tailings dam B shows a higher elevation compared to tailings dam A, and tailings dam C shows a lower elevation than tailings dam A. The increase in the southern floating dam of the tailings deposit "A" was built with thick tailings and in some sections, it was mixed with borrowed material. Likewise, the dam is a structure with a trapezoidal section and a non-uniform conformation.

The drainage system of tailings dam "A" corresponds to two drainage chimneys (decantation quenas), arranged at the rear end of the deposit and at the west end of the South dam. The discharges from said quenas are located on the location of the tailings dam C basin, close to the perimeter of the foot of the slope downstream of the collapsed section.

Possible causes of the event

Inefficient water management system, allowed water to enter the tank, causing a free edge of 0.1 m to 0.2 m.

Operational slope downstream of the South zone floating dam, higher than usual for thick tailings material.

Inefficient contingency system, it did not prevent excessive storage of the tank with tailings water, causing a length of beach that remained in critical condition and an area of the water mirror that represents 90% of the area of the basin.

Lack of technical file above the level of 4,360.5 meters above sea level, which specifies the regrowth criteria and operational parameters.

The conformation characteristics of the dam material, the heterogeneity of the dam body and the absence of a starter dam at its base generated differential settlements.

Failure of the Amethyst Tailings Deposit

On November 12, 1996, the Amatista tailings deposit spilled, because of the liquefaction of the tailings dam during the Nazca earthquake, which had a magnitude of 7.5. The tailings spill traveled approximately 600 m, reaching the Acari River and contaminating farmland. It is estimated that the volume of spilled tailings was 600,000.00 m3. The deposit is in the Acari district, Caravelí province, Arequipa region. Based on the available data, it was not possible to determine the exact location, however, due to its proximity to the Acari River, it is presumed that in UTM projection and WGS 84 datum its coordinates are E: 545108, N: 8307768, zone 18 South.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

The information obtained from (Fernández, 1982) and (Carrillo & Carrillo, 1998) indicates an earthquake as the cause of the failure event.

Failure of the Caravelí tailings deposit

On November 12, 1996, a tailings spill occurred from the Caravelí tailings deposit, because of the Nazca earthquake, which had a magnitude of 7.5. Due to this, the area was contaminated with cyanide and mercury present in the released tailings. The deposit is in the Huanuhuanu district, Caravelí province, Arequipa region. Based on the data available, it was not possible to determine the exact location of the tailings deposit.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

The information obtained from (Fernández, 1982) and (Carrillo & Carrillo, 1998) indicates an earthquake as the cause of the failure event.

Failure of tailings deposit 3A and 3B - Retamas

On March 31, 1993, a tailings spill occurred from tailings deposits 3A and 3B. As the tailings moved through the Mush Mush ravine and along the bed of the Llacuabamba river, 7 people lost their lives. Likewise, this event partially destroyed farms, eucalyptus plantations and the Chulcos – Llacuabamba highway. Likewise, plant facilities, laboratories and offices were damaged. The deposit is located in the Mush Mush area, Parcoy district, Pataz province, La Libertad region. Based on the data available, it was not possible to determine the exact location of the tailings deposit, however, due to its proximity to the Llacuabamba River, it is estimated that in UTM projection and WGS 84 datum its coordinates are E: 233161, N: 9108799, zone 18 South; place where the Integrated San Andrés tailings deposit is currently located.

Tailings dam characteristics

Tailings fields 3A and 3B were located between 3,890 to 3,930 meters above sea level. The tailings dam containment system is made up of a starting dam built with compacted borrow material to withstand the initial pressure of deposition of slats and water. The construction work on the dams was carried out between the months of February and September 1990.

Possible causes of the event

Intense rains in the area during the month of March, which contributed to the increase in the water body of the tailing's dams, and when a torrent of water from the upper part of the surrounding hill rushed in and entered violently, causing the edge to break. free, part of the tailings immediately sliding down the Mush Mush ravine (General Directorate of Mining, 1993). It was a consequence of the overtopping and subsequent erosion of the slope of the tailings dam, this suggests that the possibility of intense rains had not been foreseen in the design.

Failure of the San Nicolás tailings deposit

On June 12, 1980, the San Nicolás tailings deposit spilled because of the rupture of its tailings dam. The event contaminated the waters of the Tingo River, a tributary of the Maygasbamba River, giving rise to the exalted claim. According to the residents of the area, the escape of fine sand was 200 to 300 tons. The deposit is in the district of Bambamarca, province of Hualgayoc, Cajamarca region. Based on the data available, it was not possible to determine the exact location of the tailings deposit, however, it is presumed that in UTM projection and WGS 84 datum its coordinates are E: 760110, N: 9254583, zone 17 South.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

The collapse was due to the deficiency in the construction of the dam (Fernández, 1982).

Failure of tailings deposit No. 2 - Ticapampa

On November 27, 1971, in the early morning, a tailings spill occurred from tailings deposit No. 2, because of the rupture of a part of its concrete dam, causing 9,000 tons of tailings to slide. These had been deposited in a ravine and when the retaining wall broke, they traveled 1.5 km. This event caused the death of three people, the destruction of homes, the flooding of farmland and the interruption of the Lima-Huaraz highway. Tailings deposit No. 2 is in the district of Ticapampa, province of Recuay, Ancash region. Based on the data available, it was not possible to determine the exact location of the tailings deposit, however, due to its proximity to the town of Ticapampa and its location in a ravine, it is presumed that in UTM projection and WGS 84 datum its coordinates are E: 231908, N: 8920821, zone 18 South.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

The causes of the collapse were due to the poor location of the tailings deposit, as it was in an abrupt ravine with inconsistent soil. Furthermore, the poor construction of the retaining walls, poor collection of runoff water and poor decantation due to lack of drainage pipes in the lower part were factors that conditioned the collapse (Fernández, 1982).

Failure of the Atacocha tailings deposit

In 1971, a tailings spill occurred from the Atacocha mine deposit, because of the rupture of a part of its concrete dam, causing the discharge of 100,000 tons of tailings, which contaminated the Huallaga River and damaged road infrastructure. (Fernández, 1982). The deposit is in the San Francisco de Asís district of Yarusyacán, Pasco province, Pasco region. Based on the data available, it was not possible to determine the exact location of the tailings deposit, however, it is presumed that in UTM projection and WGS 84 datum its coordinates are E: 366964, N: 8831146, zone 18 South.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

The failure event occurred due to the lack of structural closure in the construction of the sewer (Fernández, 1982), therefore drainage problems manifested (Carrillo & Carrillo, 1998). There is no exact location or date of the failure of the tailings deposit, therefore, it was not possible to verify its relationship with an earthquake. Likewise, the available sources do not give indications that the fault had seismic causes.

Failure of the Almivirca – Quiruvilca tailings deposit (Event 2)

On May 31, 1970, a tailings spill occurred from the Almivirca tailings deposit, as a consequence of the earthquake that occurred on the same date (Fernández, 1982). The deposit is located in the district of Quiruvilca, province of Santiago de Chuco, La Libertad region. Based on the data available, it was not possible to determine the exact location of the tailings deposit.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

The information obtained from (Fernández, 1982) and (Carrillo & Carrillo, 1998) indicates an earthquake as the cause of the failure event.

Failure of the Retakeda tailings deposit

In 1969, the recuperada tailings deposit spilled, the tailings invaded the Huachocolpa cement factories and caused damage to their agriculture. The deposit is in the Huachocolpa district, Huancavelica province, Huancavelica region. Based on the data available, it was not possible to determine the exact location of the tailings deposit, however, it is estimated that in UTM projection and WGS 84 datum its coordinates are E: 506129, N: 8552906, zone 18 South.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

There is no record from other authors about the possible causes of the failure event. There is a record of major earthquakes in the months of July, August, September and October of 1969, and with an epicenter less than 152.76 km from the tailings deposit. However, the exact date of the failure is not available, therefore, it was not possible to verify its relationship with an earthquake.

Failure of the Yauliyacu tailings deposit

In 1968, the Yauliyacu tailings deposit spilled, the tailings dam suffered a failure due to a collapse on the south side of the ridge (Fernández, 1982). The deposit is located between kilometers 111 and 117 of the Central Highway, in the district of Chicla, province of Huarochirí, Lima region. Based on the data available, it was not possible to determine the exact location of the tailings deposit, however, it is estimated that in UTM projection and WGS 84 datum its coordinates are E: 362773, N: 8708440, zone 18 South.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

(Fernández, 1982) and (Carrillo & Carrillo, 1998) confirm an earthquake prior to the failure of the tailings deposit. However, the geotechnical, construction or operational factors that caused the failure are unknown.

Failure of the Almivirca – Quiruvilca tailings deposit (Event 1)

On April 18, 1962, a tailings spill occurred from the Almivirca tailings deposit, due to a seismic movement of grade 6.7 on the Richter scale, preceded by three months of heavy rains. After which special investigations were carried out and the necessary measures were taken to avoid future collapses (Fernández, 1982). The deposit is in the district of Quiruvilca, province of Santiago de Chuco, La Libertad region. Based on the data available, it was not possible to determine the exact location of the tailings deposit.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

The information obtained from (Fernández, 1982) and (Carrillo & Carrillo, 1998) indicates that an earthquake preceded by heavy rains were causes of the failure event.

Failure of the Almivirca – Quiruvilca tailings deposit (Event 1)

On April 18, 1962, a tailings spill occurred from the Almivirca tailings deposit, due to a seismic movement of grade 6.7 on the Richter scale, preceded by three months of heavy rains. After which special investigations were carried out and the necessary measures were taken to avoid future collapses (Fernández, 1982). The deposit is in the district of Quiruvilca, province of Santiago de Chuco, La Libertad region. Based on the data available, it was not possible to determine the exact location of the tailings deposit.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

The information obtained from (Fernández, 1982) and (Carrillo & Carrillo, 1998) indicates that an earthquake preceded by heavy rains were causes of the failure event.

Failure of tailings deposit No. 3 - Milpo

In 1956, the tailings deposit No. 3 spilled because of the collapse of its dam, causing the death of several people, causing environmental damage and interrupting the Pasco - Huánuco highway. The deposit is in the San Francisco de Asís district of Yarusyacán / Yanacancha, Pasco province, Pasco region. Based on the data available, it was not possible to determine the exact location of the tailings deposit.

Tailings dam characteristics

There is no evidence of the characteristics of the tailings deposit prior to the failure.

Possible causes of the event

The information obtained from (Fernández, 1982) and (Carrillo & Carrillo, 1998) indicates an earthquake as the cause of the failure event.

Failure of the Casapalca tailings deposit (Event 2)

In 1952, a tailings spill occurred from the Casapalca tailings deposit, causing numerous deaths and contamination of the Rímac River (Fernández, 1982). The tailings deposit is located on the right bank of the Rímac River, at km 117 of the Central Highway at 4170 meters above sea level, in the district of Chicla, province of Huarochirí, Lima region (Parra & Pérez, 1998); In UTM projection and WGS 84 datum its coordinates are E: 364943, N: 8711567, zone 18 South.

Tailings dam characteristics

It is an old deposit that stopped disposing of tailings in 1949. Which received the tailings from the Casapalca Mining Unit, stored approximately 600,000 m3 of tailings in an area of 7.7 Ha and has its greatest longitudinal dimension parallel to the Highway. central. It was built using the upstream regrowth system. The coarse tailings were used for the construction of the dam that formed the outer slope of the deposit, while the fine tailings were deposited upstream, forming the basin area of the deposit. (Parra & Pérez, 1998). The length of the ridge was approximately 500 m and had a variable height between 19 m and 42 m. There are variable data regarding the height of the dam, (Parra & Pérez, 1998) indicate a height of 42.00 m, while (Carrillo & Carrillo, 1998), (Fernández, 1982) and (CPS2, n.d.) indicate 60.00 m of height. height.

Possible causes of the event

Studies prior to the closure works indicated that the physical stability was affected by the steep slope of the slopes and the lack of an adequate water management system over the reservoir.ICOLD (2001) indicates that the dam failed due to seismic liquefaction. Likewise, the information obtained from [13] and [14] indicates an earthquake as the cause of the failure event.

Estadísticas de los casos de falla

From the information presented above, data was obtained regarding cases of failure of tailings dams in Peru, which are shown below as statistical graphs.

Figure 11 shows the distribution of incidents on a regional scale. A change in the distribution pattern is observable when the data set was divided into two periods: 1952 to 1999 and 2000 to the present. Incidents of failures in Arequipa, La Libertad, Lima and Pasco decreased drastically during the last period. For example, the distribution of incidents in the Lima tailings dams was 3 cases before 2000, while after 2000 there were no incidents. Similar trends were seen in Pasco.

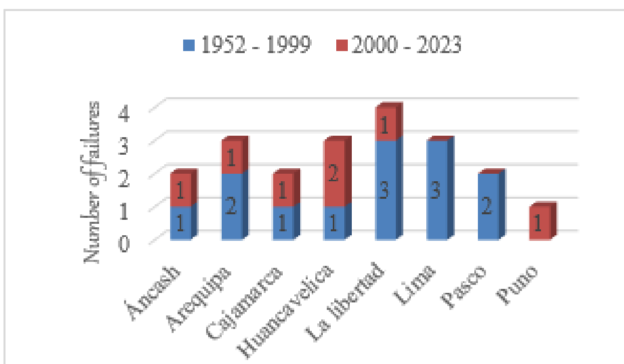

Figure 11. Regional distribution of tailings dam failures in Peru.

Although the distribution of incidents was lower after 2000 for the Arequipa, La Libertad, Lima and Pasco mines, for some regions, the number of incidents remained the same or increased. For example, the distribution of incidents in the Huancavelica tailings dams was 1 case before 2000, while after 2000 there were 2 incidents.

This provides an approximate geographic description of the distribution of tailings dam incidents in Peru.

Figure 12 shows the temporal distribution of the incidents. The first incident reported in the database was from a mine in Lima in 1952; the mine produced Cu, Ag, Pb, Zn. The number of failures in tailings dams remained low until the 1990s, which could be related to the absence of an exclusive oversight body for the specialty of geotechnics that recorded and archived the information on all cases of failure and not only of serious cases. Then, during the 2000s, no incidents were recorded, which could be related to administrative issues due to the transfer of mining supervision powers from the Ministry of Energy and Mines to OSINERGMIN.

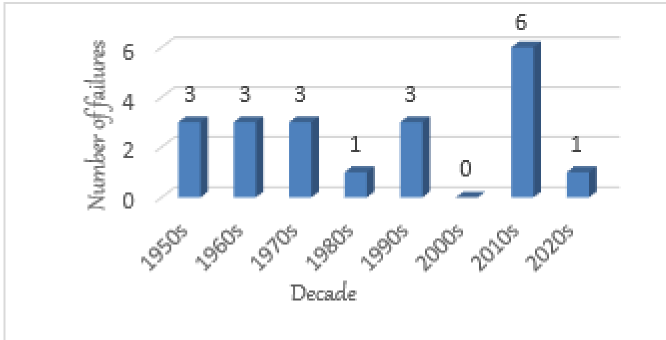

Figure 12. Temporal distribution of tailings dam failures in Peru.

In contrast, the number of failures increased significantly in the 2010s, which could be related to the global demand for metals and the transfer of environmental powers from OSINERGMIN to OEFA, thus having other organizations to record this type of events. . According to the database, from 1952 to 1999 a total of 13 incidents occurred, representing 65% of the total number of cases and from 2000 to the present a total of 7 incidents occurred, representing 35% of the total number of cases. According to the updated database, the tailings dam failure rate was ≈0.28 per year.

Figure 13 represents the relationships between regrowth methods and the number of failures. Tailings dam surge methods are generally divided into the following types: Upstream, Downstream and Centerline. The majority of incidents occurred in dams with upstream surge (≈73%, n=8), the upstream surge type was the most economical option, however, it had the greatest possibility of failing in times of extreme weather or natural disasters. In contrast, the number of incidents of Downstream and Centerline surge dams were significantly lower with (≈18%, n=2) and (≈9%, n=1), respectively.

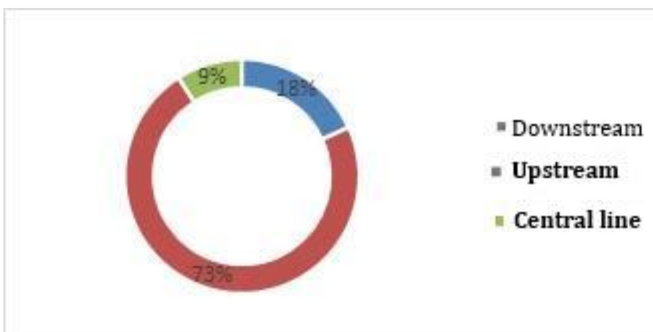

Figure 13. Failures of tailings dams according to their type of surge.

The case of the Yuracyacu filtered tailings deposit was omitted from this graph because its dam is classified as Homogeneous. Likewise, 8 cases of failure that occurred before the year 2000 were omitted due to the lack of information on the characteristics of their dams.

In Figure 14 most of the incidents occurred in dams with heights less than 50m (50%, n=10), with heights between 50m and 100m (20%, n=4), no incident occurred in dams with height between 100m and 150m, and in dams with heights greater than 150m (5%, n=1). It should be noted that data on the height of 5 tailings dams with failure before the year 2000 was not obtained.

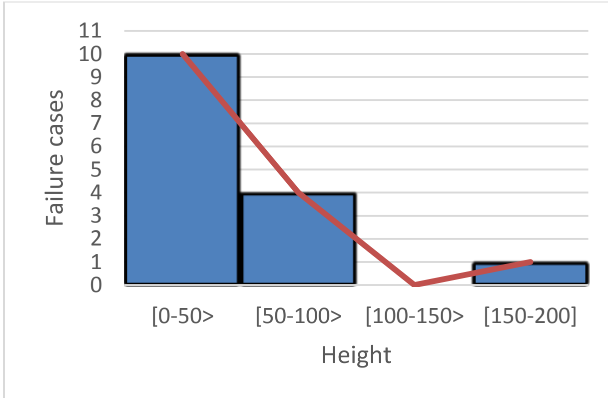

Figure 14. Frequency distribution according to height of the tailings dam

Regarding the previous paragraph, it is emphasized that increasing the height of tailings dams does not prevent failures, on the contrary, static liquefaction can be caused by an increase in pore pressure due to an excessive lifting rate of the dam. in short periods of time or other processes that alter the state of tension of the prey. However, the trend shown in the graph may be due to greater controls in the design, construction and operation of higher dams by mining owners.

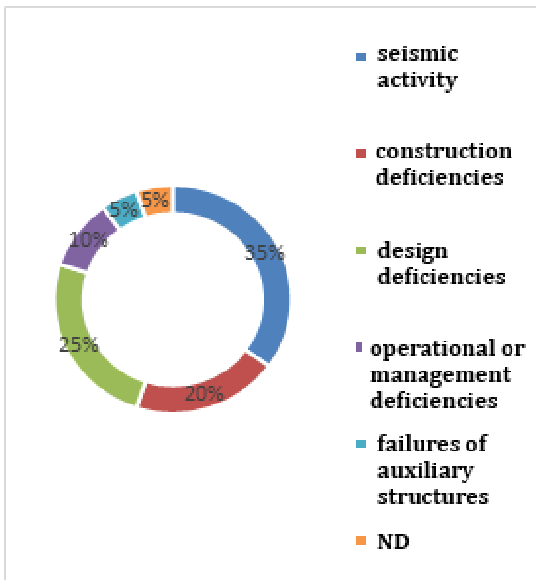

Figure 15. Tailings dam failures according to the main cause of failure

Seismic activities and design deficiencies were the two main causes of tailings dam failures, with (35%, n =7) and (25%, n =5) cases, respectively. Likewise, (20%, n=4) of the cases were generated by construction deficiencies, (10%, n=2) due to operational or management deficiencies, (5%, n=1) due to failure of auxiliary structures and the last (5%, n=1) the causes are not known.

It is well known that several problems must converge for a failure to be triggered. Therefore, Figure 16 shows the frequency of all the causes related to each of the incidents in the tailings dams. For this analysis, design deficiencies, seismic activities, operational deficiencies and construction deficiencies were the four main causes of failures in tailings dams, with frequencies of n=8, n=7, n=6 and n=6 cases, respectively.

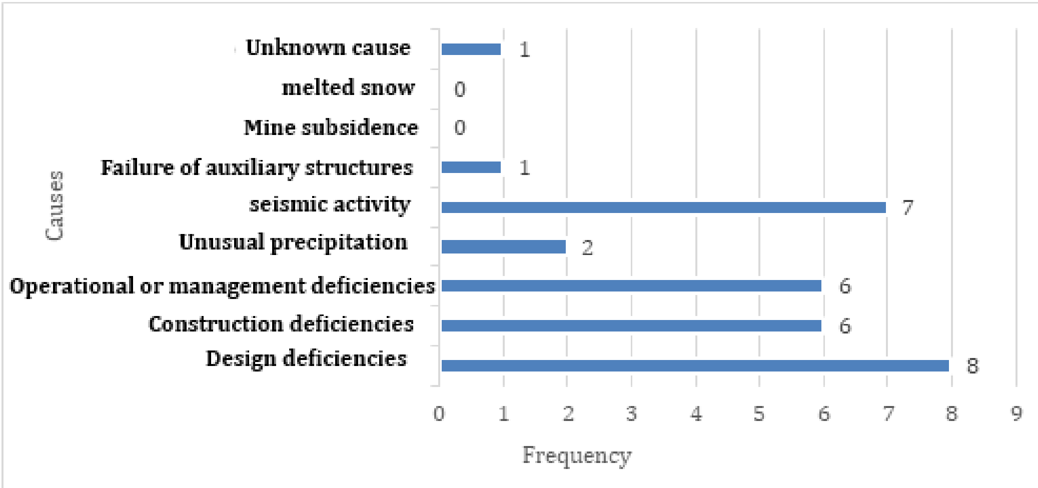

Figure 16. Frequency of all causes related to each of the incidents

On the other hand, unusual precipitation and failure of auxiliary structures were the least frequent causes, with n=2 and n=1 cases, respectively. Finally, in none of the failure cases were mine subsidence or melted snow observed as possible causes.

Figure 17 shows the percentage distribution of incidents in tailings dams based on their relationship with recorded earthquakes.

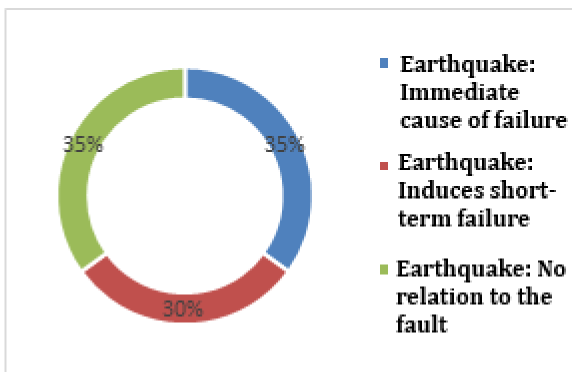

Figure 17. Relationship between failure cases and recorded seismic activity

The relationship of the recorded earthquakes with the cases of failure of tailings dams was divided into the following types: Immediate cause of the failure, Induces the failure in the short term and Has no relationship with the failure. Most incidents are related to seismic activity (65%, n=13). In contrast, only (35%, n=7) of the failure cases are not related to seismic activity.

DISCUSSION

The objective of this study was to analyze the factors that trigger failures in tailings dams in Peru, using a historical approach that covers from 1952 to 2023. The results obtained reveal that seismic activity is a predominant factor, being responsible directly or indirectly for a 65% of documented failures. This finding underscores the critical need to improve design and construction practices in regions with high seismic activity to minimize disaster risk in the mining industry.

Additionally, deficiencies in design and construction were identified as significant causes of failures, accounting for 25% and 20% of cases, respectively. These results coincide with previous studies that have shown that a lack of rigor in planning and supervision during construction can have catastrophic consequences. On the other hand, the upstream dam replenishment method, although more economical, was shown to be particularly vulnerable in conditions of extreme weather and seismic events, suggesting that its use in geologically complex contexts needs to be reassessed.

The analysis also showed that the lack of adequate continuous monitoring and the lack of a robust incident recording system contribute significantly to the occurrence of failures. This point highlights the importance of implementing advanced monitoring technologies and creating a centralized database that allows for more effective monitoring of these critical structures.

Limitation And Future Research Directions

Although the findings of this study provide valuable insight into tailings dam failures in Peru, there are some limitations that should be considered when interpreting the results. First, the research was based on a retrospective design, which limits the ability to establish definitive causal relationships between the identified triggers and failures. Although significant correlations have been identified, it is not possible to determine with certainty whether certain factors, such as seismic activity, directly cause an increase in the probability of failure.

Second, the use of satellite images for visual verification of tailings dam locations and conditions presented limitations due to the variable quality of the images and the lack of temporal coverage in some areas. This factor may have introduced a margin of error in the confirmation of certain failure events, which could affect the accuracy of some of the findings.

Furthermore, the study focused exclusively on the Peruvian context, which limits the generalization of the results to other regions with different geological and regulatory characteristics. Future research could explore tailings dam failures in different countries or compare the results with similar studies in other regions to evaluate the applicability of the findings in different contexts.

Finally, although this study focused on the technical and geological factors that contribute to failures, future research could include a deeper analysis of the socioeconomic and regulatory aspects that also influence the stability and safety of tailings dams. This would allow us to obtain a more holistic view of the problem and develop more effective mitigation strategies.

CONCLUSION

This study provides a comprehensive exploration of tailings dam failures in Peru, spanning an analysis from 1952 to 2023. The results confirm the critical importance of considering seismic activity and deficiencies in design and construction as primary factors in prevention. of failures in these structures. It is highlighted that transparency in design and construction supervision, as well as the implementation of continuous monitoring, are essential to ensure safety and effectiveness in tailings dam management.

Furthermore, it was observed that dams built with the upstream surge method, despite their lower cost, are particularly vulnerable to failure under extreme conditions. This finding reinforces the need to reevaluate construction practices and opt for safer methods in geologically complex contexts. On the other hand, the results revealed that the lack of an adequate incident recording and monitoring system has contributed significantly to the occurrence of failures, suggesting the urgent need to improve these practices.

Taken together, this study highlights the importance of adopting a comprehensive approach to tailings dam management that includes not only technical considerations, but also effective coordination between regulatory entities, the mining industry and affected communities. Close collaboration between all actors is essential to develop projects that reflect true needs and ensure the protection of the environment and the safety of local communities.

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