

## Essays and Perspectives

## Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context



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## ABSTRACT

After the collapse of the Fundão dam, 43 million m<sup>3</sup> of iron ore tailings continue to cause environmental damage, polluting 668 km of watercourses from the Doce River to the Atlantic Ocean. The objectives of this study are to characterize the Fundão Tailings Dam and structural failures; improve the understanding of the scale of the disaster; and assess the largest technological disaster in the global context of tailings dam failures. The collapse of Fundão was the biggest environmental disaster of the world mining industry, both in terms of the volume of tailings dumped and the magnitude of the damage. More than year after the tragedy, Samarco has still not carried out adequate removal, monitoring or disposal of the tailings, contrary to the premise of the total removal of tailings from affected rivers proposed by the country's regulatory agencies and the worldwide literature on post-disaster management. Contrary to expectations, there was a setback in environmental legal planning, such as law relaxation, decrease of resources for regulatory agencies and the absence of effective measures for environmental recovery. It is urgent to review how large-scale extraction of minerals is carried out, the technical and environmental standards involved, and the oversight and monitoring of the associated structures.

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## Introduction

One year after the collapse of the Fundão tailings dam, more than 43 million m<sup>3</sup> (Samarco, 2016a) of iron ore tailings are still causing environmental damage, polluting 668 km of watercourses from the Doce River Basin to the Atlantic Ocean. The volume of pollutants and the extent of ecosystems affected have assumed unprecedented proportions, involving the Brazilian Atlantic Forest – one of the world's biodiversity hotspots (Mittermeier et al., 2005), estuarine, coastal and marine environments. Furthermore, it affected other priority areas for the conservation of biodiversity and cultural heritage (MMA, 2007), such as the iron geosystems of the Quadrilátero Ferrífero (Carmo and Kamino, 2015).

In less than 48 h after the collapse of the Fundão dam, a task force was created by the Attorney General's Office of the State of Minas Gerais, whose main objective was to ascertain the facts of the environmental tragedy and the repercussions on the 17 districts and 36 municipalities directly affected by the mud wave. The Minas Gerais State Public Prosecutor's Office (MPMG) worked intensively and produced, through related teams, hundreds of technical documents and expert reports. Among these studies, the 120 technical documents of the Prístino Institute (inspection reports, technical reports, studies and maps), developed in partnership with the MPMG Geoprocessing Nucleus, identified the main environmental damage, which supported most of the results of the present work (CAOMA, 2016).

The mining company Samarco Mineração S/A (a joint venture between Vale S/A and BHP Billiton), responsible for the Fundão dam, produced technical documents stating the main emergency measures adopted and the initial planning for environmental recovery. According to the company, the emergency recovery work

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prioritized the remaining structures of the dams of the mining complex and, after that, tailings containment dams were constructed within the limits of its properties (Samarco, 2016a,b). Up to the present moment, priority has been given to the recovery of the physical environment. However, a federal agency responsible for inspection and monitoring for the purposes of environmental quality recovery, evaluated the inadequacy and inconsistency of the data presented. It stated that the actions performed by the company are still insufficient to guarantee the reduction of the damage caused by the tailings, resulting in 13 notices of infraction and an environmental fine (IBAMA, 2016a).

The main objectives of the study, based on this scenario, are: detail the structural features and possible structural failures that led to the collapse; improve the understanding of the scale of the disaster from the detailed measurement of the damage caused to ecosystems, protected areas, real estate and cultural heritage; compare and highlight this disaster in the context of global tailings dam failures; detail cases of the post-disaster actions and reflect on whether lessons had been learned about Brazilian tailings failure.

### Fundão Tailings Dam: structural features and environmental damage

#### Structural features

The Fundão dam was one of the megastructures of the Germano mining complex, located in the municipality of Mariana, Minas Gerais, southeastern Brazil. The mining complex had an installed capacity of 23 million tons/year of iron ore concentrate. In addition to Fundão, the complex contained two more dams: Santarém and Germano, the latter being the highest dam in Brazil, with a height of 175 m and a projected volume of up to 160 million m<sup>3</sup> of tailings (Samarco, 2013). Open pit mines, piles of sterile material deposits, industrial plants and pipelines are also part of the Germano Complex.

The Fundão dam began operating in 2008 and was designed to contain a total of 79.6 million m<sup>3</sup> of fine tailings (mud) and 32 million m<sup>3</sup> of sandy tailings during its 25-year lifespan (SUPRAM, 2008). In November 2015, Fundão contained 56.4 million m<sup>3</sup> of iron ore tailings deposited in merely seven years of operation, a result of the never-before attained records of Brazilian production in the years 2013 to 2015 (IBRAM, 2015). In order to accommodate this volume, it was necessary to construct dikes, using the sandy reject itself as a construction material from the upstream embankment method (Ávila, 2012).

#### Unforgiving structures

Among the most common methods of tailings disposal, the one with the greatest economic advantage is the upstream embankment. However, it poses a significant challenge to the geotechnical engineer, due to the fact that water is the primary instability agent. Indeed, dams using the upstream embankment method are considered “unforgiving structures” and represent up to 66% of the worldwide reported mine tailings dams failures (Rico et al., 2008; Ávila, 2012; Kossoff et al., 2014).

According to Prieto (2014), the main disadvantages and restrictions of this technology are: foundation of later lifts is on unstable tailing slime, unused in earthquake zones; high level of monitoring using instrumentation required during operation; and recommendation that the rate of raised tailings dams be, preferably, no more than 5 m/year.

Since the beginning of the operation, in 2008, the Fundão dam had presented several anomalies related to drainage construction defects, upwellings, mud and water management errors and

saturation of sandy material. In some situations, emergency measures were implemented (Samarco, 2016b), one of them known as retreat of the dam axis was begun in 2013. According to Samarco (2016b), the retreat represented: “. . . a temporary solution, it was decided to realign the dam on the left shoulder by moving it behind the section of the gallery to be filled with concrete, in order to allow the continuation of the landfill embankment. (. . .) The retreat would move the crest closer to the water of the reservoir and the mud contained within, but it was anticipated that the dam would quickly return to its original alignment once the buffering operations were done.”

However, the retreat was maintained until the collapse of the dam. According to Samarco (2016b): “As the dam embankment continued, surface upwellings began to appear at the retreat of the left shoulder at various elevations and on various occasions during 2013. The saturated mass with sandy tailings was growing, and in August 2014, the drainage carpet controlling this saturation reached its maximum capacity. Meanwhile, the mud under the landfill was responding to the increase in the load that was being deposited by the embankment. The way in which it responded, and the consequent effect on the sands, was what finally made the sands liquefy.”

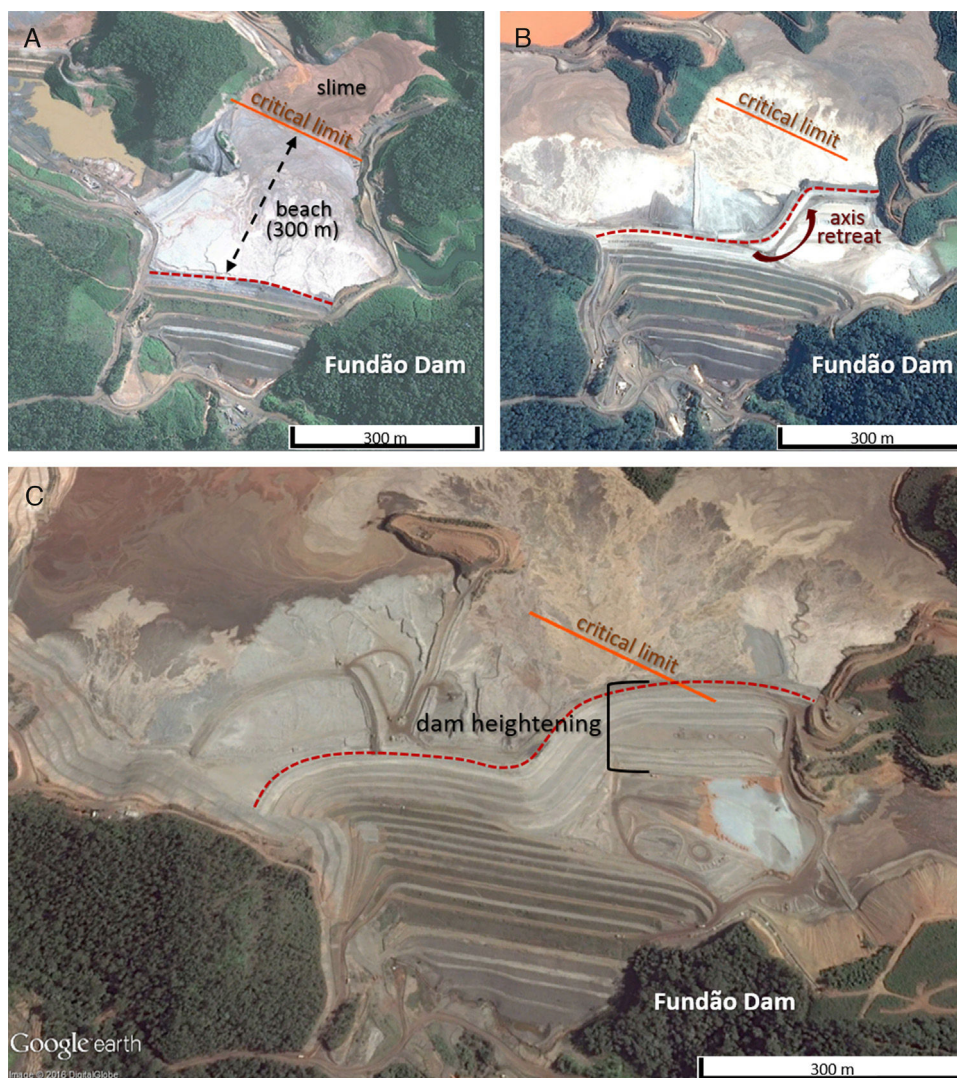
Technical reports on the Fundão disaster (Samarco, 2016b) concluded that the collapse was due to liquefaction of the material, a phenomenon that occurs when solid materials (sandy tailings) lose their mechanical resistance and present fluid characteristics. Basically, the disaster occurred because of some key factors such as: structural damage to the starter dike, resulting in increased saturation; the attempt to solve structural problems with a concrete gallery that caused the axis of the dam to retract (Fig. 1), later being raised on mud; and the unforeseen deposition of sludge in critical regions. In upstream embankment dams, it is essential for the stability of the structure that the deposition of unsaturated sandy tailing create a beach, at least 200 m wide, immediately upstream of the dam crest.

#### Environmental and cultural damage

The total collapse of the Fundão tailings dam took place on 05 November 2015, between 3:00 pm and 4:00 pm. About 43 million m<sup>3</sup> of tailings (80% of the total contained volume) were unleashed, generating mud waves 10 m high, killing 19 people and causing irreversible environmental damage to hundreds of watercourses in the basin of the Doce River and associated ecosystems (Samarco, 2016b).

Most of the tailings (>90%) remained along the 120 km stretch between the Fundão dam and the hydroelectric power plant reservoir Risoleta Neves (UHE-RN), located in the municipalities of Rio Doce and Santa Cruz do Escalvado (Samarco, 2016a). The tailings remained in the Doce River channel, downstream of the UHE-RN along 548 km, reaching the Atlantic Ocean. Forty downstream municipalities were affected and hundreds of thousands of people (included indigenous) were left without access to clean water (Neves et al., 2016; IBAMA, 2015b). Therefore, in this study, the environmental damage was grouped into two sections: one upstream and the other downstream of the UHE-RN.

High resolution orthorectified satellite images (spatial resolution of 50 cm) were used to identify the environmental damage caused by the mass displacement along the 120 km upstream stretch of the UHE-RN. Two moments were compared: (1) a mosaic of images obtained prior to the dam burst (World View-2, World View-3 and GeoEye); (2) images obtained after the dam burst (World View-2, Pléiades and World View-3). The images were imported into the Geographic Information System and the elements were converted into vectors overlapping the area stained by the tailings. Information for the 548 km downstream stretch



**Fig. 1.** Fundão dam. (A) Formation of sandy tailings beach 300 m wide and upstream mud deposition, highlighting the critical limit of contact between sandy tailings and sludge (orange line), image of 2011. (B) Retreated axis for emergency works in a concrete gallery brings the crest closer to the critical limit of contact between sandy tailings and sludge (red dashed arrow), image of 2013. (C) Embankment of the dam displaced axis in the critical limit of contact between sandy tailings and sludge (orange line), 2015 image. Adapted from *Google Earth Pro*.

of the UHE-RN, was obtained from technical reports produced by regulatory and inspection agencies and available literature.

Over a span of only 12 h, along the 120 km stretch between the Fundão dam and the UHE-RN, the mass displacement created a patch of 2020 ha and the tailings accumulated in channels, in floodplains and in the UHE-RN reservoir. This UHE-RN has not yet resumed electric power production due to the huge volume of tailings deposited in the reservoir, around 10 million m<sup>3</sup>.

The tailings directly hit 135 identified semideciduous seasonal forest fragments, in a 298 ha of vegetation suppression, located on the banks of Gualaxo do Norte and Carmo Rivers and its tributaries. The tailings also directly hit 863.7 ha of Permanent Preservation Areas associated to watercourses, which were in protected areas, as defined by the federal forest code. Santarém Stream (11.9 km impacted), Gualaxo do Norte River (68.4 km) and Carmo River (24.7 km) were the main rivers and streams completely silted by the tailings. In addition, 294 small creeks were affected by the tailings (Fig. 2 and Fig. S1). Little attention has been given to the pollution potential of the tons of chemical compounds (flocculants and coagulants), specifically sodium hydroxide, which spilled out along with the tailings.

Out of the 806 buildings directly hit by the tailings, at least 218 were completely destroyed. These were residences, public buildings, commercial real estate, centennial churches and ancient farms distributed among 10 districts of five municipalities: Mariana, Barra Longa, Ponte Nova, Santa Cruz do Escalvado and Rio Doce. Bento Rodrigues, just 6 km from the Fundão dam, was the most damaged district with 84% of the affected buildings totally destroyed, followed by Paracatu de Baixo (40% of the buildings hit were destroyed). A total of 21.1 km of rural roads, 12 bridges/passages and the small hydroelectric plant of Bicas were also damaged.

Areas of cultural heritage also suffered greatly. Damages include, at least two archeological sites, six places of historical and cultural interest, more than 2000 sacred pieces/material heritage, five caves, a 2.2 km stretch of the Estrada Real and preserved areas of the landscape complex in the junction of the Carmo and Piranga Rivers and the urban complex of Bento Rodrigues. One of the main cultural heritage assets irreversibly affected was the São Bento chapel, an 18th-century building surrounded by stone walls (Fig. 3 and Fig. S2).

Parts of three tourist routes (*Estrada Real*, *Estrada Parque Caminhos da Mineração* and *Caminho de São José*) were also severely



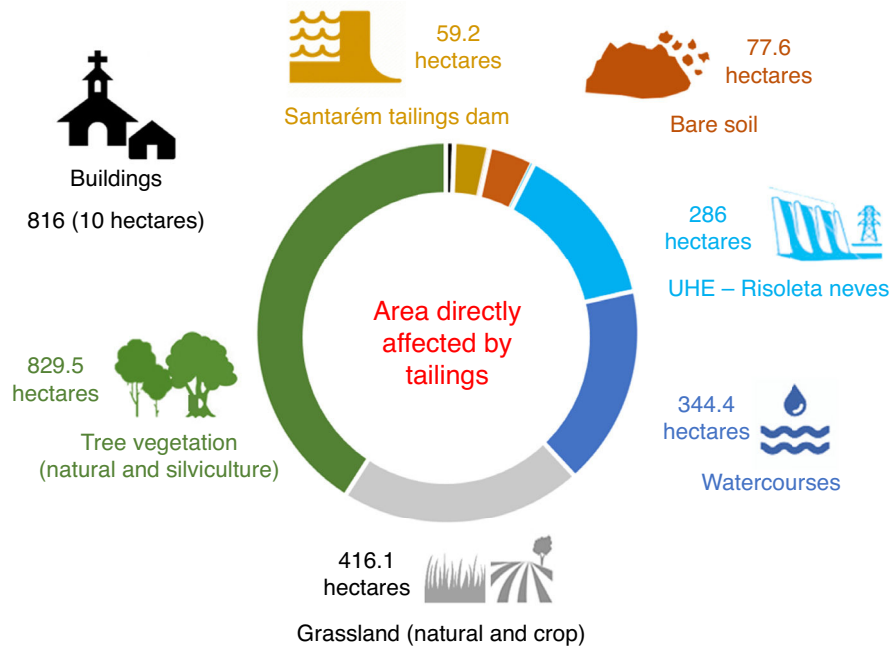


Fig. 2. Elements of natural and cultural heritage damaged by the Fundão tailings dam.



Fig. 3. Buildings affected by the Fundão tailings dam: (A) District of Bento Rodrigues, Mariana and (B) Urban area of the municipality of Barra Longa.

Biosphere Reserves of the Espinhaço Mountains and Atlantic Forest (UNESCO, 2011). There was also damage to Priority Areas for Biodiversity Conservation (MMA, 2007; Drummond et al., 2005) – named Quadrilátero Ferrífero and Florestas da Borda Leste do Quadrilátero – and in key areas for the conservation of six rare Brazilian plants (*sensu* Giulietti et al., 2009), named SE204 – Ouro Preto.

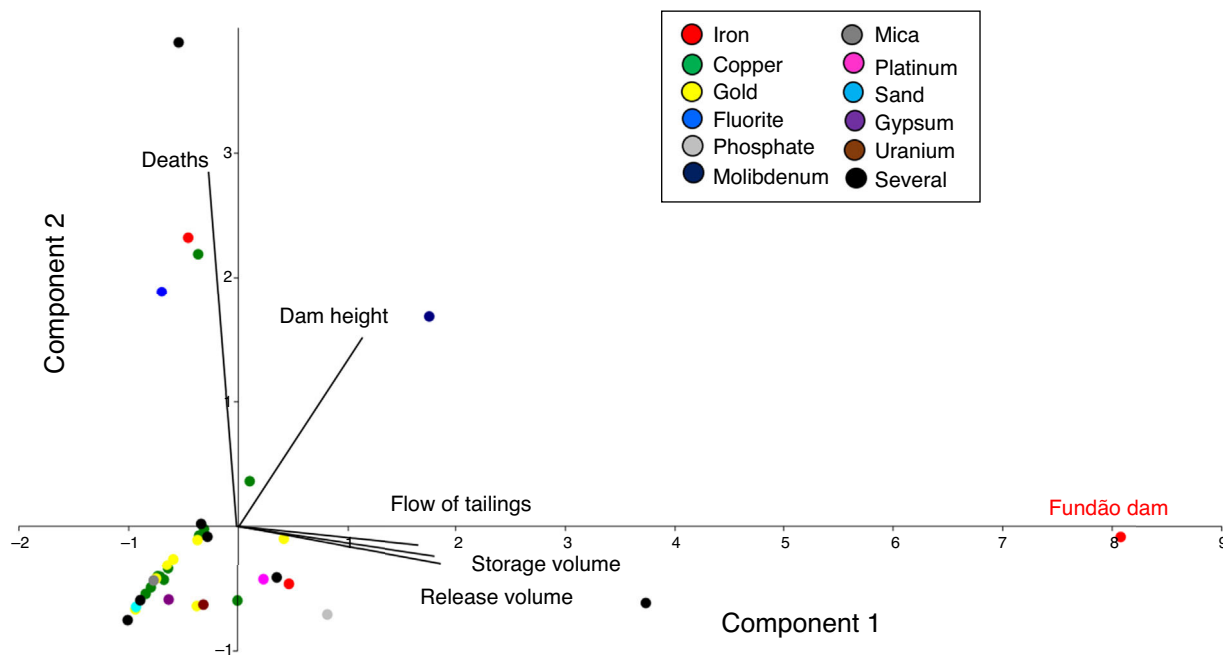
Considering that the disaster occurred in one of the most important regions for biodiversity conservation, it is estimated that the loss was significant (Fernandes et al., 2016). Tons of fish from 21 different species died in large numbers (IBAMA, 2015a). Isolated reports have identified the death of large mammals, such as the South American tapir (*Tapirus terrestris* L.), as well as turtles, birds, amphibians and invertebrates. However, no study has been published by the scientific community to account for long-term effects in main ecological components and populations of endemic species of flora and fauna.

Along the Doce River, downstream of the UHE-RN, about 5.5 million m<sup>3</sup> of tailings were deposited in the first days after the disaster (Samarco, 2016a; IBAMA, 2016a). Very fine tailing particles caused severe changes to the physico-chemical characteristics of the Doce River and estuarine region, increasing the turbidity levels in Minas Gerais up to 6000 times (600,000 NTU) higher than the upper limit established by law for this parameter (SEMAD, 2015). However, the impact monitoring conducted by Samarco presented very low volume of data and several physical and chemical parameters were not reported. This situation was a consequence of using inadequate methods for monitoring impacts (IBAMA, 2016c,d,e).

Three different types of sediment layers from the tailings (IBAMA, 2015a, 2016c,d,e) were detected at the mouth of the Doce River: a thick sediment deposited along the mouth; a plume deposited on the bottom; and another thinner widespread plume on the surface (floating plume). Some early projections predicted the plume would have little impact and the pollutant material would dissipate in a few months (Puff, 2015). A year after the dispersion started, 170 km of beaches were contaminated by mud, 110 km to the north of the Doce River mouth and 60 km to the south. The plumes have already spread over more than 770 km<sup>2</sup>, having a huge effect on protected coastal zones such as the Comboios Biological Reserve, an important place for spawning of sea turtles, Santa Cruz Wildlife Refuge and APA Costa das Algas. In the

impacted causing losses to the local economy. The mud affected, irreversibly, areas of important archeological and speleological potential had not yet been studied, made it impossible to evaluate the exact impact on the loss of scientific knowledge.

The flood plains favored a larger accumulation of tailings (Fig. S3), on average more than 50 cm high, and in some places estimated at more than 3 m thick (Samarco, 2016a; IBAMA, 2016b). The mass displacement was so intense that it excavated the soil and altered original river beds. The tailings stain damaged four protected areas: APA Barra Longa, APE Ouro Preto/Mariana and the



**Fig. 4.** Distribution pattern of 36 cases of dams disasters (colors identify the types of tailings, according to the processed ore) based on structural characteristics, distance and volume of tailing releases, and deaths by Principal components analysis. See Table S1 for details of 36 cases.

long-term, the pollution plumes could reach regions near the city of Rio de Janeiro (IBAMA, 2015a, 2016c,e; Marta-Almeida et al., 2016).

### The tragedy of the largest technological disaster of Brazilian mining in the worldwide context

Based on a survey of 308 cases of mining dam collapses in the world (1915–2016, see Table S1), the Fundão dam disaster can be regarded as the largest technological disaster, considering the volume of tailings released and the geographical extension of environmental damage. The volume of tailings released by collapse of Fundão (43 million m<sup>3</sup>) is the largest ever registered. It is followed by the one in the Philippines/1992 (32.2 million m<sup>3</sup>); Canada/2014 (23.6 million m<sup>3</sup> of gold and copper residues); and Philippines/2012 (13 million m<sup>3</sup> of copper residues). The extent of the damage caused by Fundão is the largest ever recorded with pollutants spread along 668 km of watercourses. It is followed by the one in Mexico/2014 (420 km of contamination by copper residues), Bolivia/1996 (300 km contamination by lead-zinc residues) and Canada/1990 (168 km contamination by uranium residues).

When compared with the cases registering the highest number of deaths, the case of Fundão (19 deaths) is the ninth most serious cases of the last century. The three disasters that caused the greatest number of deaths were: Bulgaria, 1966, lead-zinc tailings (488 deaths); Chile, 1965, copper tailings (300) and China, 2008, iron tailings (277).

We used principal components analysis (PCA) to understand the distribution pattern of the dams based on structural characteristics and the main damage caused by such collapses (Table S1, Fig. 4). This study used information from about 36 cases of collapses (12% of global cases), which presented data related to the parameters: dam height, storage volume, released volume, tailings flow distance and deaths. The first two variables are technical characteristics related to the national dam safety policies (Brasil, 2010) for risk potential assessment, and the other variables represent the extent of effective damage (Azam and Li, 2010; Kossoff et al., 2014).

The first two axes of the PCA explained 53.8% and 21.9% of the variation, respectively. The variables that best explained the

distribution of data in component 1 were released volume (0.96), storage volume (0.86) and tailings flow distance (0.83). The analysis indicates that most collapses are related to copper mining (11 dams), gold (7 dams) and iron mining (3 dams). Similar features keep most collapses grouped in the scatter plot (Fig. 4).

These cases exhibited distinct characteristics that make it the world's largest mining environmental disaster. However, the collapse of the Fundão dam was the most devastating and could be classified as the largest technological disaster in the context of global dam failures.

### Post-disaster management

After carrying out measures for minimizing post-disaster risks, a stage involving emergency engineering work, tailings/sediments removal is considered essential and the most frequent action adopted in events of disasters with mass displacement, including collapses of mining tailings dams (UNESCO, 2010; Kossoff et al., 2014; Bowker and Chambers, 2015).

Two examples of cases of the post-disaster management to remove tailings released by the collapse of the dam occurred in Spain and in Hungary. The collapse of the dam in Andalusia, Spain, in 1998 (UNEP, 2001) released more than 2 million m<sup>3</sup> of zinc tailings containing sulphide-related trace elements (As, Cu, Pb, Zn and Ca) and more than 4 million m<sup>3</sup> of acidic water, which were deposited over 45 km of channels and floodplains on the Guadiamar and Agrio Rivers. A plan for cleaning was presented to authorities three days after the disaster with the adoption of a cleaning protocol of the affected areas (Ginige, 2014). In 12 months, about 7 million m<sup>3</sup> of tailings and contaminated materials that had accumulated in the river channels, floodplains and on infrastructure works were removed. The material removed was then deposited in the exhausted mining pit of the company responsible for the dam (WWF, 2002). Another case occurred in 2010 in Ajka, Hungary. Damage control action was taken after the release of over 600,000 m<sup>3</sup> of tailings in the environment over 14 km. The red mud was collected along the affected areas and disposed of inside a dam, which had already been reconstructed, seven days after the collapse

(Kátai-Urbán, 2010). In the medium and long term, an extensive cleaning of debris and materials dragged by the flow of tailings was conducted (Jávör and Hargitai, 2011).

Compared with cases presented, one year after the Fundão tragedy, Samarco has conducted only 0.17 million m<sup>3</sup> clean-up actions in urban area of Barra Longa (Samarco, 2016c), and not yet removed, monitored or properly disposed of tailings deposited in rivers, streams and flood areas. This goes against the premise of total removal of tailings in rivers affected supported by federal government. According to this premise, the company Samarco should evaluate each area regarding the possibility of total removal and proper disposal of tailings, employing alternative treatment techniques. Tailing management should only be considered as a second alternative when technical infeasibility to remove it is proven (IBAMA, 2016b).

As a wide-ranging strategy of landscape recovery (UNEP, 2001; Hudson-Edwards et al., 2003), the tailings removal should be a priority action for the regions affected by the Fundão collapse. The tailing is a source of fine inhalable particulate material, composed of minerals such as hematite, martite, magnetite and goethite. Studies show that prolonged inhalation of particulate material originated from iron mining is associated with the increase in cases of respiratory and cardiovascular diseases (Braga et al., 2007; Gomes et al., 2011). Leaching tests and toxicological bioassays performed in the region of Bento Rodrigues suggest that the tailings and contaminated soils represent a potential risk of cytotoxicity and cellular DNA damage, due to the indication of a high potential of mobilization of elements such as iron, aluminum, manganese and arsenic from the tailings into the water (Segura et al., 2016). Veronez et al. (2016) also indicate genotoxic and biochemical effects induced by iron ore, from the experimental studies which indicated the Fe and Mn accumulation can induce oxidative stress during the metamorphosis of *Lithobates catesbeianus* (L.) tadpoles.

## Lessons learned?

In 2013 the Public Prosecutor's Office prepared a statement, based on a technical report from the Pristino Institute (Greenpeace, 2015), expressing concern about the risks of revalidating the Operational License of the Fundão Dam. In the statement, the Public Prosecutor's Office of the State of Minas Gerais requested that the environmental licensing body demand that Samarco carry out the following actions: perform periodic geotechnical and structural monitoring of the dikes and dam, with a maximum interval of one year between samplings; present a contingency plan in case of risks or accidents, especially in relation to the community of Bento Rodrigues, a district of the municipality of Mariana, MG; and perform rupture analysis (DAM – BREAK) of the dam, expected to be delivered to SUPRAM (Regional Superintendence of Environmental Regulation).

After the tragic environmental disaster caused by the collapse of the Fundão dam, several articles addressed a setback in the environmental legal regulations. Law relaxation, the decrease of resources for regulatory agencies and the absence of effective environmental recovery measures were often mentioned (Fearnside, 2016; Fernandes et al., 2016; Garcia et al., 2016; Wanderley et al., 2016).

In addition to the legal regulation, the case of the collapse of the Fundão dam made clear that the structures built using the upstream embankment method, widely used in Minas Gerais and Brazil, bring several environmental and social risks, which are no longer acceptable as management techniques to deal with mining waste and residues.

The Brazilian legal system includes principles that demand that entrepreneurs as well as environmental licensing bodies adopt

the Best Available Technologies (BAT) to protect the constitutional rights to an ecologically balanced environment for the present and future generations, under art. 225 of the CR/1988 c/c art. 2nd and 4th of Law 6938/1981 (Loubet, 2015).

In Brazil, the dimension of the risk generated by the method in question inspired the NBR 13028, of the Brazilian Association of Technical Standards (ABNT), which deals with the “development and presentation of dam projects for the disposal of tailings, sediment containment and water reservation”. This standard states the conditions required for the development and presentation of a project of tailings disposal, in dams and in mining, to comply with conditions of safety, hygiene, functionality, economy, abandonment and minimization of impacts to the environment, within the legal standards. In its 1993 version, item 4.2, clearly states: “the construction of dams using the upstream embankment method is not recommended”. For reasons unknown, in the 2006 version of the same standard, this recommendation no longer appears. The Public Ministry, to guarantee that the construction of dams using the upstream embankment method be avoided, filed a legal action against the State of Minas Gerais to prevent the public administration from granting or renewing environmental licenses for this type of dam structure.

In July 2016, a bill was presented by popular initiative to the Legislative Assembly of the State of Minas Gerais establishing safety standards for mining tailings dams. The draft dealt with the improvement of dam risk management. In October 2016 the bill was already being considered in the State Legislature under PL number 3695/2016.

World disasters caused by mining tailings are closely related to the increase in demand for mineral commodities by global markets, leading to a high rate of disasters occurring in a period of 24–36 months after a soar in overall prices (Davies and Martin, 2009), which was exactly the case of Fundão. Bowker and Chambers (2015) highlighted the recent increase in the rate of severe and very serious disasters caused by tailings dam failures and argued that this trend is a consequence of modern technologies that allow the exploitation of reserves with even smaller ore concentrations. This situation results in a huge increase in the storage capacity of mining tailings dams (Wanderley et al., 2016). Bowker and Chambers (2015) estimate society's billion-dollar costs related to disasters caused by tailings dams and highlight the urgent need for changes in regulatory systems to fit this global trend.

Apart from its sheer magnitude, the collapse of Fundão is the seventh such case that has occurred in Minas Gerais alone since 1986 (Felippe et al., 2016). There is an undeniable need to review environmental standards, for more rigorous control of the hundreds of mining tailings dams in Brazil. In addition, it is fundamental to review how large-scale mineral extraction is carried out, as well as to encourage the use of alternative technologies for the disposal of tailings such as disposing of them in abandoned caves or dewatered stockpiling (dry stacking) for tailings disposal (Gomes et al., 2016). These measures may contribute to minimize the conversion of new, natural areas into megastructures to contain tailings, and to avoid the potential risk of environmental damage to creeks and rivers and associated ecosystems.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.pecon.2017.06.002](https://doi.org/10.1016/j.pecon.2017.06.002).

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