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REVIEW OF TAILINGS DAM FAILURES IN BRAZIL

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RESUMO – Acidentes com barragens de rejeitos ocorrem em todo o mundo com taxas alarmantes. Na última década, ocorreram 18 acidentes em 12 países diferentes. Contudo, os dois últimos acidentes no Brasil, isto é, os casos de Mariana e Brumadinho, mudaram a percepção sobre a segurança deste tipo de estruturas no Brasil e no mundo. Após esses acidentes, a Agência Nacional de Mineração baniu o projeto de barragens alteadas a montante e anunciou o descomissionamento obrigatório do mesmo tipo de barragens até 2021. No ambito internacional, o Comitê Internacional de Grandes Barragens (ICOLD) anunciou a publicação de atualização de tecnologidas para o projeto da barragem de rejeitos enquanto o Conselho de Mineração e Metais (ICMM) anunciou a criação de um painel independente de especialistas para desenvolver um padrão internacional para estruturas voltadas ao armazenament ode rejeitos.

ABSTRACT– Accidents with tailings dams have been occurring worldwide at alarming rates. In the last decade, there were 18 accidents in 12 different countries. However, the last two accidents in Brazil, i.e., the Mariana dam and the Brumadinho dam cases, changed the perception about the safety of this type of the structures in Brazil and around the world. After these accidents, the National Mining Agency in Brazil banished the design of upstream dams and announced a mandatory decommissioning of same type of dams up to 2021. Internationally, the International Committee on Large Dams (ICOLD) announced the publication of technology update on tailings dam design and the Worldwide the International Council on Mining and Metals (ICMM) announced the establishment of an independent panel of experts to develop an international standard for storage tailings facilities.

Palavras-Chave – Ruptura de barragens de rejeito, Barragem de Fundão, Barragem de Brumadinho

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INTRODUCTION

Recently the Brazilian society suffered with two major tailings dam failures: Fundão Dam, located in Mariana Town, Minas Gerais State in 2015 and the "B1" Dam also known as Brumadinho Dam, located in Brumadinho Town, Minas Gerais State in 2019. These accidents awoke the authorities and the technical community about the safety procedures on tailings dams.

Tailings dam failure has caused great distress in Brazil and worldwide. The dam collapse causes the movement of the impounded material, which contents a dense mixture of solids, including heavy metals, and liquid. The spilled material flows under the force of gravity and the flood can travel at velocities of about 20 m/s (EPA, 2014).

In the literature, the earliest register of tailings dam collapse is about the San Ildefonso Dam failure in Bolivia in 1626, where around 4,000 people would had been killed as consequent of the flood (Kossoff et al., 2014). Recently, Rico et al. (2008) mention the historical occurrence of more than 250 tailings dam failures. However, the consent among several researchers is that there is not a complete worldwide database of all the historical failures (Davies, 2002; Rico et al., 2008; Azam & Li, 2010).

The frequency of incidents with this type of dam is worrisome. Davies et al (2000) investigated the occurrences of collapses of tailings dams considering a 30 year database, from 1970 to 1999. This period experienced 2 to 5 major incidents per year, with at least two events per year. Moreover, Davies (2002) compared the occurrences of collapses of tailings dams with the conventional dams using the same 30 years database. He concluded that the rate of tailings dam failure was approximately ten times higher than for water retention dams.

Azam and Li (2010) present a statistical analysis of tailings dam failures worldwide using a 100 year database (from 1910 to 2009). Accordingly, the number of occurrences in recent decades (1990s and 2000s) reached 20 events per decade. Nowadays, the frequency of the accidents is still high, as exposed by the registered accidents in the last decade (WISE, 2019): Karamkem 2009 (Russia), Huancavelica 2010 (Peru), Mianyang City 2011 (China), Sotkamo 2012 (Finland), Obed Mountain Coal Mine 2013 (Canada), Dan River Steam Station 2014 (North Carolina – USA), Mount Polley 2014 (Canada), Buenavista 2014 (Mexico), Fundão 2015 (Brazil), Hpakant 2015 (Myanmar), Tonglvshan 2017 (China), Mishor Rotem 2017 (Israel), Huancapati 2018 (Peru), Cadia 2018 (Australia), Cieneguita 2018 (Mexico), Brumadinho 2019 (Brazil), Muri 2019 (India) and Hpakant 2019 (Myanmar).

CAUSES AND CONSEQUENCES OF TAILINGS DAM FAILURES

Rico et al., (2008) points out that tailings dams are more prone to fail than water storage dams due some unique characteristics, including: (1) embankments built with residual material from mining activities; (2) raising of the dam in multi-stages in order to increase storage capacity; (3) lack of regulations and design criteria; (4) continuous necessity of monitoring in order to assure the dam stability; and (5) high cost of maintenance after the mine closure.

Another interesting point is that the frequency of the accidents in tailings dams can be expected to increase shortly after a cyclical boom in mining industry (Davies & Todd, 2009). During a boom period, companies often try to move quickly to increase production and get new projects. The result is often hastily issued permits, fast-tracked investigations, problematic design and construction of dams, and inappropriate designs to take advantage of the boom prices. When the boom cycle ends, many companies try to implement these projects while cutting costs or shelve the projects until prices rise slightly before another rush into production (Marshall, 2018).

The main consequences of the dam collapse are: loss of life, environmental damage (as a massive discharge of tailings in a river system with a high-priced cleanup cost), social damage in downstream communities, infrastructure damage, extended production interruption, damage to company and industry image, economic consequences and legal responsibility for the company (Azam & Li, 2010).

The discharge of tailings in river systems, which are often toxic, will potentially affect water sediment quality, aquatic and human life for hundreds of kilometers (Kossoff et al., 2014). An example of river contamination is the case of Fundão Dam in Brazil in 2015. The spilled tailings, evaluated in 32 Mm^3, were released in the Doce River basin affecting a reach of 670 km. The aftermath of this accident was 19 people kill, loss of 3 tons of fish deaths and interruption in water supply affecting more than 400,000 people (Palu & Julien, 2019).

Most incidents with tailings dams are unreported or misreported due to fears of bad publicity and legal ramifications, especially in developing countries (Davies, 2002; Rico et al., 2008). The lack of publication hinders the development of research related with this topic (EPA, 2014).

TAILINGS DAMS IN BRAZIL

According the National Mining Agency (ANM, 2019a), there are 769 tailings dams in Brazil, with 425 dams enrolled in the National Dams Security Policy (PNSB). The dams enrolled in PNSB have at least one of the following characteristics: (1) dam height equal or bigger than 15 m; (2) reservoir storage capacity equal or larger than $3Mm^3$; (3) reservoir containing harmful tailings, according the technical standards; and (4) damage potential classified as medium or high, in term of life losses, economic, social or environmental.

Accidents with tailings dams occur periodically in Brazil with undesirable consequences for society, the environment and for the mining industry sector. There are also numerous cases not disclosed by the owners. In addition, there are numerous cases where rupture does not occur, but there is spill of solids downstream with variable consequences (CBDB, 2011). Table 1 presents a compilation of tailings dam failures cases in Brazil (WISE, 2019).

Table 1– Chronology of main tailings dam failures in Brazil

Dam	Year	Dam Height (m)	Ore type	Storage Volume	Tailings Released	Tailings Travel (km)
Itabirito	1986	30	Iron	-	100,000 m³	12
Fernandinho	1986	40	Iron	-	350,000 m³	-
Pico Sao Luis	1986	20	-	-	-	10
Minera Serra Grande	1994	-	Gold	2.25 Mt	-	-
Rio Verde	2001	-	Iron	-	600,000 m³	8
Forquilha	2002	-	-	-	-	-
Cataguases	2003	-	-	-	1,400 Mm³	200
São Francisco	2006	34	Bauxite	3.7 Mm³	135,000 m³	-
São Francisco	2007	34	Bauxite	3.7 Mm³	3 Mm³	92
Herculano	2014	-	Iron	-	-	-
Fundão	2015	120	Iron ore	≈ 80 Mm³	32 Mm³	670
Brumadinho	2019	86	Iron ore	12 Mm³	-	?

Among the historic cases, it is remarkable the environmental tragedy due the Cataguases Dam collapse on 29 March of 2003. In this event about one billion and four hundred million liters of black lye, residue of cellulose production, contaminated the Paraíba do Sul River and nearby streams per 200 kilometers, reaching the interior of Rio de Janeiro State and leaving 600,000 people without water supply. Another noteworthy incident occurred in 2007, when the São Francisco tailings dam collapsed releasing 3 million of bauxite waste, flooding two towns downstream and dislodging 4,000 people.

Despite the immense damage caused by those accidents, none of them reached the environmental damage of the disaster in Mariana in 2015. Due the Fundão Dam height and its consequences, it is by far the worst environmental accident with tailings dam in Brazil, and one of the worst around the world (Carmo et al., 2017). However, in terms of life loss the recent accident of Brumadinho Dam was the deadliest accident, resulting in 233 deaths, and as of May, 2019, 52 missing people are still missing. The next two sections describe briefly the last two main accidents in Brazil.

The Fundão dam case in 2015

The Fundão Dam was a tailings dam with a height of 120 m designed to store tailings from the local iron mining activities, located in the town of Mariana, State of Minas Gerais. On 5 November of 2015 the Fundão Dam collapsed, the accident occurred at 3:45 PM (local time) being caused by liquefaction and flow sliding of the sand stored in the reservoir (Morgenstern et al., 2016). Figure 1 shows the aerial view of the dam before and after the collapse.

Figure 1 – Fundão Dam before (a) and after failure (b) (Morgenstern et al., 2016)

The Fundão Dam failure released 32 million cubic meters of tailings, not considering water (Palu, 2019). After the collapse, the floodwave overtopped the Santarém tailings dam, located immediately downstream of the Fundão Dam. The town of Bento Rodrigues with 600 inhabitants located about 5 km downstream was covered by mud and debris, resulting in 19 deaths (ANA, 2016). Based on testimony of eye-witness, Machado (2017) reports that the elapsed time between the dam collapse and the arrival in Bento Rodrigues Town was approximately 30 to 40 min.

The floodwave went over the flood plains of the Santarém creek, then to Gualaxo do Norte River and to Carmo River carrying the riverine vegetation and part of the soil, affecting an area of 15 km^2.

The mud traveled 70 km in the Gualaxo do Norte River plus 25 km in the Carmo River until the Doce River. Through the Doce River it ran for approximately 570 km passing through four hydropower plants reservoirs and finally reaching the ocean (Palu & Julien, 2019; Palu, 2019). According the measurements carried out by the National Water Agency and the Geological Survey of Brazil, the maximum concentration observed in the Doce River was about 400,000 mg/l and decreased to 1,500 mg/l as the sediment reached the ocean, approximately 2 week after the accident (Palu, 2019). Detailed modeling of the sediment propagation along the Doce River was reported by Palu and Julien (2019).

The Brumadinho dam case in 2019

The dam "B1" of the Córrego do Feijão mining, also known as Brumadinho dam, was a tailings dam with a height of 86 m and a stored volume of approximately 12 Mm^3, located in the Brumadinho Town, State of Minas Gerais. The dam collapsed on 25 January of 2019 at 12:30 approximately. From the images of the dam collapse recorded in safety cameras was possible to obtain a rough estimate of the flood wave velocity, which reached ≈20 m/s. The time of the accident (about lunchtime) and the location of the administrative facilities of Vale (few meters downstream of the dam), resulted in the deadliest accident with tailings dam in Brazil, where 233 people lost their lives, and there are still 52 people missing. Satellite images shows that the mud spread in an area of 2.7 km^2 (IBAMA, 2019) rapidly flowing to the Paraopeba River, a tributary of the São Francisco River. Figure 2 shows an aerial view from Google Earth of the Brumadinho Dam collapse in 01/02/2019.

Figure 2 – Aerial view of the Brumadinho dam collapse in 01/02/2019 (Google Earth)

Propagation of the tailings along the Paraopeba River has been tracked by the National Water Agency and the Geological Survey of Brazil (CPRM & ANA, 2019). The maximum observed concentration was about 10,000 mg/l, with a gradual reduction in sediment concentration and turbidity along the Paraopeba River. Downstream of the Paraopeba River, approximately 270 km from Brumadinho dam, there are two hydropower reservoirs: the UHE Retiro Baixo and the Tres Marias Dam. Downstream of this last dam there is the São Francisco River, which extends approximately 2,800 km and crosses five Brazilian states. This is an extremely important river in Brazilian territory, since it provides water supply, irrigation and fishing for a large population in the northeastern and southeastern regions of Brazil. Even though the sediment concentration has been reduced along the Paraopeba River, it remains uncertain whether the Brumadinho dam accident will affect or not the São Francisco River.

WHAT CHANGED AFTER THE ACCIDENTS?

The last accidents with tailings dams, especially those occurred in Brazil, raised a concern about the safety of similar structures. After the Brumadinho dam failure, the National Mining Agency in Brazil announced the ban of upstream dams (like Mount Polley (Canada), Herculano, Fundão and Brumadinho in Brazil) and a mandatory decommissioning of this type dam until 2021. Another major changing were the modification of the stability safety factor regarding to liquefaction to 1.3, for the undrained case and increase and more rigorous inspection of existing dams (ANM, 2019b) .

Some agencies around the world, as the Canadian Dam Association (CDA) and the International Commission on Large Dams (ICOLD), are also revising their state of practice guidelines. After the Brumadinho dam case the International Committee on Large Dams announced the publication of the Bulleting #181 on a Technology Update on Tailings Dam Design, to be released later in 2019 (Grenier, 2019). The bulletin proposes to cover three main subjects: tailings properties, tailings technologies and design practices, with examples of good practices.

Furthermore, the Worldwide the International Council on Mining and Metals (ICMM) announced the establishment of an independent panel of experts to develop an international standard for tailings facilities for its member companies. The standard will be based on a review of current global best practices in the mining industry (ICMM, 2019).

In addition, the standards are expected to be raised significantly for the industry in order to improve the safety and security with better design and operation of these facilities. Expected improvement include: (1) a global and transparent consequence-based tailings facility classification system with appropriate requirements for each level of classification; (2) a system for credible, independent reviews of tailings facilities; and (3) requirements for emergency planning and preparedness (ICMM, 2019).

CONCLUSION

This paper presents an overview of numerous the accidents with tailings dams in Brazil and worldwide, and their consequences in terms of public perception of tailings storage facilities. After these accidents (mainly Fundão and Brumadinho dam) the National Mining Agency announced the ban of the upstream raised dam and the mandatory decommissioning of existing dams until 2021. Moreover, it resulted in a review and update of tailings dam design worldwide, as announced by ICOLD in 2019, and improvements in international security standards, as stated by the International Council on Mining and Metals.

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