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A review of accidents in mining tailing dams in South America and the brazilian scenario

Uma revisão dos acidentes em barragens de rejeito de mineração da América do Sul e o cenário brasileiro

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Resumo: Este artigo tem por objetivo analisar os acidentes de barragens de rejeito de mineração na América do Sul nos séculos XX e XXI e avaliar o cenário atual das barragens brasileiras. Através de pesquisa na literatura pode-se verificar que existem atualmente 769 barragens de rejeito registradas no Brasil, sendo 425 inseridas na Política Nacional de Segurança de Barragens (PNSB) e 344 não inseridas. O método construtivo mais empregado é a execução em etapa única, sem alteamentos, representando 48,0% das barragens inseridas na PNSB e 60,2% das barragens não inseridas na PNSB. A partir da análise dos acidentes na América do Sul, observou-se que o país com maior frequência de acidentes foi o Brasil e a maior parte dos casos ocorreu na década de 2010. Além disso, 72,0% das barragens que sofreram acidentes foram construídas pelo método de alteamento à montante, o que vai de encontro ao que estabelece a literatura técnica, sobre o maior risco de instabilidade em barragens construídas através deste método.

Palavras-chave: Barragens de rejeito, Revisão, Acidentes

Abstract: This article aims to analyze accidents of mining tailings dams in South America in the 20th and 21st centuries and to evaluate the current scenario of Brazilian dams. Through a literature search, it can be seen that there are currently 769 tailings dams registered in Brazil, of which 425 are included in the National Dam Safety Policy (PNSB in Portuguese) and 344 are not inserted. The most used construction method is to execute it in a single step, without elevations, representing 48% of the dams inserted in the PNSB and 60.2% of the dams not inserted in the PNSB. By analyzing accidents in South America, it was observed that the country with the highest frequency of accidents was Brazil and most cases occurred in the 2010s. In addition, 72% of the dams that suffered accidents were built

using the upstream raising method, which is in line with what is established in the technical literature, about the greater risk of instability in dams built using this method.

Keywords: Tailings dams, Review, Accidents.

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1. Introdução

Many countries in the world, whether developed or underdeveloped, need mining activiies to maintain their economy. In this context, it can be observed that there is a considerable historical growth in mineral production in the world. It is worth mentioning that in 2012, mining production was six times higher than in 2000, as highlighted by the International Council on Mining & Metals (ICMM) (2014). The ICMM (2016) establishes that one of the factors for the increase in mineral production was the considerable growth in investments in Latin America, Africa and part of Asia, together with the strong increase in world demand for mineral production.

As mining activities expand, the generation of tailings also increases, that is, substances most often without relevant economic value, resulting from the chemical and physical processes of mineral production. Tailings can be disposed of separately according to particle size, geotechnical, mineralogical and hazardous characteristics (IBRAM, 2016).

The final disposal of tailings is precisely one of the major concerns of the mining activity, and therefore the intention is to minimize environmental impacts as these are residues that can present a high potential for contamination and degradation to the environment. A tailings destination commonly adopted in the mining sector is carried out through dams, built with natural soil or with the actual tailings. The purpose of a tailings dam is to safely store waste to protect the environment from aggression (INAM et al., 2011; SMUDA et al., 2014; XU and WANG, 2014; NAEINI and AKHTARPOUR, 2018).

As production of mining tailings is constant, dams are generally raised in order to increase their storage capacity. This can be done by adopting a constructive upstream, downstream or centerline raising method, depending on technical and economic criteria. The upstream method generally has a lower construction cost, requires less material consumption and allows for greater heightening speed, however, it presents a greater risk of collapse and vulnerability to vibrations and earthquakes, due to the fact of the tailings (in general, material of low geotechnical quality) that are used as the dam foundation. The downstream method, on the other hand, has greater safety against failure, as the dam raising is not supported on the tailings, but on compacted materials with better geotechnical behavior; however, it is a more expensive method, which requires a larger volume of material and a larger construction area. The centerline method is an intermediate alternative between the upstream and downstream methods.

As highlighted by Lyu et al. (2019), tailings dams are one of the largest structures built by geotechnical engineers; however, considering a global analysis, these structures have been the target of frequent incidents and collapse. Overall, 2 to 5 of the 3,500 tailings dams in the world suffer major failures each year, making these structures more than 10 times more likely to fail than conventional water storage and retention dams (LEMPHERS, 2010; BERGHE et al., 2011).

The vast amount of accidents that occur in tailings dams in the world shows the need for constantly developing legislation in different countries concerning construction and monitoring processes of these dams. In the case of Brazil, for example, due to the recent accidents that occurred in Mariana, in 2015, and Brumadinho, in 2019, law 14066/2020 was instituted, which introduces important provisions in the National Dam Safety Policy (PNSB in Portuguese). It is important to highlight that the historical evolution of regulations does not eliminate the risk of accidents in tailings dams. There are risks of collapse due to non-compliance with established standards, failure in maintenance, design and construction, cost reduction, accumulation of toxic effluents, meteorological and climatic factors, foundation failures, infiltration and many others (CARDOZO et al., 2016).

As reported by Pereira (2016), the largest mining tailings producers are Canada, the United States, Brazil, Australia and China. From the countries mentioned, China is the one with the most problems concerning collapses, but information related to accidents is not as disseminated as in other countries. The countries reported are a reference in control and legislation on dams; however, in Brazil, there are still failures in inspection and punishing those responsible in cases of failure.

In South America, the most important countries in mining development are Brazil, Chile and Peru (FINAL REPORT V.4, 2018, Chilean Government). Consequently, these countries also have a higher probability of accidents in tailings dams and have more developed legislation on the subject.

Collapse of a tailings dam causes great socioeconomic impacts with financial, human and environmental losses, causing flooding and pollution of water bodies due to the unleashing of tailings for several kilometers beyond the rupture. According to IBRAM (2016), most cases of rupture are attributed to a sudden increase in pore pressure due to heavy rains that decrease the effective stress of the dam massif or to liquefaction caused by earthquakes or explosions.

Based on the aforementioned facts, this paper aims to analyze the accidents of mining tailings dams in South America in the 20th and 21st centuries and to evaluate the current scenario of Brazilian tailings dams.

2. Brazilian regulations related to the safety of mining tailing dams and the scenario in south america

In Brazil, the National Mining Agency (ANM in Portuguese) is responsible for overseeing mining research for exploitation, as well as the structures resulting from these activities. Federal Law No. 12.334, of September 20, 2010, established the National Dam Safety Policy (PNSB in Portuguese) for water accumulation for any uses and the final or temporary disposal of tailings. This law also created the National Dam Safety Information System (SNISB in Portuguese).

According to Law 12.334, the PNSB aims to ensure that dam safety standards are followed, aiming to reduce the possibility of accidents and their consequences. Dams that are higher than 15 m and that have a storage volume greater than 3 million m³ must be included in the PNSB. The SNISB, in turn, is responsible for overseeing the implementation of the safety plans for mining dams that must be drawn up by entrepreneurs.

In addition to the law, ordinance No. 70.389 of May 17, 2017, created the National Registry of Mining Dams, the Integrated Dam Safety Management System, the periodicity of technical officers' qualifications and the Emergency Action Plan for Mining Dams. In addition to federal legislation, there are state laws, highlighting the state of Minas Gerais, which has a significant set of laws for licensing and the safety of mining dams. There is also NBR 13.028 (ABNT, 2017), which sets out requirements for preparing and presenting dam design for tailings disposal, sediment containment and water storage.

The National Water Agency (ANA in Portuguese) is the main part of this national policy and monitors the safety of dams, promoting articulation between other inspection bodies, acting directly in implementing the PNSB and managing the SNISB.

Due to recent events in 2015 and 2019, the sector has been mobilized to make improvements. Resolution No. 13 of August 8, 2019 was published, establishing regulatory measures aimed at ensuring the stability of mining tailings dams. The Resolution sets deadlines for decharacterization and decommissioning of upstream dams and promotes the inclusion of more dams with mandatory automatic monitoring in real and full time. In addition, construction using the upstream raising method is prohibited throughout Brazil.

On September 30, 2020, Federal Law No. 14.066 was instituted, which brought changes to the National Dam Safety Policy (Law No. 12.334/2010), especially regarding the risk classification and Associated Potential Damage of dams; the preparation and availability of the Dam Safety Plan; the preparation and availability of the Action and Emergency Plan; new administrative infractions and their penalties, related to non-compliance with PNSB provisions and the requirement of non-cumulative presentation of collateral, insurance, surety, or other real or financial guarantee for repairing damage to human lives, the environment and public property.

When comparing Brazil's National Dam Safety Policy with international legislation, such as the Mining Association of Canada (MAC) and the Australian National Committee on Large Dams (ANCOLD), which designate the technical guidelines in Canada and Australia, respectively, it can be observed that Brazil has modern legislation with an international quality standard, as as well as the aforementioned legislation:

- It is based on comprehensive management, with a system for registering and computerizing the situation regarding the safety of dams;
- It conducts annual reviews aiming to improve processes;
- It prepares reports and implements risk management to minimize the possibilities of environmental impacts;
- It has emergency response plans for potential failures.

In the South American scenario, Table 1 presents comparisons of some aspects of the National Dam Safety Policy in Brazil with regulations in Chile, Peru, Argentina and Bolivia, which are important countries in the South American mineral production scenario. Similarities and differences can be observed between the regulations in question. It is interesting to highlight that countries such as Bolivia, Chile and Peru are unitary, that is, they only comply with legislation at the national level, while Brazil and Argentina, in addition to national legislation, also have specific regulations in their federative units.Table 1 shows that the regulations of all countries impose the need for an Environmental Impact Assessment prior to approving tailings dam projects. The system, in general, has the same characteristics, that is, the interested party presents

a project that must meet a certain format, standards and requirements. The project is examined and, after going through several intermediate stages in which different specialized sectorial bodies participate, the project can be approved, contested or rejected. In Chile, Peru and Argentina, the owner of a project must present an Environmental Impact Statement (EIA), in cases of projects whose execution does not generate significant negative environmental impacts, or an EIA, when the execution of a project can cause significant environmental impacts. In the case of Brazil, legislation requires the mining concessionaire to carry out an environmental impact study when the mining activities began to obtain the prior license that is granted by the Ministry of Mines and Energy. Licensing procedures cover three distinct and successive phases, in which the environmental feasibility of the enterprise is analyzed (preliminary, installation and operating licenses).

Table 1 clearly shows that each country has a specific body that authorizes the operation of tailings dams in its territory, except for Argentina, which determines that each province, within its jurisdiction, must appoint the authorities for this purpose.

Another important aspect of Table 1 is the requirement of financial guarantees for mineral exploration companies for eventual damage repairs. It can be observed that the regulations of all countries require this guarantee from mining companies. It is important to note that in Brazil there was no such obligation until the enactment of law 14066/2020, which stated in its text that: "the supervisory body may require, under the terms of the regulation, the non-cumulative presentation of a bond, insurance, surety or other financial or real guarantees for the repair of damage to human life, the environment and public property, by the entrepreneur of a mining tailings dam or industrial or nuclear waste classified as medium and high risk or medium and high potential damage; and water accumulation in dams for hydroelectric use classified as high risk".

In cases of non-compliance with the law, Table 1 shows that all countries provide for the application of sanctions, which can range from warnings to fines of high pecuniary value without prejudice to other legal provisions.

Finally, it is clear that countries such as Brazil, Chile and Peru prohibit the construction of dams using the upstream raising method, which is more susceptible to failure. Chile and Peru, which are seismic countries, have banned this construction technique for a long time, for the sake of the safety of their dams. Brazil only came to prohibit this technique after the accidents that occurred in Mariana (2015) and Brumadinho (2019) with the institution of law 14066/2020.

Table 1 shows that there are similarities in the regulations of the main mineral exploration countries in South America and that each country presents its specificities, according to its legal organization. In the case of Brazil, there has been an important recent evolution in its legislation, largely as a result of the impacting accidents mentioned above. The document entitled *Informe Final* V.4 (2018), from the Chilean government, presents a comprehensive study of the legislation of several countries around the world regarding the design, construction and operation of mining tailings dams, and can be used for more in-depth consultations.

Table 1- Aspects of comparison between the regulations of South American countries regarding mining tailings dams

COUNTRIES	**COMPARED TOPICS**					
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Brazil	Federal Constitution (1988); Law 12334/2010; Ordinance 7389/2017; Law 14066/2020; NBR 13.028/2017.	Yes	National Mining Agency	Yes	Yes	Yes
Argentina	Law 25675/2002; Law 24585/1995; Law 24051/1992; Law 1919/1986	Yes	There is no specific authority	Yes	Yes	No
Bolívia	Supreme Decree 24782/1997; Law 1333/1992; Law 535/2014; Tailing Dams Environmental Guide (2001)	Yes	National Secretariat of Natural Resources and Environment	Yes	Yes	No
Chile	Supreme Decree 248/2007; Supreme Decree 50/2015; Supreme Decree 40/2013; Law 19300/1994; Law 20551/2011	Yes	National Geology and Mining Service	Yes	Yes	Yes
Peru	Resolution 19-97-EM/DGAA (1997); Law 28090/2003; Supreme Decree 2003-35-EM/2005; Supreme Decree 016-93-EM/1993; Supreme Decree 40/2014; Law 29968/2012	Yes	Ministry of Mines and Energy	Yes	Yes	Yes

Legend:
(1) Main normative instruments.

(2) Does it require an Environmental Impact Assessment?
(3) Who authorizes the operation of tailings dams?
(4) Do you require a financial guarantee for any damage to be repaired?
(5) Does it provide for sanctions in cases of non-compliance?
(6) Does it prohibit the construction of dams using the upstream raising method
Source: Own elaboration (2021)

3. Metodologia

The methodological procedure used in this article is shown in Figure 1. Considering the objective of the work, research was carried out in two aspects: one related to the knowledge of the current scenario of Brazilian tailings in operation and another related to accidents that occurred in the 20th and 21st centuries in the tailings dams in South America.

Initially, to understand the scenario of Brazilian dams, the surveys were carried out in the National Mining Agency (ANM) database linked to the Ministry of Mines and Energy of the Brazilian Government. The Agency has control of Brazilian mining tailings dams through the National Registry of Mining Dams. A total of 769 tailings dams were identified in Brazil, based on data made available in February 2019. From these, 425 are included in the National Dam Safety Policy (PNSB), while the remaining 344 are not.

Based on a literature review, accidents that occurred in tailings dams in South America in the 20th and 21st centuries were detected. Twenty-five accidents were considered, identifying the location of the dams, height, type of ore, construction method and the causes of the failures that occurred. The accidents occurred in Brazil, Peru, Chile and Bolivia.

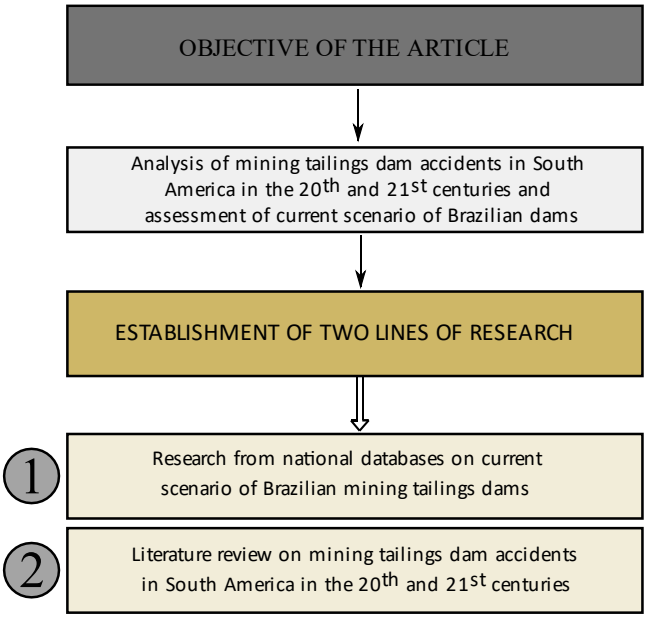

Figure 1 - Methodological procedure for the article.
Source: Own elaboration (2021)

4. Resultados e discussão

4.1. Mining tailings dam scenario in Brazil

By 2020, records of 769 tailings dams in Brazil were identified, of which 425 were included in the National Dam Safety Policy (55.3%) and 344 were not included (44.7%). Most of them are in the state of Minas Gerais, followed by Pará, São Paulo, Mato Grosso and Bahia, as illustrated in Figure 2.

Figure 3 shows the height distribution of tailings dams in Brazil. Among the dams inserted in the PNSB, most (36%) are between 10 and 20 m high, while only 1% are higher than 100 m (Figure 3a). On the other hand, in Figure 3b, it can be seen that, for dams not included in the PNSB, 80% are less than 10 m high, while 20% are between 10 and 15 m high.

Regarding the stored tailings volumes, Figure 4a shows the volume distribution for the dams inserted in the PNSB. It is observed that most dams (35.8%) store between 100 thousand and 1 million m³ of tailings. For dams not included in the PNSB (Figure 4b), it can be seen that the majority (71.8%) store less than 100,000 m³ of tailings and the largest storage does not exceed the range of 3 million m³.

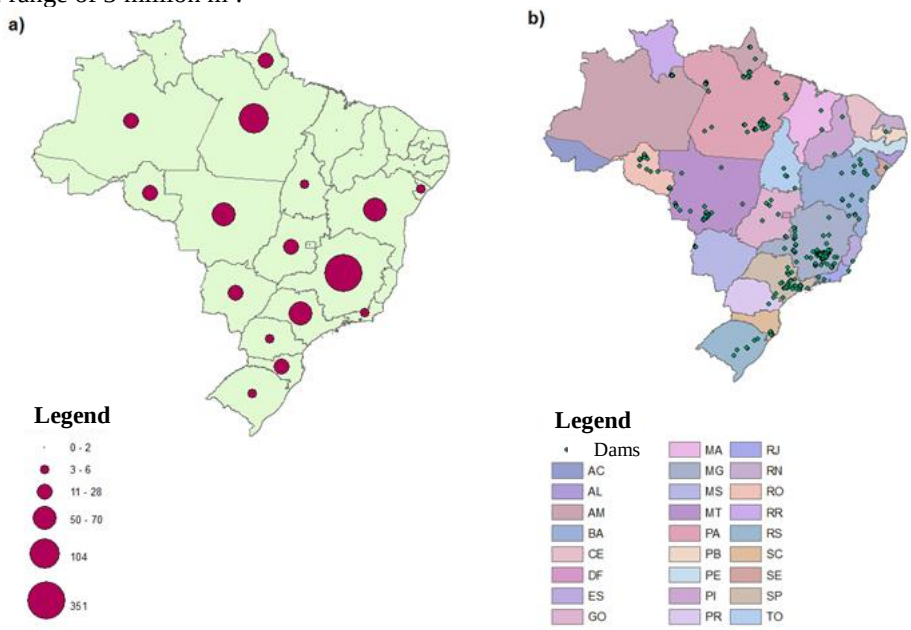

Figure 2 - a) Infographic map of tailings dams in Brazilian states; b) Spatial layout of tailings dams in Brazil. Fonte: Own elaboration (2021).

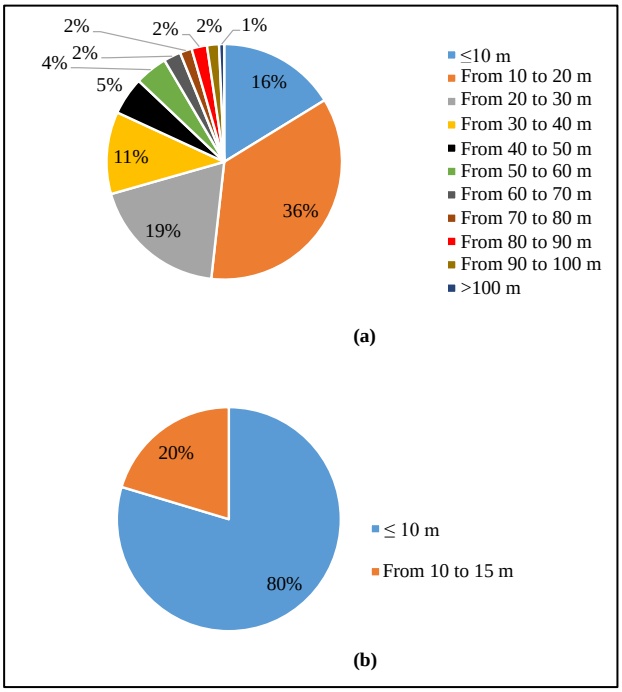

Figure 3 - Dam height distribution a) included in the PNSB; b) not included in the PNSB
Fonte: Own elaboration (2021).

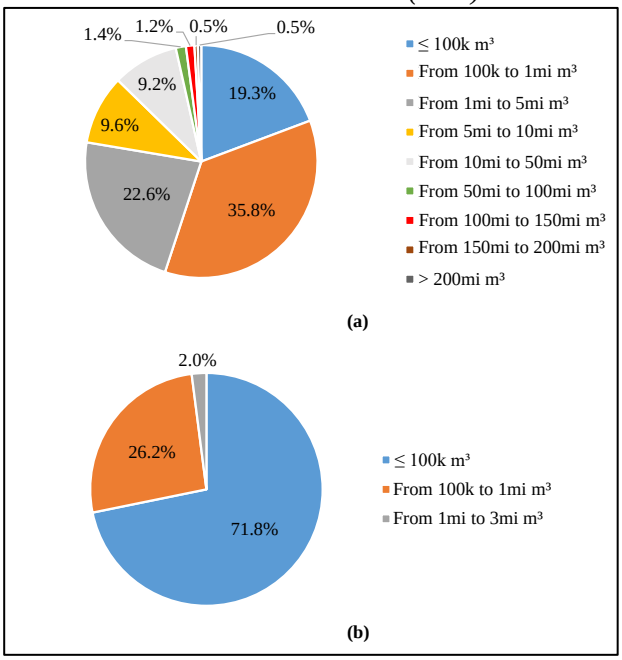

Figure 1 - Distribution of storage volumes of dams a) included in the PNSB; b) not included in the PNSB
Fonte: Own elaboration (2021).

It can be observed that the dams in the PNSB have a height and volume greater than those not included. This is expected and is due to the fact that Brazilian legislation makes the classification of larger dams mandatory (height above 15 m and volume above 3 million m³) to be included in the PNSB.

Figure 5 shows the number of dams as a function of accumulated tailings. It can be observed that iron ore tailings are the most accumulated in dams included in the PNSB (Figure 5a) and in those not inserted (Figure 5b). In the first case, there are a total of 145 dams that store iron ore tailings and in the second, 81 dams.

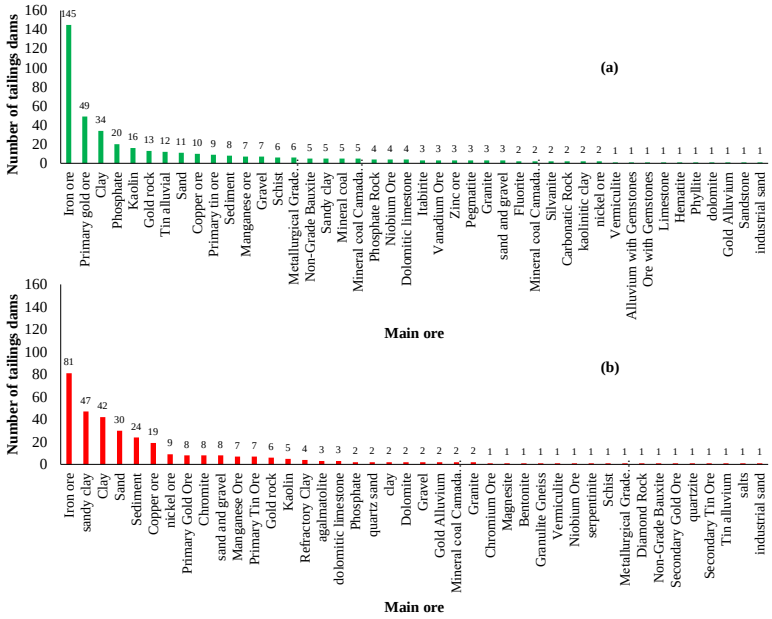

Figure 5 - Number of dams versus accumulated tailings (a) included in the PNSB b) not included in the PNSB
Fonte: Own elaboration (2021).

Regarding the construction method, Figure 6 shows how the distribution between the different construction methodologies of tailings dams in the Brazilian territory occurs. It is clearly notorious that the most used construction method is dam construction without raising, that is, construction in a single stage. However, it is observed that in states with large production of tailings, such as Minas Gerais, Pará and São Paulo, it is common to raise dams.

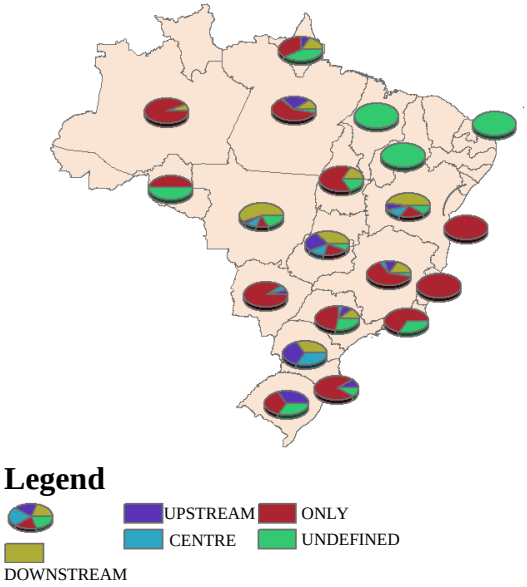

Figure 2 - Distribution of construction methodologies for tailings dams used in Brazil.
Fonte: Own elaboration (2021).

Figure 7 shows, in percentage terms, the number of dams as a function of the construction method. For the tailings dams included in the PNSB (Figure 7a), it can be observed that the most used method is executing the dams in a single step (48% of the dams), as previously shown in Figure 6. When raising is carried out, the most used method was downstream (25.2%), followed by upstream (19.5%) and by center line (7.1%). Regarding dams not included in the PNSB (Figure 7b), the method using a single construction step is also more common, occurring in 60.2% of dams, and upstream raising is the least common (1.2%). It is noteworthy that for dams that require raising, the construction method that requires the greatest investment and, according to the literature, the safest, is the downstream method, and, among the dams included in the PNSB, it was the most recurrent method used. For dams not included in the PNSB, the downstream method was also the most used in cases of rising; however, it is worth noting that approximately ¼ of the dams (23.3%) have their construction method undefined, which may incur unknown potential risks.

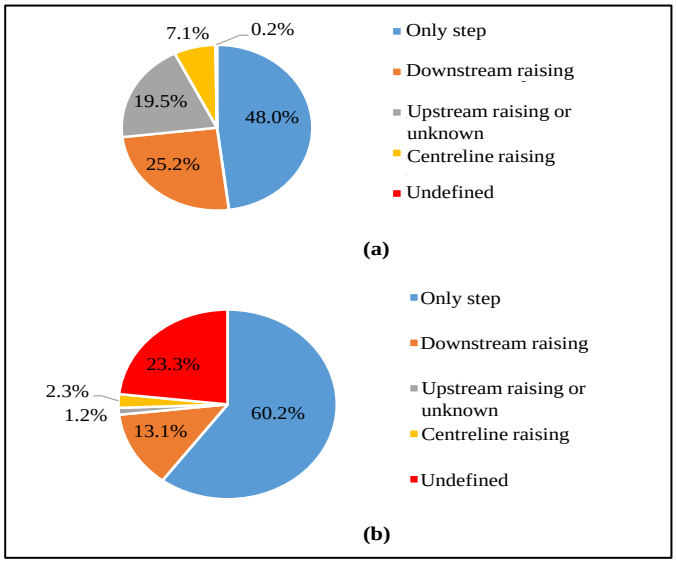

Figure 7 - Construction methods used in dams (a) included in the PNSB; b) not included in the PNSB.
Fonte: Own elaboration (2021).

Regarding the risk categories, only the tailings dams included in the PNSB present this information. Figure 8 shows that most dams (85.2%) are in a low-risk situation, while about 15% of these structures are in a medium and high-risk situation

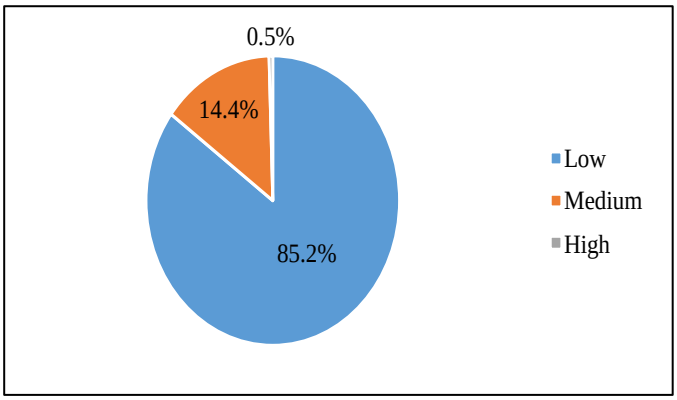

Figure 8 - Risk categories for dams included in the PNSB.
Fonte: Own elaboration (2021).

Figure 9 shows the risk categories of tailings dams as a function of the construction method used. It is confirmed that most dams are in a low risk situation. Only two dams were identified in a high risk category and both were built in a single stage. It can be observed that, among the dams built by single stage, 27 (about 13%) have a medium and high risk category, so about 87% of the dams built by a single stage have a low risk category. For dams executed by raising downstream, 21 (about 20%) fall into the medium risk category and the remaining 80%, into the low risk category. Regarding upstream dams, 13 (about 16%) are in the medium risk category, thus 84% of upstream dams are in the low risk category. Finally, it is observed that all dams executed by centerline, only 2 (about 7%) are in the medium risk category, therefore 93% of dams executed by centerline are in the low risk category.

It is important to highlight that the risk category of a dam, according to the National Dam Safety Policy, does not only depend on the executive method of the structure, but is also a function of the technical characteristics, state of conservation and age of the project, as well as other criteria defined by the supervisory body. Therefore, although, in general, dams built using the upstream raising method are more susceptible to accidents, the results show that this was not the crucial factor that determined the definition of the dam risk category.

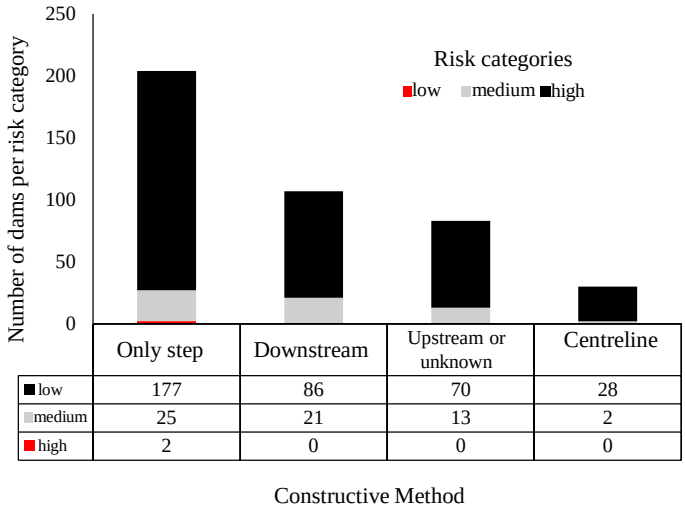

Figure 9 - Risk categories of dams depending on the construction method
Fonte: Own elaboration (2021).

4.2. Analysis of tailings dam accidents that occurred in South America in the 20th and 21st centuries

In the literature, 25 tailings dams accidents in South America occurred in the 20th and 21st centuries were found. Table 2 presents the cases, with the location of the dams, height, type of ore, construction method and the causes of the failures that occurred. Figure 10 shows the location of accidents, which occurred in Brazil, Peru, Chile and Bolivia.

Table 1: Accidents that occurred in tailings dams in South America in the 20th and 21st centuries

Year	Location	Height (m)	Type of ore	Constructive method	Accident cause
1962	Almivirca, Peru	N	N	N	Earthquake
1965	Bellavista, Chile	20	Copper	Upstream	Earthquake
1965	Cerro Negro No. 3, Chile	20	Copper	Upstream	Earthquake
1965	El Cobre New Dam, Chile	19	Copper	Downstream	Earthquake
1965	El Cobre Old Dam, Chile	35	Copper	Upstream	Earthquake
1965	La Patagua New Dam, Chile	15	Copper	Upstream	Earthquake
1965	Los Maquis, Chile	15	Copper	Upstream	Earthquake
1985	Veta de Agua No. 1, Chile	24	Copper	Upstream	Earthquake
1985	Cerro Negro No. 4, Chile	40	Copper	Upstream	Earthquake
1986	Itabirito, Brasil	30	N	Gravity	Structural

1993	Marsa, Peru	N	Gold	Upstream	Overtopping
1996	Amatista, Peru	N	N	Upstream	Earthquake
1996	El Porco, Bolívia	N	Zinc, lead and silver	Upstream	Overtopping
2001	Nova Lima, Brasil	N	Iron	Upstream	N
2007	Miraí, Brasil	35	Aluminum	N	Strong rain
2009	Barcarena, Brasil	N	Aluminum	Upstream	Strong rain
2010	Huancavelica, Peru	N	Copper	Upstream	N
2014	Mina Herculano, Itabirito, Brasil	N	Iron	Upstream	N
2015	Mariana, Brasil	90	Gold	Upstream	Strong rain
2018	Huancapatí, Peru	N	N	N	Strong rain
2018	Barcarena, Brasil	N	Aluminum	Upstream	Strong rain
2019	Nª Srª Livramento, Brasil	15	Gold	Downstream	N
2019	Mina Cobriza, Huacanvélica, Peru	N	Copper	Upstream	N
2019	Machadinho d'Oeste, Brasil	N	Tin	N	Strong rain
2019	Brumadinho, Brasil	86	Iron	Upstream	*Creep*

Note: N – Information not obtained

Fonte: Own elaboration (2021).

Figure 3 - Location map of accidents in tailings dams in South America in the 20th and 21st centuries
Fonte: Own elaboration (2021).

Figure 11 shows the temporal evolution of accidents in tailings dams. It can be observed that the greatest number of accidents occurred in the 2010s (9 cases). It is interesting to note that from the 1960s onwards the number of accidents reduced and remained stabilized, showing a substantial increase in the 2010s. Figure 12 shows the numbers of accidents by country and it can be observed that Brazil is the country where the most accidents occurred in South America (10 cases), followed by Chile, Peru and Bolivia. Figure 13 shows the types of ores stored in the dams that suffered accidents. It can be observed that in 40% of the cases the dams stored copper tailings.

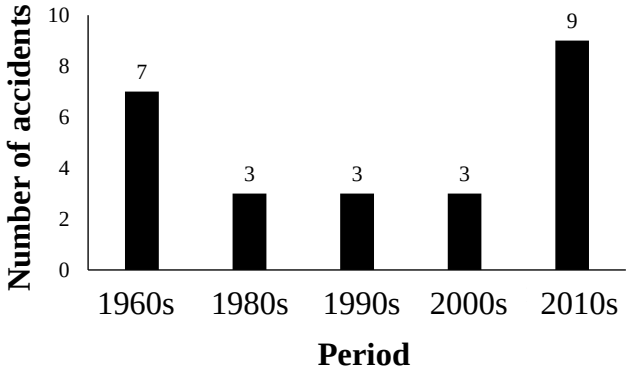

Figure 4 - Temporal evolution of accidents in tailings dams
Fonte: Own elaboration (2021).

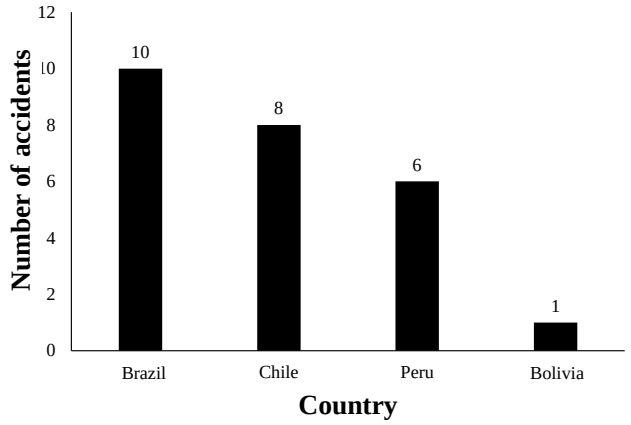

Figure 5 - Number of accidents in tailings dams by country
Fonte: Own elaboration (2021).

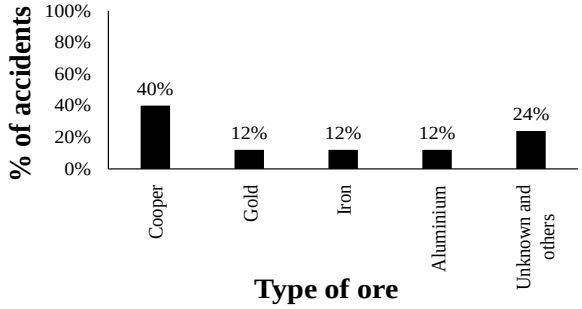

Figure 6 - Percentage number of accidents depending on the type of ore stored.
Fonte: Own elaboration (2021).

Regarding the causes that caused accidents in dams, Figure 14 shows that the most frequent cause was the occurrence of earthquakes (40% of accidents), which occur mainly in Chile. Accidents after heavy rains were also frequent, representing 24% of cases and occurred mainly in Brazil

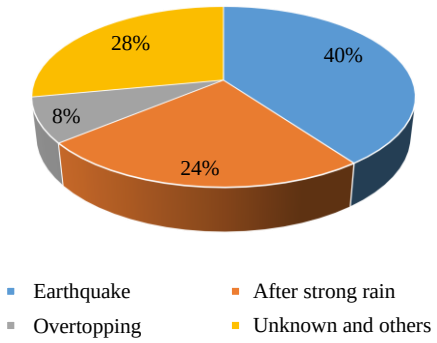

Figure 7 - Causes of accidents in tailings dams
Fonte: Own elaboration (2021).

Figure 15 shows the percentage number of accidents in tailings dams as a function of the construction method. It can be observed that 72% of the dams that failed had the constructive upstream raising method, which goes against what was observed by Lyu et al. (2019). This showed that almost 60% of the dams that suffered accidents in the world in the 20th and 21st centuries had this construction method. This confirms what the technical literature establishes about the upstream raising method, which, despite leading to more savings, is more susceptible to instability

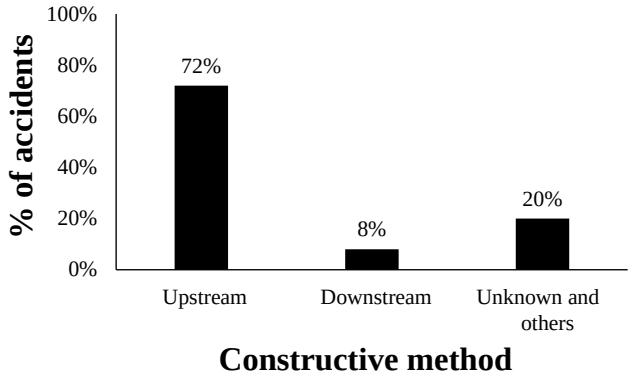

Figure 8 - Percentage number of accidents in tailings dams due to the construction method.
Fonte: Own elaboration (2021).

When analyzing the main causes of accidents in tailings dams in South America (earthquakes and heavy rains), Figure 16(a) shows that among all dams that suffered accidents due to earthquakes, 80% had an upstream raising method. This finding corroborates the studies in the literature, which point to the high risk of instability of upstream dams considering seismic actions. It is because of this situation that seismic countries, such as Chile and Peru, prohibit the upstream raising method. The Chilean government's Final Report V.4 (2018) highlights that Chile and Peru, as they are countries with active seismicity, do not implement the upstream raising method, as they represent a high risk of collapse and informs that almost all accidents and failures of tailings dams occurred in the world were in structures built by the upstream method.

Concerning Figure 16(b), it can be observed that among the dams that collapsed after heavy rains, which occurred mainly in Brazil, 50% were built using the upstream raising method. This demonstrates once again the high vulnerability of this type of dam to unstable natural events.

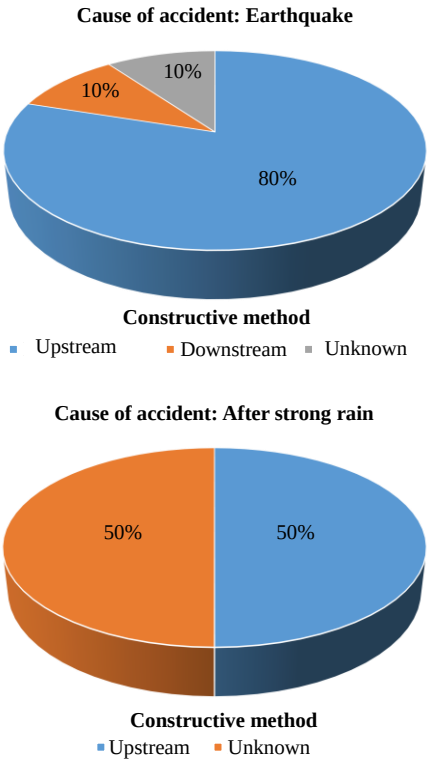

Figure 9 - Relation between the construction method of tailings dams and the causes of accidents due to: (a) Earthquake; (b) After heavy rains
Fonte: Own elaboration (2021).

Dealing specifically with accidents that occurred in Brazil, Figure 17 shows the relationship between the causes of accidents and the construction methods used in dams. The main cause of accidents in tailings dams in Brazil is related to the occurrence of heavy rains, with 5 cases, 3 of which in dams built using the upstream method. The Chilean government's study (Final Report V.4, 2018), highlights that while Chile and Peru observe more seismic risks, in Brazil the special concern is related to the implementation of drainage systems to prevent flooding, in addition to measures to prevent water erosion from dams.

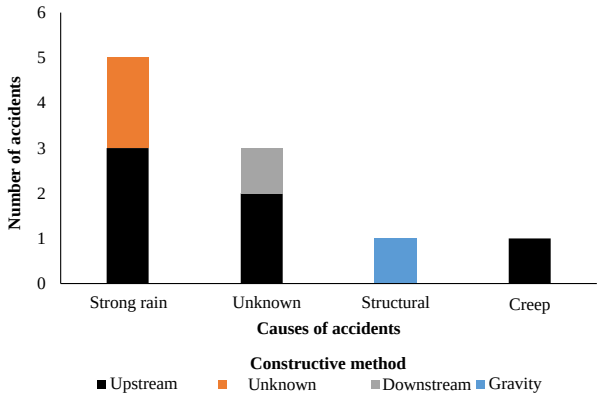

Figure 10 - Relationship between the causes of accidents in tailings dams in Brazil and their construction method
Fonte: Own elaboration (2021).

Figure 18 summarizes that among the 10 accidents found in Brazilian tailings dams in the 20th and 21st centuries, six occurred in dams built by the upstream method, attesting once again to the high risk of this type of construction, corroborating what establishes the literature. This situation shows the need for stricter national legislation regarding the raising upstream method. Infact, recent accidents in upstream dams in Mariana (2015) and Brumadinho (2019) have prompted an update on the National Dam Safety Policy in Brazil. The institution of law 14066/2020 prohibits the construction or upstream raising method in Brazil. This situation represents an advance that was necessary in the national regulation, as shown by the data obtained in this work

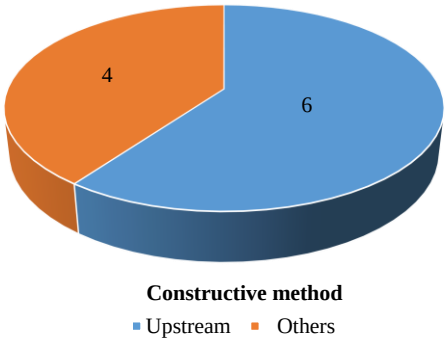

Figure 11 - Number of accidents in tailings dams in Brazil due to the construction method
Fonte: Own elaboration (2021).

4. Considerações finais

According to what was presented in this article, regarding the Brazilian scenario of mining tailings dams, it can be concluded that:

• Most of the dams are in the state of Minas Gerais, followed by Pará, São Paulo, Mato Grosso and Bahia.

• Iron ore tailings are the most accumulated in Brazilian dams.

• The most used construction method is the execution of dams in a single stage, without raising, representing 48% of the dams included in the National Dam Safety Policy (PNSB) and 60.2% of the dams not included in the PNSB.

• 48% of the dams included in the National Dam Safety Policy (PNSB) and 60.2% of the dams not included in the PNSB.

• It can be concluded that the technique most used for raising tailings dams is the downstream technique, which is characterized by the highest level of investment required and which provides the greatest security regarding its stability;

• Regarding the risk category for the tailings dams included in the PNSB, it can be noted that most of them (85.2%) are in a low risk situation;

• Among the 769 tailings dams registered in Brazil, 344 dams (44.7%) are not included in the PNSB and from these, about 23.3% do not present any information regarding the construction method used. The lack of control and basic information about these tailings dams can be understood as a factor that can increase the risk associated with these structures.

Regarding accidents involving mining tailings dams in South America in the 20th and 21st centuries, it can be concluded that:

• Most accidents occurred in the 2010s and the country with the highest frequency of accidents was Brazil, followed by Chile, Peru and Bolivia.

• The most common cause for the failure of the analyzed dams was the occurrence of earthquakes (40% of cases).

• 72% of the dams that suffered accidents were built using the upstream raising method.

• The main cause of accidents in tailings dams in Brazil is related to the occurrence of heavy rains.

• Among the 10 accidents found in Brazilian tailings dams in the 20th and 21st centuries, six occurred in dams built using the upstream method.

Finally, it can be concluded that Brazil needed an update in its National Dam Safety Policy, especially on the issue of prohibiting the execution and the upstream raising method, which occurred with the institution of law 14066/2020. Therefore, compared to the main countries in South America and world reference countries such as Australia and Canada, Brazil has quality legislation with regard to the safety of mining tailings dams. The large number of accidents observed in the country in recent years shows that, at the moment, it may be necessary to intensify the inspection and monitoring of tailings dams by the competent authorities.

Referências

*ANCOLD. **Guidelines on Tailings Dams – Planning, Design, Construction, Operation and Closure** – Revision 1 (July 2019). Disponível em: https://www.ancold.org.au/.*

*ANM. **Resolução nº 13, de 8 de Agosto de 2019**. Disponível em: https://www.in.gov.br.*

*ANM. **Classificação das barragens de mineração brasileiras**. Disponível em: http://www.anm.gov.br/.*

*Associação Brasileira De Normas Técnicas (ABNT). NBR 13.028: **Mineração - Elaboração e apresentação de projeto de barragens para disposição de rejeitos, contenção de sedimentos e reservação de água - Requisitos**. Rio de Janeiro, 2017.*

Berghe, J. F. V.; Ballard, J. C.; Pirson, M.; Reh, U. Risks of tailings dams failure. In *Proceedings of the 3rd International Symposium on Geotechnical Risk and Safety (ISGSR)*, v. 2, n. 3, 6, Munich, Germany, June 2011.

*Cardozo, F. A. C.; Pimenta, M. M.; Zingano, A. C. Métodos construtivos de barragens de rejeitos de mineração – uma revisão. **Holos**, v. 8, n. 32, 77-85, 2016.*

Chronology of major tailings dam failures. Disponível em: https://www.wise-uranium.org/mdaf.html

*DNPM. **Portaria do Diretor Geral do DNPM nº 70.389, de 17 de maio de 2017**. Disponível em: https://www.gov.br.*

*Instituto Brasileiro de Mineração (IBRAM). **Gestão e Manejo de Rejeitos da Mineração/Instituto Brasileiro de Mineração**; organizador, Instituto Brasileiro de Mineração. 1.ed. Brasília, BR: IBRAM, 2016. 128p.*

*ICMM. **The role of mining in national economies (2nd edition).** Mining's contribution to sustainable development. London, UK: ICMM, 2014. 56p.*

*ICMM. **Role of mining in national economies - third edition**. London, UK: ICMM, 2016. 68p.*

Inam, E.; Khantotong, S; Kim, K. W.; *Tumendemberel*, B; *Erdenetsetseg*, S.; *Puntsag*, T. Geochemical distribution of trace element concentrations in the vicinity of Boroo gold mine, Selenge Province, Mongolia. ***Environmental Geochemistry and Health***, v. 33, n. 1, 57–69, 2011.

Informe Final V.4. **Estudios de Normativas Internacionales de Diseño, Construcción, Operación, Cierre y Post Cierre de Depósitos de Relaves**. SERNAGEOMIN, Ministerio de Minería, Chile, 2018.

Lemphers, N. **Could the Hungarian tailings dam tragedy happen in Alberta?**, 2010. Disponível em: http://www.pembina.org.

Lyu, Z.; Chai, J.; Xu, Z.; Qin, Y.; Cao, J. A Comprehensive Review on Reasons for Tailings Dam Failures Based on Case History. ***Advances In Civil Engineering****, v. 2019, 1-18, 2019.*

Naeini, M.; Akhtarpour, A. Numerical analysis of seismic stability of a high centerline tailings dam. ***Soil Dynamics and Earthquake Engineering***, v. 107, 179–194, 2018.

PEREIRA, O. F M. ***Análise da Classificação de Barragens de Contenção de Rejeitos no Brasil, quanto ao Critério de Categoria de Risco****. 55f. Dissertação (Mestrado) - Curso de Uso Sustentável de Recursos Naturais em Regiões Tropicais, Instituto Tecnológico Vale Desenvolvimento Sustentável, Belém, PA, 2016.*

Planalto. ***Lei nº 12.334, de 20 de setembro de 2010****. Portaria 70. Disponível em: http://www.planalto.gov.br.*

Planalto. ***Lei nº 14.066, de 30 de setembro de 2020****. Portaria 70. Disponível em: http://www.planalto.gov.br.*

Smuda, J.; Dold, B.; Spangenberg, J. E.; Friese, k.; Kobek, M. R.; Bustos, C. A.; Pfeifer, H. R. Element cycling during the transition from alkaline to acidic environment in an active porphyry copper tailings impoundment, Chuquicamata, Chile. ***Journal of Geochemical Exploration***, v. 140, 23–40, 2014.

Pfeifer, H.R. Element cycling during the transition from alkaline to acidic environment in an active porphyry copper tailings impoundment, Chuquicamata, Chile. **Journal of Geochemical Exploration**, v. 140, p. 23–40, 2014.

Tailings info, *Tailings Related Accidents-Failures, Breaches and Mudflows*, 2018. Disponível em: http://www.tailings.info/knowledge/ accidents.htm.

TSM Guiding Principles (2019). Disponível em: https://mining.ca/towards-sustainable-mining/tsm-guiding-principles/

The Mining Association of Canada (MAC). ***A Guide to the Management of Tailings Facilities****. version 3.1, Canadá*,2019. Disponível em: https://mining.ca/.

Xu, B.; Wang, Y. Stability analysis of the Lingshan gold mine tailings dam under conditions of a raised dam height. ***Bulletin of Engineering Geology and the Environment***, v. 74, n. 1, 151–161, 2015