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Mining Induced Ground Motions in a Tailings Dam

Ground Motions Induzidos pela Mineração em Barragem de Rejeitos

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Abstract

Mining induced seismicity can expose tailings dams to ground motions with potential to trigger a failure, if the structure reaches a certain level of vibrations that could exceed the seismic coefficient design criteria from pseudostatic analysis. Despite the cited risk, mainly for dams that are closer to open pits, few dams in Brazil are monitored by microseismic systems, and there are no references in the literature about continuous seismic monitoring both in open pit (source) and tailings dam, which represents the motivation of this paper. A microseismic system was commissioned in Cajati Mine, São Paulo, to record seismic events continuously in an array of 16 geophones (14 Hz and 4.5 Hz), installed in boreholes near the open pit (12 sensors) and in the dam (4 sensors), has measured values of PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity) related to 2,972 induced events from rock removal in the open pit. During the period monitored, the total of 109 events have triggered sensors in both structures, producing 920 seismograms, with the highest values of PGA and PGV of 0.0135 m/s^2 (0.1358% of g) and 0.0892 mm/s. The highest PGA value is 36 times lower than the vertical coefficient of 3% of g defined by Brazilian technical standard to dam design criteria, normally used in common pseudostatic analysis from geotechnical engineers. A routine microseismic monitoring brings a new set of valuable actionable data and information to support the management of geotechnical tailings dams' risks, under the conditions of vibrations induced by mining production.

Keywords: Microseismic monitoring; Geotechnics; Mining seismicity

Resumo

A sismicidade induzida pela mineração pode expor barragens de rejeitos a *ground motions* com potencial para desencadear uma ruptura, se a estrutura atingir um certo nível de vibrações que podem exceder os coeficientes sísmicos estabelecidos em critérios de projeto para análises de estabilidade pseudo-estáticas. Apesar do risco citado, principalmente para barragens que estão mais próximas de minas a céu aberto, poucas barragens no Brasil são monitoradas por sistemas microssísmicos, e não há referências na literatura sobre monitoramento sísmico contínuo tanto em minas a céu aberto (fonte) quanto em barragem de rejeito, que representa a motivação deste artigo. Um sistema microssísmico foi comissionado na Mina Cajati, São Paulo, para registrar continuamente eventos sísmicos num arranjo de 16 geofones (14 Hz e 4,5 Hz), instalados em furos próximos à mina a céu aberto (12 sensores) e na barragem (4 sensores), e mediu valores de PGA (Peak Ground Acceleration) e PGV (Peak Ground Velocity) relacionados a 2.972 eventos induzidos a partir da remoção de rochas da mina. Durante o período monitorado, o total de 109 eventos acionaram sensores em ambas as estruturas, produzindo 920 sismogramas, com os maiores valores de PGA e PGV de 0,0135 m/s^2 (0,1358% de g) e 0,0892 mm/s. O maior valor de PGA é 36 vezes menor que o coeficiente vertical de 3% de g definido pela norma técnica brasileira para critérios de projeto de barragens, normalmente usado em análises pseudo-estáticas pelos engenheiros geotécnicos. Um monitoramento microssísmico de rotina traz um novo conjunto de dados e informações, para apoiar a gestão de riscos geotécnicos de barragens de rejeitos, sob as condições das vibrações induzidas pela produção de mineração.

Palavras-chave: Monitoramento microssísmico; Geotecnia; Sismicidade de mina

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1 Introduction

Tailings dams are massive structures that are designed to contain the waste slurry remaining after processing ore at open pit and underground mines and are some of the largest man-made structures on earth and one of the most technically challenging areas for geotechnical engineers to maintain and monitor (Olivier et al. 2017).

The recent disasters of Fundão dam (2015) and Barragem I dam (2019) are among the worst of these disasters in terms of human, social, environmental, and economic costs (Lima et al. 2020). According to Adamo et al. (2020), it is estimated from information available in 2000, there were at least 3,500 tailings dams around the world, and these structures experience about 2 to 5 known “major” failures annually, along with 35 “minor” failures. In their work, the authors showed 23 disasters that happened between 1961 to 2019.

Moreover, due to their characteristics, tailings dams can be prone to instabilities due to the presence of unwanted ground motions from different sources, like mining blasts, natural or induced seismic events (regional earthquakes or microtremors triggered by mining activities).

Site seismicity can expose tailings dams to natural seismic events with potential to trigger a failure, by the structure exposure to critical levels of ground motions and/or to a continuous vibration like experienced in Fundão Dam (Agurto-Detzel et al. 2016; Adamo et al. 2020).

Seismic waves can affect a tailings dam physical integrity in the following aspects: liquefaction of tailings sands generated in the dam, sliding collapse or failure of the dam, as the blasting particle vibration velocity reaches a certain degree (Shuran & Shujin 2011). According to Silva et al. (2017) failures occur during ground motion in saturated materials when a reduction in the shear strength of the material causes the failure, through the generation of incremental driving forces that cause the failure due to the dynamic load acting in the body of the impoundment and when a reduction in the shear strength of the material is presented, and the static gravity driven forces produce the failure.

A reliable seismic slope stability analysis requires a relatively precise evaluation of seismic acceleration generated at different levels in the dam (Nimbalkar, Annapareddy & Pain 2018). Geotechnical engineers usually perform tailings dam’s stability analysis, called pseudostatic approach, that employs a seismic coefficient under the load of a seismic event to calculate the factor of safety of a tailings dam (Ozkan 1998; Singh, Roy & Das 2007; Sousa, Ferreira & Gomes 2021).

According to Ma et al. (2015), seismic waves generated by blasts or natural seismic events can be recorded as seismograms by seismic monitoring systems, and Errington (2006) states that the most common type of seismic monitoring system deployed in mines are the microseismic ones, commonly designed to monitor microseismic events in the vicinity of a mine. According to Eaton, Baan and Ingelson (2016), microseismic events can be defined, in a classification scheme for earthquake size categories based on magnitude, as seismic events with local magnitudes ranging from -2 to 0 (M_L).

Modern digital microseismic monitoring technology has evolved over the past years (Mendecki, Lynch & Malovichko 2010; Goldswain 2020) and corresponds to an array of uni or triaxial sensors, installed across the mine site, where each seismic event detected, are classified like blasts or natural seismic ones by applying some discriminators and processing techniques (Ma et al. 2015), are recorded as a collection of seismograms that represents a specific event.

The knowledge of a site seismicity (locally induced or regional) brings new information for evaluating tailings dams stability, comprehending and predicting hazards. In this case, it is important to geotechnical engineers to complement the traditional geotechnical monitoring (as piezometers, water levels and displacement meters), with a new set of data, tools, and methodologies, to measure and evaluate the potential impact of ground motions generated by seismic events in the stability conditions of tailings dams.

The Mining Chemical Complex of Cajati (CMC), in São Paulo, Brazil, has a microseismic system to monitor the mining operations level of ground motions that reaches the tailings dam called B1. The system has a set of twelve 14 Hz geophones installed in boreholes (~330 m deep), covering the open pit slopes, and four 4.5 Hz geophones at the embankment crest (~50 cm shallow holes) to monitor the tailings dam.

Cajati Mine site is seismically active, due to the volume of rock removed that changes the stress field conditions and affects the local geological structures, promoting a certain level of vibrations that potentially can affect the dam.

The ground motions generated by natural seismic events, can be compared to standard seismic values like ELETROBRAS (2003), normally used as design criteria in stability analysis conditions through pseudostatic approach or vibration assessment.

In this paper, the microseismic systems have recorded 2,972 natural induced seismic events from April/2018 to December/2019. From all of the recorded events, 109 have triggered sensors in both systems (open pit and tailings dam), where 41 events have generated valid seismograms and PGA and PGV values were calculated, being compared with the national seismic design criteria to assess the level of ground motions that are reaching the dam.

2 Site

2.1 Geology Overview

The Mining Chemical Complex of Cajati (CMC) is at 230 km from the city of São Paulo, following the federal road BR-116 in the direction of Curitiba, Paraná (Figure 1).

This region and its surroundings are part of the center-south portion of the Ribeira Belt, and four geotectonic units are currently found, individualized based on different lithological, structural, and isotopic characteristics, called Apiaí, Curitiba, Luís Alves and Paranaguá Terrains (Figure 2), resulting of the collision between the cratons of São Francisco, Congo, Paranapanema and Rio de La Plata.

The mining site is located in the Jacupiranga Intrusive Suite (JIS) that is composed by alkaline affinity clinopyroxenites (jacupiranguite), dunites associated with carbonatites and unsaturated alkaline rocks (ijolites and clinopyroxenites), with basic terms for alkaline subvolcanic acids like gabbro and syenites.

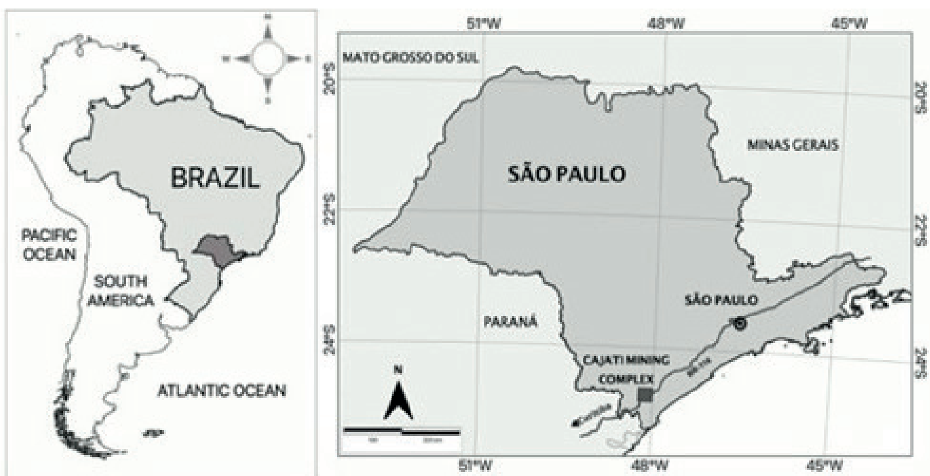

Figure 1 Location of the Mining Chemical Complex of Cajati.

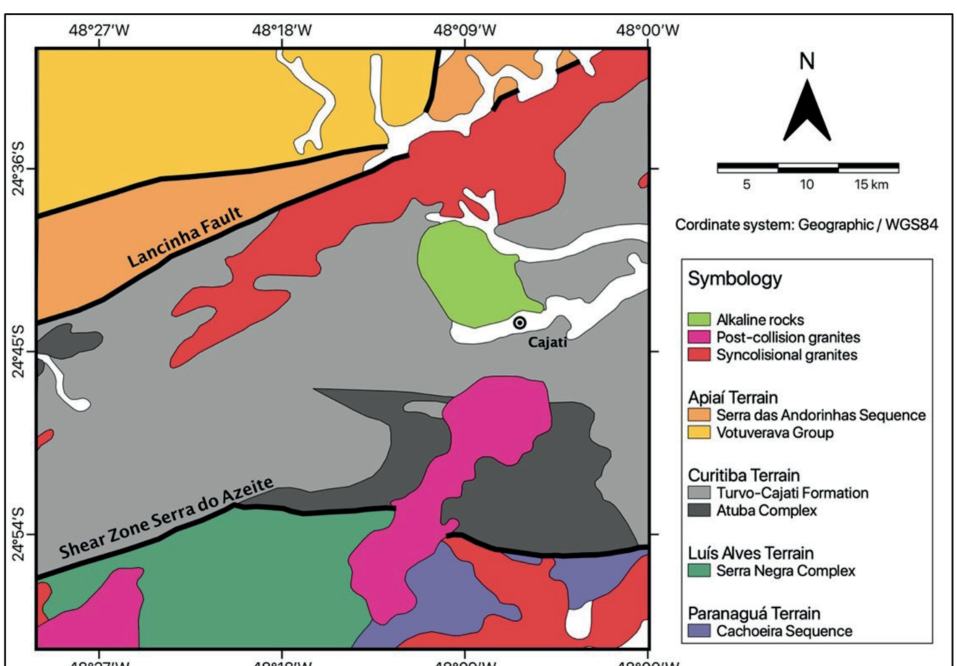

Figure 2 Simplified tectonic map showing the relationship between the Luís Alves cratonic fragment and Apiaí, Curitiba and Paranaguá domains, that are part of Ribeira Belt (CPRM 2013).

The main structural elements of carbonatites, such as joints, faults, dikes and fluid structures, are arranged in a radial and concentric manner, suggesting an intrusive body in the southern part of the occurrence, cut in turn by a posterior intrusion with a center in the north, resulted from 5 successive intrusions that led to five different types of carbonatites, according to structural, mineralogical and petrographic features (Barros 2001; Alves 2008). Faria Junior et al. (2010) and Oliveira and Sant'Agostino (2020) cited the work developed by Saito et al. (2004) in identifying a total of twelve geological units from the open pit, that considered not only geological characteristics but also relevant characteristics of the rock as ore in the beneficiation plant (Figure 3).

Drilling has demonstrated that the carbonatites extend in depth to at least 400 m below the sea level, with a general dip angle of 80º, and the structures are mainly represented by a shear zone (fault), a set of joints and fractures (Alves 2008). According to Oliveira and Sant'Agostino (2020), the fault zone corresponds to the main fault of a brittle shear regime that produced the main fault system and subsidiary faults, with N75W/subvertical direction. This zone produced a series of products such as breccias, cataclasites and gouges, in addition to allowing fissure alteration and oxidation of the carbonatite in different intensities.

2.2 Seismicity

Agurto-Detzel et al. (2017) investigated the correlation between seismicity and geotectonics provinces, besides other correlations (e.g., non-rifted interior versus passive margins, crustal thickness, gravity anomaly), and has identified that Neoproterozoic fold belts were found to be significantly more seismic than Phanerozoic basins and cratonic areas (Figure 4).

Regarding to the geology of the area, many models proposed in the literature try to explain intraplate seismicity based more on local stress concentrations mechanisms than on a direct correlation with possible surface faults.

Talwani (2017) states that there are places of stress concentrations around certain structures that act as accumulators, called LSC (Local Stress Concentrators). The author states that, when the local stress accumulated by some structures reaches magnitudes on the order of the regional stress (Figure 5), it releases their energy in the form of local seismic events.

The main LSC defined are shallow plutons, rift pillows, fault intersections, fault bends and restraining stepovers, where fault intersections account for approximately 30% intraplate seismic events, a junction of intersections in faults and shallow plutons by 35%, and the other structures represent the remaining 35%.

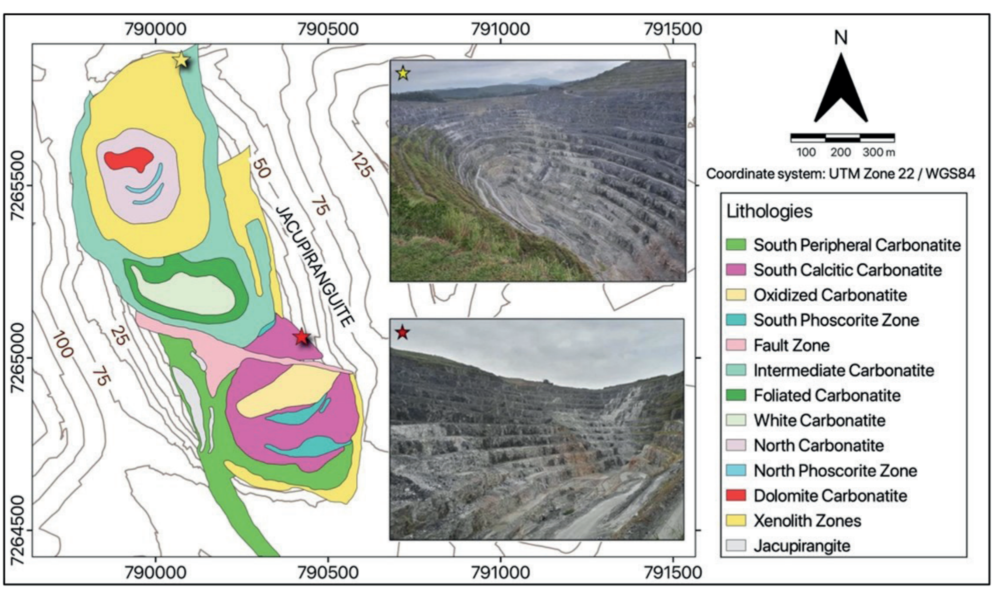

Figure 3 Simplified geological map of carbonatitic bodies in the open pit (Saito et al. 2004; Faria Junior et al. 2010; Oliveira & Sant'Agostino 2020; Oliveira 2021).

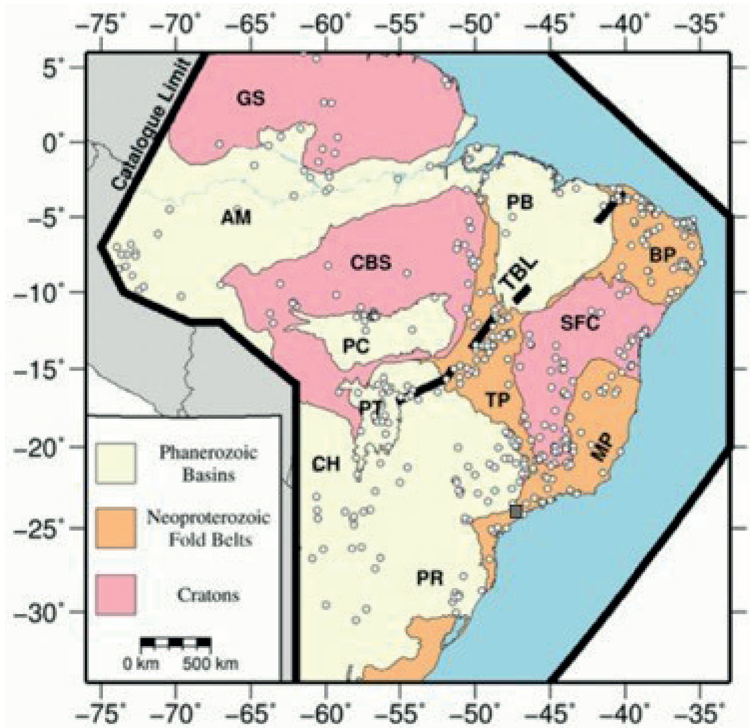

Figure 4 Map showing Cajati Mine (gray square), earthquakes and tectonic features. GS - Guyana Shield; CBS - Central Brazil Shield; SFC - São Francisco Craton; AM - Amazonian Basin; PB - Parnaíba Basin; PC - Parecis Basin; PT - Pantanal Basin; CH - Chaco Basin; PR - Parana Basin; BP - Borborema Province; TP - Tocantins Province; MP - Mantiqueira Province; and TBL - Transbrasiliano Lineament (Agurto-Detzel et al. 2017).

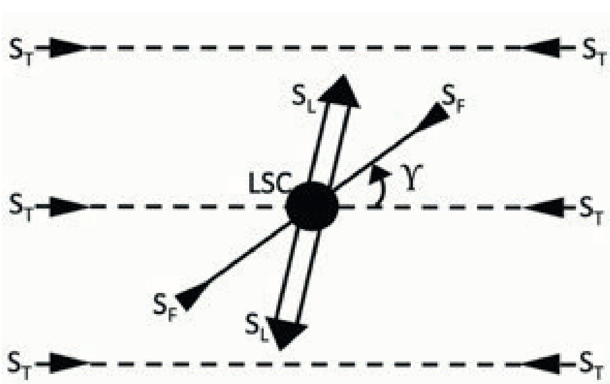

Figure 5 Intraplate setting interaction of the local stress (SL), associated with a LSC, with uniform regional stress field (ST), causing the final (ambient) stress SF (Talwani 2017).

As CMC is located inside the Jacupiranga Intrusive Suite, a mafic pluton embedded in granodiorites of the Turvo-Cajati formation, it is expected that the local seismicity is supposed to be related to the Jacupiranga Complex, as shallow plutons usually accumulate stress in their borders.

2.3 Induced Seismicity

Since the first half of the twentieth century, numerous studies about earthquakes that are thought to be caused by geoengineering operations have been documented and published, including artificial water reservoirs, underground and open pit mining, coastal management, hydrocarbon production, and fluid injections/extractions (Klose 2013).

Induced earthquakes can be considered where the stress change caused by human activity is comparable to the shear stress causing a fault to slip (Foulger et al. 2018).

In open pit mining, the extraction of a large volume of rocks can change the stress field of shallower layers, in a scenario of stress relief and reactivation of structures that may generate seismic events.

In general, induced seismicity in mining environments can pose a danger not only to human lives but also as material damage. Over the years, several cases of earthquakes induced by mining activity have been recorded, even in environments with low regional seismicity. Some of these cases even reach magnitudes on the order of 4.0 to 6.0 M_L. One such example is the case the Bachatsky earthquake (local magnitude 6.1) in Kuzbass on June 18, 2013. (Emanov et al. 2014).

Geoengineering construction mass changes have the potential to advance the clock of natural seismic cycles and induce or trigger new earthquakes (Klose 2013).

Studying a tunnel excavation, Wu, Zhao and Duan (2017) have perceived the occurrence of induced seismicity as consequence of the hard rock stress redistribution in the vicinity of the construction.

Inside the processes cited by Klose (2013), to induce or trigger seismic activities by geoengineering includes mass removal and volumetric changes that are related to mining operations. A larger unloading rate of the excavation work can reduce the strain energy consumed by particle breakage and rearrangement (Figure 6), and thus a larger amount of strain energy can be released to induce larger slip displacement (Wu, Zhao & Duan 2017).

2.4 Geotechnical Structures

CMC infrastructure is composed of an open pit, two stockpiles and two tailings dams (B1 and B2) (Figure 7). According to Kuckartz (2017) the open pit bottom is located around the elevation ~170 m with the plan to advance 100 m in depth, the global angles of the current slopes are around 57º (operational and future) with benches varying between 10 to 20 m in height.

B1 dam (Figure 8) is located approximately 2 km east of the mine open pit with the following characteristics:

Maximum height of 44 m (at the level of the foundation);

Embankment crest with 400 m of length and 8 m average width;

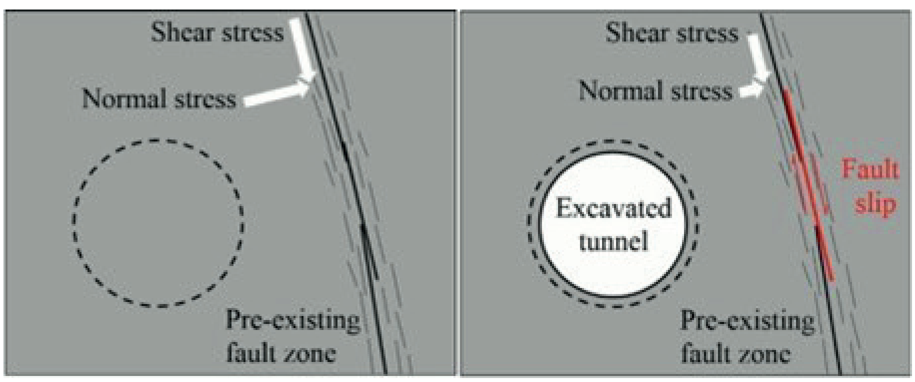

Figure 6 Excavation-induced stress field shift after a mass removal and volumetric change (Wu, Zhao & Duan 2017).

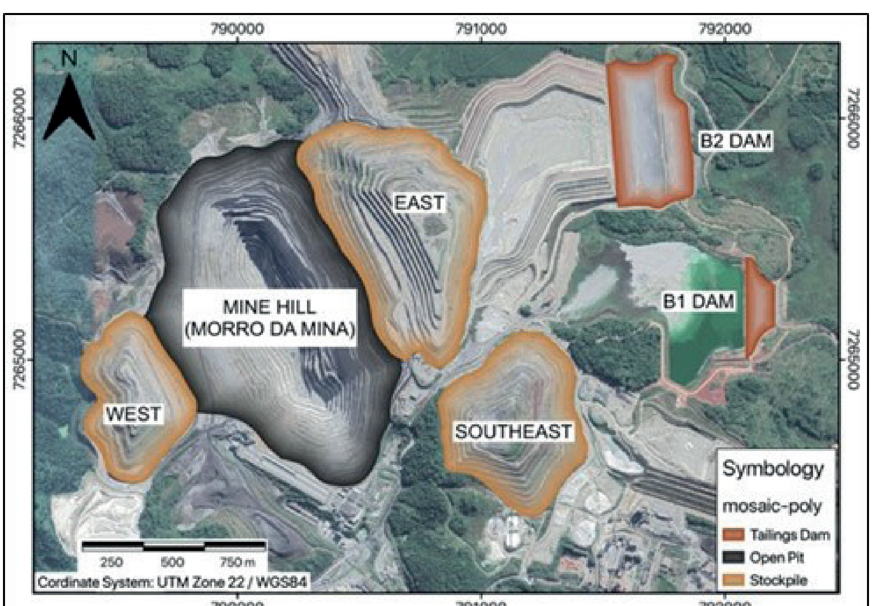

Figure 7 View of the mining infrastructure with the location of the stockpiles (East, West and Southeast), Morro da Mina open pit, B1 and B2 dams (Cajati 2020).

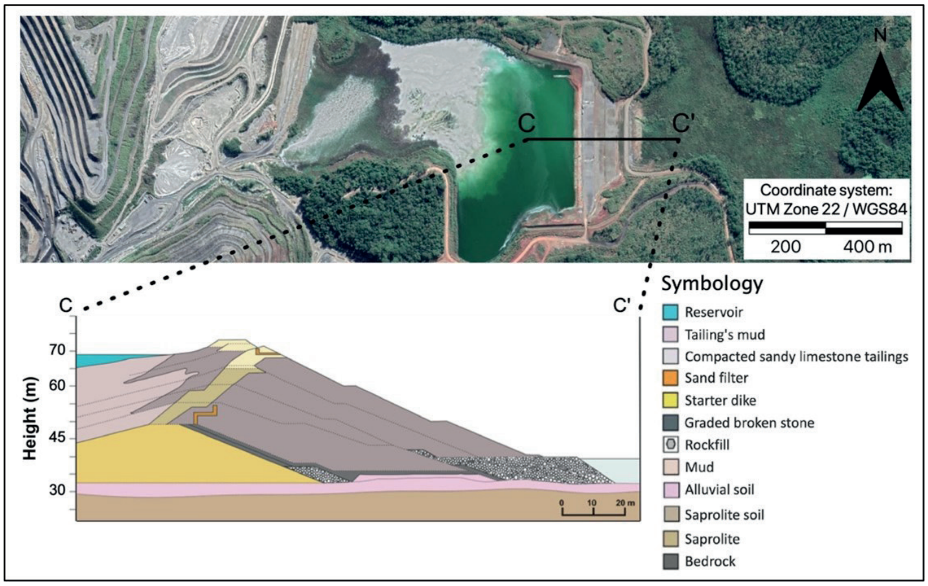

Figure 8 Typical section of B1 Dam (modified from Oliveira, 2021) (Cajati 2020).

The structure is characterized by a starter dike of homogeneous section; constituted by a compacted clay embankment, presenting a rockfill downstream;

Since 1973, the dam went through nine raisings.

2.5 Microseismic System

CMC microseismic system consists in a set of sensors that comprises 12 geophones installed in deep boreholes (~330 m) and 4 geophones in shallow holes (~50 cm) covering respectively the open pit and the tailings dam, recording data in a 24-hour and near real-time monitoring regime (Figure 9).

The sensor is the first, and arguably the most important, component that seismic signals encounter as physical quantities are transduced from physical phenomena such as ground motion to a voltage, which is then sampled and ultimately ends up in electronic form in a database where waveforms can be processed to build up a seismological catalogue (Goldswain 2020).

Mendecki (1997) states that a seismic monitoring system needs to accurately record the amplitude and timing of any significant ground motion over a wide range of amplitudes, frequencies and durations, and assembly the records at a central point for processing, within a reasonably short time so that action may be taken in response and at a high-rate maximum information retrieval.

The geophones are connected to an analog to digital converter and then to a seismic processor, that in the field are coupled to a GPS sensor to guarantee the timing precision (Figure 10). All the records are stored in a central computer that can be developed in a local or cloud-based infrastructure.

According to Mendecki (1997), for a seismic event to be stored in the database, the system goes through the following stages: monitor each sensor continuously to decide when the signal becomes significant (triggering); ensure that the signal represents a seismic event (validation); decide which records from which sensors represent the same event (association); extract source and path parameters from the raw ground motion data for each event (seismological processing); and infer from a history of these parameters the processes which are taking place within a volume being monitored (interpretation).

For all registers captured by the system, only the records that meet the trigger association rules are stored in the database, it means that to be considered a valid seismogram, an event needs to trigger a minimum of 4 geophones within a travel time tolerance of 0.1 seconds for each trigger and when the ratio between STA (Short Term Average) / LTA (Long Term Average) is higher than 8.

Once in the database, the events went through treatment and quality assessment procedures and seismological processing. Depending on the quality of the seismogram and precision in the P and S-wave picking, the events can be classified as rejected, automatically or manually processed.

The calculation of seismic source parameters requires precise signal processing, namely expertise-required and time-consuming P and S-wave hand-picking (Ma et al. 2015). In this paper, natural seismic events source parameters were calculated only for seismograms manually processed.

Ma et al. (2015) present some discriminating features, their characteristics, and applications to discriminate blasts and microseismic events, which were used in the event classification of this paper.

From the period of April/2018 to December/2019, the system has registered approximately 80,000 events, recording different types of waveforms from multiple sources, such as climate events (storms, thunders, and lightning), mining operations machinery, natural events from different magnitudes and blasts.

A total of 2,972 natural events were manually processed and recorded by the system. From these events, 109 have triggered both sensors in the open pit and tailings dam, producing 920 seismograms that exceeded the trigger levels rules of the system. For all seismograms, the values of peak ground velocity (PGV), peak ground acceleration (PGA), percentage of the gravity acceleration (% of g), period and dominant frequency were estimated. The source parameters were only estimated for manually processed events where the signal to noise ratio was large enough to accurately pick P and S-waves.

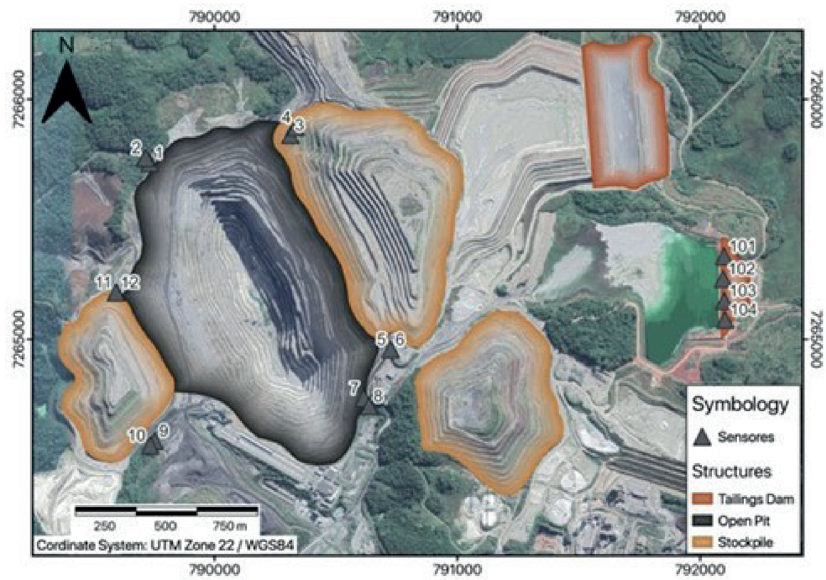

Figure 9 Sensor's array from the open pit (1 to 12) and tailings dam (101 to 104) (Cajati 2020).

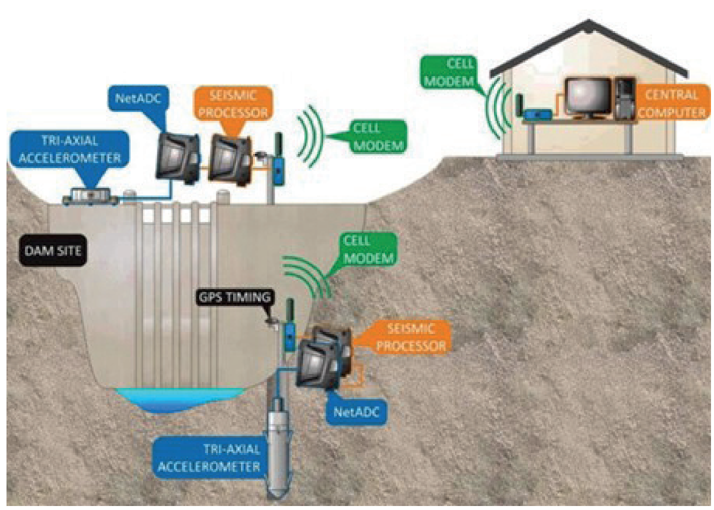

Figure 10 Schematic architecture of a microseismic system composed by a set of analogical geophones, connected to an analog to digital converter device (NetADC) and a local seismic processor linked to a GPS for timing, with a solar panel, for a tailings dam. The seismic processor communicates with a central computer.

3 Results

All 2,972 events were analyzed, which generated 19.512 seismograms and were mainly located at the bottom of the Morro da Mina pit (Figure 11), showing that the totality of the events are concentrated in the surroundings of the open pit.

The seismic events local magnitude has ranged from -3.7 to 1.7, where 318 (10.7%) events had local magnitude higher than 0.1. The 1.7 M_L event has triggered 10 sensors, being two of them in the tailings dam, recording PGV of 0.0892 mm/s (Figure 12) and 0.0337 mm/s and PGA of 0.0104 m/s^2 (0,1061 %g, for g = 9.78 m/s^2) and 0.0026 m/s^2 (0.0264% of g), for sensors 101 and 103 respectively.

From all seismic events, 109 have been recognized by sensors both in the open pit and tailings dam, reaching the association rules of the system, triggering 155 seismograms in the dam's sensors.

A total of 41 seismograms had presented a good signal to noise ratio, large enough to generate a good waveform, due to the lower energy of the seismic events.

For ground motions measured in the dam crest, the values of PGV varied from 0.0024 to 0.0892 mm/s and the values of PGA varied from 0.0003 (0.0024% of g) to 0,0135 (0.1383% of g) m/s^2. Table 1 shows the trigger statistics discriminated by sensors.

4 Discussion

Through the analysis and location of the seismic events at the mine, is noticeable that the nucleation of these earthquakes is linked to the blasting of the open pit. The changes in the local stress conditions, related to the mining production and its geological characteristics, can be considered the source induced events recorded by the microseismic monitoring system.

The region between the fault, foliated carbonatite, white carbonatite, xenolith zone and north carbonatite, concentrates approximately 54% of the induced seismic events epicenter (Figure 13). For the events with local magnitude higher than 0, the system recorded 30 events, where 22 (73.3%) are in the zone of higher concentration.

Mining operations in Brazil generally use a pseudostatic approach to assess the stability of tailings dams against the loading of seismic vibrations, such as those generated by blasting activities. These analyses represent the effect of a ground motion by applying a static horizontal and/or vertical acceleration to a potentially unstable mass of soil where the inertial forces induced by these pseudostatic accelerations, increase the driving forces and may decrease the resisting forces acting on the soil (Silva et al. 2017).

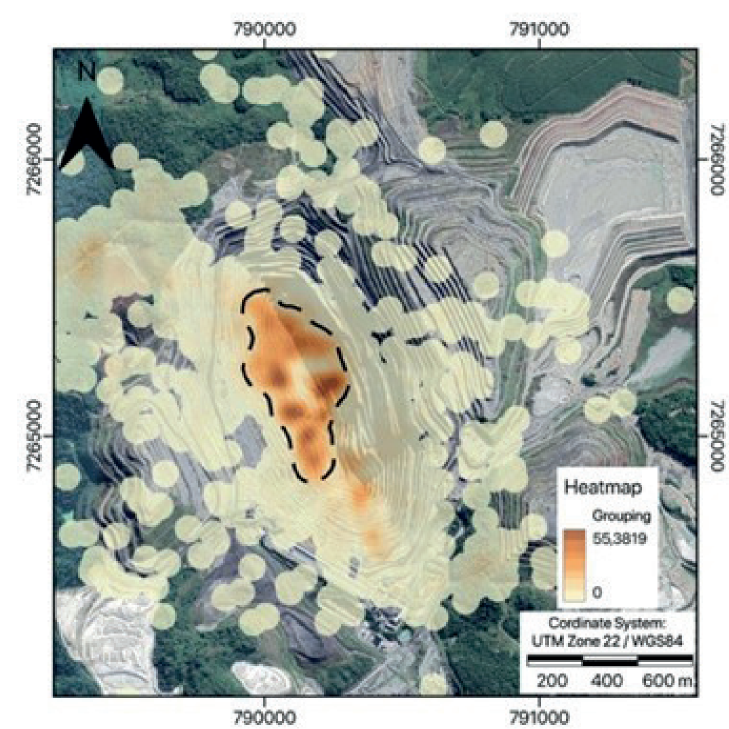

Figure 11 Heatmap from the 2.972 events showing the concentration of the epicenters in the bottom of the Morro da Mina pit (dashed polygon) and mining vicinity (Cajati 2020).

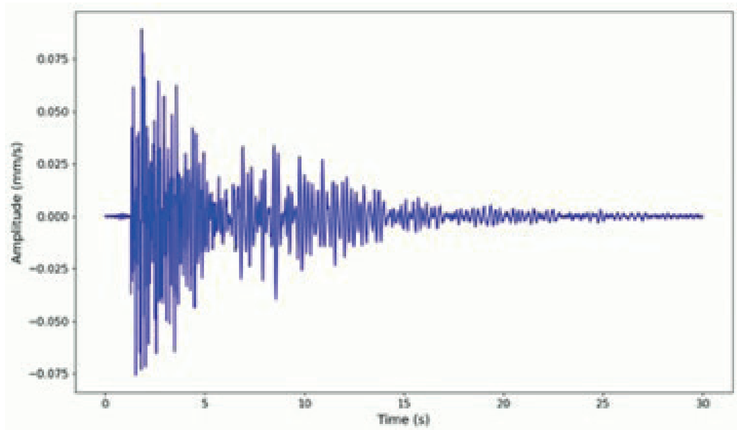

Figure 12 Waveform of the 1.7 M_L seismic event recorded by sensor 101 in the dam.

Table 1 Tailings dam's sensors trigger statistics.

Sensor	Number of triggers	Maximum PGV (mm/s)	Mean PGV	Maximum PGA (m/s2)	Mean PGA
All	41	0.0892	0.0275	0.0135	0.0041
101	10	0.0892	0.0203	0.0104	0.0027
102	17	0.0635	0.0258	0.0135	0.0048
103	10	0.0828	0.0435	0.0082	0.0049
104	4	0.0168	0.0128	0.0026	0.0022

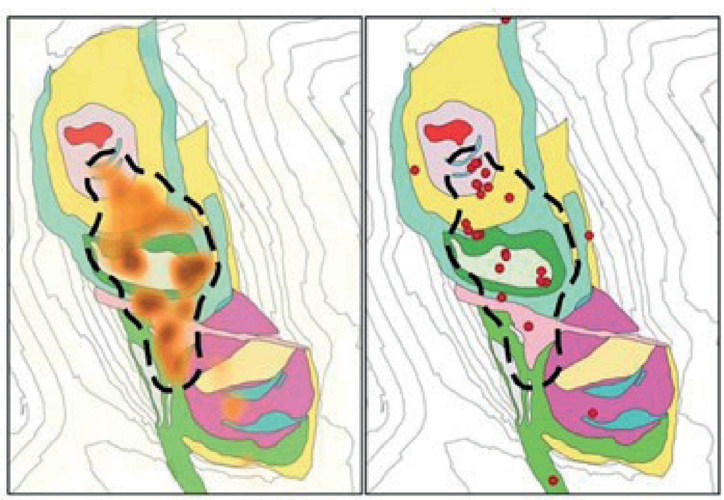

Figure 13 Zone with the highest concentration of epicenters (left) and the events with local magnitude higher than 0 (right).

Most tailings dams in Brazil consider the reference values of ELETROBRAS (2003) as the main design criteria and seismic coefficient to simulate the structure stability analysis conditions through a pseudostatic approach, that comprises the values of 3% of g to vertical and 5% of g to horizontal components, with the objective of having a safety factor greater than 1.1.

The highest ground motion value measured at the dam (0.1383% of g) was 36 times lower than the vertical coefficient of 3% of g defined by Brazilian technical standard. Statistics showed that sensors 102 and 103 registered the highest PGAs, due to the greater depth of the dam material in the center of the embankment.

5 Conclusion

The vibrations that reached the B1 dam had their source related to induced seismic events due to the unload of rock mass from mining production. The constant removal of material had led to the register of 2,972 seismic events in the open pit vicinity, where 109 events were recorded in the tailings dam with lower level of ground motions.

For the period analyzed, the dam has not experienced high values of PGA and PGV. When compared with Brazilian standards, commonly used as a geotechnical design criterion (seismic coefficient) for a pseudostatic analysis, the mining induced seismicity is not prone to cause damage to the dam.

The sensor array proved to be adequate and coherent with the objectives of this work. For future studies, a seismic ambient noise analysis of velocity change variation will be included that is related to the gain or loss of medium stiffness, obtained from an increase in the number of sensors installed in the dam.

A routine microseismic monitoring system brings a new set of valuable actionable data and information to support the management of geotechnical tailings dams' risks, under the conditions of vibrations induced by mining seismic events.

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Author contributions

Leonardo Santana de Oliveira Dias: conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization. **Marco Antonio da Silva Braga:** formal analysis; methodology; supervision; validation. **Alan de Souza Cunha:** data curation; formal analysis; validation. **Gerrit Olivier:** conceptualization; methodology; writing – review and editing. **Daniel Monteiro Machado:** conceptualization; writing – original draft.

Conflict of interest

The authors declare no potential conflict of interest.

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