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The tailings dam failure of 5 November 2015 in SE Brazil and its preceding seismic sequence

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Key Points:
- We detected and characterized a small-magnitude earthquake sequence preceding the collapse of a tailings dam in Southeast Brazil
- Seismic signals from the mudflow were recorded at regional stations for 25 min and confirmed by their polarization
- The tight spatiotemporal relation between quakes and accident makes the contribution of ground shaking to the dam rupture highly probable

Supporting Information:
- Supporting Information S1

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Abstract The collapse of a mine tailings dam and subsequent flood in SE Brazil on 5 November 2015 was preceded by a small-magnitude seismic sequence. In this report, we explore the spatiotemporal associations between the seismic events and the accident and discuss their possible connection. We also analyze the signals generated by the turbulent mudflow, as recorded by the Brazilian Seismographic Network (RSBR). In light of our observations, we propose as possible contributing factor for the dam collapse either ground shaking and/or soil liquefaction triggered by the earthquakes. The possibility of such a small-magnitude earthquake contributing to the collapse of a tailings dam raises important concerns regarding safety and related legislation of dams in Brazil and the world.

1. Introduction

On 5 November 2015, around 4 P.M. local time (UTC−02:00), a tailings dam in the Samarco Mine, state of Minas Gerais, Brazil, collapsed releasing more than 30 million cubic meters of water and mine waste [*Wise Uranium Project*, 2016]. The failure of this structure, called Fundão dam, caused the flooding of the small town of Bento Rodrigues situated less than 5 km from the dam (Figure 1). As a result, 17 fatalities have been confirmed while 2 persons remain missing (as on 13 January 2016) [*Wise Uranium Project*, 2016]. The mudflow reached the Atlantic coast through the Doce River, along more than 500 km of river course, and the spill of the mine tailings and mud is already considered one of the worst mining accidents in the history of Brazil [*Escobar*, 2015].

Samarco Mine is an iron ore deposit in which iron-rich metamorphic rocks known as itabirites are extracted [*Costa et al.*, 2001]. A previous characterization of the mine tailings showed that the waste material is of nontoxic nature, mostly composed of iron and silica [*Pires et al.*, 2003]. Nonetheless, the mud spill devastated the ecosystem of the Doce River killing innumerable fish and threatened the human water supply severely affecting local communities of fishermen and farmers [e.g., *Escobar*, 2015; *Massante*, 2015].

The Fundão dam started operations in 2008 and had dimensions of ~500 m length and ~90 m height [*SUPRAM*, 2008]. Other tailings dams (e.g., Santarém and Germano dams) are part of the Samarco Mine complex but fortunately did not break during the accident.

Although Brazil is one of the least seismically active regions of the world [*Assumpção et al.*, 2014; *Agurto-Detzel et al.*, 2015a] presenting low levels of seismic hazard [*Shedlock et al.*, 2000], small natural earthquakes are a common occurrence in this region of the country. Recently, two seismic sequences with main shocks of magnitudes 4.9 and 4.0 affected two different areas in the state of Minas Gerais [*Chimpliganond et al.*, 2010; *Agurto-Detzel et al.*, 2015b]. This seismicity results from intraplate stresses due to the superposition of an ~E-W oriented compressive regional stress field, related to plate tectonic forces, and a local stress field, related to particular geological/geophysical properties of the active areas [*Assumpção*, 1992; *Assumpção et al.*, 2014; *Agurto-Detzel et al.*, 2015a].

Less than 2 h prior to the dam failure, two earthquakes were felt in the mine area prompting the mine personnel to contact us, at the Seismology Center of the University of São Paulo. After examining the records of the RSBR, we identified two small earthquakes located within the mine area, occurring at about 2 P.M. (local time). Later that day, after the dam accident, a closer inspection revealed one other small earthquake around the time of the dam collapse. In this paper we report on the occurrence of this seismic sequence and possible association with the dam failure as observed by our seismographic network.

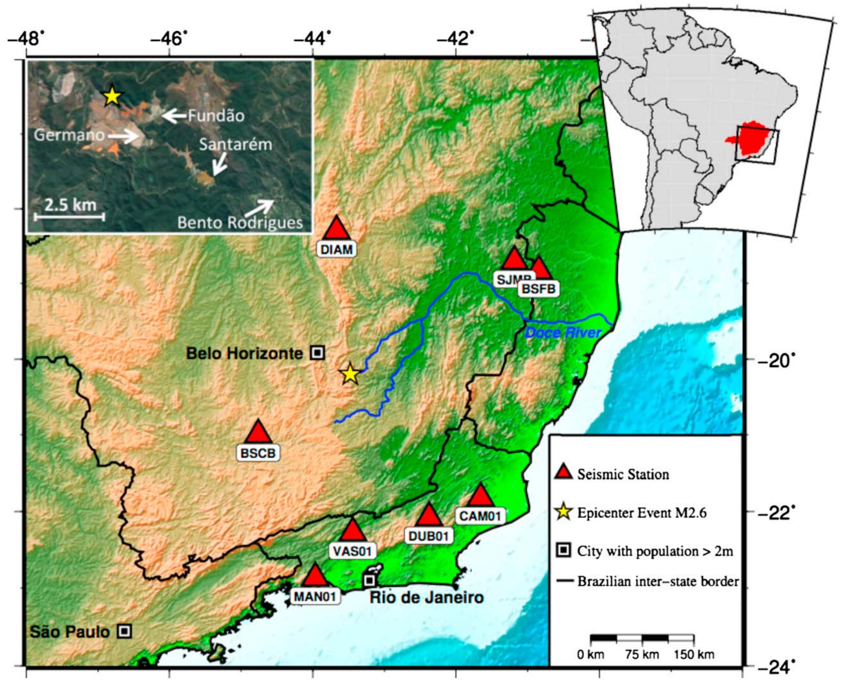

Figure 1. Location map. Top left inset shows zoom-in of mine area (Google Earth, imagery date 12 July 2015) indicating positions of dams and Bento Rodrigues village. Top right inset shows location within South America and the State of Minas Gerais shaded in red.

2. Seismic Sequence

All seismograms were collected from the open RSBR records [*Bianchi et al*., 2015]. We detected three events occurring ~1.5 h prior to the dam collapse, presenting regional magnitudes m_R [*Assumpção*, 1983] between 1.4 and 2.6. Another small event was detected around the time of the accident, and four more events with m_R ranging between 1.3 and 1.9 occurred on the following days (Table 1). The large spacing of the stations (the closest station is situated 160 km from the epicenter) and the small magnitude of these earthquakes hindered their automatic detection. Thus, only after a manual inspection we could identify and locate the events. Accordingly, our absolute epicentral estimations have uncertainties of ±10 km.

Because of this lack of resolution, we fixed the hypocentral depths to 0 km. Studies of previous seismicity suggest that earthquakes in Minas Gerais nucleate at shallow depths within the upper 5 km of the crust. Moreover, reports from the mine personnel (objects falling from table tops and small cracks near window corners; (Samarco personnel, personal communication, 2015) are consistent with seismic intensities IV–V in the Modified Mercalli intensity scale (MM), which also suggests that the events occurred at very shallow depths (<5 km). Because of the spatial association of the mine and the epicenters, the seismic events could be related to mining blasts, but the company itself ruled this out as no explosions were detonated during the time of the seismic events.

Table 1. Seismic Events Located Within the Samarco Mine Area[a]

Event #	Origin Time (UTC)	m_R
1	2015-11-05 16:12:15	2.3
2	2015-11-05 16:13:52	2.6
3	2015-11-05 16:16:03	1.4
4	2015-11-05 17:56:42	1.5
5	2015-11-08 18:00:23	1.5
6	2015-11-10 06:17:02	1.3
7	2015-11-10 07:45:58	1.7
8	2015-11-18 23:42:51	1.9

[a]Epicentral coordinates for all events are latitude −20.20, longitude −43.48 with an uncertainty of ±10 km. Relative location indicates that all events were located within 200 m of each other. Location depth was fixed to 0 km due to lack of station coverage (see section 2).

A comparison of the aligned records of some of the events (Figure 2) reveals the similarity of

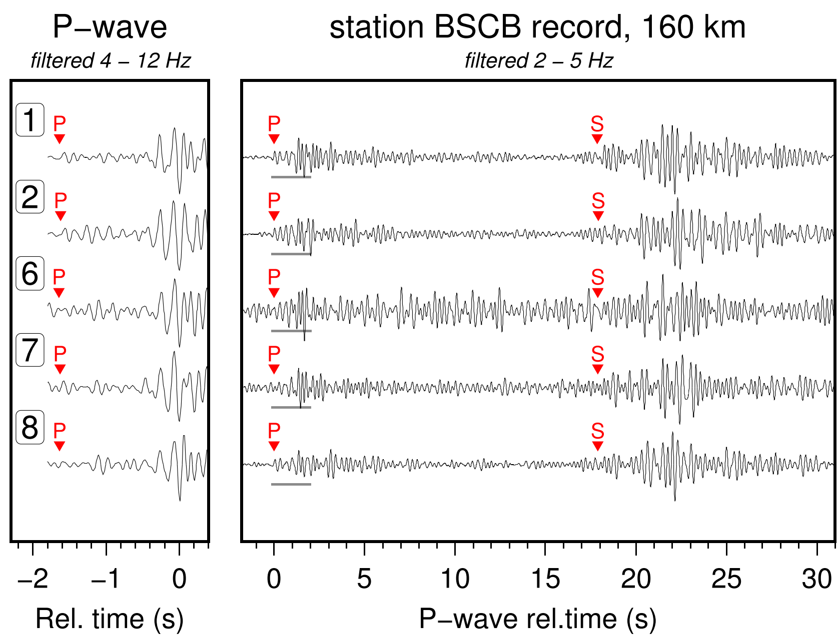

Figure 2. Aligned velocity records of some of the events as recorded at station BSCB, 160 km away. Event numbers according to Table 1. (left) *P* wave group, with *P* arrival indicated by red triangles. (right) The complete seismograms showing *P* and *S* arrivals.

their waveforms (cross-correlation coefficient >0.75), which suggests that the epicenters are colocated and present a similar focal mechanism. In fact, we carried out a relative relocation of the events based on waveform cross correlation to get accurate relative *P* and *S* wave arrival times [*Ciardelli et al.*, 2014]. The results revealed that independently of the absolute epicentral uncertainty, all events are located within 200 m of each other.

In order to further explore the spatiotemporal relation between earthquakes and accident, we calculated the probability of a seismic event with magnitude ≥2.5 occurring on the same day and area of the Fundão dam collapse. To do that, we defined our region of interest considering an area of 40,000 km^2 encompassing most of the iron mines (including Samarco Mine) located in the mining district called "Quadrilátero Ferrífero" (Iron Quadrangle). We selected this area because of the distinctive concentration of epicenters [see *Assumpção et al.*, 2014]. We call this area the "Belo Horizonte Seismic Zone" (BHSZ), owing to the largest city nearby (Figure S1 in the supporting information). We then estimated the earthquake rate (i.e., the number of earthquakes per year for each range of magnitude) for this area. Considering the available seismic catalog and using the Gutenberg-Richter frequency-magnitude relation, we found an earthquake rate of 3.2 events/yr with magnitude greater than 2.5 m_R for this area (see details in the supporting information). Taking into account our location uncertainties, we calculated the probability that an earthquake with magnitude larger than 2.5 would occur within a radius of 10 km from the dam on the same day of the rupture, given that the 40,000 km^2 BHSZ has 3.2 earthquakes per year, as

$$\text{Probability} = 3.2/365 \times \left(pi \times 10^2\text{km}^2\right)/40,000\ \text{km}^2 = 0.0088 \times 0.0079 = 1/14,000$$

3. Mudflow Signal

Soon after the dam collapse, a mixture of water, soil, and mine tailings flooded the village of Bento Rodrigues and flowed downstream following the course of the Doce River. The seismic signal generated by this turbulent current was also registered by our stations, allowing us to further analyze this aspect of the accident. Figure 3 shows a seismic section containing the waveform envelope of three events preceding the dam collapse and the signal produced by the mudflow. The envelope was produced using the software Seismic Analysis Code [*Goldstein and Snoke*, 2005] as follows: (1) Trend removal and signal tapering; (2) decimation

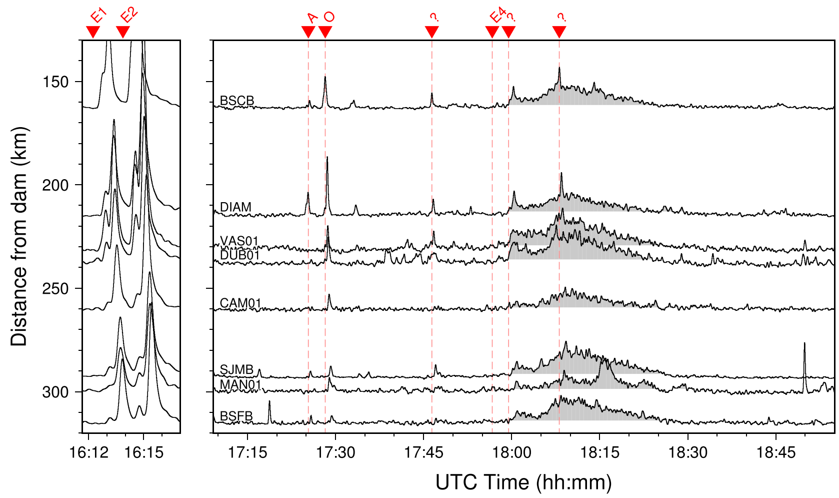

Figure 3. Seismic section with envelope of the events preceding the failure and signal produced by the mudflow (see section 3). (left) Envelope of events 1 and 2 (origin time indicated by red triangles E1 and E2). It is possible to identify the *P* and *S* wave arrivals of each event (small and larger peaks, respectively). (right) Some mine blasts outside Samarco (A and O), event 4 (E4), and the signal generated by the mudflow (shaded in gray). Other unidentified events (signal too noisy to obtain accurate location) are indicated by "?" but are also likely to be mine blasts outside Samarco Mine.

from 100 to 25 sps; (3) band-pass frequency filtering between 1.5 and 4.5 Hz; (4) envelope of amplitudes; and (5) successive envelope smoothing by a moving window of up to 128 samples, resulting in a final spike half-width resolution of 18 s. The calculated envelope indicates the average absolute amplitude of the vibrations.

The mudflow signal seems to last for about 25 min, starting at around 18 h (UTC time; see Figure 3). We observe two releases of energy or amplitude plateaus: the first from ~18:00 to ~18:05 h and the second from ~18:05 to the end of the signal. We believe that these two periods of energy release are related to two different phases of the flood. The first plateau might correspond to the initial flow of tailings and mud from the Fundão dam downstream to the Santarém dam. After arriving at the Santarém dam, which contained mostly water from the mine operations, the initial material is mixed, diluted, and gains in volume eventually overpassing the Santarém dam and flowing down the valley at a greater speed, thus releasing more energy (second plateau). Finally, the signal diminishes until disappearing due to the flood losing speed either by a decrease of its volume or by flowing through a gentler slope (e.g., flowing into the course of the Doce River). The energy bursts can also be observed in amplitude power spectrograms (Figures S4 and S5) which show that the mudflow maximum amplitude content in the frequency domain is observed up to 2 Hz. The spectrum of the mudflow signal clearly differs from that of the seismic events, which present maximum amplitudes on a wider frequency band (up to 10 Hz), but concentrated in shorter time windows.

Although the signal seems to start at ~18 h (Figure 3), this does not necessarily imply that the dam failed at that time, even after taking into account the waves travel time. In fact, the mudflow might have started slowly and only after some minutes gained enough momentum and volume to generate the observed signal. Accordingly, we conclude that the dam failure occurred the latest at 18 h UTC time (16 h local time).

Because of the long duration of the signal and its nonimpulsive start, it is difficult to accurately determine its propagation velocity. Nevertheless, a straight line approximately fitted at the start of the signal in a seismic section (Figure S6) indicates propagation velocities around 2.5–3.5 km/s, which are consistent with high-frequency Rayleigh waves velocities. Also, because the first arrival is not impulsive, it is not possible to determine the signal origin and propagation direction by conventional methods (e.g., back azimuth estimation from first-motion directions). Instead, we performed a time-frequency polarization analysis on the mudflow signal recorded at the two nearest stations (BSCB and DIAM). This methodology [*Schimmel and Gallart*, 2004; *Schimmel et al.*, 2011] uses three-component records to determine the particle motion at a given station as a function of time and frequency. Polarization attributes such as the semi-major and semi-minor vectors of the ellipse that best fits the particle motion are then used to infer the propagation direction. We used the

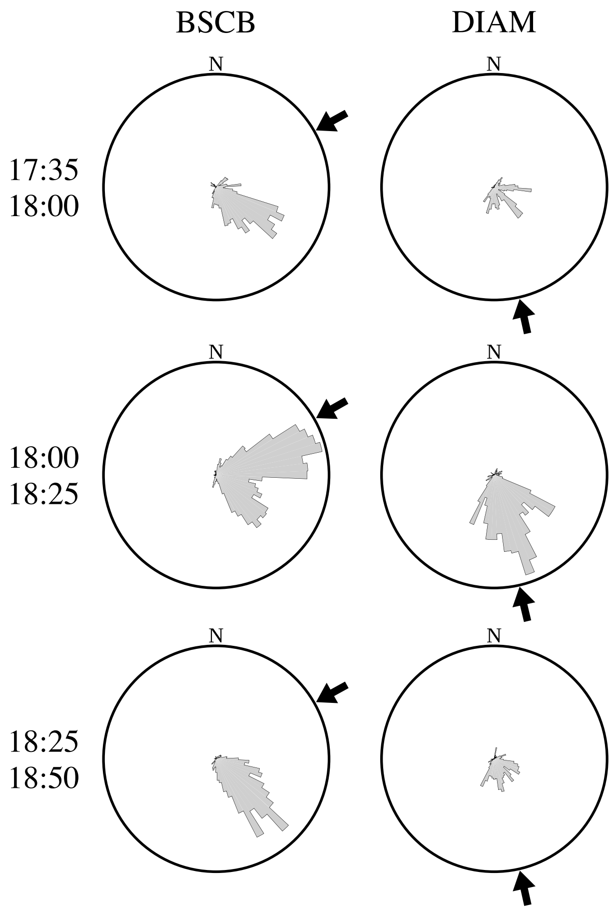

Figure 4. Histograms of number of polarized signals as a function of back azimuth (BAZ) for stations BSCB and DIAM. The analyzed time windows correspond to the 25 min (top row) before the mudflow signal, (middle row) during the signal, and (bottom row) after the signal. The black arrow indicates the theoretical BAZ for each station.

degree of polarization (DOP), introduced by *Schimmel and Gallart* [2003], as a quality measure of the wave polarization stability in time to separate arbitrarily polarized signals from less polarized noise. The mudflow seismic signals are assumed to consist mainly of fundamental mode Rayleigh waves and are detected through an adjusted DOP for elliptical retrograde particle motion in a vertical plane.

The results of the polarization analysis are shown in Figure 4. Here we used a DOP of 0.7, but we found similar results for other tested DOPs (Figure S7). The histograms show the number of signals elliptically polarized in a vertical plane as a function of back azimuth for the two considered stations, for three 25 min long time windows: previous, during, and after the mudflow signal. In the middle histograms (18:00–18:25 h, i.e., during the mudflow signal) the BAZ directions are consistent with the expected directions of theoretical BAZ for each station (see Figures 1 and 4) and clearly differ in terms of direction and amplitude from the other two time windows, which mostly show ambient noise signals (i.e., mainly microseisms from the ocean). This further confirms that the observed seismic signal does indeed come from the dam area and corresponds to the surface waves generated by the flow of the tailings after the accident.

4. Discussion and Conclusion

Analyzing the *P* and *S* wave frequency spectra of the main shock displacement records, we calculated a moment magnitude (M_W) for the largest event of $M_W = 2.0$. This suggests a relation $M_W = m_R - 0.6$ which agrees with previous estimations for a nearby area in Minas Gerais State [*Agurto-Detzel et al.*, 2015b]. This slight difference between M_W and m_R is expected for small magnitudes. A $M_W = 2.0$ event would produce maximum fault displacements in the order of 1 mm [*Nuttli*, 1983]. Despite the small magnitude and fault displacement, an event of this size could generate strong ground shaking within the epicentral area, in case of a shallow earthquake focus and favorable soil conditions. For example, empirical curves of ground motions for shallow, small-magnitude earthquakes [*Douglas et al.*, 2013] predict a peak ground acceleration (PGA) of only 0.3% of grams for a M_W 2.0 event at hypocentral distances less than 2 km, on hard rock. However, the large variability of the empirical data shows that PGA could reach 3% g (with a probability of 2.5%, two standard deviations above), which roughly corresponds to a seismic intensity V MM [*Wald et al.*, 1999], consistent with the reports of the mine personnel about the observed earthquake effects. In addition, possible site amplification (2 to 3 times amplification is not uncommon for soil and highly fractured sedimentary rocks, e.g., *Zhao and Xu* [2013]) could increase ground shaking beneath the dam.

The possibility of the earthquakes and accident occurring so close by pure chance is highly unlikely. The probability of an earthquake $m_R \geq 2.5$ occurring closer than 10 km of the dam, on the same day (within 24 h) of the dam failure is only 0.007%, that is one chance in 14,000. Furthermore, if we consider a time span of 2 h within the accident (our case), this chance is much smaller ($p < 0.001\%$). Thus, in the light of our seismological records and the tight spatiotemporal correlation between the earthquakes and the dam failure, we believe that the earthquakes did contribute to the accident. We have then two possible scenarios:

1. The dam collapse was triggered by the ground shaking of the earthquakes or
2. The earthquakes triggered soil liquefaction which in turn caused the dam failure.

On the first hypothesis, the spatiotemporal proximity of the events and dam failure, the relatively high intensities reported by the mine personnel, and the presumed shallow hypocentral depths, all suggest that the earthquake ground shaking might have contributed to the dam collapse. The largest event of the sequence, the m_R 2.6 quake of 16:13 h might have destabilized and/or created small fractures in the dam that were then enlarged by infiltration of water until the final collapse ~1.5 h later. It must be pointed out, however, that an inspection of the dam by the mining personnel soon after the main shock did not detect any signs of damage (Samarco personnel, personal communication, 2015). A similar case of delayed failure was observed in Japan, where a tailings dam collapsed 24 h after a nearby (~40 km epicentral distance) earthquake [*Ishihara*, 1984]. In contrast, there are no cases registered in the literature of a tailings dam collapse due to earthquakes with such a small magnitude. Most of the earthquakes involved in tailings dam collapses had magnitudes above 5 but, importantly and unlike our case, occurred at distances greater than 20 km from the dam [*USCOLD*, 2000]. Possible amplification and resonances of the seismic vibrations in the pool of soft sediments of the tailings reservoir deserves further investigation to elucidate the role of the earthquakes in the accident.

Soil liquefaction, the second hypothesis, is one of the most common causes of dam failure in general, and the most common cause of tailings dam failure related to the occurrence of earthquakes [*USCOLD*, 2000; *ICOLD*, 2001]. The method used in the construction of the Fundão dam is the upstream method [*SUPRAM*, 2008], which is particularly prone to earthquake liquefaction, and failure due to vibrations from earthquakes, mine blasts, or even heavy machinery traffic [*Fell et al*., 1992; *Breitenbach*, 2010; *Martin and McRoberts*, 1999]. On the other hand, no rainfall that could have caused an excess of groundwater occurred in the days prior to the dam collapse. Also, earthquake liquefaction is a process that requires larger seismic events with many cycles of shaking [*McRoberts and Sladen*, 1992], which an earthquake of magnitude 2.0–2.5 lacks due to its short duration. We note that there have been no published reports on soil liquefaction being related to M_w 2.0 (MM V) earthquakes to date and a complete site assessment would be required to validate this hypothesis.

A third scenario to contemplate is static liquefaction for which no seismic triggering is needed. *Davies et al*. [2002] found that mine tailings impoundments have demonstrated more static liquefaction events than seismic induced events. In this sense, *McRoberts and Sladen* [1992] argue that there is little practical difference in the magnitude of the shear strength induced by seismic or undrained static loading. We ignore the structural condition as well as the maintenance of the collapsed dam previous to the accident. Certainly, in order to prove the liquefaction hypothesis (seismically triggered or not), a complete characterization of the state and drainage system of the dam, plus field studies looking for liquefaction effects such as mud volcanoes would be necessary.

Lastly, another important issue to consider is the possibility of the seismicity being induced by the dam impoundment itself. In Brazil, induced seismicity related to water reservoirs is a relatively common occurrence [*Assumpção et al*., 2002]. In the case of the Fundão dam, it is not possible to prove that the earthquakes were induced because there was no preimpoundment monitoring to compare previous and later seismicity (this is not a regulatory demand for tailings dams, as it is for hydroelectric dams in Brazil). In water reservoirs worldwide and in Brazil, hydroelectric dams higher than 100 m have a probability of inducing earthquakes ($M > 3.0$) of about 20% [e.g., *Baecher and Keeney*, 1982].

Induced or not, to our knowledge, this is the first case in which an earthquake sequence of such a small magnitude is connected in relation to the failure of a tailings dam. The upstream method, used in the construction of the Fundão dam, is a popular and widely used construction method in Brazil and the rest of the world, but it has proved to perform badly in seismically active regions. In fact, in the neighboring earthquake-prone countries of Chile and Peru, the use of this method is forbidden by law since the 1990s [*Breitenbach*, 2010]. Some studies suggest that most cases of tailings dam failure are not due to a single factor but are the consequence of a series of minor incidents or special circumstances that put together prompt the dam collapse [*Caldwell and Charlebois*, 2010]. Our study demonstrates a spatiotemporal correlation between the Fundão dam failure and the preceding earthquake sequence, which strongly suggests that the small earthquakes did somehow contribute to the collapse of the dam. This means that the hazard from small, nearby earthquakes, however unlikely, should be taken into account as an additional factor in the risk evaluation during projects of tailings dams.

It is not the purpose of this paper to present a conclusive answer to the questions of how and why the Fundão dam collapsed. Further multidisciplinary analyses are being carried out by Brazilian authorities and the mine company itself in order to determine decisively the causes of the failure. From a seismological point of view, an enhancement of the coverage of the RSBR network would improve the estimation of source parameters for small earthquakes and lead to a deeper understanding of their origins and causes, and a better assessment of the seismic hazard in this region of Brazil.

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