Mine Water and the Environment (2021) 40:166–173
https://doi.org/10.1007/s10230-020-00722-6

TECHNICAL ARTICLE

Lessons Learned from the Two Major Tailings Dam Accidents in Brazil

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Received: 5 March 2020 / Accepted: 17 September 2020 / Published online: 28 September 2020

Abstract

The failures of the Mariana and Brumadinho tailings dams in Minas Gerais, Brazil, had severe environmental repercussions and caused many fatalities. What should or could have been done to prevent these kinds of accidents? This paper discusses the management practices, relevant legislation, and supervision of tailings dams in Brazil, as well as the possible causes of these dam breaks, and evaluates whether the measures taken by National Mining Agency (ANM) will prevent more such accidents. Intensive investigation of these accidents revealed some similarities and discrepancies. The failure mode for both tailings dams was liquefaction flow. Considering that many other tailings dams are in similar conditions, it is likely that further failures may occur, despite the measures taken by the ANM.

Keywords Brumadinho accident · Mariana accident · Static liquefaction · Dam management

Introduction

Many tailings dams are large structures that were intended to stand for a long time, but many tailings dams have failed during the past 60 years. The International Commission on Large Dams (ICOLD 2001) statistically analyzed tailings dams failures from 1965 to 2000, and concluded that about 37% of the total tailings volume are released by such failures, while Rico et al. (2008) estimated that the released volume averages 33% of the stored tailings. The rate of tailings dam failures is much higher than the failure rate for water retention dams (Chambers and Higman 2011). Bowker and Chambers (2015) highlight that since 1990, the consequences of dam failures have increased in intensity. Owen et al. (2020) cites the accidents of Brumadinho (Brazil 2019), Cadia mine (Australia 2018), Mount Polley (Canada 2014), and Philex Padcal (Phiippines 2012).

The relatively recent catastrophic ruptures of the Mariana and Brumadinho tailings dams, both located in Minas Gerais, Brazil, had severe environmental repercussions and caused numerous fatalities They require us to reflect on what could and should have been done to prevent these accidents. On Nov. 5, 2015, the Samarco's Fundão tailings dam in the municipality of Mariana, Minas Gerais failed, causing a huge environmental disaster that resulted in the deaths of 19 people, and flooded several houses. Approximately 32 million m^3 of tailings, corresponding to about 61% of the total tailings volume, were discharged. The tailings struck Rio Doce (the Doce River) and its tributaries, destroying districts and leaving thousands of the region's residents without water and without work. This was the biggest environmental disaster in Brazil and its environmental impacts are still evident. Four companies and 22 people were found responsible in court for the environmental disaster caused by the breach of Samarco's dam—21 of them for murder. According to the Federal Prosecutor's Office (MPF), measures to prevent this tragedy and the resulting deaths were lacking. Three years later, the Brumadinho dam failure on 25 Jan. 2019 resulted in one of the largest tailings disasters in Brazil. The tailings dam, classified as "low risk" with "high damage potential", was controlled by Vale S.A. and was in the Córrego do Feijão region, in the municipality of Brumadinho, 65 km from Belo Horizonte, Minas Gerais. The rupture of the Brumadinho dam killed 259 people; 11 are still missing. The dam breach released about 9.7 million m^3 of tailings, about 75% of the total volume. This failure was regarded as an industrial, humanitarian, and environmental disaster, and a public calamity. It is considered the second

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largest industrial disaster of the century and Brazil's largest occupational accident.

In the national register of the Agência Nacional de Mineração (ANM; the National Mining Agency), and according to the Minas Gerais Institute for Water Management (IGAM), the Córrego do Feijão dam was evaluated as a small structure with a relatively low risk of failure, though it had the classification of high associated potential damage; that is, the greatest pollutant potential, with high potential damage, including loss of human life and economic, social, and environmental impacts. The Fundão Dam was also evaluated as having a relatively low risk of failure and high associated potential damage. By law, such structures must install audible warning systems in areas that could be affected by the dam's failure. Technology is available so that emergency sirens are triggered manually and automatically, following parameters of deformations and displacements whose limits must be defined by the dam designer, or whenever the dam team considers the detected levels of the instrumentation to exceed the recommended limits. In practice, this has caused several interventions in neighboring locations, causing people to be removed when the alert sounds. Fortunately, in cases registered after Brumadinho's accident, the audible alarms were "false". This is in line with the Mining Dam Emergency Action Plan (PAEBM) that the company must have and put into practice. The engineer responsible for the PAEBM is the one who determines which and how much dam monitoring equipment should be used. In 2010, the National Dam Safety Policy determined that dams must have such a Plan, which contains, at a minimum, strategy mechanisms and "means of dissemination and alerting potentially affected communities in an emergency". Security sirens, which should have been triggered to alert staff and residents at the Feijão Dam I did not go off, because some were positioned in places affected by the failure or the flood, while others simply failed.

Several causes have been blamed for the failure of these dams, among them liquefaction, seismic activities, and bad operational practices and tailings management. Many other tailings dams in Brazil are in a similar situation to Brumadinho and Mariana, and the likelihood of new disasters occurring is significant. Some actions have been taken by the government seeking to reduce the risk of future accidents, but one of the questions that remains is: why did a low to medium-risk dam fail?

One of the key issues in today's mining debate is the socio-environmental conflicts associated with mining, particularly in Brazil. Disasters and the perception of Brazilian society, in the case of Samarco (Mariana in 2015) and Vale (Brumadinho in 2019), contribute to this debate, where actions have always been reactive, repairing environmental damage and compensating for loss of life. Several studies illustrate the growing conflicts associated with mining projects, particularly in Latin America. This view is partly justified by the lack of historical oversight of the mining industry until environmental concerns rise. Sporadically, we read in the newspaper about mining accidents, sometimes with deaths or serious damage to the environment, with images that remain in memory, because they are impactful. It´s also certain that not all mining companies act with the responsibility they should feel to society and the environment, which helps to establish its negative image.

The Fundão and Feijão I dam failures were intensively studied by panels of international experts hired by the companies VALE and BHP, and all of the documents are available to the interested public. These data served as the basis for this paper. In addition, this paper discusses the main aspects involved in management practices, the legislation and supervision of tailings dams in Brazil, as well as the possible causes of these dam breaks, evaluating whether the measures taken by the National Mining Agency will be effective or not in preventing new accidents.

Failure of the Fundão Dam

The Fundão Dam, located in Mariana, Minas Gerais, was raised by the upstream method and the construction project was complex. After several previous accidents, the dam failed on Nov. 5, 2015. The Fundão Dam failure was investigated by Morgenstern et al. (2016), who concluded that the main cause was the static liquefaction of the tailings. Approximately 61% of the tailings flowed out of the dam. Problems in the original project execution that had resulted in design changes, as well as bad tailings management, caused an increase in saturation and introduced the potential for liquefaction. Among these problems, three stand out: damage to the original Starter Dam, deposition of slimes (fine-grained mud) in inappropriate areas, and structural problems in a drainage gallery that caused the dam to be raised over these slime deposits. Although the failure resulted from several factors, Morgenstern et al. (2016) pointed out that small seismic events could have triggered the liquefaction. Despite these conclusions, it is important to highlight that there was a lot of water inside the dam and as well as an underground source of water that was flowing into the dam on the left side of the structure (Fig. 1). The first signals of the rupture showed up in the base of the dyke built over the tailings sediments, and progressed both to the top and the bottom of the dam.

The Fundão Dam was 80 m high with an overall inclination of 3 (H): 1(V). The tailings were sand mixed with silty materials and mud (with the grain size of clay). These materials were mixed in many places of the dam impoundments. The dam was active when the failure occurred.

The instrumentation and monitoring devices installed at Fundão Dam consisted of piezometers, water level indicators, inclinometers, survey markers, flow meters, rain

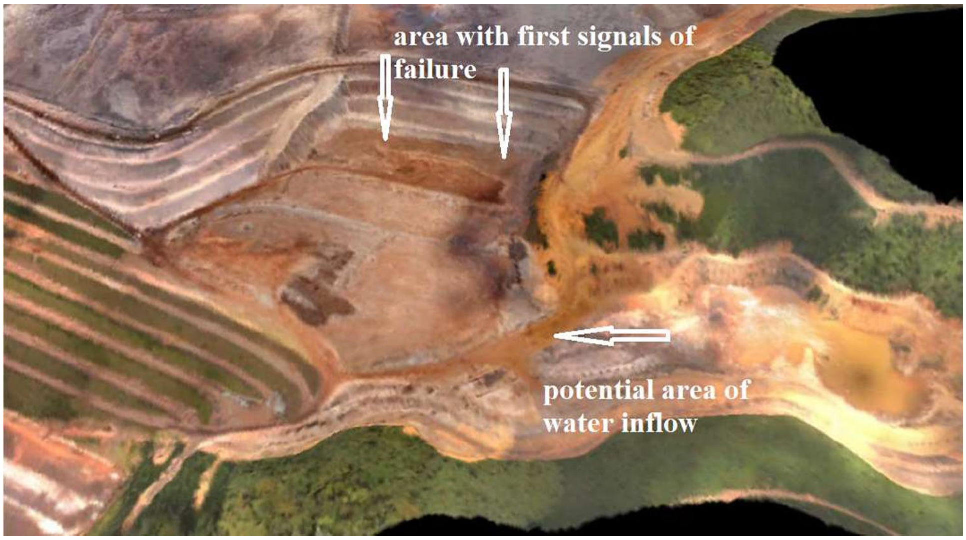

Fig. 1 Change in design of the Fundão Dam with retreat of the left dam shoulder. The new dyke was raised in saturated tailings (modified from Morgenstern et al. 2016)

gauges, a meteorological station, and a reservoir gauge. Geotechnical studies carried out before the failure included a cone penetration test undrained (CPTu), standard penetration test (SPT), chemical and physical characterization tests of the materials of the dam, and geomechanical tests (Morgenstern et al. 2016). Piezometer and water level indicators showed high pressure on the toe of the dam and under the setback.

The Fundão Dam was classified according to the ANM (2020) mining dam classification system as class B, based on its high associated potential damage and low risk category. In this system of classification, the worst dam is classified as class A and the most favorable classification is class E (low risk and low associated potential damage).

Failure of the Feijão Dam I

The Feijão Dam I, located in Brumadinho, Minas Gerais, was also raised by the upstream method. This Dam failure was investigated by Robertson et al. (2019), who concluded that the main cause was again static liquefaction of materials within the dam. They observed that unexpected cementation of the tailings grains made the tailings brittle. This feature, not seen in other iron ore tailings dams, meant that the inclinometers and motion survey markers did not indicate significant movements before the failure. The tailings in the dam showed a sudden and significant loss of strength, and rapidly became a heavy liquid that flowed downstream at high speed. Less than five minutes was enough to liberate more than 9.7 million m^3 of materials. Approximately 75% of the tailings flowed out of the dam. Figures 2, 3, and 4 shows the failure starting at the top of the dam and moving to its toe. The presence of a video camera in front of the dam allows good analysis of the failure process.

The Feijão Dam was 80 m high with overall slope of 3 (H): 1(V). The tailings composition was basically sand mixed with silty materials and mud (with the grain size of clay). These materials were mixed in many parts of the dam's impoundments.

Fig. 2 Feijão Dam I initiation point of slope failure captured by video camera in front of the dam (modified from public images first shown on TV by Globo)

Fig. 3 Toe movement and propagation of the failure at the Feijão Dam I (modified from public images first shown on TV by Globo)

Fig. 4 After a few seconds, the failure propagated throughout the Feijão Dam I (modified from public images first shown on TV by Globo)

The instrumentation and monitoring devices installed at Feijão Dam I consisted of piezometers, water level indicators, inclinometers, survey markers, flow meters, rain gauges, a meteorological station, and a reservoir gauge. With more than 200 devices for measuring the dam's properties, we could say that the dam was adequately monitored. Besides these tools, several geotechnical studies were carried out before the failure including CPTu, SPT, Vs propagation analysis, chemical and physical characterization test of the dam's materials, and a geomechanical test (Roberston et al. 2019). None of the methods of deformation monitoring showed any significant deformation prior to failure. The piezometers and water level indicators showed that the pressure of water on the toe of the dam and under the setback were high. The mining company had a team of geotechnicians dedicated to monitoring the dam and an external company audited the tailings dam's safety. The Feijão dam was classified according to the ANM tailings dam classification system as class B, based on high associated potential damage and low risk.

Similarities and Differences Between the Failures of the Fundão Dam and Feijão Dam I

The Fundão and Feijão Dams were in a similar geological terrain in a traditional iron ore mining region known as the Quadrilátero Ferrífero (QF). The lithologies of the QF are characterized by a metamorphic complex represented by supracrustal sequences of volcano sedimentary rocks, clastic and chemical sedimentary rocks, ultramafic, mafic, and felsic bodies intruded into the Archean lithologies. The rock sequence is intensively weathered, showing a deep soil profile and intercalations of hard and soft itabirites. The area is mountainous, and the climate is tropical with a rainy season from November to May.

The same type of failure affected the two tailings dams, flow (static) liquefaction. In the search for a better understanding of these accidents, it is important to highlight the similarities and differences between the two dams.

Besides the type of failure, the similarities between Fundão and Feijão dams are:

(i) *Similar tailings*: it is expected that tailings ponds with a mixture of sandy, silty, and mud materials, the different granulometric fractions will be separate, with the coarser ones being close to the dam and the fines further from the dam, preventing stratification of sand and clay materials, but in both dams, this stratification existed, creating difficulties for drainage and enabling material saturation;

(ii) *Tailings with a high iron content:* dominantly hematite, with bonding between particles that could create stiff, potentially very brittle tailings, if triggered to drain (Robertson et al. 2019);

(iii) *Presence of mud in places where only sandy material should have been deposited*: this meant that the portions of the dams overlying this weak material, resulting in inadequate drainage and potential slope instability;

(iv) *High and steep slopes:* the higher and steeper the slope of a dam, the smaller the safety factor;

(v) *Upstream dam construction*;

(vi) *High levels of tailings saturation:* this was caused by several factors, such as inefficient and damaged drains and stratification of the clay and sand layers;

(vii) *Bad management practices:* these included deviations from the original dam designs, which produced a setback that pushed the upper portion of the slope over weaker fine tailings; other changes that led to the deposition of fine tailings in places where there should only have been coarser tailings; as the dams were raised, the drains were not properly connected, creating drainage problems; several incidents during the life of the dams that were not properly addressed that increased saturation of the tailings; and many times, the water was close to the dam crest, resulting in weak tailings close to the crest and interbedded layers of fine and coarse tailings within the dam;

(viii) *The presence of many monitoring devices*: including piezometers, water level indicators, inclinometers, survey markers, flow meters, rain gauges, weather stations, reservoir gauges, and geomechanical studies that provided detailed information about the nature, consistency, distribution of materials, and pressures within the dams;

(ix) *Class B tailings dams*: high associated potential damage and low risk criteria, according to the ANM tailings dam classification;

(x) *Many geotechnical studies available:* both dams had undergone tailings characterization studies, drained and undrained strength tests, SPT, CPTu, and geophysical surveys, with the data being analyzed by an internal geotechnical team and independent consultants;

(xi) *Problems with drainage systems:* inefficient internal drainage system promoted a persistent high water level inside the dam, mainly at the toe;

(xii) *Managing the dams with low safety factors:* considering the high environmental and life risk downstream, the safety factor adopted operationally were very low, in some cases less than 1.3;

(xiii) *External consulting to evaluate the dam safety:* in addition to the company's own geotechnicians dedicated to the monitoring and evaluation of the dam safety, the companies had independent consultancy to assess the safety conditions of the tailings dams, in compliance with the ANM resolutions;

(xiv) *Mining companies assumed high level of risk running the dams without taking effective measures to reduce the risk*;

(xv) *Both failures occurred in the rainy season*: it was observed by Robertson et al. (2019) that intense rainfall at the Feijão Dam I region could have resulted in significant loss of suction, weakening the unsaturated material above the water level, although that would not have been enough to trigger the failure.

Some differences can be highlighted:

(i) *The Feijão Dam I was no longer active at the time of failure, while the Fundão Dam was fully active, receiving tailings*: it is important to consider that even an inactive tailings dam poses a high risk and needs intensive maintenance and monitoring until its complete decommissioning;

(ii) *The tailings volume of the Fundão Dam was ≈ 4 times greater than that of Feijão Dam I*;

(iii) *The volume of tailings that flowed from Fundão Dam (≈32 M* m^3*) was 3.5 times greater than the volume of Feijão Dam (≈9.7 M* m^3*)*;

(iv) *≈ 61% of the tailings flowed out from Fundão Dam and 75% from Feijão Dam I*;

(v) *The environmental damage from Fundão Dam failure was more expansive than the Feijão Dam I failure*: it affected a large area and extended for more than 600 km until reaching the Atlantic Ocean. Considering the climatic conditions of the region, total environmental recovery in the affected areas will take ≈ 20 years, the estimated cost of reclaiming the area was US$ 14 billion;

(vi) *The number of victims of the Feijão Dam I failure was ≈ 14 times the number of victims from the Fundão Dam failure:* unlike the Fundão Dam, most of Feijão's victims were from the company itself, due the concentration of mining facilities – the offices, cafeterias, workshops, and processing plant were downstream and close to the tailings dam;

(vii) *The Fundão Dam was 7 year old at the time of failure while the Feijão Dam I was ≈ 40 years old*: this indicates that tailings dams can rupture in the initial years of operation or near its closure;

(viii) *The Feijão Dam I failure occurred with no sign of distress before the failure:* none of the deformation monitoring methods showed any significant deformation prior to failure, while in the Fundão Dam failure, several signs of distress were observed previously;

(ix) *Small seismic activities were recorded at the Fundão Dam failure*: these could have helped trigger the dam failure (Morgenstern et al. 2016), but the seismic activity was very low and may not have played a role, while no seismic activity was registered at the Feijão Dam I failure. After the seismicity was observed at the Fundão Dam, ANM started to demand that a stability analysis be conducted and that the dynamic susceptibility of tailings dams to liquefaction by vibrations produced by blasting in mines near the dams be considered.

ANM Tailings Dam Classification System Based on Potential Damage and Risk

The ANM tailings dam classification system is based on associated potential damage and risk categories. All tailings dams in Brazil need to be classified using this system. The classification system takes in account a series of factors to which points are assigned and the sum of these points is considered to classify a tailings dam. Tailings dams that show one of the following characteristics, height over 15 m, tailings volume over 3 million m^3, dangerous tailings, medium or high associated potential damage, are included in the National Safety Dam Plan (PNSB – Plano Nacional de Segurança de Barragens, in Portuguese). In 2019, 425 tailings dams were included in the PNSB and another 344 tailings dams were not included. Regarding the associated potential damage, 219 dams were considered high, 157 as medium, and 49 as low. Only two dams were considered as high-risk category, 61 as medium, and 362 as low, although 84 tailings dams were raised by the upstream method, although this method was banned in several countries many years ago (ANM 2020).

Table 1 ANM tailings dam classification system based on risk categories and associated potential damage

Risk categories	Associated potential damage		
	High	Medium	Low
High	A	B	C
Medium	B	C	D
Low	B	C	E

Table 1 shows the ANM tailings dam classification system. According to this system, tailings dams are classified as A, B, C, D, or E dam type. The worst conditions are represented by the dams classified as A and the dams with low risk and low potential damage are classified as E; the others represent intermediate risk and potential damage conditions. As was mentioned previously, the Fundão and Brumadinho dams were both classified as B type tailings dams.

The risk category is based on technical characteristics (height, length, design flow, construction method and auscultation), state of conservation (reliability of the overflow structure, percolation, deformations and settlements, deterioration of the slopes), and the dam's safety plan (project documentation, organizational structure, and qualification of the dam safety team, procedure manuals, emergency action plan, dam inspection and monitoring reports, and safety analysis). Depending on the situation, each of these factors receives a point rating. The sum of these points is used to categorize the risk (Table 2). Dams with a sum of points equal to or greater than 65 are designated as high risk, those dams with sum of these point between 65 and 37 are designated as medium risk and those dams with minus than 37 points are considered low risk. In addition, if a dam has any factor in the state of conservation group that receives a score equal to 10, it is considered as high risk.

On the other hand, classifications regarding the associated potential damage are made considering the total volume of the reservoir, the population downstream of the dam, and the potential environmental and socio-economic impacts.

Table 2 ANM risk category and associated potential damage classification based on the allocation of points

Risk category (RC)	Points
Technical characteristics (TC)	(0–38)
State of conservation (SC)	(0–40)
Safety plan of the dam (SP)	(0–40)
Total RC (TC + SC + SP)	
RC classification	Total RC
High	> = 65 or SC = 10
Medium	37 to 65
Low	< 37
Associated potential damage (APD)	Points
Tailing dam volume (TDV)	(1–5)
Population dowstream (PD)	(0–10)
Environmental impact (EI)	(0–10)
Socio-economic impact (SEI)	(0–5)
Total APD (TDV + PD + EI + SEI)	
APD classification	TOTAL APD
High	> 13
Medium	13 < APD < 7
Low	< 7
Dam classification	Based on Table 1

Similar to the risk categorization, points are awarded for each of these factors depending on the conditions encountered (Table 2). Dams with a sum of points equal to or greater than 13 are designated as high associated potential damage, those with sum between 13 and 7 are designated as medium potential damage, and those with less than 7 points are considered low potential damage.

The ANM tailings dam classification system can convey an inadequate risk perception. As already mentioned, the two dam failures were classified as B, with a low risk of failure. This classification can be made by an independent reviewer and countersigned or not by the ANM. According to ANM (2020), only two tailings dams were classified as A (high risk and high associated potential damage). However, if other technical factors were considered, many dams would have different classifications, increasing the risk perception, bringing the scenarios closer to reality.

To improve this system of classification of tailings dams, I suggest the adoption of a downstream slope steepness factor and a safety factor for slope failure as technical characteristics in the risk category system. For example, a tailings dam with very steep slopes could receive the maximum weight (10 points), with the same being applied for safety factors less than 1.5. Other aspects that can be changed is the sum of points to categorize the risk.

Actions Taken by ANM to Increase the Safety of Tailings Dams

Ordinance 70,389, of May 17, 2017, created the National Registry of Mining Dams, the Integrated Safety Management System for Mining Dams, and established the periodicity of execution or update, the required qualifications of the engineer or geotechnical engineer in charge, the minimum content and the level of detail of the Dam Safety Plan, the Regular and Special Safety Inspections, the Periodic Dam Safety Review, and the Emergency Action Plan for Mining Dams, as per articles 8, 9, 10, 11, and 12 of Law 12,334 on Sept. 20, 2010, which established the PNSB. It should be noted that the Mariana and Brumadinho accidents occurred after enactment of the law that established the PNSB and that Ordinance 70,389 was prepared after the Mariana accident but prior to the Brumadinho accident.

After the latter, the ANM issued Resolution 13, on Aug. 13, 2019 (ANM 2019), prohibiting the construction of mining dams using the upstream method and establishing regulatory measures for tailings dams, notably those built or raised by the upstream method or by a method declared as unknown. Among other demands, this ANM resolution defines the need for mining companies to install automated dam instrumentation systems to allow real-time and full-time monitoring, and, for dams classified as high associated potential damage, the installation of sirens to alert the neighboring populations of the dam. In addition, it prohibits maintaining mining facilities downstream of the dams. Most of the people who died in the Brumadinho's accident were company employees who were in the offices, cafeterias, and other mining facilities.

Analysis and Lessons Learned from the Tailings Dam Failures

Unfortunately, two major disasters were necessary for tailings dams built by the upstream method to be banned in Brazil. It has become clear that this method requires very well controlled construction and maintenance procedures, which can be very difficult to maintain in a mining environment and may not be consistently followed. Bearing in mind that upstream tailings dams have been banned in Brazil, recommendations on how they should be built or maintained are not relevant. ICOLD (1996, 2001), CDA (2014), McLeod et al. (2015), and MAC (2017) are good references for safety guidelines and management of tailings dams.

However, some aspects need to be highlighted that are suitable for all types of tailings dams. High tailings dams with steep slopes, and/or a mixture of sand and fines with high levels of saturation, have a great risk of failure. Therefore, it is important for dams built with tailings that the downstream slopes of the dams be raised with gentle slopes (e.g. 8H:1 V or 10H:1 V). The type of tailings is important though. For example, we are successively using 8H:1 V slopes for coal tailings dams, because these tailings are weaker than iron ore tailings; a steeper ratio can be applied for dams at iron mines (i.e. 5H:1 V or 6H:1 V). Additional guidance on this point can be found in CAD (2014). In addition, the drainage system must be efficient; as we saw in the two failures, the tailings dams did not have sufficient internal drainage and had a high water level in the downstream slope, resulting in areas with saturated tailings, which is a prerequisite for undrained flow liquefaction. Finally, a minimum tailings beach is necessary; water should not be allowed to approach the crest of the dam and accumulate fines near the dam body.

Static liquefaction flow was identified as responsible for the failures of the Fundão and Feijão I tailings dams. Apparently, there was inadequate knowledge about the potential and risk of failures due to liquefaction. Many dams have been built without any study on their potential risk for liquefaction. Bearing in mind that there are many other tailings dams in Brazil that are remarkably like Fundão and Feijão I, there is a possibility that similar failures will occur in the future. ANM's Resolution 13 established the need for companies to analyze the stability of tailings dams and susceptibility to liquefaction considering an undrained condition, and a minimum safety factor of 1.3 for peak strength. Additionally, ANM established the need to reinforce the tailings dams and proceed with the decommissioning and closure of dams built by the upstream method, giving a deadline of Sept. 17, 2027 for dams with volumes > 30 million m^3, and a reduced deadline for smaller dams.

Mining companies need to deal better with the risk of dam failures. They need to assess the potential consequences of failure as well as the probability or risk of failure, and from there, take the necessary measures to avoid failures, as well as actions to reduce the impact and contain the released tailings in case a failure occurs. Risk perceptions should be put aside, and the environmental risk analysis should be effectively assessed.

A non-operational tailings dams built by the upstream method has the same risk of failure as an operational one, as was observed with the Feijão I dam. Considering a dam that is no longer receiving tailings as being stable can turn out to be a serious mistake.

The failures of Fundão (with ≈ 7 years of operation) and Feijão I (after 40 years) revealed another interesting aspect related to the age of tailings dams: relatively new tailings dams appear to have a similar risk of failure as older dams. Previous studies of water retention dams have indeed shown that the likelihood of dam rupture is higher in the first few years after construction, then levels off at a relatively low rate, and then increases as the dams age, growing rapidly after 30 years (Costa 1985). Although there is not much data about the ages of tailings dams vs. the probability of failures, the cases of Mariana and Brumadinho are consistent with this finding.

The many instruments that were being used to monitor the behavior of the Fundão and Feijão I tailings dams did not guarantee their safety. In addition, the two dams had flood maps showing the area that would be affected if the dams collapsed. Thus, companies were already aware of the potential for damage that could occur. One surprising aspect, however, was speed of propagation of the tailings waves, estimated at 11 m/s, which was much faster than estimated by the software used to estimate flood maps.

Conclusion

The disasters involving the Fundão and Feijão I dam caused immeasurable damage to the environment, to the surrounding population, and to the mining companies. In addition, they have affected the image of mining globally. The environmental damage and loss of human life motivated public actions, with boards of directors and company engineers being taken to court.

The failure mode of the two tailings dams was liquefaction flow, and several factors contributed to the disasters. The tailings in the dam underwent a sudden and significant loss of strength and rapidly became a heavy liquid that flowed downstream at high speed. Changes in design, dam raising in an uncontrolled manner, steep slopes, and bad tailings management mixed sandy and mud materials all contributed to increased saturation and introduced the potential for liquefaction. Both accidents occurred in the rainy season, revealing the need for care to be intensified during this period.

The classification system for tailings dams proposed by the ANM proved to be inadequate, since, in the two major disasters in Mariana and Brumadinho, the tailings dams were classified as class B, in the low risk category with high potential damage. Classification of tailings dams as being low risk can induce a false perception of risk. Moreover, the actions taken by the ANM after the disasters are not enough to guarantee the safety of many tailings dams, particularly those located in the state of Minas Gerais, which continue to present a high risk of failure.

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