Development of a Microseismic Monitoring System for Tailings Dams: Methodologies, Software and Sensors

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Abstract

Tailings dams are one of the largest man-made geotechnical structures. These constructions are generally more vulnerable to failure by liquefaction or piping than other types of retention facilities due to a variety of factors and, therefore, need to be monitored carefully. Currently, most dam monitoring techniques provide only punctual information about the state of the internal structure or deformations in the external walls, but such measures are only superficial and unable to detect internal changes. A robust alternative for assessing the safety of tailings dams is microseismic monitoring, which provides information about the containment structures as a whole. The main technical objective of this work is to present a system – set of methodologies, software and sensors – for the microseismic monitoring of tailings dams. The methodology for obtaining microseismic information capable of assisting in the safety and stability of dams is based on a processing flow of the microseismic data recorded by the sensors, developed by Invision Geophysics, which considers the type of data to be analyzed. For conventional monitoring, the data to be processed are the waveforms recorded by the sensors, originated by the occurrence of an event (detonations, failures, movement of machines, people, animals, etc.), while for the passive monitoring, the data analyzed is the ambient noise. A specific processing strategy must be designed for each of these data. The microseismic sensors developed here, which can be uniaxial or triaxial, are capable of performing conventional monitoring, by triggering events, as well as passive monitoring, through the recording of ambient noise.

Introduction

Tailings dams are one of the largest geotechnical structures built by man. These landfills are often built on steep slopes using the tailings themselves, in order to minimize costs (Azam and Li, 2010).

According to Rico et al. (2008) tailings dams should last forever, but experience shows that small and large spills pose a serious environmental threat. Generally, these containment facilities are more vulnerable to failure than other types of retention structures due to the following main reasons:

i. Construction of dikes with residual materials from mining operations;
ii. Sequential increases in dams and increase in effluents;
iii. Lack of regulation/legislation on specific design criteria;
iv. Lack of dam stability requirements in relation to continuous monitoring and control during the positioning, construction and operation phases;
v. High cost of maintenance works for dams after mining activities are closed.

Currently, most of the techniques used to monitor dams provide only punctual information about the state of the containment structure, such as piezometers, water level indicators and flow meters. Such tools are important in assessing the safety of dams, but they may not indicate the first signs of failure. In addition to these techniques, radars and high-resolution cameras are also used to monitor small deformations on the external walls of the structures, but such measures are only superficial and unable to detect internal changes. According to Azam and Li (2010), heavy rains are a significant contributing factor to the failure of the tailings dams wall. Thus, another concern with the current monitoring technology is its low performance during heavy rains, as small deformations in the dam's structure become difficult to detect due to the fluid present on the wall surface.

The relevance of investment in integrated technologies of tailings dams investigation has become even more evident with the recent dam failure disasters in Brazil, which occurred in the cities of Mariana and Brumadinho in 2015 and 2019, respectively. The rupture of the tailings dams had tragic consequences, resulting in the loss of hundreds of human lives and immeasurable environmental and economic effects.

A robust alternative for assessing the safety of tailings dams is microseismic monitoring, which provides information on the containment structures as a whole. Planès et al. (2016) demonstrated that the use of passive seismic interferometry to monitor temporal changes in landfills caused by internal erosion is very promising. This technique uses the seismic noise of the environment that propagates along the structure. Laboratory-scale and field-scale experiments detected temporal variations in the velocity of seismic waves as internal erosion progressed.

In this way, the Invision Geophysics team has developed a microseismic monitoring system that consists of a set of innovative methodologies, software and sensors. This system consists of two microseismic monitoring strategies: conventional and passive. For conventional monitoring, the data to be processed are the waveforms registered by the sensors, originated by the occurrence of an event (detonations, failures, movement of machines, people, animals, etc.), while for the passive monitoring, the data analyzed is the ambient noise. A specific processing strategy should be designed for each of these data.

Microseismic

According to Kamei et al. (2015), micro-earthquake events are a kind of small earthquakes that occur on a very low spatial scale. They may be the result of forces of nature (natural seismicity) or anthropogenic activities (induced seismicity).

Microseismic monitoring has several applications. It is an essential technology in the oil industry, such as, for example, hydraulic fracturing, advanced oil recovery, reservoir characterization and well casing integrity. In addition, applications in mining pits, tailings dams and subsurface imaging (Eaton, 2018).

The passive seismic monitoring method, known as ambient noise correlation, reconstructs the response of the seismic impulse, revealing the velocities of the P, S and surface waves. This method, as the name itself predicts, does not depend on the use of an active source and allows continuous monitoring of the instrumented structure (Planès et al., 2016).

Planès et al. (2016) studied the use of passive seismic interferometry to monitor temporal changes in landfills caused by internal erosion. Landfill failure experiments were monitored on a laboratory scale and on a field scale. The impulsive responses were reconstructed from the ambient noise and the temporal variations in the velocity of the seismic waves observed throughout each test. The application of seismic interferometry in a landfill tested until failure by internal erosion revealed reductions of up to 20% in the velocity of propagation of the surface wave as the internal erosion progressed. The monitoring of a field landfill assessed with partial failure revealed a 30% reduction in the velocity of the surface wave.

Olivier et al. (2017) demonstrated that this method can be used to monitor the stability of tailings dams over time. The results of this study indicate that the ambient seismic noise recorded by geophones are suitable for the construction of regular and robust virtual seismic sources. The relative velocity variations achieved were sensitive enough to measure and locate increases in soil fluid saturation due to rain. The method also indicated some permanent subsurface changes in the dam wall, in locations consistent with observations of increased infiltration.

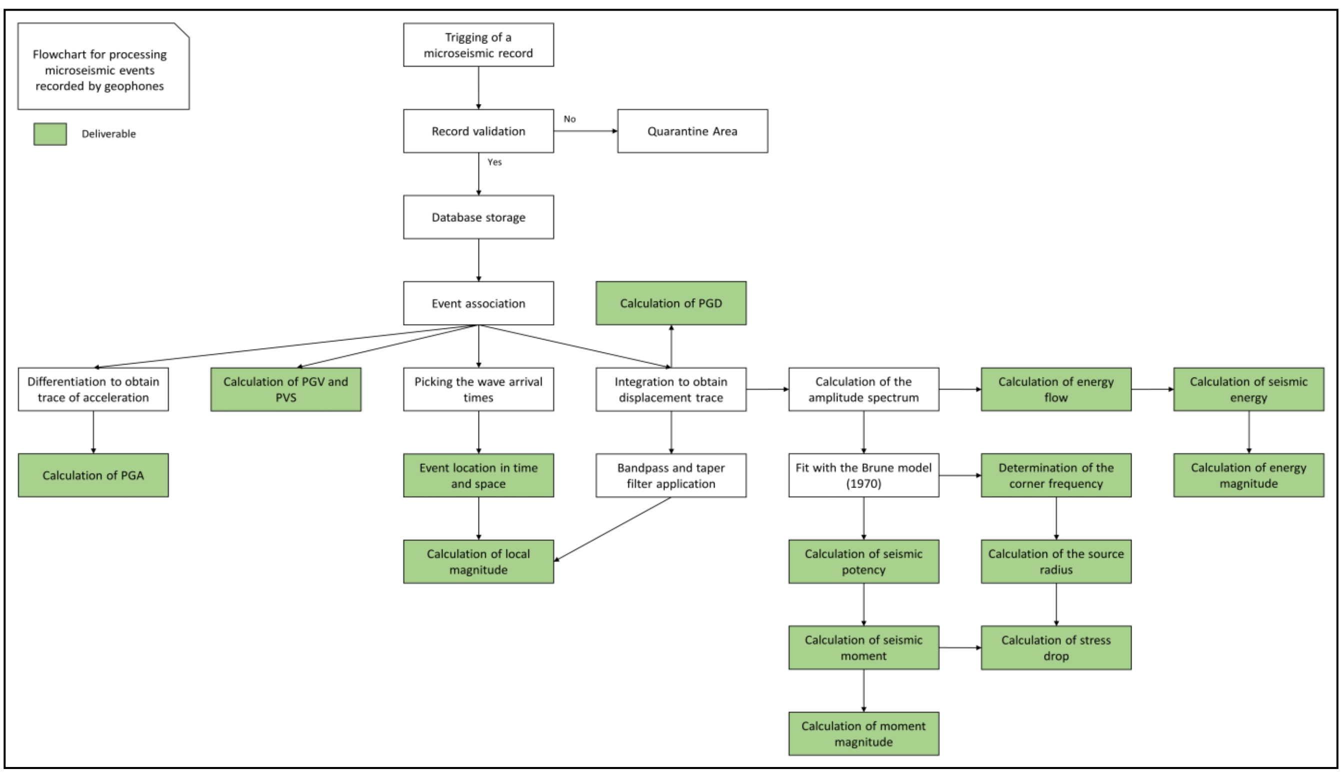

Figure 1: Flowchart for processing microseismic events

Conventional Microseismic Monitoring

In a conventional microseismic monitoring system, a set of uniaxial and/or triaxial sensors are installed along the dam, at strategic positions, in order to capture local, natural or anthropogenic microseismic events, enabling their spatial and temporal location. After associating a set of records to a given event, ground motion estimates and spectral analysis of the event can be performed.

Spectral analysis can be used as a basis for characterizing various properties of seismological events, known as quantitative source measurements (Mendecki, 1997; Mendecki et al., 2010; Hofmann and Scheepers, 2010; Havskov and Ottemoller, 2010; Eaton et al., 2014; Baruah et al., 2018).

Initially, the Fourier transform is applied to the seismological data, transforming the data in the time domain to the frequency domain and then an adjustment is made with the model proposed by Brune (1970). This parameter is fundamental for the estimation of the quantitative source measurements, among which stand out: seismic potency; seismic moment; magnitude; peak ground displacement, velocity, and acceleration; stress drop; radiated seismic energy and attenuation.

In this project, we elaborate a processing flow for microseismic events (conventional microseismic monitoring) recorded by sensors installed in the monitoring site. Figure 1 presents the flowchart with the steps from triggering of a microseism to estimates of its properties.

Passive Microseismic Monitoring

Ambient noise tomography is a fast growing field of seismological research. Theoretical studies have shown that the cross-correlation of diffuse wave fields can estimate Green's function between stations (Campillo and Paul, 2003; Bensen et al., 2007).

The integration between sensor networks and geophysical imaging techniques enables the creation of systems for monitoring and analyzing seismic data in real time. The Ambient Noise Seismic Imaging technique is used in exploration geophysics to investigate subsurface structures using ambient noise data collected by sensors (Valero et al., 2018).

The pre-processing of the signal, for each station individually, is performed in order to prepare it for the future application of the cross-correlation. The intention is to accentuate the ambient noise, by removing events and irregularities that tend to mask it. After pre-processing, the cross-correlation between the signals recorded by each pair of sensors is applied, in order to obtain the Green function of the medium, that is, the impulsive response. Stacking is usually applied to increase the signal-to-noise ratio (Bensen et al., 2007; Lin et al., 2008; Fang et al., 2010; Valero et al., 2018).

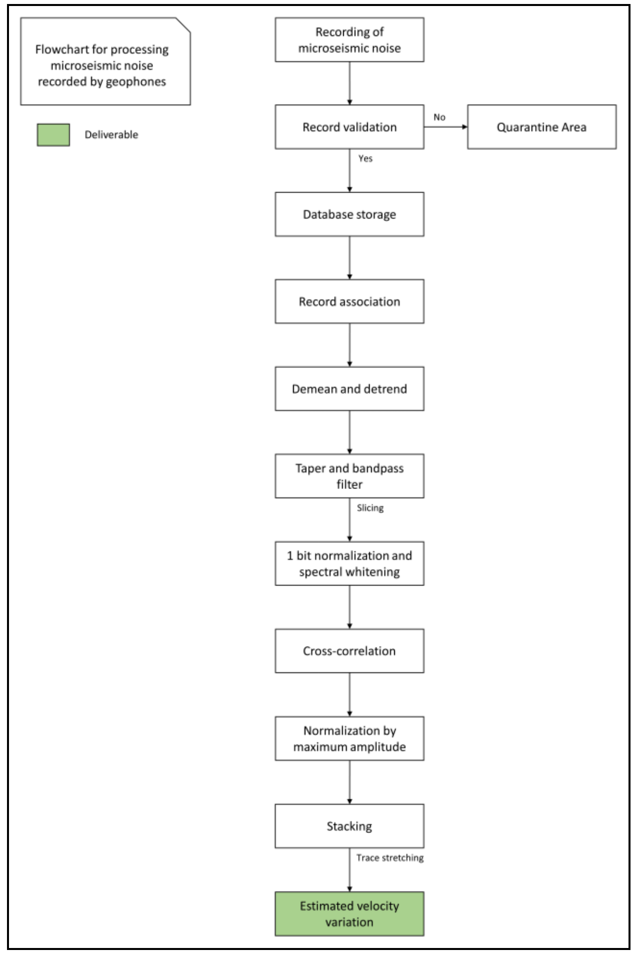

Figure 2: Flowchart for processing microseismic noise

In our system, we develop a microseismic noise processing flow, which is performed using the passive seismic interferometry technique, in order to estimate the variation in the velocity of propagation of seismic waves in the medium under analysis over time. Figure 2 shows the main stages of this flow, considering data recorded by geophones.

Sensor Development

The microseismic sensors are powered by renewable sources through solar panels being the data transmission done by wireless technology, and they must be able to perform conventional monitoring, by triggering events, as well as have an application for passive monitoring, through the recording of ambient noise.

To achieve this goal, we started with the sensor encapsulation project, prototyping was carried out through 3D printing for validation and machining of the equipment. The developed system includes robust computational hardware with processing and storage servers. The hardware development cycle of electronic circuits and mechanical projects is illustrated in Figure 3.

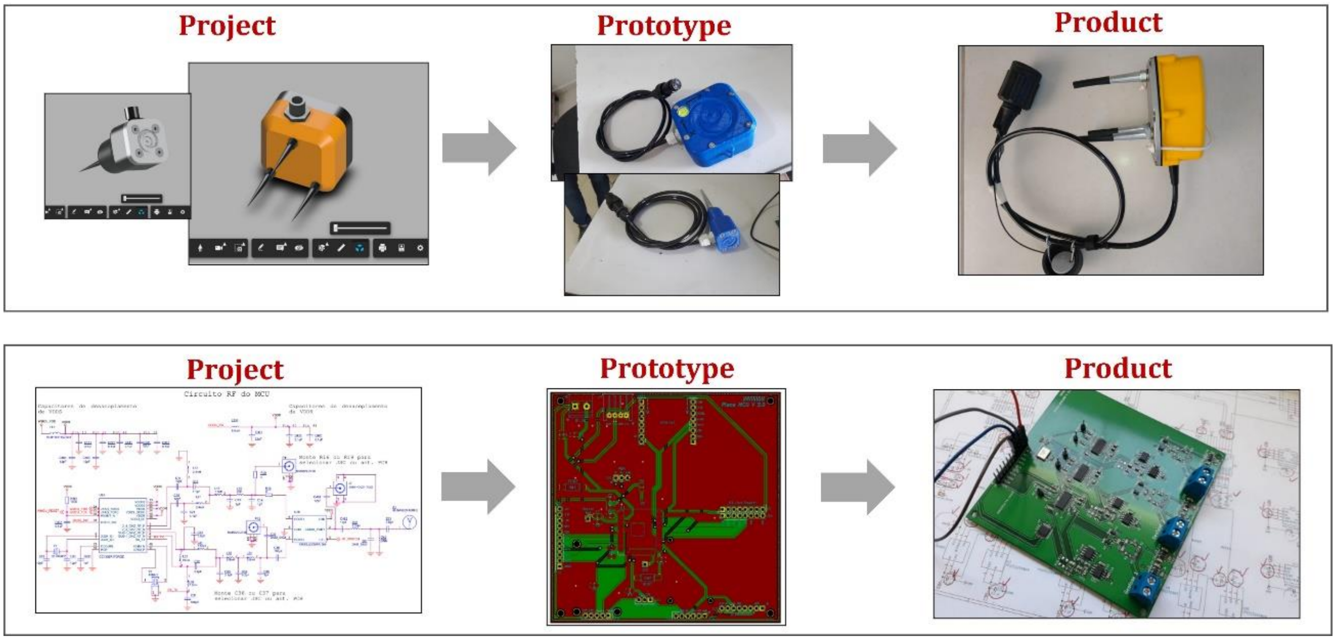

Figure 3: Stages of development of mechanical and electronic circuits projects of the microseismic sensors

Then we raise the requirements and design the recording unit, which is responsible for acquiring, storing and transmitting the information coming from the sensors (geophones and accelerometers), in addition to maintaining the timing and the geographical position of the measurements.

Therefore, this unit has some characteristics for its correct operation and application, such as: case with IP67 degree of protection, sensitivity of 78.9 V/m/s, operating temperature between -40ºC and 80ºC, 24-bit ADC, one millisecond sampling rate, power supply via photovoltaic cell and battery, operation via mesh network with wireless communication between nodes and concentrator for data transmission to server.

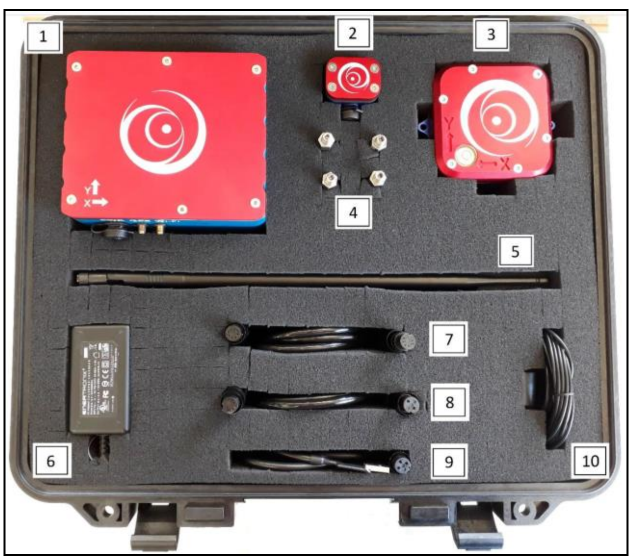

Figure 4: Microseismic sensor kit developed by Invision Geophysics

After defining the basic requirements, the hardware design process started, which includes the specification of the electronic components and the development and manufacture of printed circuit boards. The project was modularized in four different boards, separated by their main functions:

i. Main board of the microcontroller: main circuit of the sensor housing the microcontroller, GPS and data storage unit;

ii. Analog to digital converter board: circuit responsible for capturing the signals from the sensor elements and digitizing, this board has several auxiliary circuits with functions to supply the reference voltage, operational amplifiers and noise filters;

iii. Main power board: responsible for supplying all electrical energy to the system, considering that different voltage values are required for each electronic component;

iv. Auxiliary interface power board: responsible for charging the internal battery and regulating the voltage of the source.

Furthermore, the developed microseismic sensors can be uniaxial or triaxial. Figure 4 shows the sensor kit, where the numbers highlight the following components:

1. Data acquisition/transmission module;
2. Uniaxial geophone;
3. Triaxial geophone;
4. Spikes for coupling the geophones to the ground;
5. Wi-Fi antenna;
6. Charger;

7. Signal cable for triaxial geophone;
8. Signal cable for uniaxial geophone;
9. Programming cable;
10. GPS antenna.

Conclusions

We are developing a Brazilian microseismic monitoring system designed to tailings dams, which are susceptible to many failure mechanisms, such as liquefaction and piping, and need to be monitored carefully. Using geophysical methods, it is intended to identify anomalies related to possible areas of high saturation, fracture plans and failures associated with the structures of the dams, which can compromise their safety and stability. Conventional monitoring of microseismic events, which occur daily in dams and mining pits, allows the estimation of the quantitative properties of sources and ground motion, that are important for assessing the risks of damage induced by vibrations. In relation to passive seismic monitoring, the reconstruction of the seismic impulse response is able to identify changes in the wave propagation velocities over time, which may indicate changes in the medium, such as variations in fluid saturation, being able to be associated with areas of weakness in the structures. The sensor development was built on top the nature of microseismic events, environmental conditions and the location of tailings dams. In addition to its high sensitivity, the photovoltaic power supply and operation via mesh network with wireless communication facilitate the installation and maintenance of the system in areas of difficult access. The permanent microseismic monitoring system will provide several benefits, the main one being the increase in the safety and stability of the structures, with greater predictability of possible accidents, thus avoiding social, environmental and economic disasters, caused by the rupture of tailings dams.

Acknowledgments

The Financier of Studies and Projects (FINEP) and the Brazilian Company for Industrial Research and Innovation (EMBRAPII) for the financing of this project, the Fluminense Federal Institute (IFF) innovation pole Campos dos Goytacazes for the technological support for the development of the sensor and the Center for Applied Geophysics Research (CPGA) at the Federal University of Rio de Janeiro (UFRJ) for technical support.

References

A. J. MENDECKI, 1997, Seismic Monitoring in Mines, Chapman e Hall.

A. J. MENDECKI, R. A. LYNCH and D. A. MALOVICHKO, 2010, Routine Microseismic Monitoring in Mines.

D. W. EATON et al., 2014, Scaling Relations and Spectral Characteristics of Tensile Microseisms: Evidence for Opening/Closing Cracks During Hydraulic Fracturing, Geophys. J. Int.

D. W. EATON, 2018, Passive Seismic Monitoring of Induced Seismicity: Fundamentals Principles and Applications to Energy Technologies, Cambridge University Press.

F. LIN, M. P. MOSCHETTI, M. H. RITZWOLLER, 2008, Surface Wave Tomography of the Western United States from Ambient Seismic Noise: Rayleigh and Love Wave Phase Velocity Maps, Geophys. J. Int.

G. D. BENSEN et al., 2007, Processing Seismic Ambient Noise Data to Obtain Reliable Broad-band Surface Wave Dispersion Measurements, Geophys. J. Int.

G. F. HOFMANN and L. J. SCHEEPERS, 2010, Simulating Fault Slip Areas of Mining Induced Seismic Tremors Using Static Boundary Element Numerical Modelling.

G. OLIVIER et al., 2017, Monitoring the Stability of Tailings Dam Wall with Ambient Seismic Noise, The Leading Edge.

J. HAVSKOV and L. OTTEMOLLER, 2010, Routine Data Processing in Earthquake Seismology, Springer.

J. N. BRUNE, 1970, Tectonic Stress and the Spectra of Seismic Shear Waves from Earthquakes, Journal of Geophysical Research.

L. FANG et al., 2010, High Resolution Rayleigh Wave Group Velocity Tomography in North China from Ambient Seismic Noise, Geophys. J. Int.

M. CAMPILLO and A. PAUL, 2003, Long-range Correlations in the Diffuse Seismic Coda, Science.

M. RICO et al, 2008, Reported Tailings Dam Failures: A Review of the European Incidents in the Worldwide Context, Journal of Hazardous Materials.

M. VALERO et al., 2018, Real-time Cooperative Analytics for Ambient Noise Tomography in Sensor Networks, IEEE Transactions on Signal and Information Processing over Networks.

R. KAMEI, N. NAKATA and D. LUMLEY, 2015, Introduction to Microseismic Source Mechanisms, The Leading Edge.

S. AZAM, Q. LI, 2010, Tailings Dam Failures: A Review of the Last One Hundred Years, Geotechnical News.

S. BARUAH, 2018, Study of Fault Plane Solutions and Stress Drop Using Local Broadband Network Data: the 2011 Sikkim Himalaya Earthquake of Mw 6.9 and its Aftershoks, Annals of Geophysics, 61(1).

T. PLANÈS et al., 2016, Time-lapse Monitoring of Internal Erosion in Earthen Dams and Levees Using Ambient Seismic Noise, Géotechnique.