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Assessment of Geoelectrical and Seismic Methods for Tailing Dams – Catalão – GO.

Avaliação de Métodos Geoelétricos e Sísmicos para Barragens de Rejeitos – Catalão – GO.

Gilvan Sá[1]; Anne Karine Nunes da Mata Silva[2]; Ewerton Aparecido Rodrigues[3]; Marco Antonio da Silva Braga[4]

[1] Federal University of Ouro Preto – UFOP, School of Mines, Engineering Department, Ouro Preto – Minas Gerais – Brazil. E-mail: gilvansa1972@gmail.com.br
ORCID: https://orcid.org/0000-0001-7303-0778
[2] Federal University of Rio de Janeiro – UFRJ, Geology Departament, Rio de Janeiro – Rio de Janeiro – Brazil. E-mail: annekarine@geologia.ufrj.br
ORCID: https://orcid.org/0009-0002-8166-1435
[3] Technological Federal Center – CEFET, Araxá – Minas Gerais – Brazil. Mosaic Company, Araxá – Minas Gerais – Brazil. E-mail: ewerton.rodrigues@mosaicco.com
ORCID: https://orcid.org/0009-0008-2854-5615
[4] Federal University of Rio de Janeiro – UFRJ, Geology Departament, Rio de Janeiro – Rio de Janeiro – Brazil. E-mail: marcobraga@geologia.ufrj.br
ORCID: https://orcid.org/0000-0002-0244-4655

Abstract: Mining tailings dams are engineered structures designed for the disposal of waste materials generated during mineral processing. These structures require continuous geotechnical monitoring, including visual inspections and manual or automated instrumentation, to ensure their safety and stability. This paper presents the application and results of geophysical methods used to monitor and investigate a tailings dam. In Brazil, recent dam failures have prompted significant improvements in legislation, technical standards, and geotechnical investigation protocols. Electrical resistivity was employed to map low-resistivity zones, which are associated with higher degrees of saturation within the dam structure. Ambient noise seismic interferometry enabled real-time monitoring of variations in S-wave velocity (Vs), with reductions reaching 11% at the dam crest. This reduction was linked to higher saturation levels near the right abutment, likely intensified by seasonal rainfall. Additionally, the multichannel analysis of surface waves confirmed the decrease in Vs in areas correlated with those of low resistivity, suggesting increased saturation. Ambient Noise Seismic interferometry also detected a partial recovery in Vs over time. The integration of these geophysical techniques allowed for the identification of structural anomalies and supported the implementation of corrective engineering measures, contributing to improved dam safety and risk management.

Keywords: Multichannel Analysis of Surface Waves (MASW); Electrical Resistivity; Ambient Noise Seismic interferometry.

Resumo: Barragens de mineração são projetadas para disposição de materiais provenientes do processo mineral. Possuem contínuo monitoramento geotécnico (inspeções visuais e instrumentações manuais ou automatizadas), para garantir a segurança destas estruturas. Este artigo apresenta os resultados da aplicação de métodos geofísicos no monitoramento e investigação de uma barragem de rejeito. No Brasil, após incidentes envolvendo barragens de mineração, houve a necessidade do aprimoramento das legislações e normas técnicas, bem como das investigações e monitoramentos geotécnicos. Através da eletrorresistividade, foi possível mapear zonas de baixa resistividade, relacionadas a áreas de maior saturação. A interferometria sísmica do ruído ambiente, possibilitou o monitoramento em tempo real da variação da velocidade da onda S (Vs), onde foi verificado uma perda até 11%, na região da crista da barragem, associado a área de maior saturação próximo a ombreira direita e contribuição do período chuvoso. Através do método MASW, verificou-se a diminuição da Vs e sua correlação com áreas de maior saturação obtidos pelo método da eletrorresistividade. A interferometria sísmica do ruído ambiente, possibilitou também verificar a recuperação na variação da Vs. A integração dos métodos geofísicos permitiu identificar anomalias e adotar medidas de engenharia corretivas, colaborando para a segurança da barragem monitorada.

Palavras-chave: Multichannel Analysis of Surface Waves (MASW); Eletrorresistividade; Interferometria Sísmica do Ruído Ambiente.

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1. Introduction

A significant amount of solid tailings are produced during the life of a mine, a mining operation, requiring the creation of adequate storage spaces. For this purpose, dams are constructed, which can be made of rocks, soil, or even the tailings themselves. These structures serve the primary function of storing water and/or tailings produced during the beneficiation process.

There are three primary construction methods for tailings dam construction and raisings: a) Upstream, b) Downstream, and c) Centerline. Following the Mariana and Brumadinho incidents in Brazil, significant legal adjustments and changes at both federal and state level regulations led to the explicit prohibition of the upstream construction method. Additionally, all existing dams constructed using this method were prohibited from operating, with defined legal deadlines set for the de-characterization process.

According to Leal et al. (2023), Brazil has 769 registered tailings dams, of which 425 are included in the National Dam Safety Policy (PNSB) and 344 are not. Among the dams under the PNSB, the majority (48%) were constructed using the single-step method. For those not included in the PNSB, the downstream raising method is also predominant in cases where the construction method is defined. However, it is noteworthy that approximately ¼ of these dams (23.3%) have an undefined construction method, which represents a potential risk due to the lack of clear information regarding their stability and safety conditions.

The monitoring of these dams typically includes visual inspections and geotechnical instrumentation. However, more advanced monitoring techniques are necessary to acquire a more thorough understanding of these structures and accurately assess current and future conditions. Geophysical methods, due to their capacity to rapidly gather large amounts of data and broad survey coverage, provide a valuable supplement for examining the physical characteristics of these structures.

These methods include seismic interferometry of ambient noise, MASW (Multichannel Analysis of Surface Waves), and electrical resistivity. The first method, seismic interferometry of ambient noise, monitors changes in the rigidity modulus of the structure by observing the variation in the speed of the S wave. It has been a continuous monitoring method for mining dams and has been developed and applied successfully in Brazil since 2018 (Dias, 2022). Moreover, continuous monitoring through microseismic application facilitates the constant recording of seismic events, providing essential insights into the exposure of the dam to seismicity. This is a vital tool for guiding prevention actions, classifying and defining alerts (TARPs), and preparing a geotechnical risk map (Mendecki et al., 2010). Additionally, MASW is employed to calculate the S-wave velocity (Vs) at depth, while electrical resistivity is used to map areas with potential changes or anomalies within the massif.

This article aims to present the results of the ambient noise seismic interferometry method and MASW and to correlate these findings with the electroresistivity data obtained by Sá (2023), thus corroborating the application of these geophysical methods to improve the understanding of the variations in the physical properties of these structures over time. These analyses were conducted during the reinforcement stages at the mining dam, providing insights into the outcomes that were attained throughout the reinforcement project.

2. Study area

The dam being studied (Figure 1) is situated in the heart of the state of Goiás, approximately 22 km from the city of Catalão, and is part of the Catalão Mining and Chemical Complex. Throughout its operation, the dam underwent four construction stages to meet the demands of the industrial process. The initial stage involved building the initial dike at El. 743.00 m, in 1982, and later raised to El. 763.00 m. The second raising stage, in 2012, reached the elevation of 773.00 m, followed by a third stage in 2016, raising the landfill to El. 778.00 m. The landfill spans approximately 1,040.00 m and covers a reservoir of around 695.00 ha. Furthermore, seven sumps were established at the elevation of 778.00 m to collect tailings, allowing them to dry and subsequently reusing them in the construction process after they reached the acceptable level of humidity content outlined in the project. A combination of centerline and upstream methods was used in the raisings.

The dam underwent a centerline reinforcement process in 2020 in order to comply with current legislation (Figure 2). At the base, rockfill were used to improve support conditions downstream. Additionally, magnetite and tailings from the beneficiation process itself were utilized. Transitional materials with granulometries adjusted to the design requirements, including gravel 3, gravel 0, and sand, were used (Figure 3). The tailings underwent a drying process in sumps located on the crest of the dam, specifically in sumps 1 to 7 (Figure 6).

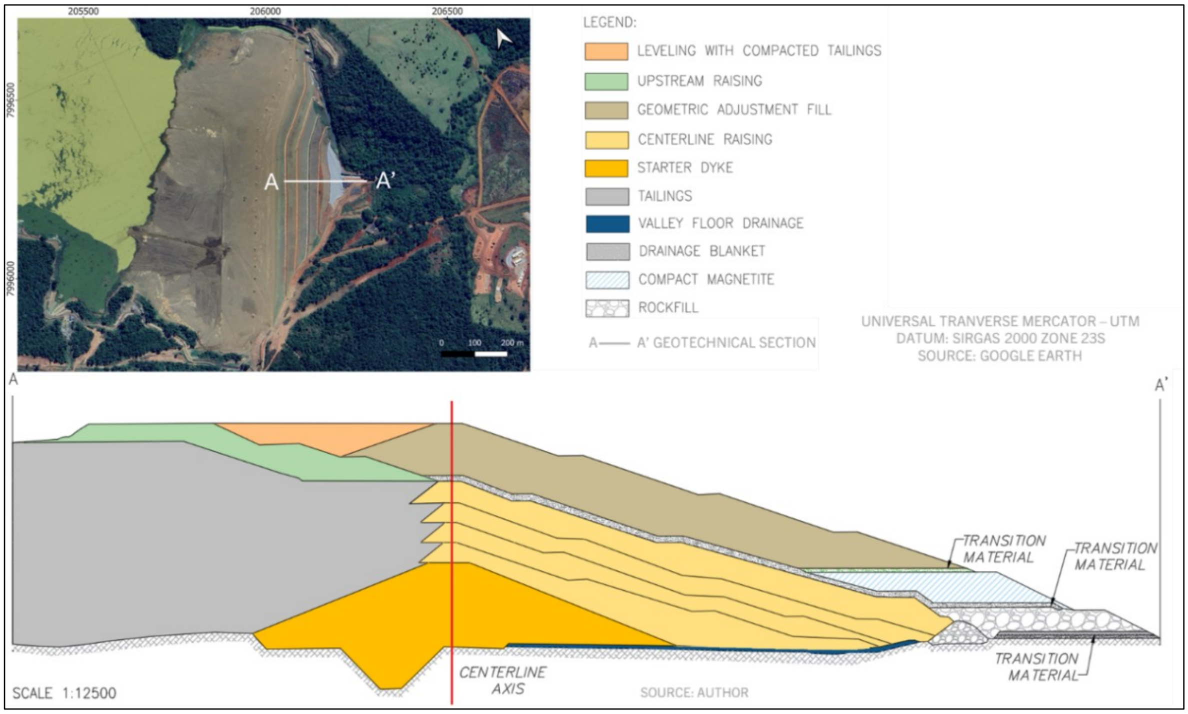

Figure 1 – Schematic representation of the dam's main components and a representative cross-section detailing the embankment's constituent materials Coordinate system: SIRGAS 2000, UTM Zone 23S.
Source: Authors (2024).

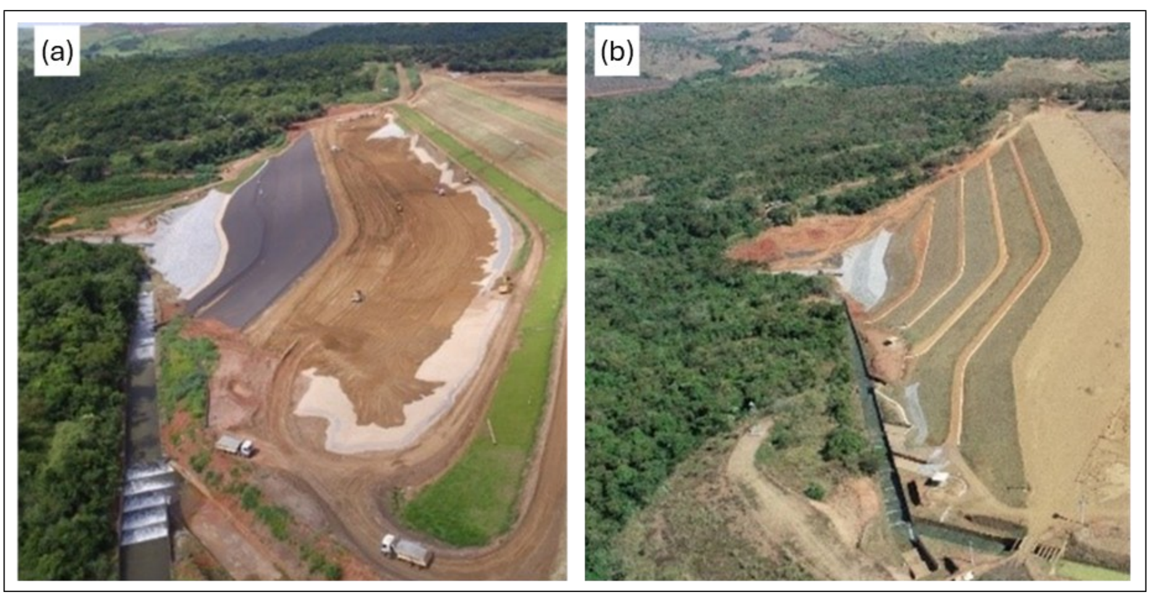

Figure 2 – Construction stages of the dam. (a) Different construction stages with application of transitional materials. (b) The final stage of the work after completion of the reinforcement.
Source: Authors (2024).

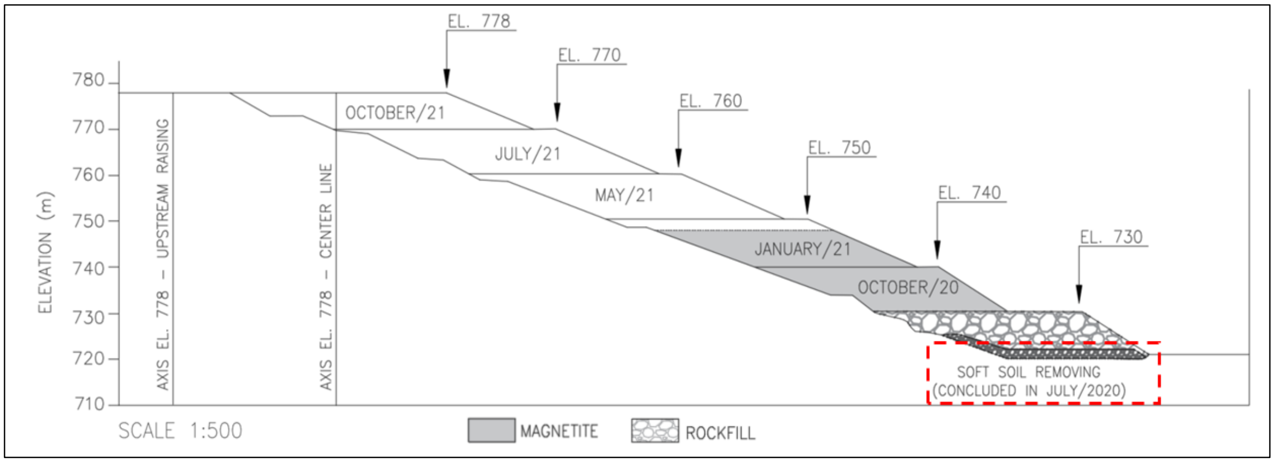

Figure 3 – Construction stages of the centerline reinforcement project.
Source: Authors (2024).

3. Material and Methods

3.1. Data Acquisition

To assess the construction safety of the dam, geophysical monitoring methods were implemented, such as electrical resistivity, microseismic, including seismic interferometry of ambient noise, and the MASW (Multichannel Analysis of Surface Waves) method. These geophysical methods were integrated with conventional monitoring techniques, which play a critical role in supporting geological and geotechnical investigations. Conventional methods, including water level indicators and piezometers, also contribute to the assessment of surface water and groundwater conditions. Figure 4 illustrates the layout of the conventional instrumentation, showing the locations of water level indicators and piezometers.

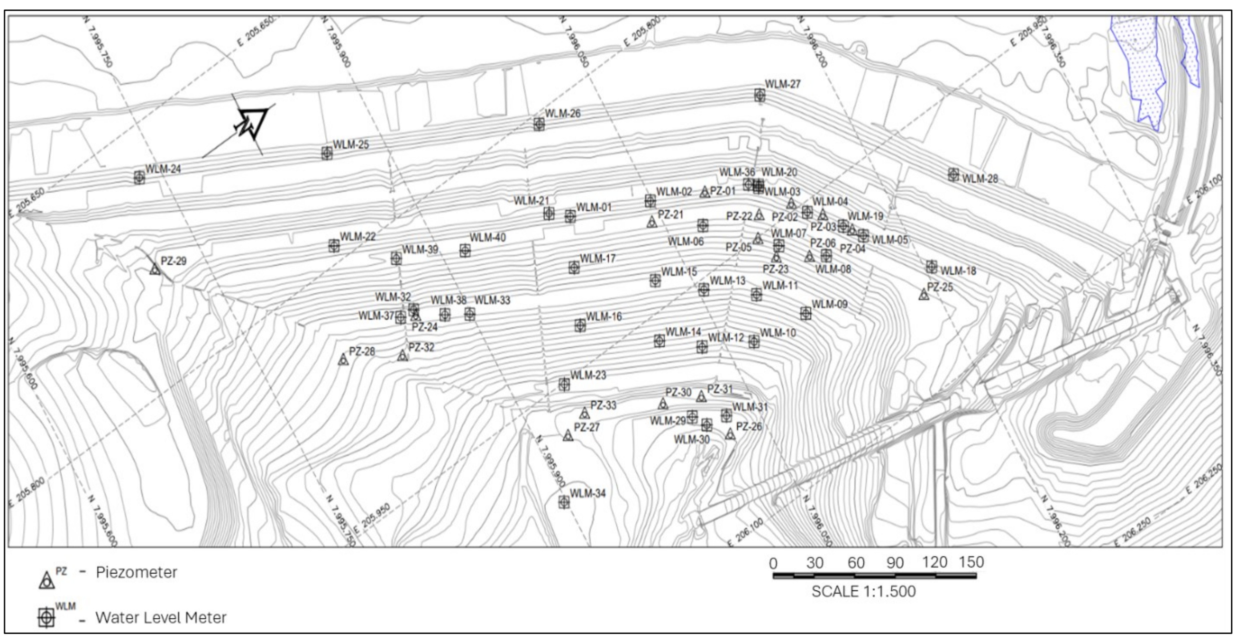

Figure 4 – Location of water level indicators (WLM) and piezometers for monitoring the dam.
Source: Authors (2024).

The electrical resistivity method is based on the injection of electrical current into the ground and the measurement of potential differences between pairs of electrodes, allowing for the determination of subsurface material resistivity (Sá et al., 2024). In 2020, a total of 23 electrical resistivity profiles were conducted using the electrical imaging method. These profiles were positioned along the dam body, the beach, and the abutments of the BR Dam, arranged parallel to the crest of the structure. A SpertSing resistivity meter was employed, configured with a 4-meter electrode spacing, a dipole-dipole array, and 84 channels, achieving investigation depths ranging from 40 to 85 meters. The results focusing on the right abutment, in the vicinity of Sites 2, 5, and 6, are presented in Figure 8. Further details are available in Sá et al. (2023).

Seismic interferometry of ambient noise allows continuous monitoring of the variation in the propagation speed of seismic waves within the massif of the monitored structures, using ambient noise as a passive source (Olivier et al., 2017; Planès et al., 2016). According to Wapenaar et al. (2010), this method refers to the principle of generating an impulse response through the cross-correlation of seismic observations at different receiver locations. This method enables real-time monitoring of the variation in the stiffness modulus of the structure through changes in shear wave velocity (VS).

It is essential to maintain the integrity of the collected records to ensure effective monitoring. Randomness in the distribution of noise sources is necessary to observe heterogeneities by comparing records at pre-established time intervals (Curtis et al., 2006). This comparison is conducted on the coda wave to assess environmental changes (Figure 5). Coda waves, due to their dispersive nature and complex travel path, are sensitive to environmental changes, making them ideal for evaluating changes in the environment within a given geological setting. This sensitivity is not observed in body waves. Consequently, seismic interferometry of ambient noise records, under the microseismic approach, captures variations in the propagation speed of seismic waves, estimated from changes in the transit time of the coda waves between the source and the receiver within the considered environment (Planès et al., 2016).

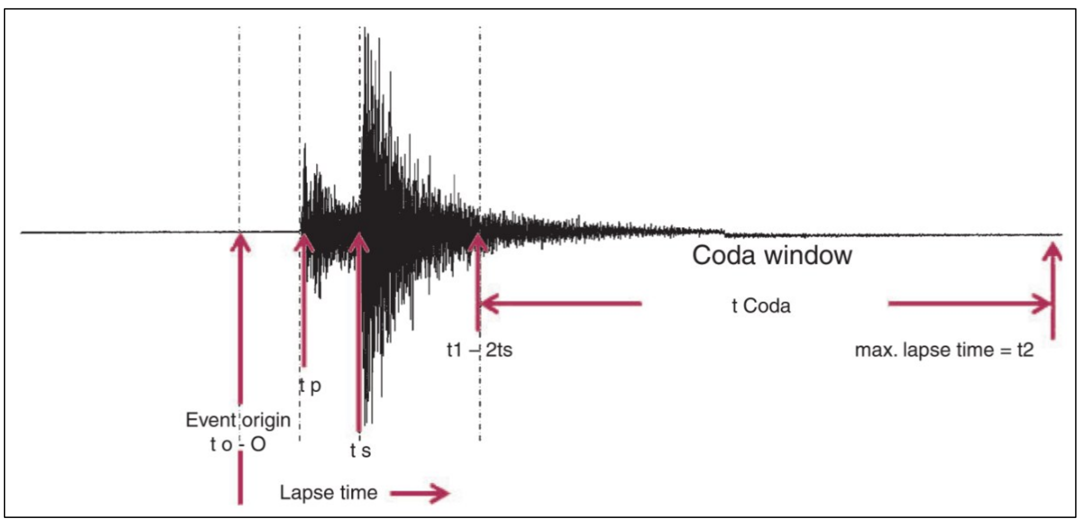

Figure 5 – Seismogram indicating the origin and arrival times of P and S waves, and the late region recorded as coda wave.
Source: Kim et al. (2017).

Seismic interferometry of ambient noise, focusing on the analysis of the coda window, effectively highlights variations in the speed of S waves, signifying changes in the medium's stiffness. According to Rodrigues et al. (2019), this method measures the seismic speed variation continuously, which is linked to material stiffness. Such stiffness is influenced by factors including changes in pore pressure, loading, fracturing, and even internal erosion.

When an increase in the arrival time of S waves is detected, it indicates a reduction in velocity and, therefore, stiffness of the material. This means that the change in velocity of the S wave is closely connected to the equation describing pure shear. As per Breton et al. (2021), the alteration in the velocity of shear waves S (Vs) is directly linked to the shear modulus (G) and the density of the medium (ρ):

$$Vs = \sqrt{\frac{G}{\rho}} \qquad (1)$$

The microseismic monitoring array was designed to cover the entire dam mass by considering its history of heightening, adaptation work, and internal drainage structures, as well as the pairing between the seismic sites. The proposed system consists of eight seismic sites, including six uniaxial seismic sites (SMGU) of 4.5 Hz installed on the dam body, and two triaxial seismic sites (SMGT) of 14 Hz, all manufactured by the Institute of Mine Seismology (IMS), located on the abutments near the contact with the natural terrain. The installation was divided into two stages. In the first stage at El. 778.00 m, seismic sites 01 to 06 were installed on the dam crest, with sites 03 to 06 being uniaxial and 01 and 02 being triaxial.

In the second stage, after completion of the adaptation phases involving the application of rock material (rockfill) at El. 730.00 m and backfill with magnetite up to El. 740.00 m, sites 07 and 08 were installed on intermediate berms, both being uniaxial (Figure 6).

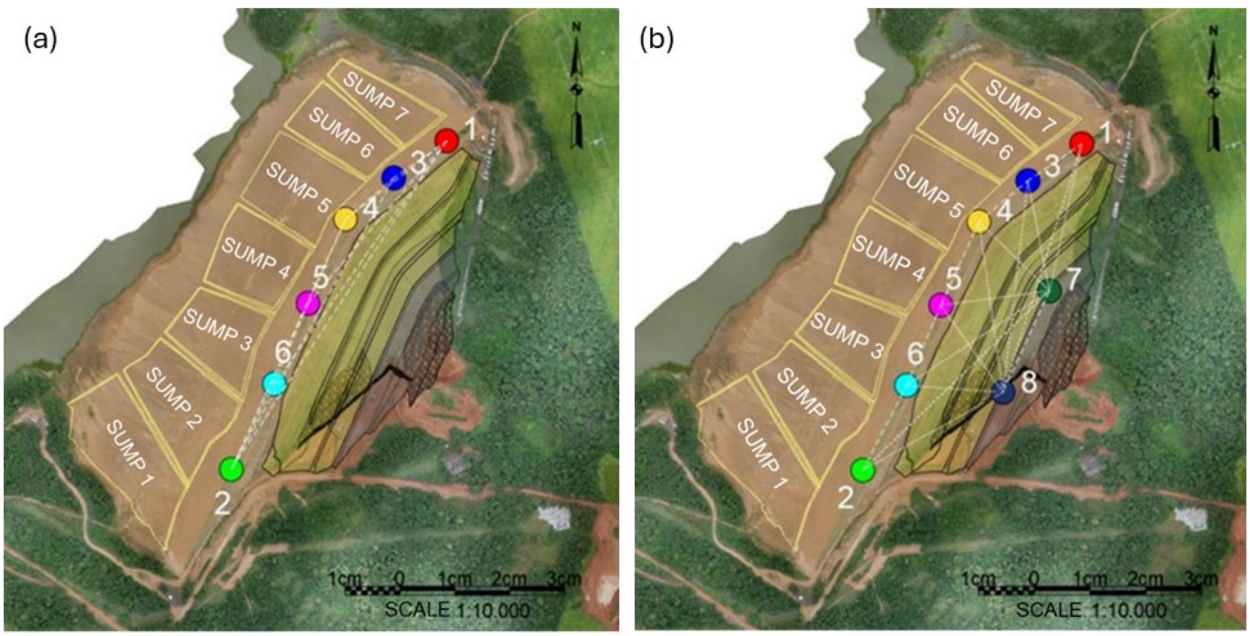

Figure 6 – Seismic sites + sumps – (a) 1st. stage (b) 2nd. stage.
Source: Authors (2024).

The MASW method, as described by Lin et al. (2004), is utilized to examine the elastic properties of soil and subsoil by analyzing surface waves, particularly Rayleigh waves. This method involves collecting seismographic data from multiple channels to record the wave propagation originating from a seismological source, such as a hammer or controlled explosive. Analyzing these waves enables the generation of essential shear velocity profiles (Vs), which are crucial for geotechnical soil characterization, identifying subsurface layers, and assessing potential zones of weakness or instability. In July 2021, four seismic sections were acquired downstream of the dam using 24 geophones spaced 5 meters apart.

The results of the S wave obtained from ambient noise monitoring and MASW were compared to validate the findings. Additionally, these results were correlated with variations observed in the monitoring instruments (WLMs and PZ).

To summarize, the seismic interferometry of ambient noise demonstrates the percentage variation in S wave velocity (Vs), while MASW provides this velocity in meters per second (m/s).

3.2. Data Interpretation

The information in this article pertains to the timeframe from October 2020 to July 2021. The analysis of ambient noise seismic interferometry data involves cross-correlating signals from various locations to calculate Green's Function, which aids in determining the velocity of seismic waves.

When interpreting the data, we considered the behavior of the S wave variation, considering several factors, such as the impact of the rainy season, the influence of spigotting, and the sequencing of reinforcement work during this period. We compared the influence of the reinforcement on the rigidity modulus of the dam and the increase or decrease in the speed of the S wave (Vs) by considering the variations in water level in the piezometers and WLMs, as well as the construction sequence of the reinforcement. This allowed us to evaluate the geophysical conditions of the structure for the analyzed period.

4. Results and Discussions

The S-wave velocity (Vs) variation data were assessed from October 2020 to July 2021 (Figure 7). Furthermore, it is possible to correlate geophysical monitoring with the interpretation of WLMs and PZs for each site, as well as with graphs of the rainy season and reservoir monitoring. WLMs 24, 25, 26, 32, 40 and PZ 29 were considered because they were located closer to sites 2, 5, and 6, which exhibited greater losses in S-wave speed (Vs), as observed in Figure 7.

Between 10/01/2020 and 07/31/2021, while the reinforcement work was being carried out on El. 770.00 m, a gradual decrease in the dv/v% curves from the interferometry readings of the six sites situated on the crest of the dam was observed. This decline continued until July 2021 (Figure 7). During this period, the tailings spiking in the sumps located on the crest of the dam were operational, aiming to dewater and dry the tailings for use in the reinforcement process. The material deposited into the sumps comprised 65% water and 35% solids.

Figure. 8 indicates the variation of the water level from the WLM from 1 to 6.89 m and the PZ with a variation of about 5 m. Additionally, the influence of the rainy season is evident, with precipitation ranging from 20 to 25 mm, peaking at 60 to 80 mm, and occasionally exceeding 100 mm.

In the central part of the massif, Site 5 experienced the most significant decrease in velocity, followed by Sites 2 and 6 on the right abutment (Figure 6). These velocity decreases amounted to approximately 11%, 10%, and 10.5%, respectively, likely due to the impact of spiking operations during the rainy season. As a result of these changes in the dv/v % curves, the spiking process was relocated to the sumps closer to the left abutment (sumps 5, 6, and 7), as depicted in Figure 6. Starting from July 2021, the dv/v % rate stabilized and showed a slight increase of around 2 to 3% until early October. Additionally, in June 2021, two more monitoring sites, 7 and 8, were introduced downstream of the dam, with Site 7 positioned near the left abutment and Site 8 near the right abutment (Figure 6).

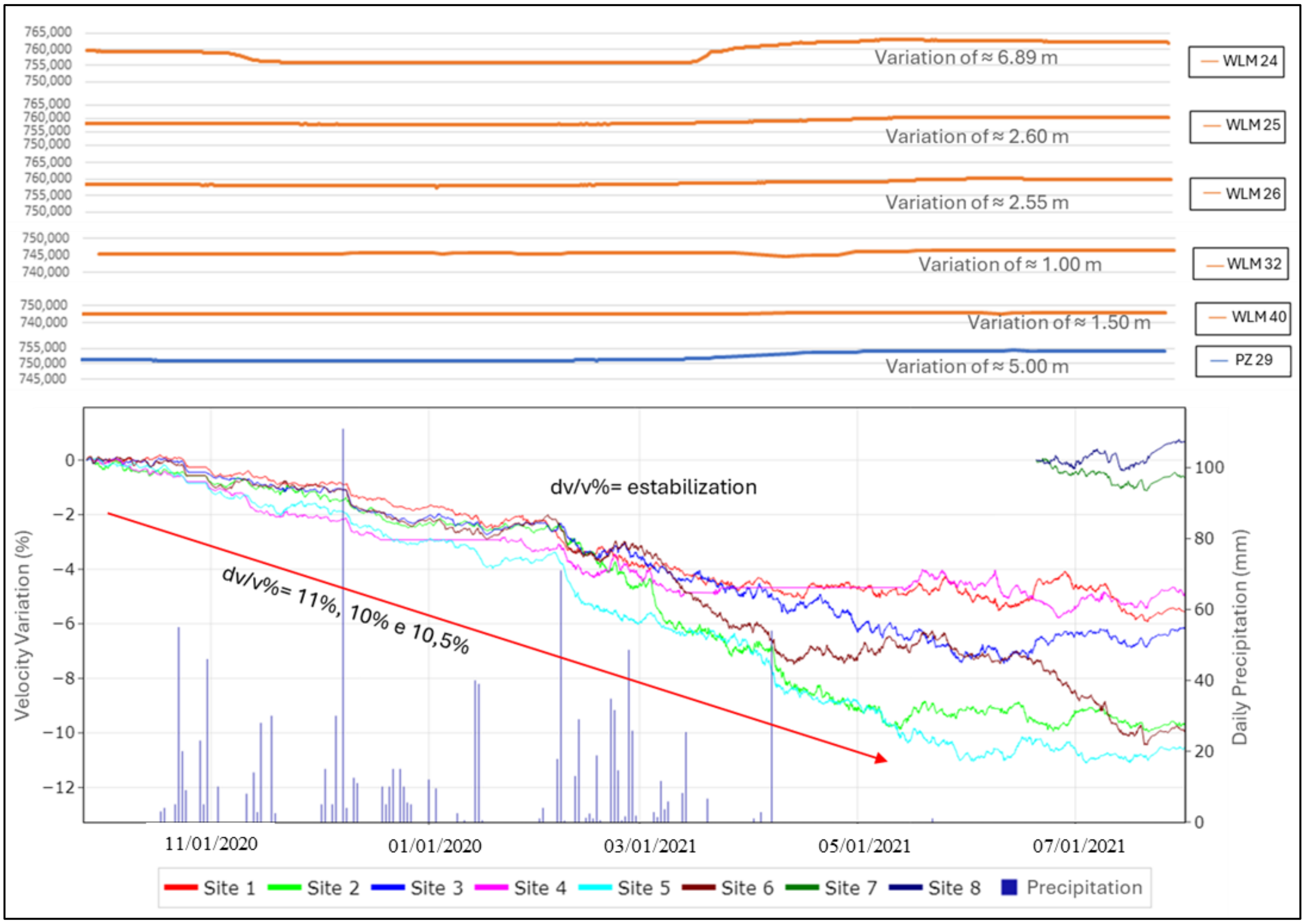

Figure 7 – Interval analyzed in the period from 10/01/2020 to 07/31/2021. The figure shows the water level variation measured by Water Level Meters (WLM) and piezometers, compared with S-wave velocity variation (dv/v%) over time and daily accumulated precipitation. The top section displays water levels measured by different WLMs (24, 25, 26, 32, 40) and piezometer PZ 29, with variations between 1.0 m and 6.89 m, indicating changes in saturation behavior. The bottom section shows the percentage variation in S-wave velocity (dv/v%) at several sites (1 to 8) over time, correlating this with precipitation (blue bars). Stabilization is observed after a significant 10% to 11% reduction in S-wave velocity, related to increased moisture. The red line highlights up to an 11% decrease in velocity.
Source: Authors (2024).

According to Sá et al. (2023), a zone of high electrical conductivity was discovered on the right abutment through electrical resistivity surveys. A noteworthy decrease in the S-wave velocity was observed in the ambient noise seismic interferometry data at sites 2, 5, and 6 in the same (Figure 8). Furthermore, the MASW analysis also confirmed a low S-wave velocity (Vs), consistent with the findings from the ambient noise seismic interferometry.

When reviewing the MASW survey conducted at the dam, anomalies with S wave (Vs) velocities below 200 m/s were observed near sites 2, 5, and 6 (Figure 9). As indicated by Sá (2023), these anomalies, situated on the right abutment near sites 2, 6, and 5, are associated with zones of high electrical conductivity LRZ (Figure 8). This corresponds with the observed behaviors at sites 2, 6, and 5, where there are no increases in the S wave (Vs) as seen in the other sites (Figure 8).

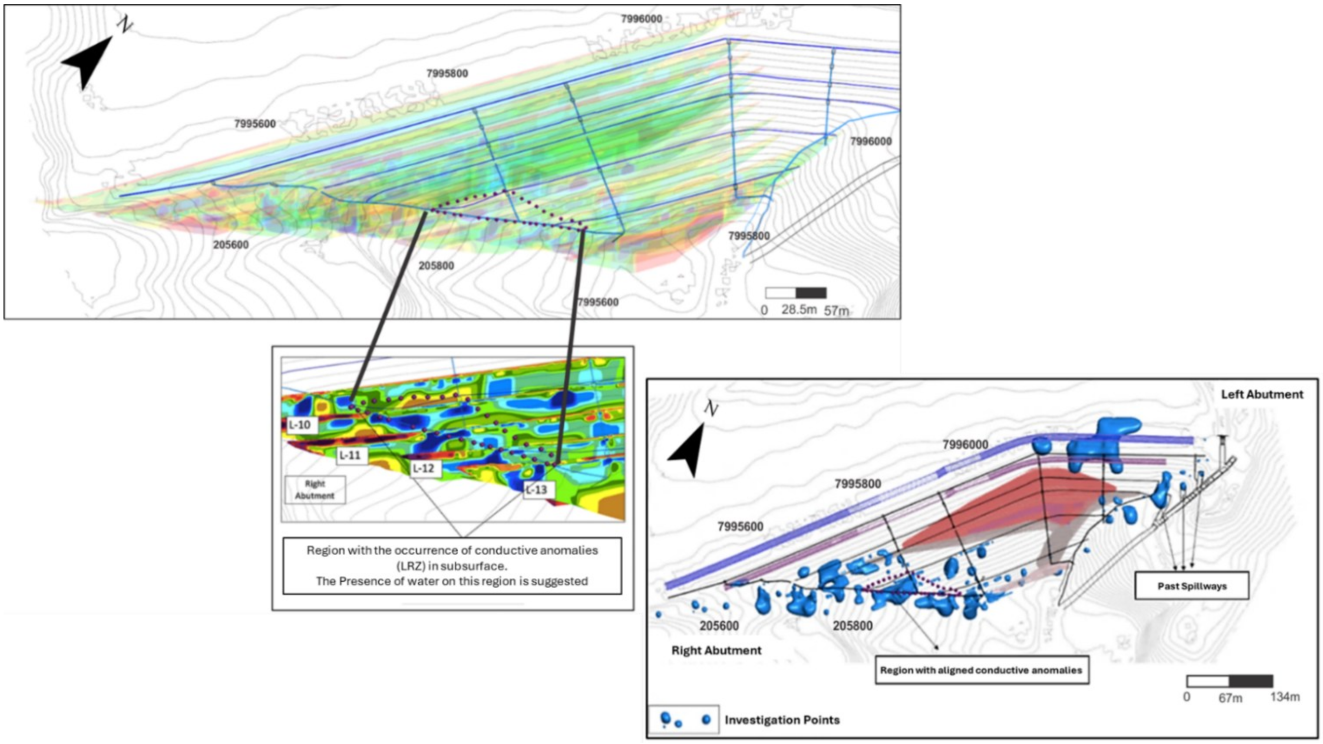

Figure 8 – Sections L-10, L-11, L-12 and L-13 in detail, showing the right abutment and the conductive anomalies in the subsurface. The blue lines represent the dam's drains. ERT dataset modeling and investigation zones, key indicators for high moisture zones.
Source: Sá et al. (2023).

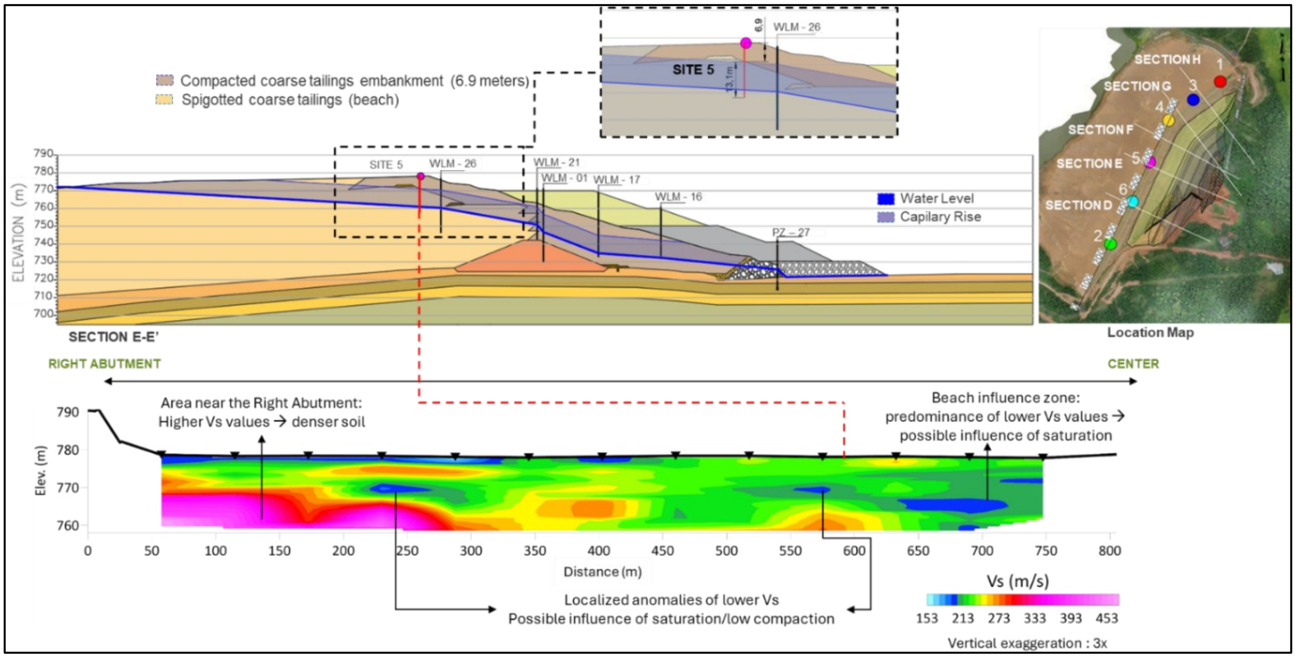

Figure 9 – Seismic survey by the MASW method, low S-wave velocities (Vs) in the right workbench.
Source: Authors (2024).

5. Final remarks

Through the application of the electrical resistivity method, a low resistivity zone (LRZ) was identified in the area of sites 2, 6, and 5, as shown in Figure 8.This phenomenon is associated with the presence of areas with high water saturation or more porous and conductive materials, which directly influences the characteristics of seismic wave propagation. This high conductivity explains the low shear wave velocity (Vs) observed in the region.

The MASW (Multichannel Analysis of Surface Waves) method also confirmed a significant loss in velocity (Figure 9). The reduction in shear wave velocity occurs due to the decreased stiffness of the material in the saturated or high-conductivity zone. This means that the material beneath the dam presents higher moisture concentration or contains less consolidated internal structures, such as fractures or weak zones, which reduce the efficiency of seismic wave propagation.

This area of high electrical conductivity is related to the increase in moisture, caused by the spigotting process in sumps 1, 2, and 3, which are used for tailings storage and drying, with the material used as part of the dam reinforcement works. This process, combined with the significant rainfall recorded during the analyzed period, had a direct impact on the S-wave velocity (Vs) readings. As a result, the sites located in this area showed reduced velocities compared to other sites, even after the sump operations were shifted to the left abutment of the dam (Figure 7).

The integration of electrical resistivity, ambient noise seismic interferometry, and MASW methods enabled the comparison of low resistivity zones (LRZ), indicating that areas with excess moisture and zones affected by operational interventions, such as tailings deposition in sumps 1, 2, and 3, may influence the stiffness modulus and the mechanical properties of the materials that compose the dam.

The water present in the material's pores affects wave propagation, reducing the soil or rock's resistance and, consequently, the shear wave velocity (Vs). This reduction in S-wave velocities represents an important geophysical indicator for identifying areas with a higher potential for structural instability, which could compromise the integrity of the dam if not properly monitored.

Following the identification of a decrease in shear wave velocity (Vs) of approximately 11%, 10%, and 10.5%, respectively (Figure 7), along with the reductions in Vs indicated by the MASW method, the decision was made to relocate the spigotting activities to the left abutment, specifically in sumps 5, 6, and 7. This operational adjustment led to a stabilization in the Vs loss observed at sites 2, 6, and 5 (Figure 7).

It is of utmost importance to continue monitoring after the reinforcement work, and the installation of sites 7 and 8 was essential for understanding and refining the information obtained about the hydrogeotechnical behavior of the dam, improving the investigation coverage. This will allow for the refinement of applied geophysical methods, providing a longer history of observed data.

After the dam reinforcement work, an increase in shear wave velocity (Vs) values was expected due to the increase in the stiffness modulus (G), which was not observed in this case study. This indicates that the decrease in shear wave velocity (Vs) is directly related to the increase in humidity in the structure's mass. Although stabilization of the S-wave velocity (Vs) was observed, followed by an increase of approximately 2 to 3%, it is essential to maintain continuous monitoring to verify these trends. Operations using spigotting processes on the crest of this type of geotechnical structure must be rigorously evaluated, instrumented, and monitored. Significant losses in S-wave velocity (Vs) should trigger action plans to ensure safer operations, minimizing risks to workers and preventing geotechnical or construction engineering issues.

Through continuous monitoring, it is possible to improve reliability and safety in future interpretations and decisions, as well as enable the construction of an integrated model that correlates geotechnical instrumentation data with geophysical monitoring data. It is important to validate and correlate the various geotechnical monitoring methods in order to improve the understanding of areas with higher moisture content. An example of this approach can be found in Sá et al. (2023), who correlated data obtained from electrical resistivity surveys with the position of the phreatic surface, as determined by INAs and PZs instrumentation. This correlation enabled the identification of low resistivity zones (LRZ).

In this context, the present paper identified reductions in shear wave velocity (Vs), obtained through ambient noise interferometry and MASW methods, associated with spigotting operations in sumps 2, 5, and 6, which correspond to the low resistivity zones mapped by Sá et al. (2023).

This model is important for validating the hydrogeotechnical behavior of mining dams, ensuring the integrity and safety of the structure.

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