RELISE

HISTORICAL AND TECHNICAL ISSUES OF MINING TAILINGS DAMS: LONG-TERM ENVIRONMENTAL LIABILITIES[1]

QUESTÕES HISTÓRICAS E TÉCNICAS DAS BARRAGENS DE REJEITO DE MINERAÇÃO: PASSIVOS AMBIENTAIS DE LONGO PRAZO

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ABSTRACT

Dams are physical infrastructures usually used to dam watercourses, however, such structures also serve for the deposition of other materials, in the case of this work, mineral tailings. In this sense, this literature review presents the history and background of mining dams, reporting the most diverse developments. It describes the main dam disruptions throughout contemporary history, from the 1960s on, at the time of the intensification of the productive scale. Finally, it presents the forms, instruments, methods, and procedures related to tailings dams, as well as the main causes of disruption, by a critical approach. We realize, therefore, that dams constitute spatial roughness of high impact, with considerable risks to the natural environment and society. Therefore, one should take into account not only the environmental liabilities related to dams, because at the time of a rupture, passives derive from social suffering. This liability, from social suffering, must be understood as the cultural, social, physical, psychological, health and memory cost of those affected, something not yet measurable. As advanced as engineering techniques are, little progress has been made, if any, on this type of liability.

Keywords: mining, tailings dams, history of disruption, constructive methodologies, disruptions.

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RESUMO

As barragens são infraestruturas físicas utilizadas usualmente para represar cursos d’água, entretanto, tais estruturas servem também para a deposição de outros materiais, no caso desse trabalho, rejeitos minerais. Nesse sentido, essa revisão bibliográfica apresenta a história e o histórico das barragens de mineração, relatando as mais diversas evoluções. Descreve os principais rompimentos das barragens ao longo da história contemporânea, a partir dos anos 60, momento da intensificação da escala produtiva. Por fim, proporciona as formas, instrumentos, métodos, e procedimentos relacionados às barragens de rejeito, bem como as principais causas de rompimento, por uma abordagem crítica. Percebemos, portanto, que as barragens constituem rugosidades espaciais de elevado impacto, com riscos consideráveis ao ambiente natural e sociedade. Logo, deve-se levar em conta não apenas os passivos ambientais relativos às barragens, pois no momento de uma ruptura, deriva passivos do sofrimento social. Esse passivo, do sofrimento social, deve ser compreendido como o custo cultural, social, físico, psicológico, de saúde e memória dos atingidos, algo ainda não mensurável. Por mais avançado que sejam as técnicas de engenharia, pouco se avançou, se é que avançou, sobre esse tipo de passivo.

Palavras-chave: mineração, barragens de rejeitos, histórico de rompimento, metodologias construtivas, rompimentos.

INTRODUCTION

In the process of contemporary mineral extraction, the fate of high-entropy materials follows a course in which they are considered waste of low or no commercial value. At the operational level of mining, the ore deposit is divided into ore and waste, the latter comprising overburden, effluents, and tailings. The focus of this work is on tailings, for which one of the most commonly used techniques within the production process is tailings dams.

Silva (2018, p. 21) reinforces the importance of distinguishing between waste and tailings, since “[...] the former may still have a destination, be reused. Tailings are something useless, no longer recoverable”, although this latter concept may change over time with technological advances, turning them into waste. Many are already assessing the possibilities of re-mining tailings from dams as well as creating new uses for these resources, with bricks being a good example.

Thus, dams can be understood as earthen structures built for the purpose of storing tailings derived from the production process. Tailings, in turn, have diverse characteristics that depend on the type of material being extracted, which presents important peculiarities when considering the formation of slurries.

The present study, consisting of a literature review from a critical perspective, is organized into seven sections, including this introduction. It begins by analyzing the structure of mineral tailings dams, presenting some technical elements and demonstrating them as spatial roughness. Next, it discusses the history and background of mineral tailings dams, continuing with the forms, instruments, methods, techniques, and procedures related to this structure. Finally, it details the main causes of tailings dam failures and how such events affect all spatial elements (society, companies, the natural environment, state institutions, and infrastructure), presenting the final considerations through a critical approach.

MATERIAL AND METHODS

This is a theoretical article, based on a literature review, of a descriptive nature, adopting a qualitative-descriptive approach. Through content analysis, it develops a rationale for understanding the historical and technical issues of tailings dams, using mineral extraction as the central element. This work also contains philosophical aspects, both from an ontological and an epistemological perspective (ECO, 2008).

The text is related to subjective assumptions, from which information and data emerge, complementing existing theories, since theories often do not adequately explain the phenomenon. This allows the researcher to collect as much information as necessary about the problem with the aim of analyzing, interpreting, or theorizing about the phenomenon (GIL, 2002). Therefore, the methodology that underpins this article is based on a survey of the topic, while acknowledging the subjectivity of the author (FLICK, 2004).

The hypothesis of this study is that the logic of the hegemonic model produces and reproduces a rationality incompatible with biological and physical primacy, a fact that is made evident by recent dam failures in Brazil and worldwide.

The objective of this work is to carry out an analysis, from a bibliographic perspective, of the structure of tailings dams, as well as their background and history, forms, instruments, construction methods and techniques, and the main causes of dam failures.

To this end, this article adopts a literature review, understood as a process of searching, analyzing, describing, and comprehending a body of knowledge, with the aim of achieving specific results. The guiding question of this study is: what is the historical and technical-evolutionary process of dams, and what are the main causes of their failure?

Drawing on an integrative review - given its multi- and interdisciplinary scope - this study incorporates results from diverse fields of knowledge. Accordingly, it is guided by two main purposes: (i) constructing a contextualization of the topic and the problem related to dam failures; and (ii) analyzing the possibilities, techniques, tools, methods, and procedures related to the design of the research's theoretical framework.

RESULTS AND DISCUSSION

The structure of mineral tailings dams

This work aims to advance analyses of the safety of mining tailings dams, their risk management, and mine closure plans. Initially, the framework was considered in a global context, and later in a national (Brazilian) context. The updated dam safety design criteria were considered in accordance with the national PNSB policy (Law 12,332/2010) and AMN/ANA/ANEEL legislation, as well as current legislative changes and

> [...] Engineering structures designed to safely store waste from ore dressing, an operation that concentrates minerals containing substances of interest (in this case, iron oxide minerals, primarily hematite), separating them from other minerals. Ore processing requires crushing and grinding, producing grains fine enough to allow physical or physicochemical separation of the ore from other minerals. The concentrated ore undergoes further processing, often at other sites, but the tailings are disposed of in the immediate vicinity of the mine. Although designed to last their entire operational life and beyond (after proper closure), tailings dams (or other tailings storage facilities) can fail, which occurs much more frequently than water dams. (SÁNCHEZ, et al., 2018, p. 1).

According to Chammas (1989), there are three types of behavior for tailings slurries: 1) Liquid-like behavior, with flocculation of smaller particles; 2) In the process of sedimentation, presenting a semi-liquid and semi-viscous behavior; and 3) In the process of consolidation, behaving like soil. It is important to note that tailings are not strictly speaking soil, but for geotechnical purposes, their behavior is considered equivalent to that of a soil with low shear strength characteristics.

Machado (2007, p. 28), analyzing the manual "Instrumentation of Embankment Dams and Levees," notes that dams follow a specific number, type, and location for their implementation; thus, they present individual solutions. However, it is important for the technical team to understand the physical and mechanical phenomena involved in this project. Machado (2007, p. 28) presents four central objectives for a geotechnical instrumentation plan:

> 1) Analytical assessments - consists of the analysis of data obtained from geotechnical instrumentation and should be used to verify the parameters adopted in the project;
> 2) Future performance prediction - refers to the instrumentation data obtained that indicate the future behavior of the dam;
> 3) Legal assessments - important instrumentation data are used to resolve disputes related to the construction of the project; and
> 4) Development and verification of future projects – refers to the economics of new projects.

Machado (2007) adds the basic objectives discussed in the symposium on dam instrumentation (1996), which were grouped into three topics that deserve attention: construction, filling and operation. However, Machado (2007, p. 29) presents the following structure:

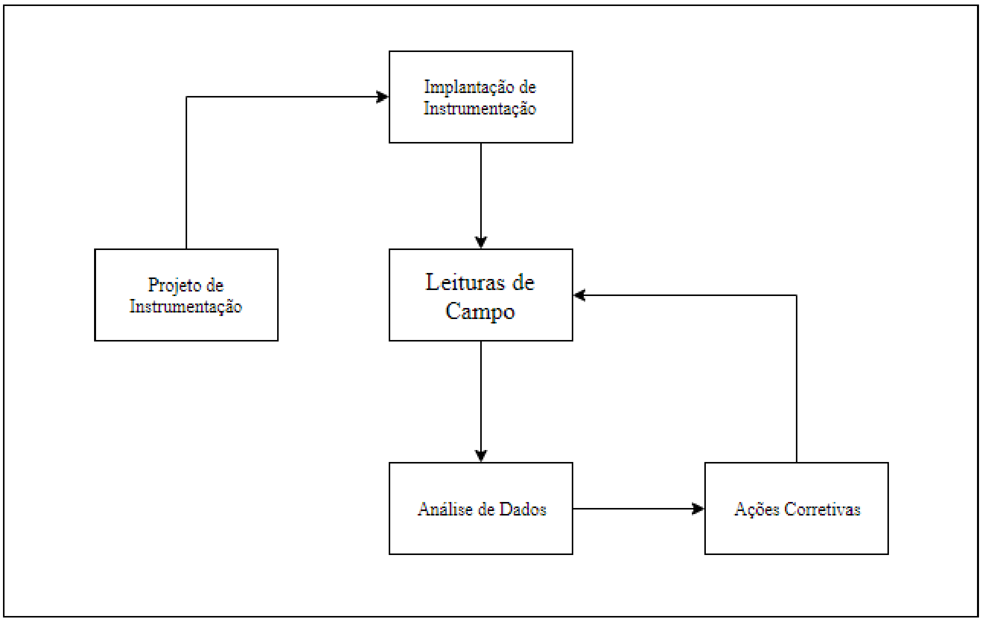
> Construction period:
> 1) Alert to the occurrence of possible anomalies in the dam's behavior;
> 2) Enable less conservative solutions, resulting in significant project savings;
> 3) Provide information, through retro-analysis of instrumentation data, regarding the values of the parameters of the materials that make up the dam and its foundation;
> 4) Enable design revisions during the construction period, allowing, if necessary, restudy in time to avoid significant losses.
> Reservoir filling period:
> 1) Alert to the occurrence of possible anomalies that could jeopardize the safety of the structure;
> 2) Enable assessment of the structural, geotechnical, and hydraulic performance of the project, based on comparisons between in-situ measurement quantities and those predicted by theoretical or experimental analysis models;
> 3) Verify the adequacy of the simplifications introduced in the design hypothesis.
> Operational Period:
> 1) Verify that the dam is performing satisfactorily overall, as anticipated in the design. However, it is during this period that important conclusions can be drawn regarding the quality and performance of this structure;
> 2) Characterize the behavior of the soils and/or foundation rock mass over time, determining the time required for stabilization of displacements, internal stresses, uplift pressure, drainage flows, etc.;
> 3) Characterize the behavior of the dam structures over time as a function of hydraulic load, also taking into account the effects of thermal and environmental conditions.

This symposium took place in 1996, before the major dam failures, and thus demonstrates some important points from the engineers' perspective, including that less conservative solutions aimed at cost reduction were and continue to be the focus of the projects. This demonstrates a disregard for nature and people, as the instrumentation lacks any points that demonstrate these concerns.

Thus, it imposes the idea that mining is a closed system with little impact on nature and populations, a fact that the recent dam failures demonstrate to the contrary. There are undoubtedly concerns about reducing the risks of these projects, especially regarding dam failures. However, the central issue is based on operational and reputational costs and risks, rather than social and environmental issues. The way they address these issues fails to legitimize society and the natural environment as central elements of their strategic policies.

Figure 1 presents a classic example of the strategic routine in relation to dams, requiring an understanding of how society and the natural environment are related to the processes and tools, as well as the weight, intensity and amplitude directed at them.

Figura 1 - Routine of a dam instrumentation program.



***Source**: Adapted from MACHADO (2007, p. 33)*

Oliveira (2010, p. 18), when discussing the requirements and guiding principles for managing tailings dams, considers "[...] the safe disposal of this waste and the careful and dynamic planning of the actions involved in the disposal activity during operation." Therefore, these are the essential metrics for ensuring dam safety. He also reports that the biggest difference between tailings dams and hydroelectric dams "[...] lies in the fact that the construction of tailings dams is a continuous process, in constant development," making them dynamic during their construction and operation (OLIVEIRA, 2010, p. 19).

Another important highlight regarding tailings dams is that they are one of the largest visible structures in mining, becoming a spatial roughness. Therefore:

> [...] for mining, which is an activity that handles large quantities of natural materials, adopting effective and safe waste disposal techniques (sterile and tailings), which guarantee their long-term stability, may be more important than adopting waste reduction strategies (SÁNCHEZ, 2001, p. 164).

History and background of mineral tailings dams

Thus, it is evident that dams remain unstable structures, even when relying on robust engineering techniques and procedures. Table 1 shows their development from 4800 B.C. up to the 1940s. Regarding failures, there is a considerable history of occurrences both in Brazil and worldwide.

A major accident was recorded in 1889 in the city of Johnstown, Pennsylvania, USA. The resulting wave reached approximately 10 meters in height, moving at a speed of 15 m/s toward the city. The death toll was estimated at around 2,200 victims, in addition to material losses, environmental damage, and collective memory impacts.

In 1928, also in the USA, in Los Angeles, California, a dam failure caused approximately 600 fatalities. The incident occurred due to the filling of a reservoir that developed cracks and seepage; at the moment of rupture, the wave reached 43 meters in height.

In 1959, the Malpasset Dam in France collapsed, resulting in 423 fatalities, as the wave reached 50 meters in height and left 79 children orphaned.

Another catastrophic failure took place in 1963, on the Vajont River in Italy. In this case of corporate crime, at least 2,500 lives were lost when, in just a few minutes, 115 million cubic meters of water completely blocked a valley of approximately 2,500 meters (BUENO; DELPUPO, 2017, pp. 2136–2141).

Table 1 - Historical data on the evolution of dams.

YEAR	RECORD OR OCCURRENCE	PLACE
4800 BC	Sadd-El-Katara Dam Height - 12 m Destroyed by overflow	Egypt
500 BC	Earth dam Height - 12 to 27 m 13,000,000 m3 of material	Sri Lanka
100 BC	Roman arch dams	Northern Italy Southern France
1200 AD	Madduk-Massur Dam Height - 90 m Destroyed by overflow	India
1789	Estrecho de Rientes Dam Height - 46 m Destroyed shortly after the first filling	Spain
1820	Telford introduces the use of clay cores in earth and rockfill dams	England
End of the 19th century	Fort Peck Dam Height - 76 m Material Volume - 100,000,000 m3	USA
1856	Darcy's Experiments Water Percolation Rate	France
1859	Patent for the first steam roller compactor	England
1904	The first sheepsfoot type roller appears	USA
1930-40	Soil mechanics is consolidated as an applied science	USA

***Source**: Adapted from MASSAD (2010, p. 174).*

Using the Wise Uranium database, which presents in chronological order the major tailings dam failures worldwide since the 1960s, some events deserve particular attention.

The first major recorded failure listed by Wise Uranium occurred in China, at the Yunnan Tin Group Co. dam, in 1962, in the region of Huogudu, Gejiu, Yunnan. The disaster destroyed 11 villages, caused 171 deaths, injured 92 people, and displaced 13,970 others. The construction method - an upstream type, which will be discussed in more detail in the following sections - failed after moderate rainfall in the area. In 1965, a copper dam failure in Chile left approximately 200 dead, triggered by liquefaction due to an earthquake. In 1966, in Sgorigrad, Bulgaria, another failure killed 488 people, caused by overtopping and deficiencies in the diversion channel during heavy rainfall. Also in 1966, in Aberfan, United Kingdom, 144 people died in a failure linked to operational negligence. In the United States, the Buffalo Creek disaster in 1972 was caused by heavy rainfall, killing 125 people and generating approximately US$ 65 million in property and highway damage. In Stava, Trento, Italy, in 1985, 268 people died in a collapse. That same year, in Niujiaolong, China, another upstream dam failed, killing 49 people. In the Philippines, in 1996, 1,200 people were evacuated due to a failure on Marinduque Island, which caused about US$ 80 million in damages. In Romania, in 2000, the failure of the Aurul gold mine dam polluted the Tisza River, a Danube tributary, affecting other countries such as Hungary and Serbia, turning it into an international and transboundary disaster. Hungary itself suffered another disaster in Kolontár in 2010, where several towns were affected, with 10 people dead and 120 injured. Brazil also presents several cases, with two in particular standing out: the 2015 failure in Mariana/MG, in the subdistrict of Bento Rodrigues, which caused 17 deaths, and the 2019 Brumadinho disaster, with 248 deaths and 22 missing persons (WISE URANIUM, 2019).

The above survey shows that, beyond environmental liabilities, these structures create liabilities of social suffering. Many lives are lost in such failures, and, over time, these tragedies tend to fade from memory. However, even in cases without deaths, the social suffering is no less significant. Many families are displaced, many individuals are injured, and countless others lose their sources of income, their collective memory, and their health. These impacts often affect the most vulnerable populations: mine workers, rural and urban laborers, Indigenous peoples, and those who own little but lose everything.

Silva (2017, p. 2) emphasized that in Brazil, legislation and regulations were often absent or acted too late. Nevertheless, even if belatedly, mechanisms

must be created to mitigate risks and future damage, focusing on those affected and on future generations. There are risks to present-day society, risks that directly and indirectly affect "[...] downstream, upstream, and adjacent communities, but diffuse, transindividual, and transgenerational impacts may be perceived in the medium and long term in fact, perceived, but immeasurable" (SILVA, 2017, p. 2).

Therefore, it is necessary to understand the different types of dams, the main causes of their failures, and their relationship with the soil, since failure is not the only way these structures affect the natural environment and society. Subsequently, we must address national and international legislation on the subject.

Today, in light of recent failures, the general population has only a partial understanding of the differences between dam construction methods. Due to the high-profile accidents, the issue has been widely debated and publicized in the media, generating broader public concern, which is fundamental for public policy. Cardozo, Pimenta, and Zingano (2016, p. 78) review the main techniques used in dam construction, noting that "alongside waste rock piles, dams are the largest geotechnical structures built by humans." Azam and Li (2010), analyzing the issue on a global scale, found that 1.2% of mining dams present problems, compared to only 0.01% in civil dams - a difference that is more than significant.

For this reason, it is essential to distinguish between mining tailings dams and other types of dams. According to Machado (2013) and Duarte (2008), conventional dams can serve a wide variety of purposes, but none are designed for the containment of tailings. The notion of tailings is understood as solid waste, once they no longer have any commercial value. Tailings are therefore considered an inevitable, undesirable by-product of human activity, since they cannot be reused with current technology. This occurs because "[...] as they result from linear processes, tailings cannot return to their original physical state prior

to the productive process,” due to the laws of thermodynamics, particularly entropy (TOLEDO, RIBEIRO, THOMÉ, 2019, p. 22).

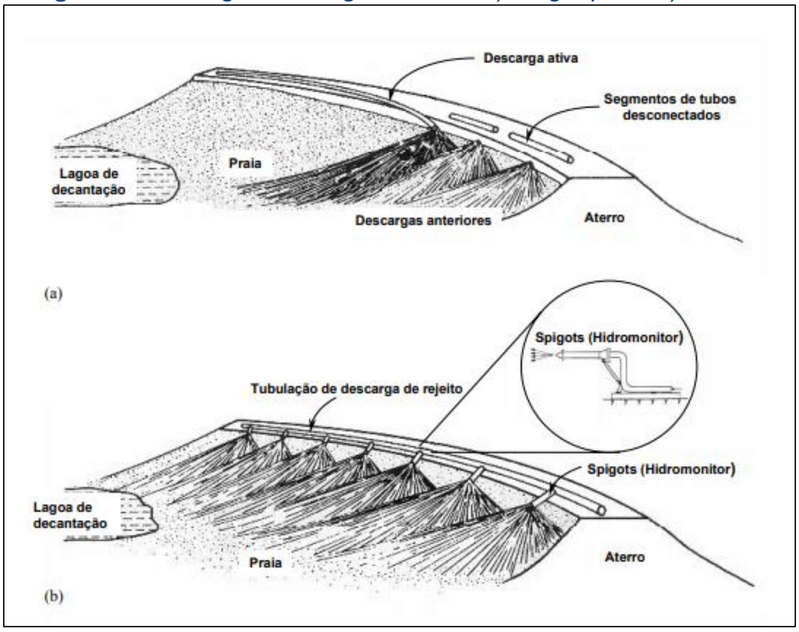
Toledo et al. (2019) point out that in the 1980s, international trade in tailings was common, with the aim of giving unwanted waste a destination by shipping it elsewhere in exchange for financial compensation. This global trade strategy sought to transform certain regions of the planet into vast dumping grounds for tailings - clearly a neocolonial solution.

Forms, instruments, methods, techniques and procedures related to tailings dams

There are three main methods for tailings disposal: subaqueous, underground, and surface (open-air). The first method (subaqueous) is not widely used, as it produces significant environmental impacts, making it a discontinued practice. The underground method involves disposal in chambers that are created as mineral extraction expands. This expansion corresponds to the process by which ore is mostly pumped, filling these chambers. Finally, the method most relevant to the present study consists of surface disposal, which may occur either in controlled piles or in structures located in basins or valleys for tailings containment (LOZANO, 2006).

Mining dams and open-air tailings disposal systems fill their interior (beach/reservoir) through point discharge or line discharge (Figure 2), using hydrocyclones or spigots. These devices allow for the granulometric separation of tailings with the same density. Hydrocyclones use centrifugal force to separate coarser particles (underflow) from finer ones (overflow). The finer particles form the solid fraction of the slurry discharged into the dam reservoir. The coarser, more granular particles, on the other hand, present more favorable characteristics for deposition near the crest of the dam, where they can later be used as construction or raising material (ALBUQUERQUE FILHO, 2004, p. 18).

Figure 2 - Tailings discharge method: a) single point b) in-line.



***Source**: Ribeiro (2000, p. 28).*

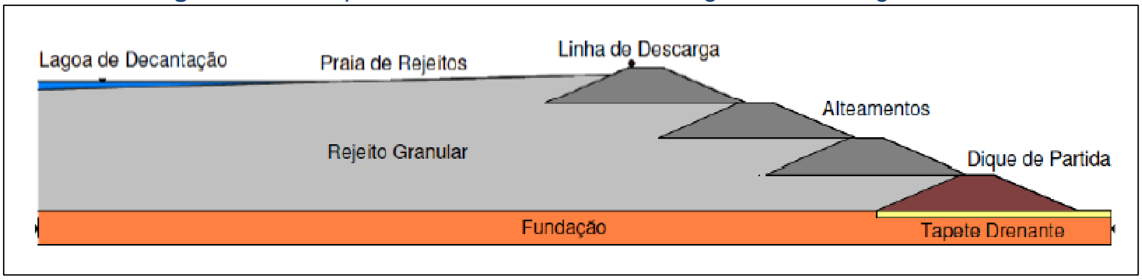
When addressing the types of dams and their construction methods, it is necessary to distinguish the three main techniques used in surface disposal: the upstream method, the downstream method, and the centerline method. Albuquerque Filho (2004, p. 17) highlighted that the main advantage of tailings dam construction methods lies in cost amortization, since “[...] by optimizing construction methods through prior experience and by using the tailings themselves as construction material.” However, it must be noted that, according to several international studies, there are multiple recommendations for such projects to adopt additional measures in order to increase the safety of structures that use tailings as part of the dam body.

In this regard, the first type of dam to be analyzed is the upstream construction method (Figure 3), as it is the oldest, simplest, most economical, and most dangerous among the three mentioned above. The upstream method has been associated with several dam failures in recent years. Consequently, albeit belatedly, legislation has been enacted prohibiting its use for new constructions and requiring the deactivation and decommissioning of existing upstream dams in the state of Minas Gerais, under State Law 23.291/2019.

According to Araújo (2006), the initial stage of this type of structure begins with the construction of a starter dike, usually built with clayey material or compacted rockfill. Once this stage is completed, tailings are discharged through spigots toward the symmetry line of the dike, thereby forming a tailings beach. This process gradually makes the tailings themselves part of the foundation and, if the dam is later raised, part of the construction material. Araújo further emphasized that, despite its widespread use by mining companies, this method offers limited construction control, which makes it highly risky. The problem is aggravated by the fact that raisings are carried out with unconsolidated materials which, when saturated, exhibit low shear strength, potentially leading to both static and dynamic liquefaction.

Lozano (2006) adds that after the construction of the basin dikes, raisings occur according to operational needs of the mine, with the starter dike always higher than the subsequent ones. Finally, Duarte (2008, p. 9) notes that this method faces “[...] difficulties in implementing an efficient internal drainage system to control the water level inside the dam, creating an additional problem with direct implications for the stability of the structure.”

Figure 3 *- The upstream method of constructing mineral tailings dams.*



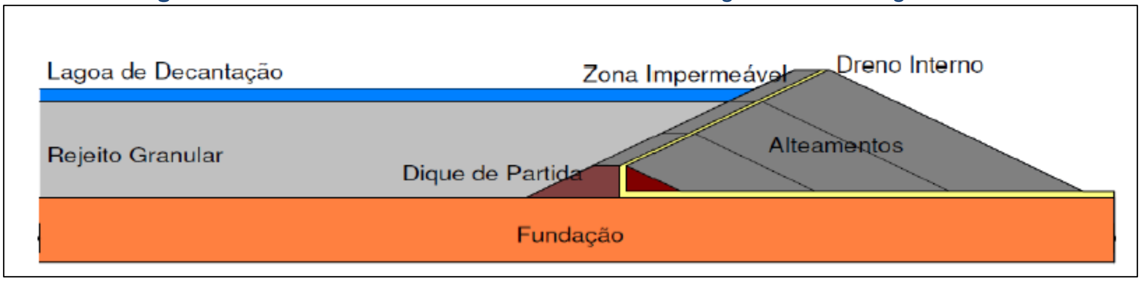
Source*: Albuquerque Filho (2004, p. 21).*

The downstream method (Figure 4) consists of shifting the dam raises downstream from the starter dike. An impermeable dike is constructed with an internal drainage system composed of a filter and a drainage blanket. The inner slope of the dam is also waterproofed during the raising process. It is worth noting that impermeabilization in the upstream method is not mandatory, particularly when the tailings present a high degree of permeability. In the downstream method, tailings are cycloned and discharged onto the downstream slope of the raise, where only the coarser fractions are used (LOZANO, 2006).

Duarte (2008, p. 9) emphasizes that the advantages of this method lie "[...] in the control of placement and compaction, in accordance with conventional construction techniques". Importantly, no part of the dam is built over previously deposited tailings, which allows drainage systems to be installed throughout the entire process and enables "[...] control of the phreatic surface within the dam structure, thereby increasing its stability" (DUARTE, 2008, p. 9).

According to Araújo (2006), the downstream method requires larger volumes of construction material, making its cost higher compared to the upstream method. Moreover, the occupied area is much greater, given the need for raising during operational progress. Finally, Machado (2007, p. 64) argues that this method "[...] is more efficient for controlling the phreatic surface and begins with a starter dike made of compacted soil."

***Figure 4** - The downstream method of constructing mineral tailings dams.*

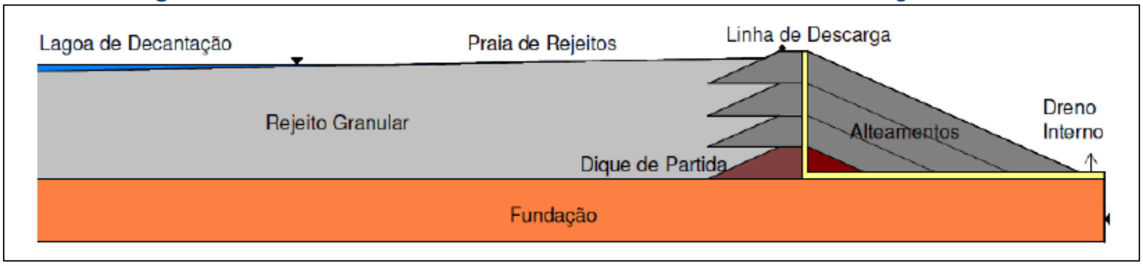


***Source**: Albuquerque Filho (2004, p. 23).*

Machado (2007, p. 65) considers that the centerline method (Figure 5) presents an intermediate solution and, therefore, presents a solution that is suitable for both the downstream and upstream methods, "[...] although its structural behavior is similar to the downstream method". Thus, the dam begins with a starting dike through which the heightening occurs with the dam axis

unchanged. He highlighted that throughout this process, it is possible to use internal drainage zones, as is the case with the downstream method. For Albuquerque Filho (2004, p. 25), this method presents greater construction ease and requires relatively smaller volumes of material within the construction process.

Figure 5 *- Centerline, the method of construction of mineral tailings dams.*



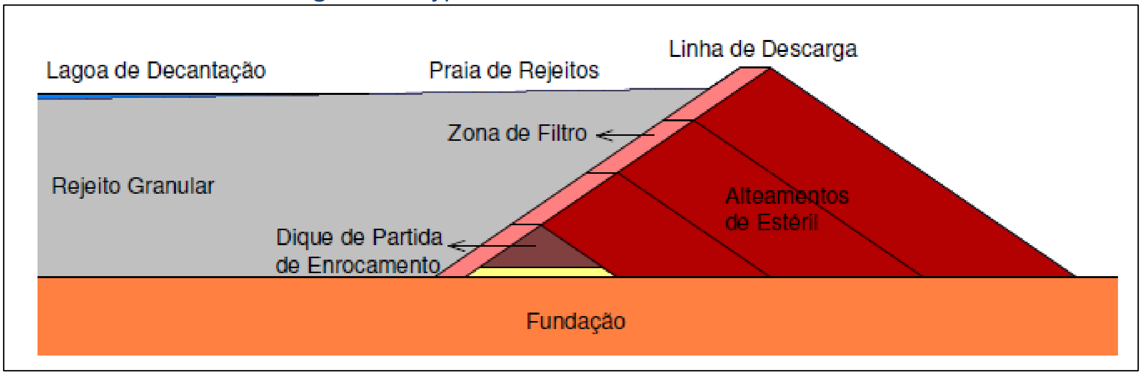
Source*: Albuquerque Filho (2004, p. 24).*

We must keep in mind that the choice between one method or another depends on the nature of the mining process, the geological and topographical conditions of the region, as well as issues related to the mechanical properties of the materials, as well as the environmental impact of the tailings to be stored in the dam (DUARTE, 2008).

Soares (2010) further adds that we must consider several variables, such as: topography, geology, subsoil types and properties, tailings grain size and concentration, deposition rate, storage capacity, required elevations, earthmoving equipment, compaction capacity, and finally, the control teams.

Albuquerque Filho (2004) adds that within the dam construction method, we can choose between conventional waste rock dams or borrowed material dams. Regarding a dam built with waste rock, Albuquerque Filho (2004, p. 25) demonstrates that "[...] the granular waste itself is used as construction material, containment dams can also be built conventionally using waste rock, rockfill or materials from the borrow area" (Figure 6).

Figure 6 - Typical section of a waste rock dam.

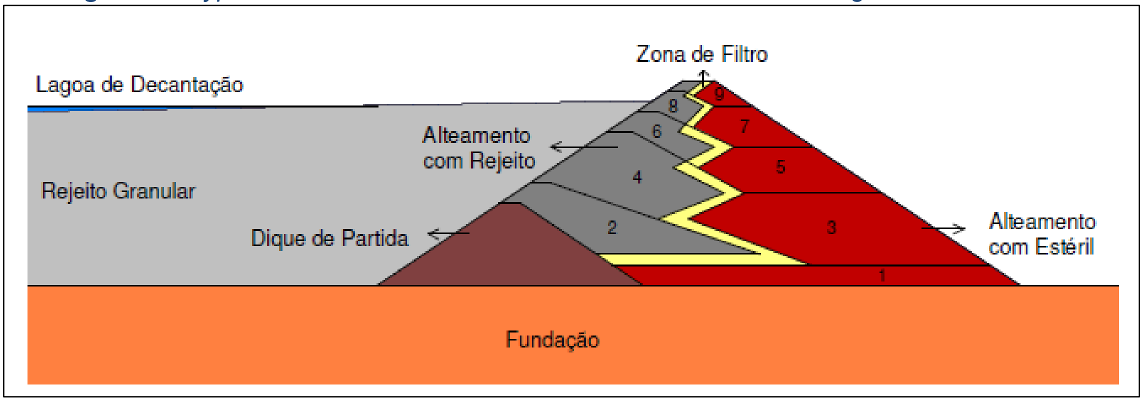


Source: Albuquerque Filho (2004, p. 25).

According to Albuquerque Filho (2004, p. 25), due to the strict legal and environmental requirements that have been introduced in recent decades regarding tailings control, primarily aimed at ensuring the safety of these structures, it is necessary to "[...] adopt designs and executive procedures similar to those developed for water reservoir structures."

Thus, for these structures, a combination of waste rock and tailings is used in the raising stages, which results in the formation of a filter zone, in which "[...] the numbering of the bands shown in the figure indicates the construction sequence used to build this tailings dam," which can be seen in Figure 7 (ALBUQUERQUE FILHO, 2004, p. 25).

Figure 7 - Typical section of a dam built with a combination of tailings and waste rock.



Source: Albuquerque Filho (2004, p. 26).

We note that a fundamental issue in ensuring dam safety lies in the drainage system. According to Cardozo, Pimenta, and Zingano (2016, p. 81), the drains are the main factors responsible for "preventing excessive pore pressure in the dam's water flow." These pore pressure forces favor the movement through which, in the event of drainage system inefficiency, the phenomenon known as piping can occur, which is nothing more than internal erosion of the structure. Therefore, the drainage system is fundamental to all methods, as we know that each has advantages and disadvantages, summarized in Table 2.

Table 2 - *Comparative summary of the main construction methods for tailings dams.*

	Upstream	Downstream	Centerline
Type of tailings	Low density for segregation to occur	Any type	Low plasticity sludge sands
Tailings discharge	Peripheral	Independent	Peripheral
Water storage	Not recommended for large volumes	Good	Acceptable
Resistance to earthquakes	Low	Good	Acceptable
Heightening	Ideal less than 10 m/year	No restriction	Little restriction
Advantages	Lower cost, used where there is area restriction	Greater security	Construction flexibility
Disadvantages	Low safety, susceptibility to liquefaction and piping	Large amount of material required, protection of the downstream slope only in the final configuration	Need for an efficient drainage system

Source*: Adapted from Cardozo; Pimenta e Zingano (2016, p. 82).*

Dam failure and its main causes

After understanding the main dam construction methods and their respective advantages and disadvantages, it becomes necessary to assess the primary causes of dam failure - the phenomenon this study seeks to analyze. Dam failures are not new in human history, as multiple recurrences have been documented. According to Mota (2017, p. 22), there are two main factors behind such events throughout history. The first refers to natural phenomena that can weaken the structures. The second relates to poor planning of the structure, including flaws throughout the entire life cycle of the project and even after its closure.

For Luino and De Graff (2012), the Stava disaster in Italy - where mining activities have been recorded since at least 1528 - became a milestone, as this corporate crime, like others, could have been avoided with stronger and more effective regulation. In their study, Luino and De Graff present five reasons explaining why tailings dams are more susceptible to failure compared to conventional dams. They highlight that the most common causes are processes known as liquefaction and seepage, which occur due to a prolonged state of consolidation following sedimentation. Essentially, given the high cost of dam maintenance, the sedimentation process of tailings, the increasing volume of impounded material, weak legislation, and the lack of continuous monitoring protocols during the project’s life cycle and after mine closure are the factors responsible for failures. “The term ‘mine’ includes all facilities necessary for the production of mineral substances, in particular excavations, waste and tailings disposal sites, ore storage areas, inputs and products, processing plants, and support facilities” (SÁNCHEZ, 2001, p. 49).

Due to their scale, tailings dam failures in recent years have caused severe impacts, such as the loss of human and animal life, the destruction of ecosystems, properties, rivers, and lakes, along with many other affected biotic and abiotic resources. These failures can therefore be considered catastrophes, accidents, tragedies, or crimes; for the purposes of this study, we adopt the latter terminology, which will be further detailed in the course of the research.

Mota (2017, p. 24) stresses the importance of advancing knowledge in soil mechanics and water resources, providing engineers with essential tools to “[...] quantify the magnitude of such damage and to predict and eliminate it as early as the design phase”. The author emphasizes that dam failures result from

both internal and external forces, with multiple causes for potential structural collapse, such as seepage, internal erosion, overtopping, and liquefaction, among others. Santos, França, and Almeida (2007) describe dam types and their relation to the most frequent types of failures (Table 3).

***Table 3** - Causes of dam rupture.*

TYPE OF DAM	FORM OF RUPTURE
Embankment	Overtopping Internal erosion Foundation slippage Reservoir wave action Foundation erosion downstream of the dam
Concrete Gravity	Material deterioration Dam foundation failure Dam body stability Dam foundation erosion downstream Acts of war
Arch concrete	Failure of the lateral abutments of the foundation valley Saturation of the rock foundations Excessive load resulting from excessive reservoir filling Sliding of the dam body Erosion of the foundation downstream of the dam

Source: Adapted from Santos, França e Almeida, (2007, p. 24-25)

The main causes of dam failures will be presented in a very summarized and simplified format, based on the survey by Mota (2017) (Table 4). Internal erosion (piping) is one of the main causes of failures in old and small dams, occurring when water infiltrates the foundation or compacted soil, creating a channel within the dam. Overtopping is also common worldwide and generally occurs when the reservoir's water level rises above the dam crest, often due to heavy rainfall, causing material to be carried away and overloading the dam. Sliding occurs when certain areas of the dam are displaced downstream, which can cause both the foundation and the dam to slide due to an imbalance of forces. Finally, Mota (2017) emphasizes that the collapse process occurs in concrete dams and is caused by structural imbalances.

Table 4 *- Relationship between types of dams and their forms of rupture*

		Type of dam				
		Earth	Concrete	Arch	Arch with Buttresses	Multiple Arches
Forms of rupture	Piping	x	x	x	x	x
	Overtopping	x	x	x	x	x
	Slide	X	x			
	Overthrow		x	x	x	x

Source: Adapted from Mota (2017, p. 32)

Robertson (2011) presents interesting information regarding the historical evolution of mineral production and the height of tailings dams, as shown in Table 5. We can observe that as the production scale increases, dams are reconfigured to accommodate the demand for tailings from mining processes. The strategies adopted by mining companies are based on expanding carrying capacity by increasing dam heights. Dams measuring 120 meters, 240 meters, and even 400 meters are unrealistic; their projects should not be approved, as mineral extraction has not become more efficient and maintains a sustainable scale. What we see are operational processes that are highly wasteful, requiring storage of their inefficiency. The government simply cannot accept projects of this scale, because the risks, no matter how good the technology, are not worth it for society. They may even be worth it for the company, but they need to be curbed so that new, more efficient techniques can be developed, generating less waste and mitigating latent side effects.

Table 5 - *Growth of mineral activity X height of tailings dams.*

Evolution of world production	Evolution of dam heights
1930 - 100 tons/day	1900 - Maximum dam height - 30 meters
1960 - 1,000 tons/day	1930 - Maximum dam height - 60 meters
1990 - 10,000 tons/day	1960 - Maximum dam height - 120 meters
2000 - 100,000 tons/day	2000 - Maximum dam height - 240 meters
Current - 670,000 tons/day	Current - 340-meter dam under construction
2030 - 1,000,000 tons/day (forecast)	A dam with a planned height of 400 meters is currently in the design phase.

Source*: Adapted from Robertson (2011).*

According to the table above, it becomes evident how mining has been evolving worldwide and becoming increasingly accelerated, particularly in terms of production and scale, which consequently requires ever larger dams. These projects are transforming society, adding risks and vulnerabilities that are increasingly difficult to measure. A motto in the financial market suggests that the greater the risk, the greater the return - and apparently, the mineral sector is playing with this logic, seeking large-scale short-term returns.

In this way, society and the natural environment are the ones who bear the unaccounted-for liabilities. In the event of a dam failure, although companies may face some penalties, it is ultimately the population that pays the price. Moreover, if the failure occurs while the company is still operating, the State can, through its mechanisms, hold the company accountable. But what happens if the company no longer exists? What happens when nothing happens?

After the corporate crime committed by Samarco S.A. in Bento Rodrigues, a subdistrict of Mariana/MG, many believed that the mining companies responsible would solve the problems. However, it became clear that even after all the destruction, the companies chose to use second-rate materials in their projects, reinforcing arguments of corporate crime and even disregard for society. On August 21, 2019, the newspaper Estado de Minas published a report denouncing mining companies for using low-quality materials in the construction of dikes. The obvious objective was to cut costs, but the projects already showed

flaws at their inception, compromising environmental recovery (ESTADO DE MINAS, 2019).

We must recognize that today these companies continue to operate with their shares traded on stock exchanges (financial market). But what if, in the future, capital becomes dispersed? What if mergers or acquisitions occur with other companies, changing the corporate structure? Or if the companies simply go bankrupt over time, leaving behind spatial scars such as tailings dams - who will bear the losses? Answering these questions will provide indicators of the path human action is taking, supported by technical systems, legal frameworks, and symbolic structures.

CONCLUSION

Dams are constructions whose techniques have evolved alongside human history itself. Designed to create artificial barriers to retain water or other materials, modern dams are increasingly larger, with massive load capacities. Obviously, when these structures fail - regardless of the quality of engineering - the resulting destruction is unacceptable for a civilized society. The risks are not worthwhile, as there is a limit, a carrying capacity, something that should represent a sustainable productive scale. To disregard the effects of dam failures, grounded solely in monetary metrics and an outlook of economic growth at any cost, constitutes a grave mistake. It is insufficient to merely assess ecosystem services, functions, or environmental liabilities; ignoring the liabilities of social suffering renders the entire operation irrational.

Focusing on tailings dams (infrastructure), we observe that a public good (mineral resources), exploited by a monopoly (company), through concessions (the State), when ruptured, impacts entire populations (society) and the natural environment (ecosystems) - in other words, all spatial elements. A dam collapse represents a contradiction to the conventional economic model, since the

marginal gains of companies are achieved through the social and environmental costs borne by communities and populations. Even if a dam appears safe, considering the law of entropy, it tends to dissolve over time; therefore, no dam is truly safe, as safety is only temporary.

There have been advances in risk management, considering updates in dam design criteria under the National Dam Safety Policy (PNSB – Law 12.332/2010), its subsequent amendments such as Ordinance No. 70.389/2017, and the creation of the Integrated Dam Safety Management System for Mining Dams (SIGBM). Nevertheless, these frameworks do not take into account intergenerational relations, nor do they encompass many important aspects discussed throughout this research.

Furthermore, when analyzing the relationship between the State and companies, we find numerous cases of abuse involving mining corporations and other spatial elements. The collapses of their dams, and the way these cases are handled, at times appear as strategies aimed at corroding human resilience. To this day, the consequences of dam failures have not been properly addressed. For instance, in the case of Samarco S.A. (2015), a foundation was created to protect the company’s image, while its reputation was already tarnished before society, revealing a deliberate attempt to avoid corporate depreciation (compliance risk). When examining the market value trends of one of its major shareholders, Vale S.A., it reinforces the thesis that crime pays. Fines are often not paid, and compensation lawsuits are delayed in the courts, which overwhelmingly serve corporate interests. It is worth noting that today it is easier to access the English justice system than the Brazilian one, especially for those affected by dam failures, as in the case of Samarco S.A. and its corporate crime.

Therefore, understanding the historical evolution and background of tailings dams - their forms, instruments, methods, and procedures - becomes central to developing these reflections. As productive scale increases, risks also

intensify, and dams are built to be ever more robust. However, if technological or human failures occur, the social and environmental costs are immeasurable. Dams are spatial scars that will remain in the landscape if not adequately addressed; thus, it is crucial to understand the main causes of dam failures in order to develop mitigating measures.

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REFERÊNCIAS

Albuquerque Filho, L. H. (2004). **Avaliação do comportamento geotécnico de barragens de rejeitos de minério de ferro através de ensaios de piezocone**. Dissertação (Mestrado em Engenharia Civil), Departamento de Engenharia Civil, UFOP, Ouro Preto, Minas Gerais.

Araújo, C. B de. (2006). **Contribuição ao Estudo do Comportamento de Barragens de Rejeito de Mineração de Ferro**. Dissertação (Mestrado em Engenharia Civil), Faculdade de Engenharia Civil, COPPE/UFRJ. Rio de Janeiro, RJ.

Azam, S.; LI, Q. (2010). Tailings dam failures: A review of the last one hundred years. **Geotechnical News**, 28(4), p. 50-54.

Bueno, J. G. R.; Delpupo, M. V. (2017). Responsabilidade civil pelo dano decorrente do rompimento de barragem. **Revista Quaestio Juris**, Rio de Janeiro, v. 10, n. 3, p. 2135-2168, 2017.

Cardozo, F.A.C.; Pimenta, M. M.; Zingano, A.C. (2016). Métodos construtivos de barragens de rejeitos de mineração: uma revisão. **Revista Holos**, ano 32, vol. 08, pág.: 77-85; 2016.

Chammas, R. **Barragens de Contenção de Rejeitos**. (1989) Curso de Especialização em Engenharia de Barragens (CEEB), Departamento de Engenharia Civil, Universidade Federal de Ouro Preto.

Duarte, A. P. (2008). **Classificação das barragens de contenção de rejeitos de mineração e de resíduos industriais no estado de Minas Gerais em relação ao potencial de risco**. Dissertação de Mestrado, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brasil.

ECO, Umberto. **Como se faz uma tese**. São Paulo, Perspectivas, 2008.

ESTADO DE MINAS. **Rompimento de dique construído com material de segunda ameaça a recuperação ambiental no Rio Doce**. (2019). Disponível em: https://www.em.com.br/app/noticia/gerais/2019/07/21/interna_gerais,1071226/rompimento-de-dique-construido-com-material-de-segunda-ameaca-recupera.shtml?utm_source=onesignal&utm_medium=push&fbclid=IwAR3SWyZCTk2L67y7Riub62T7c4qrAtgNQAm2kmGgc61IzTpcuAtDi92QrRI. Acesso: 23 de ago. 2019.

FLICK, Uwe. **Uma introdução à pesquisa qualitativa**. 2. ed. Porto Alegre: Bookman, 2004.

GIL, Antônio Carlos. **Métodos e técnicas de pesquisa social**. 4. ed. São Paulo: Atlas, 2002.

Lozano, F. A. E. (2006). **Seleção de locais para barragens de rejeitos usando o método de análise hierárquica**. Dissertação (Mestrado em Engenharia Geotécnica), Departamento de Engenharia de Estruturas e Fundações, USP, São Paulo.

Luino, F.; De Graff, J. V. (2012). The Stava mudflow of 19 July 1985 (Northern Italy): a disaster that effective regulation might have prevented. **Natural hazard and earth system sciences**, vol. 12, p. 1029-1044.

Machado, P. A. L. (2013). **Direito Ambiental Brasileiro**. 12º Ed. São Paulo: Malheiros Editores.

Machado, W. G. de F. (2007). **Monitoramento de barragens de contenção de rejeitos da mineração**. Dissertação de Mestrado. Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia de Minas, São Paulo.

Mota, K. R. R. (2017). **Rompimento hipotético e delimitação da área inundada da barragem Salto Moraes em Ituiutaba/MG**. Dissertação (Mestrado), Universidade Federal de Uberlândia, Programa de Pós-Graduação em Engenharia Civil, Minas Gerais.

Oliveira, J. B. V. R de. (2010). **Manual de operação de barragens de contenção de rejeitos como requisito essencial ao gerenciamento dos**

rejeitos e à segurança de barragens. Dissertação de Mestrado. Universidade Federal de Ouro Preto. Escola de Minas, Minas Gerais.

Ribeiro, L. F. M. (2000). **Simulação física do processo de formação dos aterros hidráulicos aplicados a barragens de rejeitos**. Tese (Doutorado), Departamento de Engenharia Civil e Ambiental. Universidade de Brasília.

Robertson, A. C. (2011). Solutions Beyond Incremental Changes. In: **Tailings and Mine Waste**, Vancouver, BC, 2011.

Sánchez, L. E. (2001). **Desengenharia**: o passivo ambiental na desativação de empreendimentos industriais. Edusp/Fapesp, São Paulo.

Sánchez, L.E., et al. (2018). **Os impactos do rompimento da Barragem de Fundão**. O caminho para uma mitigação sustentável e resiliente. Relatório Temático no 1 do Painel do Rio Doce. Gland, Suíça: UICN.

Santos, J. B. dos.; França, M. J.; Almeida, A. B de. (2007). Risco associado à ruptura por galgamento de barragens de aterro. **Inginieria del Agua**, Córdoba, v. 14, n. 4, p. 260-278.

Silva, A. M. (2017). **Sociedade de risco e as barragens de rejeitos**. Rio de Janeiro: Lumen Juris.

Silva, L. C. do N. (2018). **Barragens de rejeito da mineração**: análise do sistema de gestão do Estado de Minas Gerais. Rio de Janeiro: Lumen Juris.

Soares, L. (2010) Barragem de rejeito. In: Luz, A. B. da.; Sampaio, J. A.; França, S. C. A. **Tratamento de minérios**. Rio de Janeiro: CETEM/MCT, p. 831-896.

Toledo, A. de P.; Ribeiro, J. C. J.; Thomé, R. (2016). **Acidentes com barragens de rejeitos da mineração e o princípio da prevenção**. Rio de Janeiro: Lumen Juris.