METHODOLOGY FOR AUTOMATED MONITORING OF INDUCED VIBRATIONS IN TAILINGS DAMS BUILT UPSTREAM

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ABSTRACT:
Induced vibrations in tailings dams in Brazil became subject to studies after two major accidents in upstream-built structures. These ground vibrations may be responsible for liquefaction triggers and that motivated the development of this paper, which consists in the presentation of a methodology to perform homogeneous vibration monitoring tests along the entire embankment with an initial offline stage that later progressed to an automated process that represents the core object of the paper. Data collected from the initial monitoring enabled analyses of dam stability when correlating vibration levels in the embankment. As a consequence of such analyses, it was possible to parameterize control levels associated to safety criteria. Monitoring methodology, analysis techniques and gains resulting from the use of automated monitoring systems are presented herein. Parameterized control levels regarding the structure under study as well as their association to the stability condition, analysis of liquefaction trigger set for vibration values, advanced analysis of seismographic records and an automated operational vibration control system from monitoring using seismographic stations are shown. The implementation of the automated monitoring system associated to safety control levels allowed a robust diagnosis of eventual structural damages caused by vibrations in dams. That methodology was applied to a dam in operation and permitted evaluation of operation continuity concerning industrial plants and different operations with earthworks equipment on the embankment and its surrounding area.

Keywords: Dam automation; Induced vibration in dams; Wave routing; Seismography; Tailings dams; Liquefaction trigger

1. INTRODUCTION

Induced vibration monitoring was not a part of the systemic practice of auscultation to check structural damages to tailings dams in Brazil. That concept changed after the accidents of Fundão Dam in 2015 (Carmo et al., 2017; Queiroz et al., 2018) and Brumadinho in 2019 (Petley and Monticelli, 2020), when the dynamic liquefaction (Gu et al., 1993; Zhang and Chun-He, 2006; Fuyou et al., 2012) started to be seen as a possibility together with static liquefaction (Kramer e Seed, 1988; Fourie et al., 2001) as a possible cause of dam failure, which is regarded by the Brazilian mining sector as having maximum relevance due to the severity of environmental, social and economic damages, but mainly due to the number of human losses.

Therefore, monitoring the methodologies and controlling induced vibrations on tailings dams, especially the ones built through the upstream method, which is the scope of this paper, as well as better understanding the impact and the influence of the vibrating waves from operational activities (beneficenct plants and civil works on the embankment) on the stability of existing geotechnical structures is extremely necessary.

Within the context of researches using automated seismographic monitoring in dams, the focus is concentrated on events generated by mining and plant operations and blasting with a highlight on concrete embankment monitoring (Fuhr and Huston, 1993; Darbre and Proulx, 2002; Oliveira and Câmara, 2012).

Studies with characteristics and objectives that are similar to the ones herein are still scarce in the literature. The focus of this paper is to propose a monitoring methodology for induced vibrations resulting from blasting, traffic of large-size equipment and industrial plants, and to evaluate its relationship with the potential for liquefaction of tailings dams. That monitoring methodology may potentially be applied once there are currently about 80 dams undergoing the decommissioning process in Brazil (Sousa and Gomes, 2018).

Monitoring in the dam under study was performed in two different ways (offline and automated). The first one aimed at characterizing induced vibrations generated by mining operations (blasting), the plant and material handling systems using conveyor belts as well as at defining ground vibration limits at the dam using geotechnical safety criteria established in pseudo-static analyses of the locations for automated monitoring. The second worked towards the measurement protocol and online data transmissions to enable studies, analyses and ongoing decision making.

In what refers to large structures, Pereira (2018) states that it is an advantage to use digital equipment in the monitoring routine along the entire extension of the dam and that continuous monitoring is crucial for decision making. Automation routines also have to be developed for data collection and analysis.
Likewise natural earthquakes, induced seisms and other sources of vibration have to be analyzed once they may affect the stability of the structures. In regards to blasting, the possibility of damages depends on the strategies and techniques used to handle explosives, once there are methodologies to control and minimize vibrations to avoid possible liquefaction triggers. Naturally predictable systems that involve automated monitoring with robust wave propagation analysis software in areas that represent surrounding geological features and on the embankment itself have to be implemented.

This paper proposes a monitoring methodology and vibration analyses by means of automated seismographic stations in strategic sections of the pilot dam having the instrument called engineering seismograph as the main component. It is important to say that monitoring is homogeneous, that is, “automated” stations were used throughout the dam. The functions of automated seismographic stations, measurement sensors (geophones), measured magnitudes and data transmission are also described.

2. METHODOLOGY

Figure 1 tables a summary of the methodology used, which will be detailed below.

Figure 1 - Methodology Flow.

2.1 Vibration monitoring

Monitoring vibration waves through the ground aims at characterizing their intensity and also at evaluating its possible impact on the stability of geotechnical structures (tailings dam) in regards to the transit or the propagation of vibrational waves induced by mobile operational sources, mechanic excavations or blastings (Dowding, 1985; Gupta et al., 2003; Nateghi, 2011), which produce undesirable effects such as: ground vibration, acoustic pressure, dust, etc. (Tripathy et al., 2016). The objective of this paper was to study the impact of vibration waves induced in a tailings dam and their potential to generate excessive poropressure (Tian-song et al., 1983; Charlie and Lewis, 2001; Charlie et al., 2013.).

Seismographic monitoring consists in characterizing the elements of a wave using engineering seismographs, which have two measurement sensors that capture wave propagation through air and ground. Geophone sensor is responsible for monitoring vibration waves and it considers land as an elastic medium that propates waves according their variation and velocity (Figure 2).

Figure 2 - Ground measurement sensors – Geophones.

Geophones are extremely sensitive and they have to be calibrated and certified at least once a year. They allow for the individual measurement of particle velocities (mm/s) and their frequency (Hz) as well as for some calculations such as vectorial resultant (mm/s), acceleration (g) and particle displacements (mm).

When it is impossible to simultaneously send data, the equipment stores them and retransmits them soon after. They may have different frequency variations so as to comply with standards in each country or area. In Brazil, for example, they have to comply with standard ABNT NBR 9653/2018, which defines that frequencies must be between 2 and 250 Hz (ISEE) and between 1 and 315 Hz (DIN).
Standard processing capacity is 1024 samples per second for each channel with options of 2048 or 4096 samples per channel. Data records start once PPV = 0.127 mm/s is triggered and may reach up to PPV (Peak Particle Velocity) = 254 mm/s with a 0.0159 mm/s resolution.

Geophones can be set to automatically start recording as of a certain value defined by the team of experts because there may be residual vibrations that do not match the characteristics of the object under study. For this study, trigger considered was PPV = 0.250 mm/s.

2.2 – Offline monitoring

Offline monitoring started from mapping and characterization of dam area. The characteristics of the tailings and the surrounding terrain were taken into account. The location of monitoring points was defined according to Figure 3 so as to encompass the entire dam that was subject to this study and especially the embankment, an area that is more prone to damages resulting from vibrations in structures built with tailings themselves.

![Figure 3 – Seismographic study in a dam – offline.](image)

After the points were defined, 23 (twenty-three) seismographs were installed for offline data acquisition to characterize the intensity of vibration waves per source of emission. The strategies described below were adopted:

- The belt conveyor inserted in the dam body was turned off for 90 minutes and monitoring to characterize other possible interferences as a consequence of vibrations from sources further away such as other operational units, open pit mining, peletizing plant, railway terminal and rock blasting (Figure 4) was carried out during that period of time.

![Figure 4 – Main sources of vibration.](image)

- The other strategy used was to activate the belt conveyor located on the dam with and without transport for 90 minutes to define and monitor vibratory oscillations. Once the tests were concluded, the stopped belt was monitored again to understand the effects of induced vibrations after the operational process.

2.3 Definition of control levels

Standard ABNT NBR 9653 does not contain legislation regarding structural damage resulting from resonance in geotechnical structures (tailings dams) and, comparing to international standards, pseudo-static analyses were performed to simulate the effect of accelerations calculated based on individual velocities of measured particles to assess the impact of vibrations on the Safety Factor (SF), according to Table 1, generating data to define safety levels for the “pilot dam”, checking vibration limits accepted by the structure (McGrew, 2009).

Thus, safety levels were defined per limit scale with descriptions for Normal, Attention, Alert and Emergency, according to Figures 5 and 6.
### Table 1 – Maximum reference values Offline Tests.

| Reference       | PPV (mm/s) | Ap (g) | SF Variation |
|-----------------|------------|--------|--------------|
| Stopped conveyor| 0.189      | 0.000  | 0.00%        |
| No load conveyor| 0.302      | 0.008  | -4.31%       |
| Load conveyor   | 0.349      | 0.012  | -5.20%       |
| Blasting        | 0.315      | 0.006  | -3.45%       |

As a result of the analyses, it was established that the emergency alert process should be calculated per zone or section, according to Figure 4, where the emergency level consists of the identification of simultaneous alert activation of the seismograph instrument layout per section and the division is as follows: Section 1 – SMAs (1, 2, 3, 9 and 14) or Section 2 - SMAs (4, 5, 6, 10 and 13) or Section 3 - SMAs (7, 8 and 11).

#### Figure 5 – Safety limits for the pilot dam.

#### Figure 6 – Seismographic assessment per section.

### 2.4 ‘Automated’ Monitoring

Having the calculations regarding the safety limits of the dam, the process of installing automated seismographic stations was started. That stage starts from instrumentation evaluation, measurement sensors, data transmission forms and sequencing of position of stations on the geotechnical structure.

Seismographic stations used follow the standards and the rules required by ABNT NBR 9653/2018, as well as its maintenance and calibration schedules. Those remote monitoring stations consist of a photo-fed system with robust autonomy to load internal batteries, an antenna, a modem for WiFi transmission, an engineering seismograph, backup batteries, a protection system against storms (Figure 7).

#### Figure 7 – Autonomous monitoring station for automated transmission.
The data transmission system (Figure 8) consists of an engineering seismograph and a modem that works as a datalogger. Then, communication happens via radio with redundancy using several towers with unidirectional antennas that feed analysis software that replicates such analyses to another system that compiles the analyses and the alert criteria and sends data to the Geotechnical control center in an automated way. Those systems may be remotely accessed to recover data continuously 24 hours a day and 7 days a week.

Figure 8 – Automated seismographic data transmission system.

Sequencing of the seismographic station position, Figure 9, was initially defined to encompass the entire extension of the embankment. It was also necessary to evaluate station alignment on the vertical and compulsory requirement of having instruments in the natural material that is before the dam and in the starter dam so that it is possible to record superficial and body seismographic waves as well as range changes throughout the dam.

Figure 9 – Automated and homogeneous seismographic monitoring on the pilot dam.

System maintenance and controls are remotely ‘automated’. Whenever technical adjustments are necessary, professionals carry them out on the field.

That aspect allowed for the technological innovation of the continuous measurement process on geotechnical structures and for the creation of maintenance, programming and adjustment methods in regards to seismographic stations without losing quality in terms of accuracy, precision and confidentiality and also obtaining gains in the speed and safety of the technical team.

2.5 Analysis of the liquefaction trigger

The geotechnical characteristics of the tailings deposited on the dam under study showed variations according to Table 2.

Table 2 – Geotechnical characteristics of the tailings deposit.

| Reference                              | Variance       |
|----------------------------------------|----------------|
| Bulk specific weight (g/cm³)           | 2.03 - 2.89    |
| In situ moisture (%)                   | 9.15 - 26.75   |
| Grain density                          | 4.30 - 4.55    |
| Permeability (cm/s)                    | 8.3E-06 - 2.08E-05 |
| Void ratio                             | 0.65 - 1.24    |

In what concerns the liquefaction analysis process, after test points were established on the dam, accurate and detailed calculations were used according to the characteristics of the pilot dam. Those calculations were based on the studies by Charlie et al. (1985, 1987), which showed that liquefaction is not induced for peak particle velocities PPV lower than 75mm/s and that deformations smaller than $10^{-4}$mm are enough to avoid porepressures once soils have elastic behavior within that deformation range.

Therefore, calculations were made by simulating a harmonic balance of the entire dam extension (Figure 10). Those calculations used the following formulas:
\[ V_c = S_2 - S_1 / \Delta t \]

Where:

- \( V_c \) = Shear Velocity;
- \( S_2 \) and \( S_1 \) = Secondary waves simultaneously recorded by two seismographs or in up to 7 (seven) seconds;
- \( \Delta t \) = Variation of the acceleration time.

**Figure 10 – S waves encounter.**

The process of assessing liquefaction generated by vibrations was calculated by thinking of limits per section and through the entire embankment body, that is, when a maximum value is recorded in all stations of an embankment area (section) or maximum limit of the embankment when all stations are recorded simultaneously or in up to 7 (seven) seconds. Calculations were developed based on formulations proposed by Charlie et al (1985) and Charlie et al (1987):

\[ \varepsilon = \ddot{u} / -c \]
\[ \varepsilon = V_p / V_c \]
\[ V_p = \varepsilon \times V_c \]

And they were adjusted to attend to the objective of this paper using mathematical formulations:

\[ D = V_{pn} / -V_{pm} \]
\[ D = V_p / V_c \]
\[ V_p = D \times V_c \]
\[ V_c = S_2 - S_1 / \Delta t \]

Where:

- \( \varepsilon \) = Deformation;
- \( \ddot{u} \) = Particle velocity;
- \( C \) = Velocity of wave particles in the embankment;
- \( V_p \) = Particle velocity;
- \( V_c \) = Shear wave particle velocity;
- \( V_{pn} \) = Particle velocity in natural terrain;
- \( V_{pm} \) = Particle velocity in the embankment;
- \( S \) = Secondary waves;
- \( \Delta t \) = Time of acceleration;
- \( V_r \) = Particle resultant velocity.

### 3. RESULTS

After the test stages, additional tests were carried out and then technologies applied are validated as well as is data transmission and record system functionality.

In the process of data analysis and their transformation into safe and detailed information on the behavior of vibrations induced in the material deposited on the dam, generating sources were evaluated as well as amplitudes acceptable via graphic analysis of S waves encounter in the embankment and safety factors for possible liquefaction triggers generated by induced vibrations.

#### 3.2 Records at monitoring stations

The seismographic record for each generating source was carried out (Figure 11):
Figura 11 – Signature of induced waves – sources operating equipment.

Seismographic records were checked and analyzed using software called Blastware and then graphs were developed to define the intensity of individual particle velocities per channel, which are direct records and calculated records such as particle acceleration and displacement. Figures 12, 13 and 14 show examples of seismographic records analysis graphs on the three directions:

Figure 12 – Graphs with seismographic test records on the dam transverse channel.

Figure 13 - Graphs with seismographic test records on the dam vertical channel.

Figure 14 - Graphs with seismographic test records on the dam longitudinal channel.

3.3 Reference values for liquefaction triggers
In regards to the S waves encounter, it is calculated and exposed to show at what point in space wave overlapping or constructive wave formation can be registered and what may they generate concerning structure damage. In that case, we evaluated that S waves are on the last raise of the pilot dam and vary between 3.04 and 6.11 meters of depth.

Safety values for dams in terms of liquefaction were defined using formulas proposed by Charlie et al (1985) and Charlie et al (1987) and adapted to the characteristics of the structure under study. As a product of that calculation, the limit of Peak Particle Velocity (PPV) was defined as being 5.03 mm/s.

Even with records that were lower than the normality standard and in the face of liquefaction studies that show that sections withstand values above allowed limits calculated via stability analyses for the beginning of liquefaction, more restrictive values were maintained on safety purposes to make sure operational activities in the surrounding area of the dam would be resumed and people working in the area of the operations would go back to work.

3.4 Operational management for vibration levels

To insure no damages are made to embankment structures, some control measures were adopted to maintain limits set. The principles of those controls are agile response and use of technology. The main measures come through embankment measurement process automation.

Alert devices and protocols were developed according to dam safety levels, automated e-mails are triggered when vibration amplitude increases and there are also internal procedures to engage the team in charge of the embankment for event analysis. The protocol below is to be followed in those situations:

- Redundant communication between pieces of equipment and the control center;
- Redundant communication between collaborators in the center and the operational team in charge of the dam;
- Remote assessments for preliminary diagnosis of effects and sources of emission for quick change decision making or to stop operations.

Initially, the effects of the vibration level variation were assessed by the team of experts to evaluate eventual damages to the structure. After that, sources and ways to minimize the intensity of vibrations were identified.

- Automated e-mail;
- Interaction between the monitoring center and geotechnics;
- Daily bulletin of ground vibration levels:
- Decision making at the time of communications.

Some of the following simple and effective actions were implemented: definition of large-size equipment operation direction especially for crawler-mounted ones and efficiency using the energy allocated to rock blasting.

4. DISCUSSION

Field test stage was useful to develop the automated monitoring system, to define geotechnical alert ranges and to define the maintenance and calibration schedule according to the standards for the dam under study.

Then, studies were developed for a better understanding of ground vibrations on the embankment and, consequently, to make operational continuity possible in the surrounding area of the embankment with several services using earthworks equipment on the structure.

Therefore, after tests and validation of the methodology used in this paper, it was noticed that vibrations generated by mechanical operational activities have low propagation in natural soil and react differently when tailings are disposed because when there is no water seepage, vibrations are usually concentrated at up to 200 meters, but when there is water, there is propagation to up to 400 meters.

In regards to excavation using explosives, propagation has larger routing and that is due to the difference of energy dispersion at the source. When it is well-controlled, it is possible to blast with less energy dispersion to move particles, which avoids plastic unbalance and increasing the magnitude of vibrating oscillations in the area of blasting and adjacent areas inside and outside the mineral project area. That process was studied and then several controls were generated both for mechanic and explosive sources.

Studies carried out showed ground vibrations generated at mining fronts and ore treatment plants. Control and monitoring implemented indicate that vibrations generated cannot put dam structure at risk.

The greatest achievement of the automated seismographic monitoring system (SMA) is that it enables monitoring dynamic events in an ‘automated’ way, which helps the immediate and the future control processes in a more efficient and agile way.

Records evidence that ground vibrations are controlled once they are within limits established for dam safety, especially when peak particle velocities (PPV) that are directly measured at each channel of geophone sensors are evaluated.
To conclude the test process, Figure 15 presents the measurement network with operational movements. Measurements are homogeneous and the stations protect the embankment with an automated, dynamic customizable measurement process that covers the embankment as a whole.

Figure 15 – Automated and homogeneous seismographic monitoring with redundant communication on the pilot dam.

5. CONCLUSIONS

The greatest wave range according to source position and wave oscillation frequencies on the disposed material is between 10 Hz and 25 Hz, which shows that the rock blasting operation cannot generate resonance and fewer high levels of wave overlapping because frequencies generated from blasting ferrous material are historically between 2 and 7 Hz. Thus, among all technical and technological actions quickly performed without wasting knowledge obtained along 1 (one) year. It was observed that there were no relevant behavior changes to induced vibrating waves, which evidences the efficiency of the methodology.

The proposed methodology allowed for the generation of enough data to build and configure an automated tailings dam monitoring network and then to define control levels and their automatic programming in the form of an analysis algorithm.

The limit value for PVS (Peak Vector Sum) = 2,331 mm/s was defined to maintain structure stability in good conditions to avoid liquefaction triggers and it served as a basis to validate the alert system set for each monitoring point and, after a year of operation, it shows to be efficient identifying and eliminating vibration generating sources.

Implementation of the monitoring methodology and analysis allowed for the operational continuity of mining activities, ore treatment plants, shipment terminal and pelleting plants with appropriate safety and transparency before regulating agencies and external auditors.

Another factor that helps control is that the entire seismographic monitoring process is guided by metrologic requirements to maintain data reliability and traceability, that is, data recorded are reliable and process is transparent from equipment calibration to uncertainty analysis of each sensor in the seismographic station. That is a strict control and it helps data analysis.

Counting on a maintenance team working 24 hours a day, 7 days a week (24hx7d) allows for quick corrective actions and for no measurements to be lost, that is, data are intact and reliable.

According to technical discussions with several professionals who helped configure monitoring layouts, the parameter of ground vibration is key as is also peak particle velocity – PPV and not acceleration. Peak particle velocity - PPV is directly proportional to deformation and, in turn, deformation is directly proporcional to the excessive generation of porepressure. Therefore, the engineering seismographs (instruments) selected for the study directly measured the parameter of peak particle velocity (PPV) and velocity is not a calculated quantity, which matches the authors’ opinion when planning for the tests.

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