In Brazil, two devastating disasters have caused uncountable death and endless mourning and destruction. Both occurred at iron ore tailing dams in the Iron Quadrangle region, near the Minas Gerais state capital Belo Horizonte (Figure 1). Brazil is the second iron producer in the world, with reserves of 34 billion tonnes [5].

The first disaster occurred in the Fundão Dam, in the Bento Rodrigues district, municipality of Mariana (Figure 1). It was operated by the company Samarco. It caused 19 deaths and extreme environmental impacts in Barra Longa municipality and other cities of the Rio Doce basin, reaching the Atlantic Ocean in the city of Linhares, 600 km away (Figure 1) [6,7]). The second disaster occurred at Dam B1 of the Córrego do Feijão mine in the municipality of Brumadinho, operated by the mining company Vale. It was responsible for 270 deaths and significant social and environmental damage [8, 9].

![Fig. 1. Main localities in the text related to the tailings dam disasters of Vale (2019) at Brumadinho municipality and Samarco (2015) at Bento Rodrigues Village.](https://doi.org/10.1051/e3sconf/202341505018)

Even though these disasters are of anthropogenic origin, there are many similarities with gravitational mass movements, at least in the first moments when the potential energy was high [10]. There are many similarities to avalanches, debris flows, and mudflows, where channel erosion is extreme, causing numerous
changes in river morphology. After losing strength, these materials are passively transported along the river channel as bottom sediments or suspended\[1\]. In these stretches, the material can silt up the river and change the dynamics of the channel. With the presence of tailings materials in the order of $10^6$ m$^3$, these changes reach large scales. On the other hand, the characteristics of each tailing material are very different from natural deposits, which depend on the mining and beneficiation process and the obstacles that the material encounters along the pathway.

The present work shows some of these aspects, their similarities and differences, and the changes made along the river channel during the failure of significant tailings dam episodes in the 2015 Fundão tailings dam - Samarco and 2019 Córrego Feijão Mine - Vale disasters.

The Fundão and the Santarém dam are in the Germano mine complex, comprising numerous dams with sandy-silty and silty-sandy tailings\[12\]. The dam was built in 2005 by the upstream method from an earth dike. According to the authors, the ore tailings dam presented several structural problems in 2009, 2012, and 2014. The Fundão mine disaster occurred at 3:42 pm on 5/Nov/2015 and involved the release of 32 million m$^3$ of tailings\[12\]. The tailings overtop the Santarém dam and enters at Santarem stream talweg. The tailings spread beyond the small stream, destroyed the village of Bento Rodrigues (Figure 2) and caused 19 deaths\[13\]. A geomorphological trap in the mouth of the Santarem stream over the Gualacho do Norte River blocked the flux. Most of the flux overcame the barrier and continued downstream, whereas the flux rose upstream of the river (Figure 2). Afterward, the material continued flowing down the Gualacho do Norte River until it reached the Carmo River and invaded part of Barra Longa city, 40 km from the ruptured dam. The marginal and basal erosion slowed down as the flux lost strength. At this point, the deposition rate was higher than the erosion rate, forming central sand bars at the channel of the Carmo River (Figure 3)\[13\]. The material flew down from the Carmo River, reaching the Doce River. Most of the material was retained in the hydroelectrical Candonga dam (Figure 4). Around 22 million m$^3$ of tailing were accumulated in the Santarém stream, Gualacho do Norte, and Rio do Carmo rivers upstream to Candonga dam, while 10 million m$^3$ were drained through the Doce river channel\[12\]. The fine-grain fraction took only 17 days to pass Linhares city, in the Espírito Santo state, and reach the ocean, where it was dispersed (Figure 1)\[13\].
The B1 dam at the Córrego do Feijão Mine was built between 1974 and 1976 and was operated until 2015[14]. The tailings dam has had ten expansion works during this period, reaching 720 m of crest length, 86 m height, an area of 249.5 thousand m², and a volume of 11.7 million m³. The tailing comprised hematite and goethite minerals containing quartz and kaolinite [8]. It consisted of poorly graded silty sand with densities between 4.02 and 5.11 [8].

The failure occurred by liquefaction inside the tailings, resulting in a sudden rupture at 12:28 pm on January 25, 2019 [8]. The material flew along the Ferro-Carvão stream until it was deposited in the Paraopeba river, causing a sudden block [10]. The dam collapse led to several types of gravitational movements, such as debris avalanches, debris flows, and mudflows, covering 8.4 km in about 45 minutes. This disaster caused 270 casualties, most of them in Vale facilities, which were in the ore tailings path.

There is a relationship between energy and mass movement types in the tailings path (figure 5), depicting four zones of destructive capacity from ZDC4 (the highest) to ZDC1 (the lowest) [10]. At the beginning of the rupture, the dam's driest material behaved as a debris avalanche, with speeds of up to 100 km/h, measured in images from security cameras [10]. Whereas the wet tailing material behaved as high-energy debris flow, eroding the ground and destroying most of the mine facilities in its path. The resulting wet materials consist of tailings and eroded soil mixture. In the lower declivities, the material behaves like a low-energy mudflow, deposited in the Paraopeba River and passively dispersed by fluvial dynamics.

The tailings dam failures damages are associated with the potential energy, the channel declivity and format, and the presence or absence of regolith. The regions of most significant damage were upstream, where the material behaved like a dense, high-energy fluid. Trees and regolith blocks floated in the denser fluid [10]. In these places, the more minor drainages, such as the Ferro-Carvão stream in Brumadinho and the Santarém stream valley in Bento Rodrigues, were completely buried, with drainage avulsion and intense basal undermining in their upper portions [10, 13]. In the Ferro-Carvão stream, an avalanche and a flow of high-energy dense debris reached speeds of more than 90 km/h [10] and devastated the downstream areas. This material was entrained into the stream channel through a channeled debris flow. The regolith eroded by the basal and lateral erosion was incorporated into the tailings.

![Fig. 4. Candonga hydroelectric dam, on Doce River, completely silted up after the passage of the flow.](image)

![Fig. 5. Schematic visualization of the Córrego do Feijão dam 1, ranging from a debris avalanche in the most proximal area to low energy mudflow in the Paraopeba river [10]. After the failure, a high-energy debris flow developed in the tailings, destroying the Vale Headquarters. The zones of destructive capability (ZDCs) discussed in the text are indicated as ZDC1 (medium or low destructive capability), ZDC2 (high destructive capability), ZDC3 (very high destructive capability), and ZDC4 (extreme destructive capability)](image)
The curves in the streams contribute to slowing down the direction due to the higher frictional energy. In downstream areas, the declivity and the material behaved like a mudflow, with less energy being deposited, blocking the Paraopeba River 40 minutes after the dam rupture. In the Paraopeba River, the material flow was predominantly passive, governed by the river's fluvial regime (11). The same behavior could be attributed to the tailing's material downs at the Candonga Hydroelectric dam in the Doce River.

The extensive formations of sand bars in the Channels of Carmo River are not verified in the Paraopeba River. The Carmo River had bars in the same area before the disaster. After the disaster, the most significant difference was the extensive silt up of the channel. On the other hand, the Paraopeba river does not have significant material to form bars in its channel.

The 2015 Samarco/Mariana and 2019 Vale/Brumadinho disasters show the occurrence of gravitational mass movements of an anthropogenic nature, with many similarities and differences between them. When reaching water courses, the flow of these materials was very significant, on the order of 8.4 km in the Corrego Ferro-Carvão in Brumadinho and more than 40 km in the case of the Guaiuído Carmo and Doce Rivers. The Vale/Brumadinho disaster had higher energy, with avalanches and debris flows with great destructive power. On the other hand, the Samarco/Mariana disaster had less energy but, with the large volume of spilled material, showed remarkable fluidity and behaved like a high-density mudflow for tens of kilometers.

Major disasters involving mining tailings dam failures in Brazil are still a disaster in the process. By violently destroying the riverbanks and silting the channels with tailings mud, the mining companies took away the landscape and the memory of all the people who inhabited their territory. In addition to deaths, mourning, damage to the economy, and environmental destruction, the destruction of riverbanks meant a profound change in the lives of people who lived on their banks, not just fishers and farmers. Therefore, an inventory of this destruction and the means to remedy it is necessary so that the rivers can return to their traditional uses.