Seismic site response analysis of an upstream tailings Dyke in a tectonically stable region

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ABSTRACT

Despite seismic studies in Brazil not being common in the engineering practice as Brazil is a tectonically stable continental region, recent Brazilian regulations require seismic evaluation as supporting studies for decommission and decharacterization projects. Although there exist some critical issues such as limited laboratory data because of sampler processes related to the upstream raised tailings dams, standard tailings and soil foundation characterization, in addition to the field investigation including piezocone (CPTu), seismic piezocone (S-CPTu) and geophysical surveys are the main sources for supporting the characterization of the dynamic properties of the geostructures. This paper presents a brief discussion about the main aspects concerning to the site response analysis carried out for an upstream raised tailings dam (case study), located in Minas Gerais, Brazil. Frequency domain 1-D amplification analyses were conducted by relating local-like representative seismic records and dynamic natural characteristics of the soil profiles to evaluate the seismic response of the case study. Results showed that the maximum accelerations along the profiles are greatly influenced by the presence of the soft foundation tailings layers, and the level of amplification or attenuation is strongly influenced by the tailings layer thickness as well as the frequency content of the applied ground motions. The study pointed out that the site-specific response can support the definition of the appropriate seismic parameters to be used in engineering projects in Brazil.

Keywords: decharacterization projects, site response analysis, upstream tailings dam.

1. Introduction

The accidents that occurred in recent years in tailings dams built by the upstream method in Brazil, motivated the prohibition of this constructive method, through the Resolution of the National Mining Agency (ANM) n° 4/2019. In addition to prohibiting the construction of upstream dams, the ANM resolution requires the decommissioning and decharacterization of the existing structures built by such method, as well as established deadlines for the preparation of the decharacterization projects of these structures.

The decharacterization works are a complex process, which require a project with different stages of study before proceeding with the detailed engineering project. Some of the studies focused on acquiring information to subsidize the decharacterization project are, for example: geological-geotechnical investigation campaign to characterize the various materials of the structure, from foundation, tailings, mass and raises; geotechnical analyses aimed at assessing the potentials of static and/or dynamic liquefaction; geotechnical analyses of physical stability; etc.

The current legislation (ANM Resolution n° 13/2019) presents the updates on the understanding of upstream structures, as well as decharacterized mining dams and their minimum evolutionary process of decharacterization stages. This resolution invokes the Brazilian standard NBR 13.028/2017 for seismic criteria definitions and establishes the minimum requirements for the preparation and presentation of dam projects in mining. The standard guides that, in the initial stages of the seismic studies, particularly for pseudo-static stability analyses, the criteria proposed by the Canadian Dam Association (CDA) (updated in 2013) should be adopted, which, for initial screening, suggests the use of seismic acceleration (g) related to return periods when using the probabilistic approach or to the Maximum Credible Earthquake (MCE) by the deterministic approach, depending on the classification of the consequences of the structure. The deterministic Seismic Hazard Analysis (DSHA) is applicable in some areas, but not in the case of regions of low seismicity or that present diffuse seismology, as is the case of Brazil (Martinez et al., 2019). Due to this deficiency and lack of detail in the aspects related to seismicity, NBR 13028/2017 is under revision as informed by the Brazilian Mining Institute (IBRAM) in October 2022.

The seismic activity in Brazil is active and notoriously low, which can be explained by the fact that Brazil is located in the interior of a very extensive tectonic plate that includes edges of cratons and sedimentary basins (Assumpção et al., 2014), therefore far from its active edges, where earthquakes are numerous, large and very hazardous, such as in Chile and Peru. However, many intraplate regions such as Brazil also have potential for high magnitude seismic events with potential for great destruction. Some happen where there was no history of important earthquakes or even no current seismicity.

In this sense, it is important that a local seismic evaluation be included in the projects of the structures of impact for the population, such as the containment or stacking structures of tailings, an uncommon practice. According to Assumpção et al (2014), the seismic hazard in Brazil is low, but not null. In all of Brazil, it is believed that two earthquakes of magnitude 6.0 or greater occur per century. A study of 300 earthquakes in the USA between 1958 and 1977 showed that the smallest earthquakes that produced landslides had local magnitudes of about 4.0 (Keefer, 1984).

Due to the lack of practice in conducting seismic studies in Brazil, several dams have a scarcity of geotechnical information necessary for the elaboration of a local seismic study, for example: lack of shear wave velocity (Vs) measurements, few data on the temporal history of local seismic events, lack of dynamic tests for damping and shear modulus characterization, which have a direct relationship with the level of shear deformations of the material.

This paper describes the interpretations and limitations of the geotechnical and seismic data, which supported the elaboration of a local seismic study, developed for an upstream tailings dam (dyke), located in the state of Minas Gerais, in addition to presenting the development of peak ground accelerations (PGA) along the studied soil profiles.

The main contribution of this paper is to inspect the development of the PGA along an analysis column, and to verify the influence of the seismic demand and the dynamic characteristics of the materials that make up the profiles.

2. Description of the case study

The case study consists of a 20 m-high structure comprised of a starter dyke and three upstream raises, as shown in Figure 1.

The structure was built inside the reservoir of a tailings containment dyke, to serve as a topographic saddle dyke and, consequently, increase the storage capacity of the reservoir. Due to this condition, the dyke was built over a thick layer of tailings. No information reaching the natural ground is available.

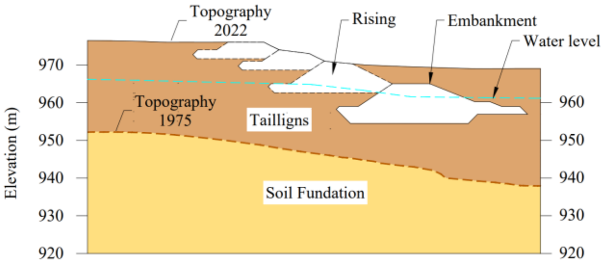


Figure 1 Typical section of the structure.

3. Existing Information and complementary geotechnical investigations

To perform the Site Response Analysis (SRA) it is necessary to understand the geotechnical characteristics and the thicknesses of the material layers of the soil profile columns that will be analyzed.

Prior to the beginning of the study, investigation campaigns had already been carried out in the region of the structure, comprising mixed Drillhole (DH), Piezocone (CPT) and Seismic Piezocone (S-CPT) tests, mainly with the purpose of characterizing the foundation tailings. However, the existing investigations did not allow to determine reliably what the real thickness of foundation tailings was, much less the depth of the rocky basement around the structure.

In addition to the existing soundings, there is a primitive topography from 1975 that covers the region of the structure, which allows an initial estimate of the tailings thickness in the region. However, as it is a very old topography and carried out by aerial survey, it may present discrepancies and is not accurate.

Currently, there are several decharacterization projects of upstream dams under development in Brazil. Frequently, these projects require complementary information, which must be obtained through geotechnical investigations. One of the major concerns of the geotechnical community is the risk of the complementary investigations causing a trigger that leads to the rupture of a dam. Recently, the ANM informed that it is not allowable to use a percussion system with water circulation (washing) and use of water and/or any types of fluids for the soundings inside the tailings reservoir. Due to these restrictions and aiming to minimize the inherent risks of the complementary campaigns, alternative investigations and sounding methodologies were used. Indirect tests, such as the geophysics of the MASW (Multichannel Analysis of Surface Waves) or MAM (Microtremor array method) type, have become attractive alternatives due to being minimally invasive, and for providing a quick and low-cost response.

For the SRA discussed in this paper, a complementary investigation plan was carried out containing geological-geotechnical investigations (sample collection and laboratory tests), prospecting tests (mixed drilling) and geophysical tests of the MASW (2D) and MAM (1D) type to better understand the stratigraphy and characteristics of the foundation materials and structure. The investigations were used to define the thicknesses, geotechnical parameters, reference curve of shear modulus reduction and damping and shear wave velocities (Vs) of the layers of the analysis profiles. Figure 2 show the existing investigations and the investigations completed for this study.

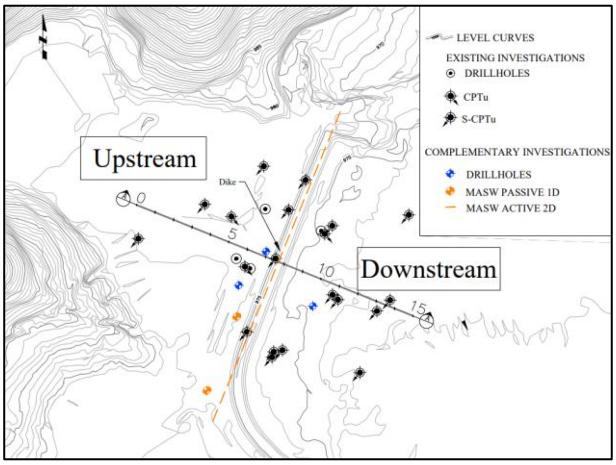


Figure 2 Geotechnical and geophysical investigations

Considering the limitations for the execution of complementary mixed drillholes, the few drillholes performed were intended to improve the understanding of the foundation tailings layer thickness and the depth of the bedrock. It is important to mention that in accordance with the ANM guidance, no Standard Penetration Tests (SPT) were performed on the reservoir tailings and the minimum amount of water was used, only for circulation and cooling of the dill bit.

The geophysical tests MASW and MAM, in turn, were strategically chosen to assist in the definition of the thicknesses of the most superficial layers and, mainly, for the definition of the (Vs).

4. Seismic Hazard

4.1. Limitation of the Brazilian seismic events records

The earthquake time-history records were selected from the acceleration database of the Pacific Earthquake Engineering Research Center (PEER, 2018). This occurred due to the limitations of the seismic record data in the region of Brazil.

Prior to the SRA being carried out for the case study, a site-specific Probabilistic Seismic Hazard Analysis (PSHA) was prepared, where uniform hazard spectra (UHS) were calculated, for Site Class A (NBR 15421), for different return periods (TR) including 500, 2,500 and 10,000 years. The UHS and the seismic hazard deaggregation results were used as a reference for the seismic records selection that were used in the SRA.

From the analysis of the deaggregation of the results obtained in the PSHA, it was possible to verify that the average moment magnitude (Mw) values, which are associated with the return periods equal to and above 500 years, are above 5.0. According to (Assumpção et al, 2016), in Brazil, an earthquake of magnitude 5.0 occurs every five years, on average and these occur in areas of thinner lithosphere, under the occurrence of flexural stresses (Figure 3). In the Andean region, earthquakes of magnitude 5.0 occur on average twice a week.

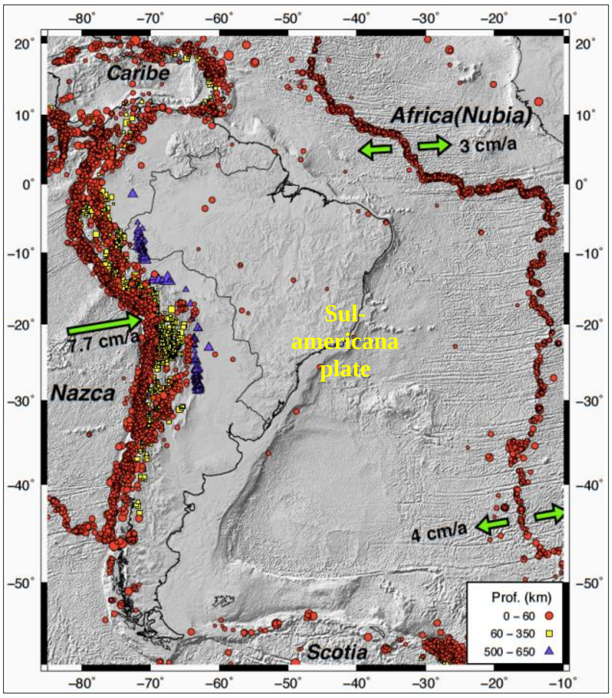


Figure 3 Seismicity of the South American Plate. Earthquakes from the ISC (International Seismological Centre, UK) EHB catalog with magnitudes ≥ 4.7. Red circles are shallow earthquakes (focal depth < 60 km), yellow squares are intermediate, and blue triangles are earthquakes between 500 and 650 km deep. Green arrows show the relative movement of the Nazca Plate and the movement of the African plate at the mid-ocean ridge. (Assumpção, 2016).

The Brazilian seismic catalog has data on events since 1720. According to Assumpção (2016), throughout Brazil, it is believed that two earthquakes of magnitude 6.0 or greater occur per century. On the other hand, as can be seen in Figure 4, earthquakes of lower magnitudes are not uncommon. Many earthquakes occur in Brazil without being detected because they are small or because they occur in uninhabited regions (Assumpção, 2016). Still in Figure 4, the regions with the highest population density, such as the southeast, seem to be more active, however this condition would be linked to the fact that the region has a larger number of seismographic stations and because they have been operating for longer.

Due to the scarcity of records of events with magnitude above 5.0 in Brazil, the NGA-West2 database of shallow earthquakes in active tectonic regions was used due to the similarity with the context of Brazil.

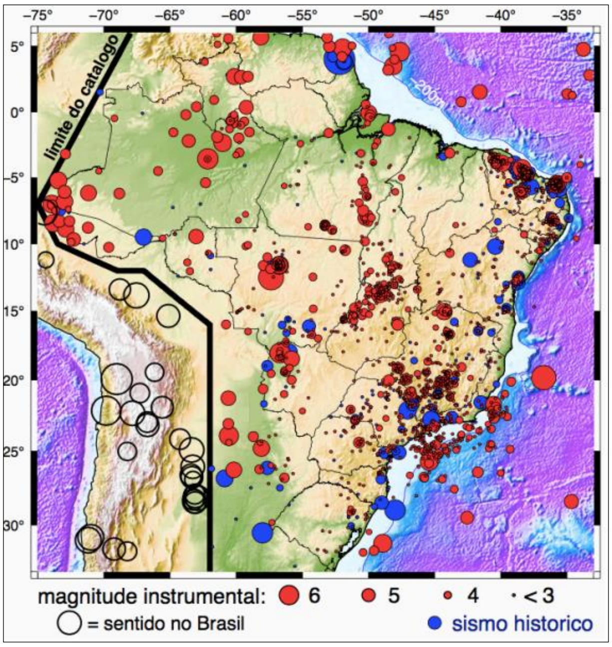


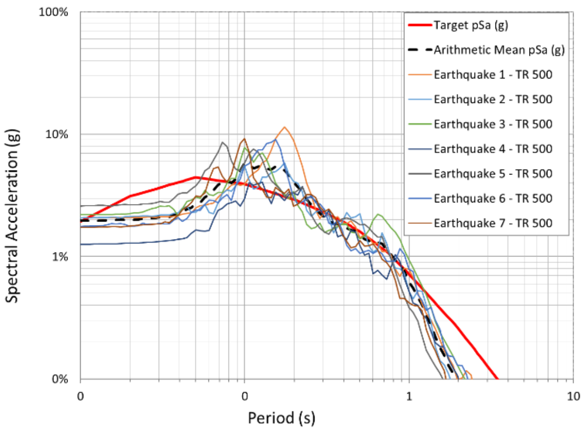
Figure 4 Brazilian Seismic Map, Brazilian Seismic Catalog - 1720 to 2016 (Assumpção, 2016)

4.2. Selection of time-history events

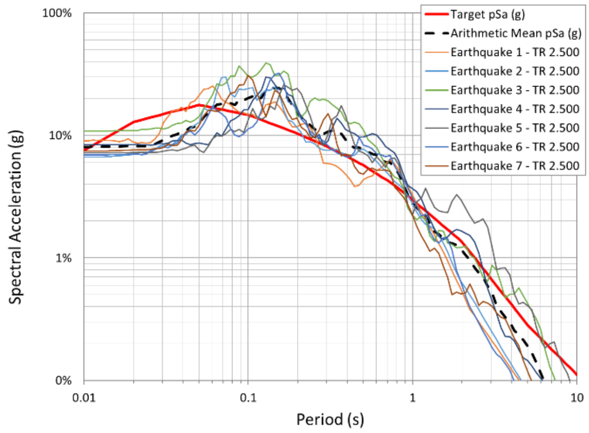
Twenty-one events (seven for each return period) were selected that have acceleration response spectra similar to those of the UHS of the respective periods, as well as magnitude, intensity, duration and site class. All events were applied as outcropping motions at the base of the columns as an elastic half-space.

4.3. Event scaling

The recorded events of the selected seismic records were scaled in the time domain (uniform scaling) to determine an average response spectrum that approximated the UHS results from the seismic hazard analysis. Figure 5 shows the response spectra of the events for each of the return periods, in addition to the reference UHS spectrum. As can be observed, a reasonable average response spectrum was achieved mainly in the structural periods of interest of the structure (defined in the range of 0.2 to 1 s).



(a)



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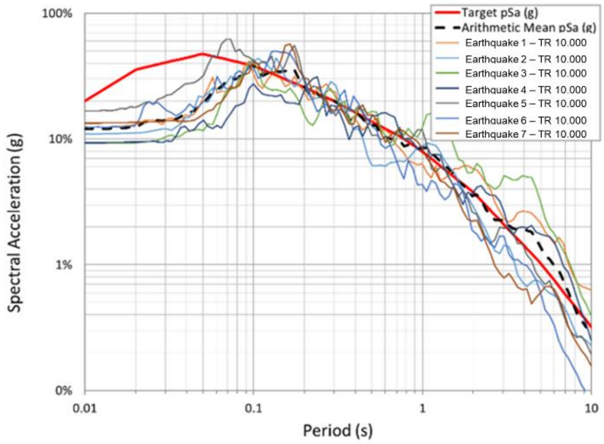

(c)

Figure 5 Time-history records of earthquakes scaled for a UHS for a return period of a) 500 years, b) 2,500 years and c) 10,000 years.

5. Site Response Analyses (SRA)

5.1. Methodology

The Site Response Analysis was developed in one dimension (1D) in the frequency domain by using the equivalent linear method (ELM). In the equivalent linear approach, in the frequency domain, the slope of the hysteresis loop represents the secant shear modulus G, while the loop area is proportional to the energy dissipated in the cycle by the hysteretic damping ξ (Figure 6).

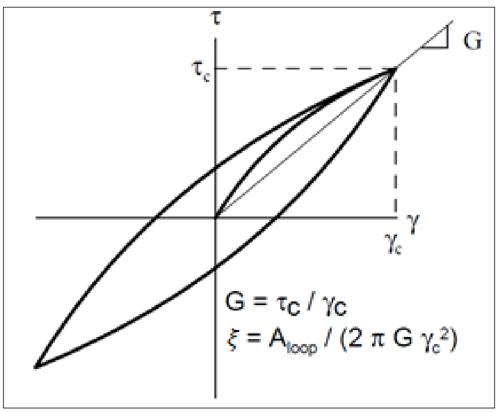

Figure 6 Hysteresis loop in soil under cyclic shear illustrating the secant modulus G and the hysteretic damping factor ξ (Kramer, 1996¨)

The main advantage of the equivalent linear model is the ease of use and the need to specify few parameters for the characterization of the soil layers. Modulus G and damping vary with strain using the modulus reduction and damping curves and there is an iteration procedure used in this method that allows variation of G and damping throughout the column.

The SRA followed the sequence outlined below:

- Selection of a cross section.
- Determination of two analysis columns.
- Select and prepare the time-history records that represent the local seismic hazard (PSHA).
- Determination of geotechnical and seismic parameters, such as: Shear wave velocity, damping curves etc.
- Development of the response analysis.

5.2. Section and analyzed columns

A cross section was selected in the central region of the dyke and two analysis columns were selected: Column 01, positioned at the crest of the third dyke raise; Column 02, located at the toe of the structure. The two columns were used to present the seismic responses considering different positions and conditions of the materials, representative of the structure. Figure 7 shows the section selected and columns analyzed.

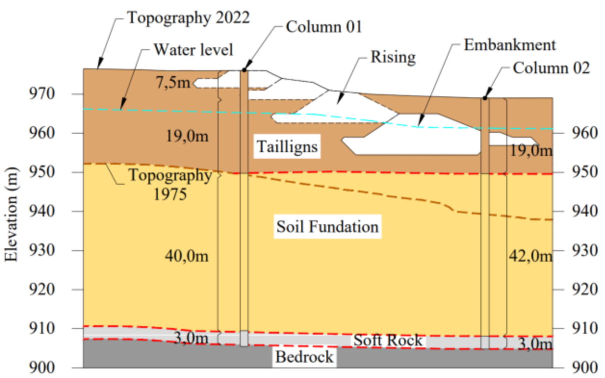

Figure 7 Cross section with columns positions.

5.3. Definition of layers and geotechnical parameters

To complete the SRA, it is necessary to define the stratigraphic profile of the analysis columns that will be evaluated, as well as the reference curves of reduction of the shear modulus and damping that will be used as well as the shear wave velocities in each layer.

5.3.1. Thickness of the layers

Columns 01 and 02 (Figure 11 and Figure 12) are composed of layers of tailings, natural soil, soft rock and bedrock. As described in Section 2, the existing geotechnical information did not allow the definition of the layers of the columns. Despite the existence of S-CPTu and CPTu tests, which together with the 1975 topography, indicated the possible contact between the natural terrain and the foundation tailings, this information was not enough due to the lack of direct investigations to confirm these contacts.

After carrying out the complementary mixed drillings, it was possible to verify that the thickness of foundation tailings in the region beneath the dyke crest is consistent with the 1975 topography and with the change of behavior presented in the penetration tests. However, in the region of the toe of the dam, the complementary drilling indicated that the layer of tailings is smaller than that indicated by the 1975 topography.

The Figure 8 shows the information evaluated to define the thickness of the layers.

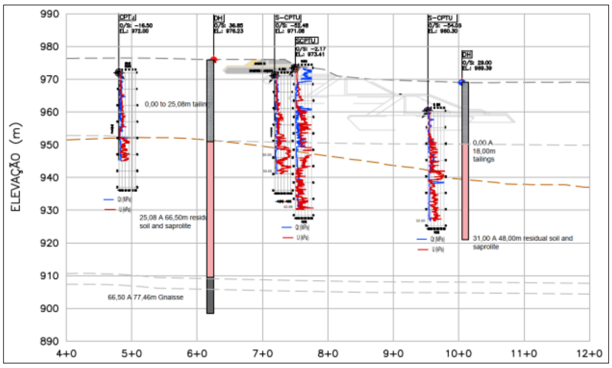

Figure 8 Section Analyzed with interpretation of layer thicknesses.

5.3.2. Damping curves

Reference curves from literature for the shear modulus and damping were used, based on the geotechnical characteristics of each material (see Table 1).

Table 1 Dynamic properties curves

Layer	Unit Weight (kN/m³)	Reference curve
Tailings	22,0	Winckler (2014)
Natural soil	19,0	Darendeli (2001)
Soft rock	20,0	Silva et al. (1996),
Bedrock	23,0	-

The literature review shows that there are no published dynamic tests available to characterize the damping and shear modulus of the iron ore tailings found in most of the Brazilian decommissioning projects. Therefore, the curves of reduction of shear modulus and damping of Winckler (2014) were adopted. The curves were obtained from a database of resonant column and torsional shear tests performed on copper tailings samples. To use the curves of Winckler (2014) the only parameters required, in addition to the curves, are the unit weights of the material. The tailings unit weight was defined by the CPTu, using the Robertson (2010) methodology as shown in Figure 9.

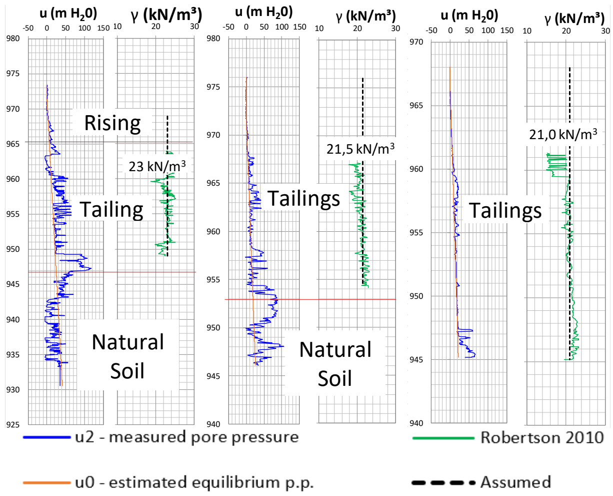

Figure 9 Behavior of the tailings based on cone penetration test

The curves of reduction of the shear modulus and damping used for the natural soil layers, were defined based on the analysis of the characterization tests of the complementary drillings carried out. A summary of the results is presented in Table 2 including the Unified Soil Classification System (USCS) classification and material plasticity. The unit weight (Table 1) was estimated by correlation of the physical indices.

Table 2 Laboratory results for the natural soils

Column	Granulometry (%)				Atterberg limits (%)		USCS
	Clay	Silt	Sand	Gravel	LL	LP	
01	5.4	61.6	32,8	0.2	52.0	NP	MH
02	4.0	55.3	39,9	0.7	37.6	NP	ML
03	1.7	63.4	34,9	0.1	37.3	NP	ML
04	10.2	52.7	36,2	0.9	31.7	NP	ML

Finally, according to the material characteristics, the curves of reduction of shear modulus and damping proposed by Darendeli (2001) were adopted.

In general, the influence of the soft rock basement on the response analyses is not significant, however, in the case of the present study, it was necessary to add it to take into account the thickness of this layer before reaching the bedrock.

The dynamic behavior of the soft rock basement was represented by the curves of reduction of the shear modulus and damping of Silva et al. (1996). The curves of these authors were obtained from a database of 20 resonant column (RC, resonant column test) tests performed on argillite, sandstone, and limestone rock samples.

The thickness of bedrock is considered in the analysis as the base of the analysis columns. For the purposes of the response analyses, this material was simulated as an elastic medium (Elastic Half-space) because the earthquake records used are specified as "outcrop motions".

5.3.3. Shear wave velocity (Vs)

To define the shear wave velocities of each layer, the results of the seismic tests (S-CPTu, MASW and MAM) and data from the table of terrain classes of NBR 15421/2006 were analyzed. Table 3 shows a summary of the Vs used.

Table 3 Shear wave velocity

Layer	Vs (m/s)	Reference curve
Tailings	Exponential Function	Winckler (2014)
Natural soil	450	Darendeli (2001)
Soft rock	760	Silva et al. (1996)
Bedrock	1500	-

For material used for the raisings, the average of the velocities recorded in the MASW 2D tests performed was adopted. For the tailings layers, a trend of increasing velocity with depth was defined, prioritizing the information from the S-CPTu tests.

For the natural soil that precedes the bedrock, velocities between 320 and 550 m/s (layers of residual soil and saprolite) were verified in the MASW tests. A constant velocity of 450 m/s was adopted for the entire layer, consistent with the terrain class "C", Altered Rock or Very Rigid Soil, from the table of terrain classes of NBR15421/2006.

For the bedrock, the MAM (passive) test recorded an increase in velocity (approximately 1,200 m/s) after the saprolite layer. In this way, a shear wave velocity of 760 m/s was inferred for the transition layer (altered rock) and velocities referring to terrain class A from NBR15421/2006, sound rock, 1,500 m/s were considered for the bedrock.

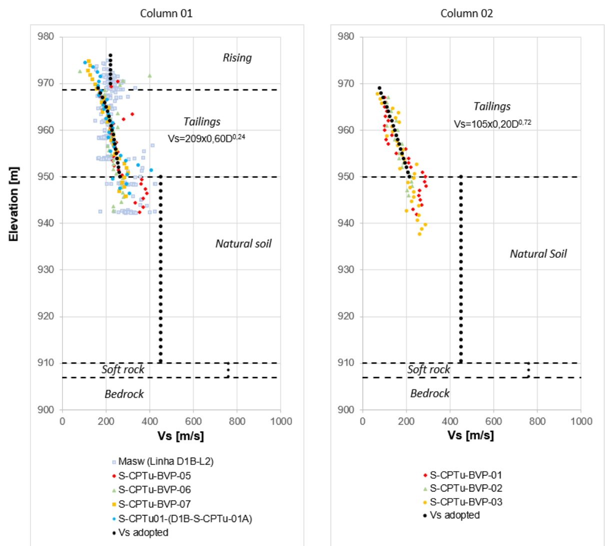

Figure 10 Shear wave velocity evaluated.

5.4. Results

The SRA calculates how the time-history records propagate, in depth to the surface, for the condition of the structure's site and whether they are amplified or attenuated along the soil profiles.

For the realization of the analyses, the software DeepSoil, Version 7.0 (Hashash et al., 2020), was used, where the layers of each soil column are inserted into the program manually. DeepSoil is a program that performs different types of seismic response analysis in one dimension (1D), among them, the equivalent linear type. For each layer, a name, thickness, unit weight and shear wave velocity (Vs) were defined. Subsequently, the modulus reduction and damping curves to be applied in the different horizons are defined.

As the objective of this study was to verify the influence of the earthquakes on the weakest layer, which in this case is the tailings, it was decided to discretize this layer meter by meter to assess more clearly the seismic responses in this layer.

The amplification of acceleration along the columns is presented in Figure 11 and Figure 12.

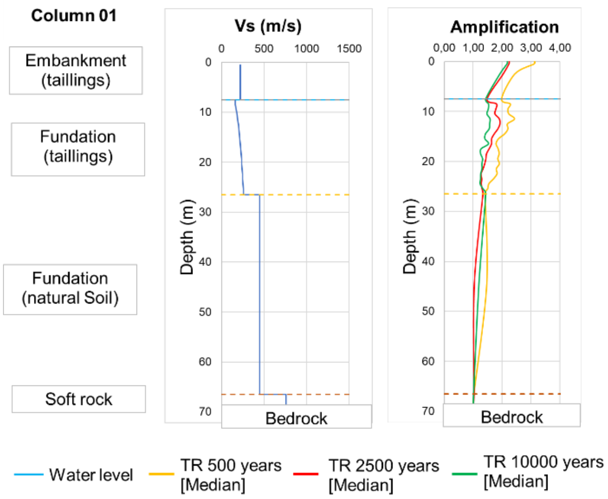

Figure 11 Column 01 - Amplification result

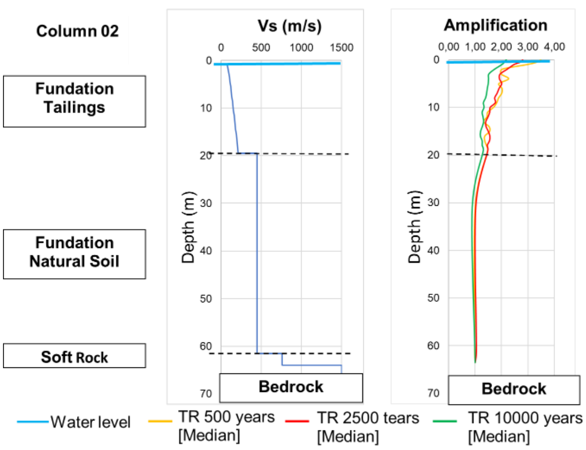

Figure 12 Column 02 - Amplification result

It can be observed that the amplifications presented at the top of the bedrock and the foundation layer in natural soil are very low. On the other hand, the amplifications in the tailings layer tend to increase from the base to the surface.

It can be seen in Figure 11 and Figure 12 that the higher return periods present the lowest amplifications. Accelerations for shorter return periods can amplify more than accelerations associated with longer periods, especially in places with low strength/stiffness soils. This fact can be explained, for example, by the greater degradation of material stiffness in inputs of higher amplitude, with consequent damping reduction.

6. Conclusion

A literature review shows that there are no published dynamic tests available to characterize the damping and shear modulus of the iron ore tailings found in Brazilian decommissioning projects. As most of these projects are in the Iron Quadrangle (Minas Gerais), the tailings are unique, presenting high iron content (ferrous) that gives the tailings a high unit weight of 24 kN/m^3 - 26 kN/m^3. Due to these particularities, dynamic tests are necessary. For screening analysis, the curves of Winckler (2014), defined for copper tailings, were initially considered.

As described in Section 4, due to the small amount of data on the history of seismic events in Brazil, seismic events from other stable regions (for example, Canada and Australia) were considered. However, it should be noted that each seismic event has its own characteristics of frequency, amplitude, etc., which directly impact the result of the seismic response.

For the response analysis, it is necessary to determine the thickness of the layers, shear wave velocities and damping curves up to the base layer used in the PSHA (site class A – Rock, for this study). As discussed in Section 3 before the beginning of the response study, there was not enough information to make these definitions. Normally, the upstream raised dams, especially the oldest ones, in the decommissioning phase do not have sufficient geotechnical investigation data for the elaboration of a local seismic response study.

The SRA showed that the tailings layers showed the greatest seismic responses (amplification), which can be justified by being the weakest/softest layers, which have a considerable thickness. This condition accentuates the need to expand the studies to characterize the damping curves of these layers.

The high amplification rates presented highlight the importance of site-specific seismic studies to determine seismic parameters for dam analyses.

For high levels of deformation, non-linear analyses with the application of numerical methods that incorporate elastoplastic constitutive models specific for the representation of the cyclic behavior of soils should be considered.

Acknowledgements

The authors are grateful for the technical support provided by Geotechnical Engineers Joseph Quinn and Jackeline Huertas in the review of this paper.

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