Multi-purposing of passive seismic acquisition for characterisation and monitoring of tailings dam performance

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Passive seismic methods have been gaining momentum in the last two decades as geophysical tools allowing for both characterisation and monitoring of the subsurface physical properties in an innovative, cost-effective and non-invasive way. Their relevance for the surveillance of geotechnical objects such as earth levees, tailing dams, or open-pit slopes has also been increasing, particularly thanks to the unique monitoring capabilities of the methods. Continuous, passive measurements of ambient seismic noise can primarily be used to track microseismic events, analyse their origin and study the response of the monitored geotechnical structure. Here we illustrate how passive recordings of ambient seismic noise can be multi-purposed to provide enhanced monitoring and characterisation capabilities and increase the level of understanding and performance of geotechnical structures.

Ambient noise seismic interferometry is a passive seismic approach that provides a way to monitor continuously the shear wave velocity (Vs) variations occurring within geotechnical structures, with a 3D volumetric sensitivity, relying solely on the recording of ambient seismic noise. Physics links Vs changes to the dynamics of geotechnical parameters such as pore pressure and vertical stress, which are critical in tailing dams or open-pit slopes management strategies. Applied to tailing dams, this technology opens the way to a volumetric monitoring tool able to detect and report on anomalous evolution of geotechnical parameters such as pore pressure and compaction degree within the structure, at the foundation level and below the tailing dam itself. In addition to the surveillance of relative Vs changes, the same data set can also be used to derive a 3D model of absolute Vs values, revealing the internal structure of the dam wall. The multi-purpose potential of passive seismic recordings also extends to the derivation of key geotechnical parameters such as fundamental resonance frequency (through horizontal to vertical spectral ratio analysis), or damping ratio evaluation (through the random decrement technique).

This set of passive seismic methodologies is at the heart of an integrated technical solution which can provide the mining industry actors with the capacity to characterise the 3D structure of their assets, study their response to seismic excitations, and monitor their internal evolution. This solution encompasses a fully autonomous acquisition system, coupled with the Internet of Things equipment that allows for real-time data transfer to a data processing centre, where automatic routines provide quasi-real time monitoring of the internal evolution of the dam wall and other geotechnical parameters. Results can be delivered through a dedicated platform or integrated into the client's own monitoring dashboard. The objective of this integrated solution is to provide the mining industry with the capacity to enhance their monitoring capacity of geotechnical assets. The multiplicity of information (microseismicity, damping parameters, resonance behaviour, Vs models and evolution), powered by unique technical capacities (automation, continuity in time, non-invasive and volumetric assessment) and coupled with a client-oriented design (interoperability, security, auditability) provides new geophysical insights to complement and strengthen the strategies deployed for tailing dams management and performance monitoring.

INTRODUCTION

Continuous monitoring of geotechnical assets such as tailing dams, earth levees or open-pit slopes is crucial for early detection of potential instabilities, helping to prevent critical failures that could lead to significant environmental and human disasters. Additionally, continuous monitoring enhances our understanding of the complex interactions between the dam structure, underlying geology, and external factors like water infiltration, contributing to better understanding of the risks enabling safer and more effective dam management practices. A surveillance strategy and monitoring plan for those geotechnical assets generally relies on geotechnical, hydrogeological and geophysical measurements. Onsite investigations comprising in-situ geotechnical techniques such as cone penetration tests (CPTu) provide direct measurements of various physical parameters, allowing for better direct assessment of the geotechnical characteristics (e.g., Robertson, 2010; Torres Cruz, 2016). Other instruments such as vibrating wire piezometers (VWP) or inclinometers can be installed in-situ across a facility to provide information (displacement and pore pressure, respectively) continuously in time (Illanes *et al.,* 2015 ; Clarkson *et al*., 2021). These types of digital monitoring techniques and solutions provide accurate in-situ measurements and high temporal resolution sampling, but the spatial extension of information is limited to quasi-punctual locations. Satellite interferometric synthetic aperture radar or ground-based radar surveillance methods support the monitoring of surface displacements across a wider extent, but information is limited by providing an evaluation of surface movements (Thomas *et al*., 2019). This is also true for aerial drone surveys.

Geophysical methods are often used to fill in the lack of spatially distributed information for they have the capacity to infer subsurface properties in a volumetric way to provide models of the geotechnical target geophysical properties continuously with both depth and lateral extension, in a non-invasive way. Among them, electrical resistivity tomography methods are sensitive to moisture content, saturation levels and porosity values hence allowing to image the distribution of material types and reflect hydrogeological behaviors within the targeted structures (e.g., Oliveira *et al*., 2024). Seismic methods are also used to derive models of seismic properties. Seismic refraction methods use compression wave analysis to detect significant vertical interfaces within the structure, delineating material types and /or bedrock depth for instance (e.g,. Guedes *et al*., 2023). Multi-channel analysis of surface waves is another active seismic technique allowing to derive shear-wave velocity (Vs) models of the targets; a relevant parameter to assess the stiffness and strength characteristics of the geotechnical structure (e.g.,- Prodoscimi *et al*., 2021). The main limitation with such active geophysical surveys is that they are difficult to repeat regularly in time for logistics reasons (repeated access to a dam, with repeated installation of technical devices) and high ongoing costs and are therefore not well-suited to performance monitoring with high temporal resolution.

In summary, accurate, continuous monitoring of a structure's geotechnical parameters is generally achieved by means of in-situ measurements, which are disadvantaged by limited distribution in space. As such monitoring and surveillance strategies are more readily deploying geophysical methods to investigate an asset's internal structure with depth and lateral extension, they rely on volumetric, non-invasive measurements. In this paper, we present how passive seismic methods can be multi-purposed to enhance both the characterisation and the performance monitoring aspects of a tailings dam surveillance, closing the gap between dynamic geotechnical and static geophysical measurements. The same data can be processed in different ways to provide multiple types of geotechnical and geophysical parameters, with both lateral and deep spatial distribution as well as continuity over time. In addition, the passive seismic monitoring method has the potential to deliver earlier indications of developing weakness in the structure, permitting sufficient time for the responsible engineers and asset owners to intervene to mitigate the risk of failure or damage.

Passive seismic methods rely on the recording of the ambient seismic signal using autonomous or semi-autonomous seismic sensors with long-term data storage or wireless data transmission capabilities. The information contained in the ambient seismic noise signal is rich, and various analysis methods can be deployed to extract this information. A powerful, innovative approach consists of using ambient noise seismic interferometry (ANSI) to extract coherent shear waves from the ambient noise, analysing the reconstructed wavefield to infer Vs values (Shapiro & Campillo, 2004; Mordret *et al.*, 2020). Vs is a particularly relevant geophysical parameter in tailings dam or open-pit slope management because it is primarily controlled by pore pressure and vertical stress (Fokker *et al.*, 2021), two critical parameters that control the soil's mechanical behaviour and hence the stability of dams and slopes. One major strength of ANSI is its capacity to provide information quasi-continuously in time, for Vs values can be inferred sequentially at multiple time-steps (usually hours or days depending on the ambient noise characteristics) during the period of the ambient seismic signal recording (Mordret *et al.*, 2020). In addition to continuity, in this paper we illustrate in the context of tailings dam monitoring how Vs variations can be determined and visualised in 3D space, hence revealing differential lateral and depth behaviours, providing indirect estimation of hydrogeological parameters (pore pressure, phreatic surface level variations) and geomechanical evolution, offering combined spatial and temporal insight within the geotechnical structure that no other method commonly used in tailing dams surveillance can achieve.

Another approach that can be derived from the same passive seismic data is more commonly known as microseismic analysis. By analysing the seismic signals generated by microseismic events or blasts and changes in the dam's structure, operators can assess the integrity of the dam in real-time, monitor continued changes or implement timely mitigation measures. Beyond microseismic analysis, passive seismic recordings can also provide valuable parameters such as resonance frequency and damping ratio. These parameters characterise the dam's resonance behaviour and its response to seismic event solicitations, such as blasting and earth tremors. Fundamental resonant frequency values can be extracted from ambient seismic noise using horizontal to vertical spectral ratio (HVSR) techniques. They indicate a specific seismic frequency range for which the soil layers overlying the bedrock enters in a resonance behaviour when submitted to seismic excitation. These methods are widely used in geotechnical studies within urban environments to assess the seismic response of sedimentary layers and/or structures (Bonnefoy-Claudet *et al.*, 2006a, b). In this paper, we demonstrate how single-sensor measurements at the surface can reveal the thickness and seismic velocity distribution of the resonant part of the dam at any given location. Furthermore, multiple measurements across various locations provide insights into the lateral variations of the dam's resonant layer, shedding light on its internal structural heterogeneities. In addition to resonance frequency, damping ratio values are often used within geomechanical modelling processes to simulate and anticipate the geotechnical asset resistance to seismic excitation. They indicate how fast seismic energy will dissipate during a seismic event propagation within a structure. Such values are often extracted from literature, and potentially from laboratory measurements. In this paper we illustrate how damping ratio values integrated over the entire soil column can be derived from ambient seismic noise recordings, providing in-field evaluation of this critical parameter.

The subsurface geotechnical and hydrogeological parameters are difficult to monitor continuously both in time and space. We present in this paper an integrated solution based on passive seismic recordings which offers an effective way to respond to both challenges, using a single passive seismic dataset, to provide volumetric assessment and quasi-continuous monitoring of the tailings dam, with reduced maintenance and on-site logistics compared to active geophysics or invasive in-situ measurements.

PASSIVE SEISMIC ACQUISITION

Recording the ambient seismic signal is done through the deployment of seismic sensor stations. Such stations can have different configurations depending on the geotechnical monitoring or characterisation objectives. For a temporary analysis (a few weeks or months duration), as would be required for a feasibility study, 1-component (1C) or 3-component (3C) geophones can be seismically well coupled with the target structure through burial in holes to tens of centimetres depth, and associated with semi-autonomous acquisition units, or seismic recorders (e.g., 1b), which require regular replacement on a weekly or monthly basis to retrieve the data and recharge the internal batteries. For permanent monitoring and characterisation, fully autonomous stations can be installed (e.g., 1c), which are equipped with the Internet of Things equipment and allow for real-time data transfer to the data processing centre where Vs analysis is performed. 1a) illustrates the seismic sensor network that was installed at the surface of a tailings dam for a period of eight months, with some stations in place for only three months. Continuous 3-component ambient seismic noise records were acquired at a sampling rate of 250 Hz, using geophones with a cut-off frequency of 4.5 Hz. Note that such an instrumental response allows retrieval of seismic signal at frequencies as low as 0.5 Hz (e.g. Kremer *et al*., 2023).

In the following sections, we present a multi-purpose processing sequence applied to this passive seismic dataset which provides multiple outputs and insights into the tailings dam structure, composition and geotechnical evolution. This single geophysical dataset delivers a set of tools and metrics that have the potential to significantly enhance the current performance monitoring and geotechnical characterisation capabilities of engineers. The passive seismic approach provides a non-invasive, continuous, near real-time volumetric assessment of the structure that both complements, and cross-validates point measurements usually made by geotechnical engineers.

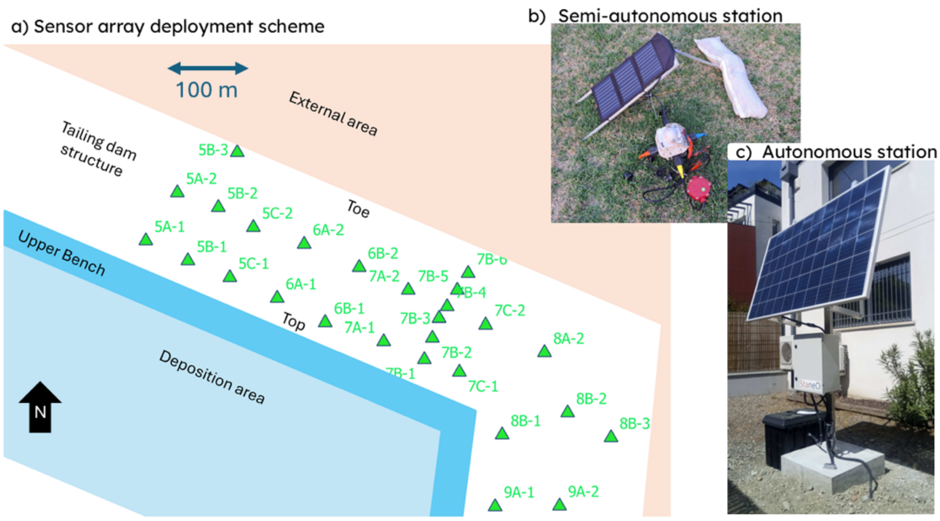

Figure 1. a) Illustrative scheme of seismic sensors deployment on a tailings dam. 27 semi-autonomous stations have been deployed for eight and three months to record passive seismic signals.

MONITORING – 4D SHEAR WAVE VELOCITY ANALYSIS

Methods

The internal physical properties of geotechnical assets such as tailing dams and earth levees are often challenging to characterise and monitor. In-situ instruments and measurements are accurate but only provide local information and are based on invasive methods. In this paragraph we illustrate in the context of a tailings dam monitoring use-case how passive seismic recordings can be processed to obtain Vs evolution time-series through the whole dam volume. Imaging techniques then provide ways to obtain temporal information in depth and with a large lateral coverage, complementing the lack of information between local investigation data (e.g., CPTu or seismic(s)CPTu), and in-situ instrumentation measurements (VWP and inclinometers).

The ambient seismic signal recorded over a network of seismic sensors can be processed by means of ambient-noise seismic interferometry (ANSI) methods to extract a coherent seismic wavefield (Wapenaar *et al*., 2010a). Such wavefield is composed of coherent seismic arrivals both in the ballistic part (early arrivals) and in the coda part (late arrivals resulting from multiple wave diffusion processes). The wavefield is generally dominated by surface waves, making it possible to retrieve Vs relative variations by analysing how the time arrival of coherent phases changes with time, using for instance the so-called stretching method (Sens-Schönfelder and Wegler, 2006). In the context of tailings dam surveillance, the seismic noise components used for analysis are associated to relatively high frequencies (> 1 Hz) to accommodate the depth sensitivity of surface wave to the geotechnical target decametric scale. At those frequencies, the seismic noise is mostly composed of signals with anthropogenic origin, which usually confer some instability on the wavefield reconstruction process (Afonin *et al.*, 2022) due to variations in the noise source distribution (e.g,. night vs day, working days vs weekends). To reduce the effect of noise source instability and the resulting uncertainty in Vs variations measurements, we chose in the following analysis to focus on the coda part of the reconstructed signals (Wang *et al.*, 2008). To summarise, in the following, all Vs variations time-series were computed analysing time-shifts within the reconstructed coda wavefield, by means of the stretching method. A satisfying uncertainty level was obtained by deriving such measurements every 48 hours, taking advantage of signal-to-noise enhancement related to stacking processes.

Figure 2 illustrates the depth and lateral sensitivity distributions associated with the analysis of coda waves reconstructed through ANSI processes applied to single stations measurements. Figure 2a) shows an example of the 2D lateral sensitivity distribution computed for a synthetic array of 36 sensors deployed regularly in space. The resulting distribution is globally homogeneous with an increase of sensitivity in the centre of the array. Figure 2b) illustrates how the sensitivity in depth is dependent on the frequency range chosen for seismic data analysis. In the following, both types of sensitivity distributions are used and combined within inversion and imaging processes to provide the spatial and temporal visualisation required for tailings dam volumetric monitoring of Vs variations within the tailings dam.

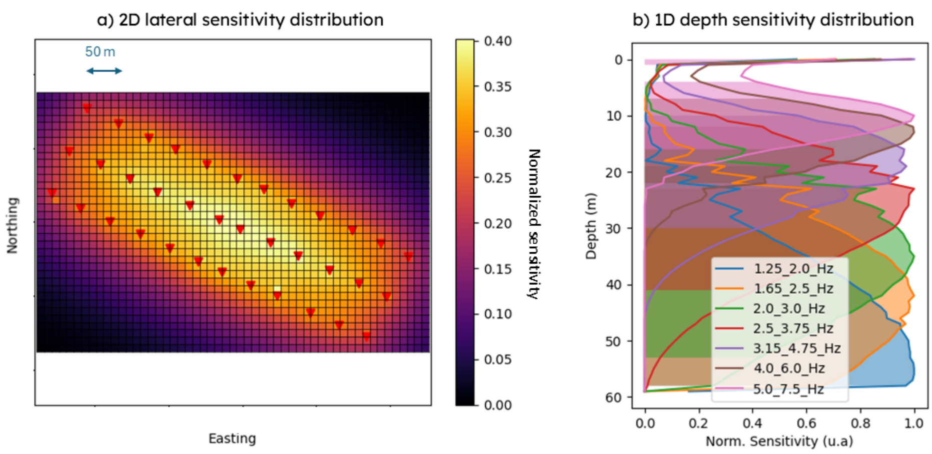

Figure 2. a) 2D lateral sensitivity distribution associated with Vs measurements on coda waves reconstructed through interferometry. Illustration for a synthetic regular array. b) Depth sensitivity distribution depending on the frequency content of the seismic wavefield. Filled area under the curve corresponds to 80% sensitivity for each frequency range.

Sensitivity to geotechnical and hydrogeological parameters

Figure 3 illustrates how Vs variations are correlated with various types of geotechnical, hydrogeological parameters and surveillance data, illustrating how passive seismic monitoring informs on the physical processes occurring within the tailings dam. The multi-coloured curves on Figure 3 represent Vs variations measured at some locations of the tailings dam, with distance in between stations ranging from 50 to 100 m (cf. Figure 1). They represent Vs evolution for a frequency range associated with a depth sensitivity ranging from 20 to 50 m (Figure 3b). All curves show similar behaviours, indicating that with this small spatial extent (~100 m) the tailings dam internal evolution at those depth is rather homogeneous. Error bars are not represented for readability, but indicate that the resolution of Vs change measurements (*dv* or *dv/v*) is on the order of 0.2%

Figure 3 highlights how internal Vs changes are primarily representative of the hydrogeological evolution of the medium. A clear anti-correlation can be observed relating the phreatic level time series and Vs evolution, confirming that Vs is primarily sensitive to pore pressure evolution; in that case induced by phreatic surface level variation. The elevation of the phreatic level does indeed induce a small pore pressure variation that affects the whole water column within the tailings dam wall, thereby inducing a change in Vs affecting the saturated tailings layer. Assessing quantitatively, this relationship (through a linear correlation for instance) and considering the resolution of Vs variations measurements previously cited (~0.2%) implies that in the present case, the observed Vs changes reflect relative phreatic level changes on a centimetric order.

Another insight from Figure 3 is the effect of precipitation events on the internal composition of the dam, which shows on the Vs change time-series. In particular, a strong drop of Vs is observed after the first significant rain events that occurred at the beginning of November 2024. Sudden Vs decrease can be interpreted as an increase in pore pressure associated with infiltration of the meteoric water within the tailings dam formations. Other rainfalls with similar daily magnitude occur in the following weeks, but do not result in such a strong decrease of Vs. One explanation of this difference can be found in the dynamics of those rain events, as illustrated within the dashed-line rectangles. It is likely that strong, intense rainfalls result in a lot of surface run-off and little infiltration within the tailings material, whereas slow, continuous rainfall favours such infiltration and the associated modification of the dam seismic properties. Those observations illustrate how passive seismic Vs monitoring can be used to assess the effects of meteorological events on geotechnical structure composition; a tool that will be increasingly necessary in the upcoming changing climate – which is expected to produce an increased number of events with high intensity.

Another indication of Vs relationship with the evolution of the tailings dam can be found while observing cyclic behaviours of Vs evolution that may relate to deposition patterns, i.e., modification of the dam structure following the deposition of new amounts of tailings material. Such cyclicity is highlighted in Figure 3 by the black rectangle and double arrows. It shows as relatively fast decrease of Vs, which could be associated with infiltration of deposition water within the dam layers, followed by a slower increase of Vs that suggests desaturation or decrease of the phreatic surface level, possibly associated with progressive compaction processes.

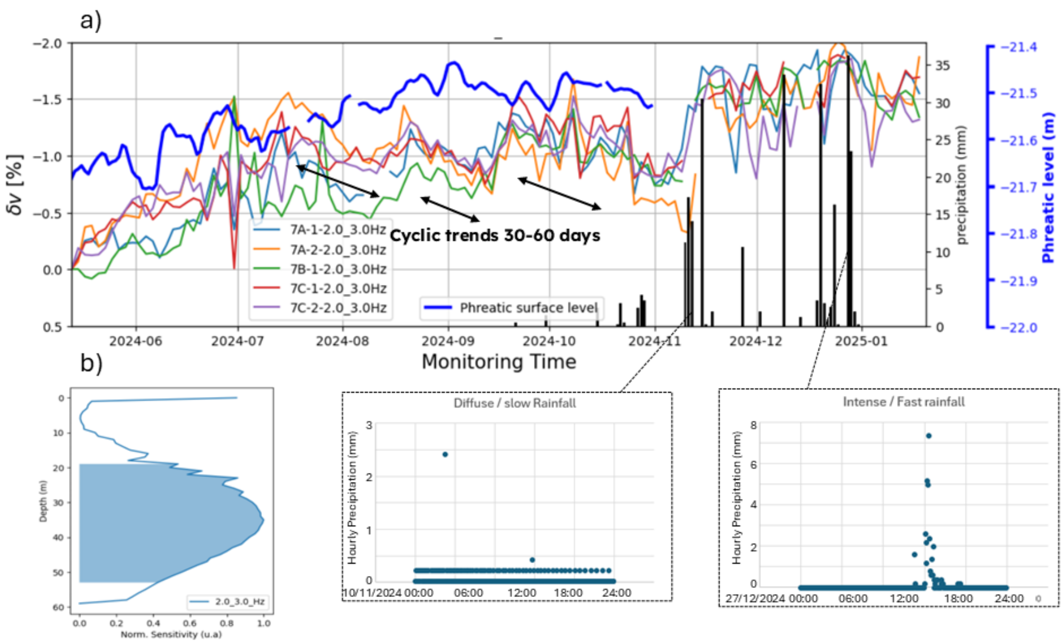

Figure 3. a) Vs variations curves (dv, multi-colours curves) in comparison with various types of data. Black histogram reports precipitation history. The thick blue curve reports phreatic level estimation derived from VWP data installed at the same location on the dam (data missing after 11/2024). The black rectangle highlights cyclic trends possibly linked to deposition patterns. Dashed-line rectangles emphasise the different dynamics of two rainfall events. b) Depth sensitivity distribution for frequency range [2.0 Hz -3.0 Hz].

Evolutive 2D Vs maps

A more advanced interpretation of Vs variations time-series with respect to their localisation in space can be achieved using imaging techniques such as interpolation and inversion processes. Figure 4 shows an example of how 2D Vs maps can be produced at multiple times during the monitoring period, for different frequency ranges and hence depth sensitivity. Figure 4a) and 4b) illustrate that, within the shallow part of the dam, the Vs variations spatial distribution with respect to a reference date (19/11/2024) has been rather homogeneous in space, remained quite low at the beginning of the period (29/11/2024, Figure 4a) and showed a significant increase several days later (23/12/2024). Figure 4b), suggesting pore pressure decrease associated with desaturation and/or compaction effects. Figure 4c) and 4d) illustrate that for the same period of time, at deeper locations within the tailing dam, the Vs variations have been slightly increasing at first, and then a differential behaviour is observed between the western part of the dam where Vs values are globally decreasing, possibly suggesting preferential infiltration pathways on this location and subsequent pore pressure increase, whereas the eastern part of the dam still shows slight Vs increase compared to the reference date.

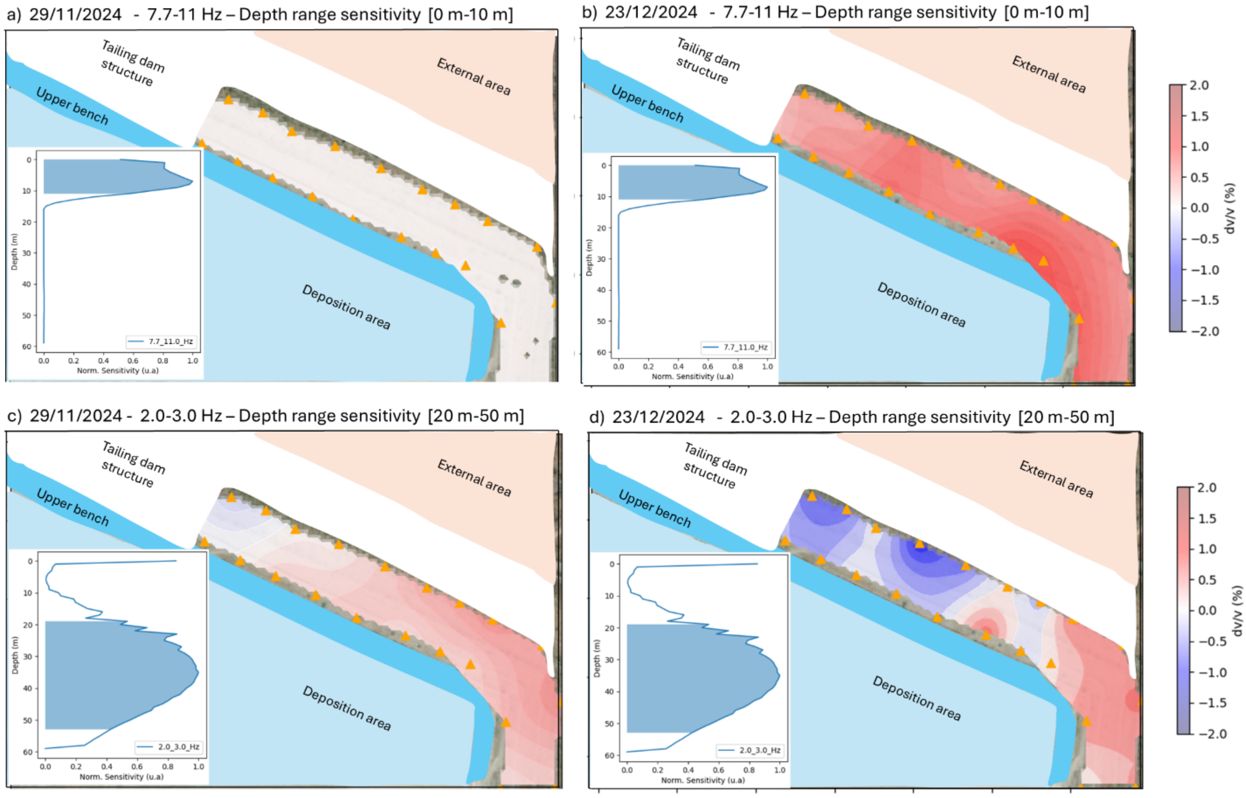

Figure 4. Examples of 2D Vs maps produced for multiple depth ranges and time-steps. a) and b) 2D Vs maps at two different dates with shallow depth sensitivity (0-10 m). c) and d) 2D Vs maps at two different dates with deeper sensitivity (20-50 m). Reference date for relative variation computation is 19/11/2024.

Evolutive Depth profiles

Another imaging procedure based on inversion processes allows for retrieving the evolution in time of Vs values related to depth around a given seismic sensor location. Such inversion processes take advantage of the depth sensitivity distribution presented in Figure 2b) to transform Vs variations time series associated with multiple frequency ranges into a temporal matrix that describes how Vs varies in time and depth, with a volumetric sensitivity around each location of the dam where a seismic sensor is installed.

Figure 5 illustrates such imaging for the sensor 7B-1, which is located at the top of the dam, close to some VWP installations. A first noteworthy feature of this visualisation is the highlighting of dam layers where Vs is globally increasing versus layers where Vs is decreasing. In tailings dam monitoring context, Vs decrease can usually be attributed to pore pressure increase, for instance associated with phreatic surface level elevation, whereas Vs increase can possibly denote compaction processes enhancement or desaturation effects. Hence, Figure a) and Figure b) potentially highlight multiple physical behaviours occurring within the dam. The transition zone between layers with positive or negative Vs variations possibly indicates an estimate of the phreatic surface level, as suggested by comparison with estimated phreatic surface level evolution based on VWP measurements. Another interesting feature of this image is the alternance of positive and negative variations in the shallow part of the model (0-5 m) which may relate to alternance of deposition periods and drying periods and may also reflect the effect of precipitation events in November and December 2024.

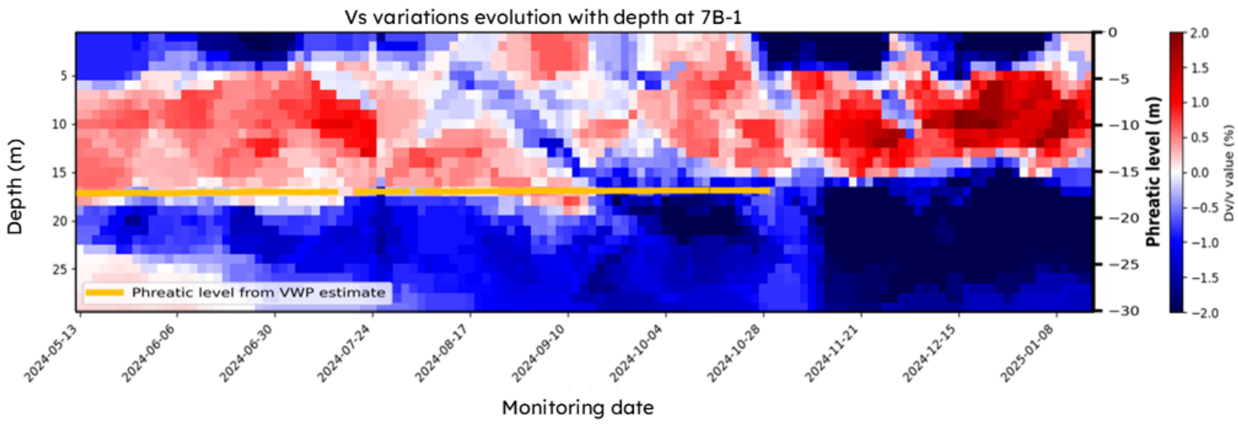

Figure 5. Temporal matrix of Vs variations in depth at the location of sensor 7B-1. The yellow line indicates the phreatic surface level evolution at the same location based on VWP estimates.

Hence, visualising Vs variations in depth provides an understanding of the hydrogeological and geotechnical response of the different compartments of the tailings dam structure and provides a way to estimate the absolute phreatic surface level at any location of the dam where a seismic sensor is installed.

MONITORING – MICROSEISMIC SURVEILLANCE

Understanding the seismic environment of geotechnical assets such as tailing dams supports a better understanding and knowledge base. Continuous seismic monitoring allows for a near real-time classification of seismic events by their waveforms, amplitudes (peak particle velocity for instance) and any other characteristics. Figure 6a illustrates a now classical approach based on template matching. A seismic event is chosen as a template and is correlated with the complete time-series to identify similar events occurring every now and then in the dam. In this example, the similarity of the waveforms is higher than 90%, which suggests that these events share similar physics and plausibly have a common origin and location. By multiplying the templates and performing a thorough analysis of the recordings, it becomes possible to identify areas within the dam prone to producing seismic events, i.e., a must-have information for the engineers.

Seismic events occurring in the immediate vicinity of the structure can have several effects. In the first place, even moderate shakings (moderate earthquakes, or blasts) can trigger small seismic events inside the structure that underlie the brittle behaviour of parts of the dam. In addition, moderate shakings can excite the resonance of the tailing dam and trigger a transitory response of the structure; a small decrease in the resonance frequency followed by a recovery to the initial state. In the worst-case scenario, strong shaking may induce permanent damage that translates into a permanent decrease in the fundamental frequency. Figure b illustrates the impact of a nearby blast sequence on the tailing dam. The blast recording is transformed using a continuous wavelet analysis to reveal the time-frequency pattern of the ground motion. Before the occurrence of the blast, the wavefield is dominated by 10-30 Hz waves. At 20s the blast is recorded and radiates seismic energy from 3 to 300 Hz. This energy rapidly decays and soon after the blast sequence we retrieve the dominance of the wavefield by the 10-30 Hz range. In the dozens of seconds following the blast's strong shaking, we identify a gain of energy around 5 Hz, which is close to the fundamental frequency measured at this station. This observation means the blast sequence was strong enough to excite the resonance of the dam for about 40 seconds. Those results illustrate the utility of a permanent survey of the impact of blasts and strong shakings on the structural integrity of the tailing dam.

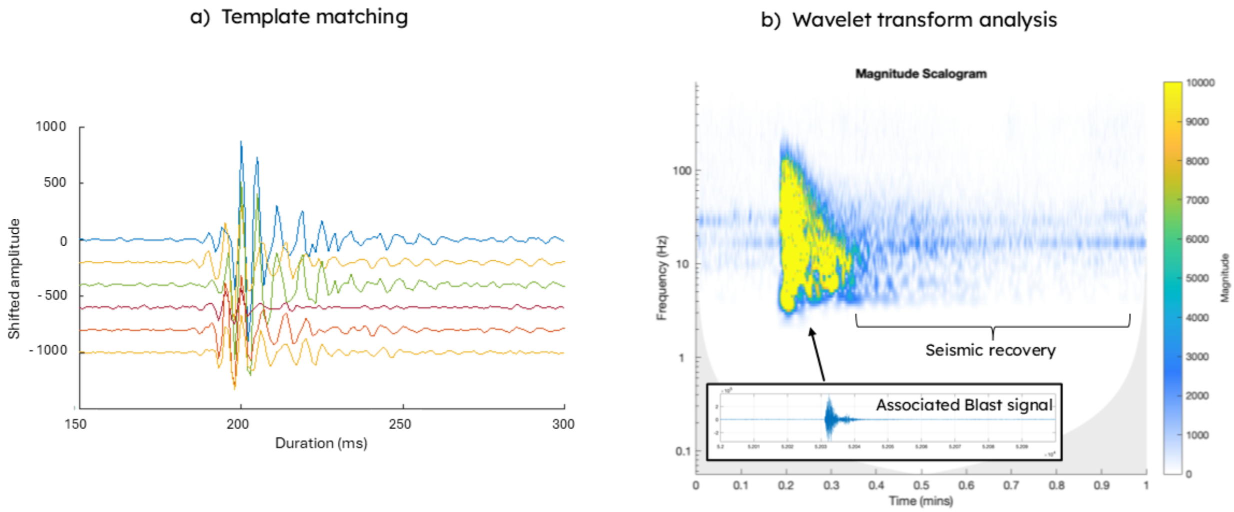

Figure 6. a) Illustration of template matching performance to identify seismic events with the same origin. Six different seismic signals with coherency > 0.9 were identified within the same day. b) Illustration of wavelet transform analysis for assessment of structural and recovery response to seismic events.

CHARACTERISATION – RESONANCE FREQUENCY AND DAMPING RATIO

Resonance frequency and damping ratio are two geotechnical parameters that describe the seismic behaviour of geotechnical assets. Resonance fundamental frequency can be derived from the analysis of horizontal to vertical spectral ratios (HVSR) computed on passive seismic noise recordings. The spectral ratio between the horizontal and vertical components of the noise signals exhibits maximum amplitude at the frequency associated with the fundamental resonance mode. The fundamental frequency identified in HVSR is generally associated with the strongest amplification factor, which means that the seismic response of the dam at this frequency will be strongly amplified and that seismic events with high energy levels at those frequencies should be particularly scrutinised as should their effect on the geotechnical asset health status post-event. Along with the amplification factor, engineers should also determine the damping ratio to complete the modelling of the seismic response of the dam to a strong shaking. Here again, continuous seismic noise measurements can be used to infer the damping factor of soil through the random decrement technique (Castaletto *et al*., 2024).

Figure 7 (left) shows a map of fundamental frequency values measured at each location of the 3C sensors array deployed at the tailings dam surface. The distribution of values well reflects the structure of the dam, with low fundamental frequency at the top (thick resonating layers) and higher values moving toward the toe or outside the dam (thin resonating layers). One can also observe variations along the longitudinal direction of the wall, indicating potential differences in the internal layering and structure of the dam. Such observations can be useful in comparison with other geophysical characterisation investigations to support lateral heterogeneity identification and interpretation. Figure 7 (right) shows examples of damping ratios values computed for a subset of the sensor array, for each respective fundamental frequency value. Observed damping ratios are also consistent with the dam structure evolution from top to toe, with lower damping ratios at locations of the wall where less attenuating tailings material are present.

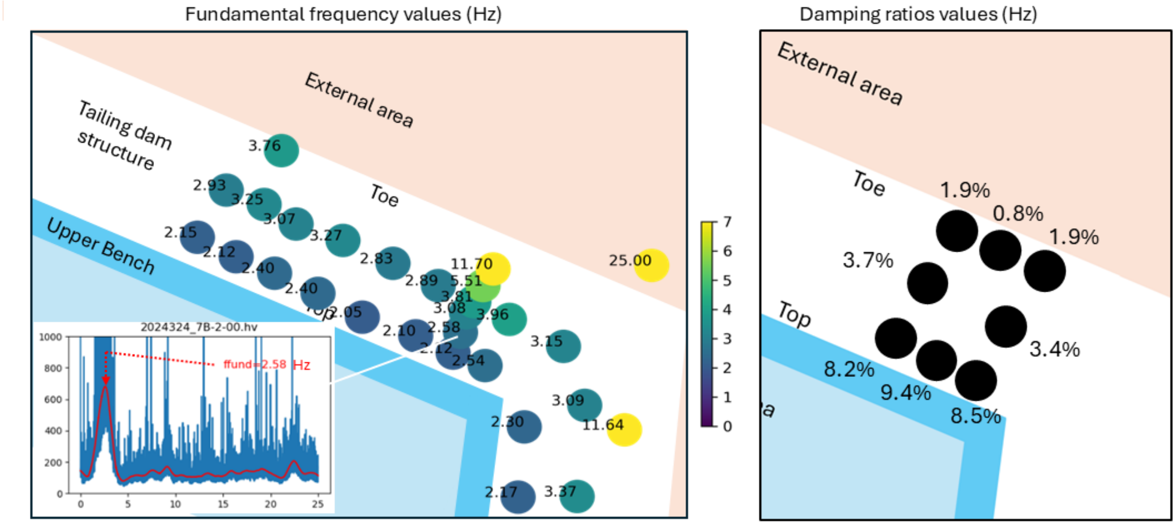

Figure 7. Left: Distribution of fundamental resonance frequency value measured for the whole array of sensors. Right: distribution of damping ratios values measured for a subset of the array during an initial phase of the project.

When used for geomechanical modelling purposes or put in comparison to microseismic analysis, both fundamental frequency and damping ratios can help anticipate the seismic response of the geotechnical asset and hence improve its management. When measured over a large array of sensors, with multiple positions, those measurements also provide insight into the lateral heterogeneities of the internal structure of the asset.

CONCLUSIONS

In this paper we have demonstrated how passive seismic measurements of the ambient seismic noise signal can be multi-purposed to bring high-value information supporting the characterisation and performance monitoring strategies of geotechnical assets such as tailings dams. The integrated solution that we propose uses one unique ambient seismic noise dataset to provide:

- **Microseismic surveillance**, following two distinct objectives:
  - Microseismic classification allows understanding the seismicity characteristics of the local and regional environment of the geotechnical asset, providing classification of the various seismic and microseismic events occurring in the area.
  - Response analysis to significant seismic events. Spectral analysis tools can help monitor the asset response following important seismic events, verifying a full recovery of the structure or indicating how it may be ageing or degrading.

- **Seismic and geotechnical characterisation:** Measuring geotechnical parameters such as fundamental resonance frequency and damping ratio values, at any location where a seismic sensor is installed, assisting engineers to anticipate through seismic response modelling how the structure will react to seismic solicitations. Note that another noteworthy seismic characterisation process that we did not address within this paper can also be derived from ambient noise signal using ANSI approach. This process is referred to as ANSI tomography (e.g,. Gerrit *et al.*, 2018) and provides a 2D or 3D static model of Vs values.

- **Seismic monitoring through ANSI application:** Providing spatial and temporal quantification of seismic Vs variations, which are known to be primarily sensitive to pore pressure evolution and geomechanical evolution. We have shown that the passive seismic Vs monitoring approach provides additional and complementary tools to:

  - Track the evolution of hydrogeological parameters: Mapping variations that are due to external events (e.g., precipitation) or mining operations (e.g., tailings deposition), within and throughout the asset.
  - Monitor the relative changes in phreatic surface level: This is achieved with a vertical accuracy and resolution in the order of 2 cm.
  - Estimate the absolute phreatic surface level depth.

  The most innovative and useful feature associated with those Vs change measurements and their physical sensitivity is the capacity of the solution to provide images of the associated phenomena, both in lateral and depth dimensions, opening the way to an accurate tracking of hydrogeological and geotechnical parameters anywhere on and within the geotechnical asset using only non-invasive, passive seismic sensors.

In conclusion, the integrated passive seismic solution presented in this paper can serve multiple objectives, from seismic characterisation to seismic monitoring, taking advantage of volumetric sensitivity features to provide a full spatial and temporal coverage of the asset. The direct link between Vs measurements and hydrogeological parameters illustrates the complementarity of this solution with the existing geophysical, geotechnical and hydrogeological tools, leading to safer and more effective dam management practices.

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