Early warning of structural deformation and deterioration processes using acoustic methods

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ABSTRACT
A serious problem with the longevity of water-retaining earth structures is their vulnerability to internal erosion (IE). Part of the energy produced during e.g. soil deformation and particle transport by fluid seepage is converted to heat and sound. The high-frequency (>10 kHz) component of this sound is called acoustic emission (AE) and its monitoring offers the potential to sense particle-scale behaviors that lead to macro-scale responses of soils. The AE detection method is unique in its capacity to specifically detect particle transport by fluid seepage (or internal instability), as has been shown in laboratory experiments. Data processing and interpretation using the amplitudes and the spectral signature of the produced signal make it possible to use AE to differentiate between fluid flow with and without particle transport – especially the transition from one to the other, or the onset of internal erosion – as well as observing the progression of erosion.

RÉSUMÉ
Un problème sérieux avec la longévité des structures en terre retenant l'eau est leur vulnérabilité à l'érosion interne (IE). Une partie de l'énergie produite pendant, par ex. la déformation du sol et le transport des particules par l'infiltration de fluide sont convertis en chaleur et en son. La composante haute fréquence (> 10 kHz) de ce son est appelée émission acoustique (AE) et sa surveillance offre la possibilité de détecter les comportements à l'échelle des particules qui conduisent à des réponses à l'échelle macro des sols. La méthode de détection AE est unique dans sa capacité à détecter spécifiquement le transport de particules par infiltration de fluide (ou instabilité interne), comme cela a été démontré dans des expériences en laboratoire. Le traitement et l'interprétation des données à l'aide des amplitudes et de la signature spectrale du signal produit permettent d'utiliser l'AE pour différencier l'écoulement de fluide avec et sans transport de particules - en particulier la transition de l'un à l'autre, ou le début de l'érosion interne - ainsi en observant la progression de l'érosion.

1 INTRODUCTION

When particulate materials undergo deformation and particle displacement part of the dissipated energy is converted to heat and sound. The high-frequency (>10 kHz) component of this sound energy is called acoustic emission (AE).

Despite being used in many industries for non-destructive examination of structural elements and materials, it is rarely used in geotechnical applications mainly due to the complexity and difficulty to measure and interpret the acoustic signal produced by particulate materials. However, AE monitoring can detect particle-scale dynamics that lead to macro-scale responses of granular materials (Smith and Dixon 2019).

Seepage-induced internal erosion (IE) is one of the main causes of embankment dam failures. It is a gradual process that tends to occur second to the particularities of each situation and structure, such as the grain size distribution, hydromechanical conditions (e.g. effective stress, hydraulic gradient, flow rate through the medium). Externally apparent structural stability is in principle maintained before deterioration has sufficiently developed internally, potentially hiding the ongoing process until it becomes critical. IE can affect the soil skeleton and lead to structural collapse.

Although it is possible to infer the presence of fluid in a structure (e.g. using electrical resistivity) or observe [advanced] external signals of its occurrence, current techniques still cannot detect its onset and the difference between seepage flow that does and does not transport particles.

Given the aforementioned and effective unpredictability of the occurrence of IE and other deleterious processes, despite attempts using e.g. computer simulations, risk estimations, scale modelling, especially in older structures that may precede modern project and construction best-practices and knowledge or even have a [somewhat] unknown internal structure) a method capable of detecting such processes in its earliest stages could offer early-warning capabilities and prevent disaster. (Foster 1999, Fell et al. 2003, Farrar et al. n.d.). AE has this potential.

AE generation is intrinsic to such occurrences since a portion of the energy involved is, essentially, inevitably converted into acoustic waves. Among the mechanisms of AE generation in soils are processes like the rearrangement of particle-contact network (release and redistribution of contact stresses) and inter-particle friction (Michlmayr and Or 2014, Smith et al. 2017, Heather-Smith et al. 2018, Biller et al. 2019) as well as seepage-induced phenomena.

The applicability of AE for soil monitoring has been demonstrated by several authors (Koerner et al. 1977, Smith et al. 2014, Heather-Smith et al. 2018, Smith and Dixon 2019). Following a series of developments that overcame previous obstacles, Smith and Dixon (2015) effectively developed a highly accurate system for monitoring and quantifying soil deformation using AE, among other developments.

Mechanical disturbances in an elasto-plastic medium can generate an acoustic response which mainly propagates longitudinally – particle oscillations occur in the direction of the wave motion, resulting in cycles of slight compression and rarefaction of the medium.

Waves can also have rotational, torsional or shear components, which are transmitted based on the material properties (Raichel 2006, Smith and Dixon 2015, Kadam and Nayak 2016). The obtained data from measuring such signals can be processed and analyzed in several ways.

Koerner et al. (1981) demonstrated the applicability of AE for soil monitoring, showing that seepage-induced internal erosion produces characteristic acoustic signals caused by particle collisions and frictional interactions, including that these emissions can be used to characterize seepage-induced phenomena (Figure 1).

Ensuing several developments that overcame previous obstacles, Smith et al. (2015) effectively developed a highly accurate system for monitoring and quantifying soil deformation using AE, among other developments. How soil properties influence the generated AE is summarized in Table 1.

The use of AE for detecting geohazards has the following prospective advantages:

- Non-intrusive
- Low cost
- Remotely monitored
- Capable of early warning

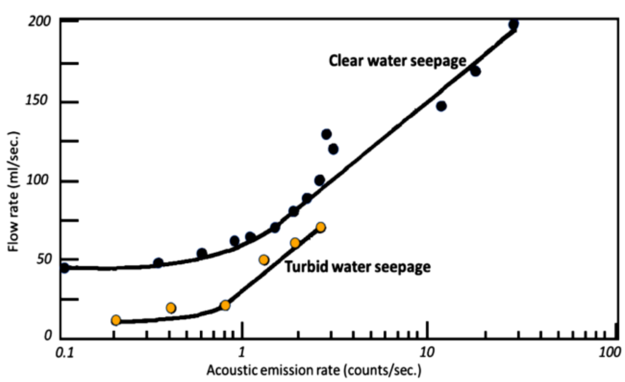

Figure 1: Relationship between AE and fluid flow in clear and turbid water seepage. Modified after Koerner et al. (1981).

Acoustic signals detected by sensors are generally converted into an electric signal that is normally amplified before being transmitted to an acquisition board, which then converts it into a digital format.

The time and frequency domains are relevant ways to analyze the produced data. In the time domain the rate and intensity of electric pulses is analyzed over time, while in the frequency domain the pulses are translated into its oscillatory components with corresponding amplitudes as illustrated in Figure 2.

Ring-down count (RDC) is one way to analyze the data in the time-domain, and is computed counting the number of times the signal exceeds an amplitude threshold in a set period of time. Figure 3 clarifies the principle of RDC that can be used for AE measurement. The use of ring-down-counts (RDC) is considered to offer a good balance considering data acquisition, storage and ease of processing. The use of RDC for AE interpretation has been successfully demonstrated by Smith et al. (2014), where slope movements have been clearly detected by the AE measured through an ingenious waveguide system inserted into the soil.

Previous to the start of measurements the AE sensors are calibrated and the output data subjected to filters with the purpose of reducing noise and focusing on the portion of the acoustic signal supposed to best represent the targeted phenomena.

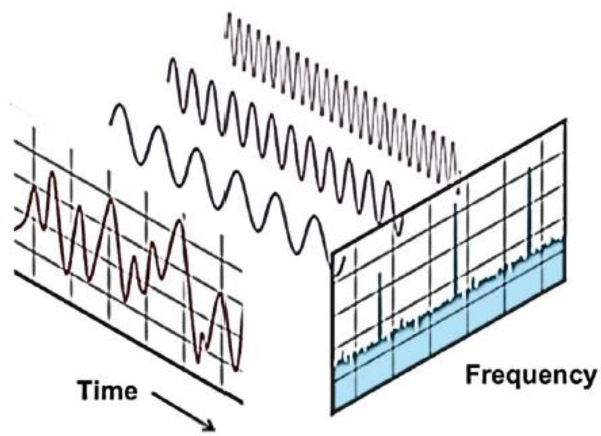

Figure 2: Illustration of Fourier Transform (FFT). The relationship between the time and frequency domains is shown by decomposed the signal into a series of sine waves - each sine wave with a particular frequency as individual peaks.

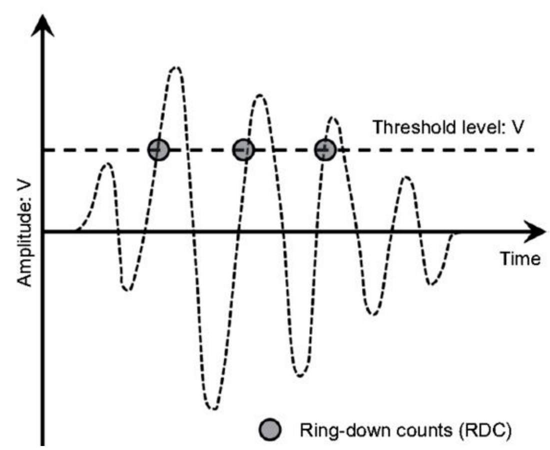

Figure 3: Illustration of the concept ring-down counts (RDC) for AE measurement (Smith et al. 2014).

Table 1: Relationship been soil properties on AE behaviour (Smith 2015).

	Property	Influence on AE
Granular soil	Coefficient of uniformity	Soils with more uniform grading and smaller values of coefficient of uniformity produce greater AE. This is because a greater surface area is achieved over which frictional interactions can occur.
	Particle shape	Angular particles generate greater magnitude AE than rounded particles.
	Particle size	Soils with larger particles generate AE with greater magnitude than those with smaller particles; however, smaller particles give rise to a greater number of AE events (due to a greater number of particle-particle interactions per unit volume).
Fine-grained soil	Plasticity index	The higher the plasticity index the lower the AE response of the soil. This is partly due to the higher clay content (i.e. greater proportion of 'quiet' soil grains) found in high plasticity soils. The influence of clay mineralogy is yet to be investigated.
	Water content	The higher the water content, and thus lower the inter-particle contact stresses, the lower the AE response.
General factors	Soil structure	The majority of research has been conducted on remolded samples and therefore the AE response of samples containing discontinuities (e.g. fissures) has not yet been investigated. It is anticipated that the soil structure has a significant influence on the AE generated, and therefore understanding the influence of soil structure is important when interpretation of AE from undisturbed soil is required
	Stress history	Due to the Kaiser effect, soils have been shown to exhibit greatly increased AE activity when stress levels exceed the pre-stress/ pre-consolidation pressure

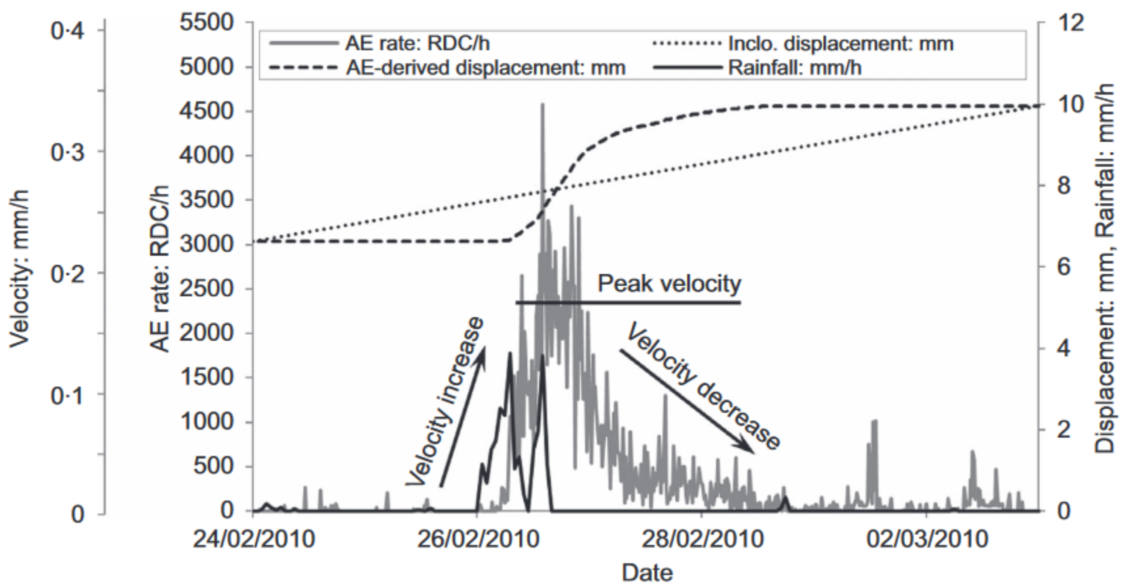

Figure 4: Demonstration of AE for the detection of slope movements. AE data is associated with rainfall and corroborated by borehole inclinometer measurements (Smith et al. 2014).

2 FOCUS

The relevance of this methodology in terms of real-world applicability is intimately related to the capacity of establishing effective and reliable monitoring systems.

A system in which real-time AE data is produced and analyzed in order to offer early-warning in the case of potential IE-related structural damage, as well as other applications of passive acoustic monitoring is to be offered. The *DMT Safeguard* platform has this potential.

It is targeted at the provision of valuable, reliable and meaningful information that allows for well-grounded decisions and actions regarding the avoidance, mitigation or remediation of structural damage.

3 APPROACH

With the installation of an adequate sensor suite being treated separately, the acquired data is transmitted to a server that then stores it gives the possibility to apply wide range of operations. Naturally, the volume and modality of data transmission can be adjusted if circumstances require. In short, the central objective of a system as proposed is to consistently monitor, analyze and transmit useful information.

Data processing may need to be calibrated to the local conditions in order to distinguish irrelevant measurements or environmental noise from the targeted signal Figure 5, Figure 6.

Figure 7 exemplifies one way of detecting signal anomalies by applying Moving Fast Fourier Transform (MFFT; FFT of a moving window of data points from a time series) to prediction error (PE) signals, which are analyzed to detect anomalies corresponding to anomalous structural behavior or structural damage - MFFT for anomaly detection applied to the frequency content of the PE signal is tracked to identify changes in structural performance, for instance mainly considering the amplitude of the lowest frequency component (Kromanis and Kripakaran 2021). This methodology implies steps such as a pre-processing phase, definition of a reference period computation of statistical features before the actual anomaly detection. Once the detection parameters are tuned to the monitored site, effectively full measurement automation may follow.

The successful completion of this step is instrumental towards to the scalability of monitoring capacity, or to the practicality of incorporating a relatively large number of sensors and surveilled assets to the platform.

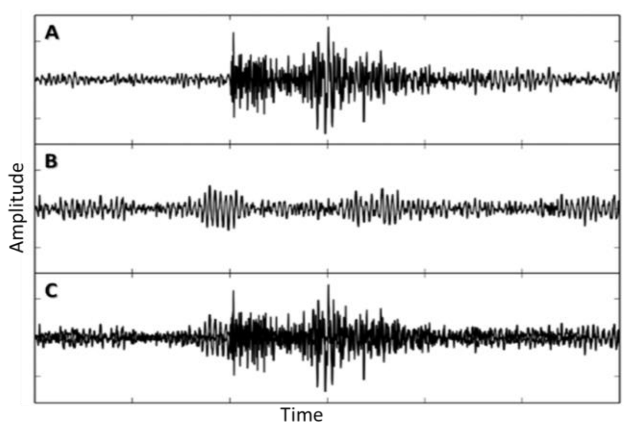

Figure 5: Example of separation of signal from noise. A) Extracted environmental noise; B) Extracted signal; C) Original measurement.

Intuitive data visualization, in a way that not only allows for easily interpretation of the obtained information but to do so for a considerably large number of data channels is a very valued feature. Therefore, the use of powerful data visualization tools, emphasis on tailoring data presentation to user needs and ample capability of employing clever, sophisticated statistical tools are already operational (and constantly improved) attributes of the monitoring platform being offered.

Cluster and dendrogram analysis, or the representation of correspondence relationships among different data arrays, can be used to e.g. classify and compare data from different sensors in order to facilitate the comparative evaluation and interpretation of measurements. Such categorizations can be then summarized in correlation matrices, further enhancing interpretative potential. Figure 8 exemplifies the implementation of this approach applied to acoustic measurements (Li Vigni et al. 2013).

Associated with the aforementioned is the ability of the system to broadcast automated alarms. Although active data examination by a trained professional is indispensable, it is quite beneficial to have a system in which notifications are automatically issued as soon as measurements reach (or approach) predefined thresholds. The definition of such thresholds, which may be linked to the direct measurements or to the results of statistical analysis, is a crucial element that requires profound knowledge of the particularities of the assets and circumstances at stake, being ideally made by both the ones responsible by the design/construction of the structure(s) and the monitoring specialists.

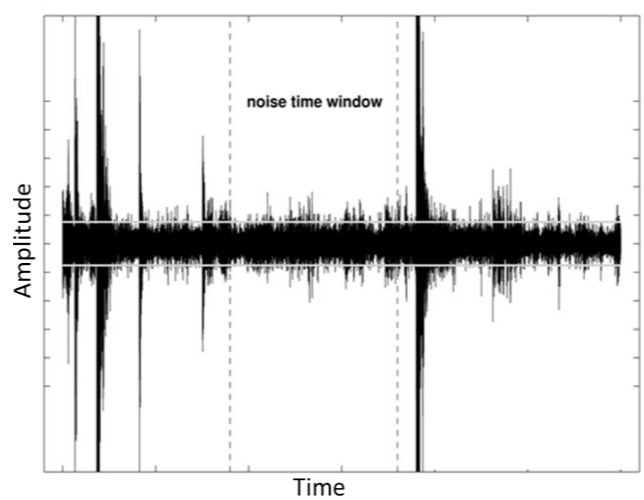

Figure 6: Illustration of acoustic signal over time in which one way of separating signal from noise is exemplified – a time window where measurement conditions are considered “neutral” (i.e. not displaying measurements corresponding to hazards) can be used to select a range of amplitudes to be effectively ignored.

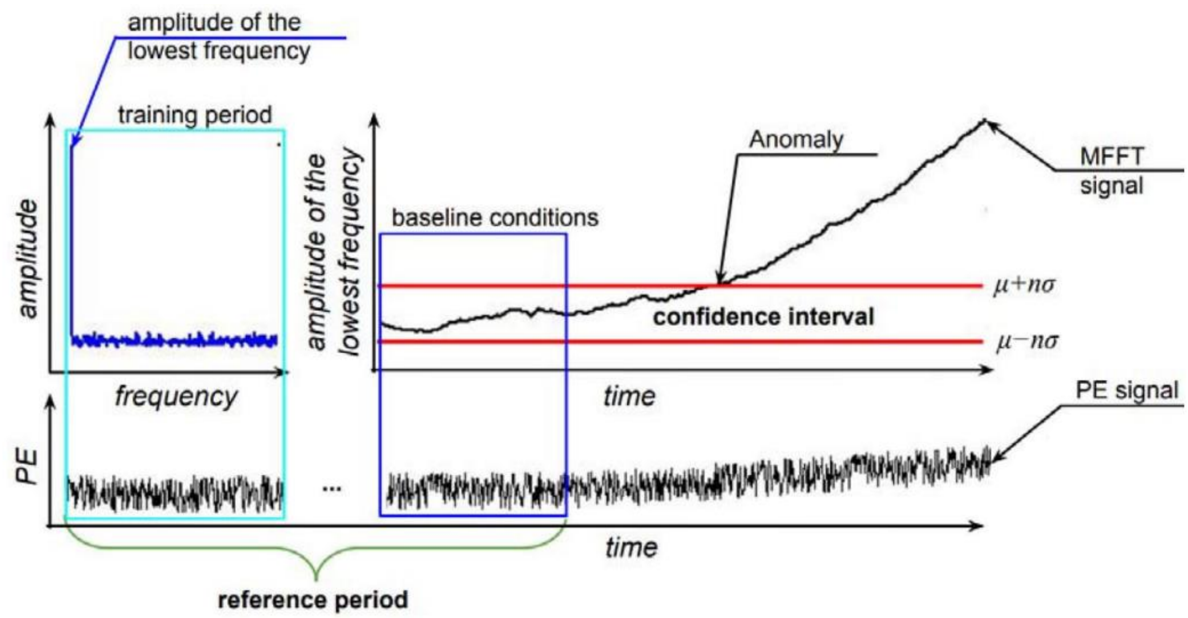

Figure 7: Illustration of signal anomaly detection using PE, MFFT and the statistical analysis. The shown confidence interval, delimited during a reference period where baseline conditions are defined, can be delineated considering Gaussian variables parameters; μ, σ and n are respectively the mean, standard deviation and an integer value greater than zero (Kromanis and Kripakaran 2021).

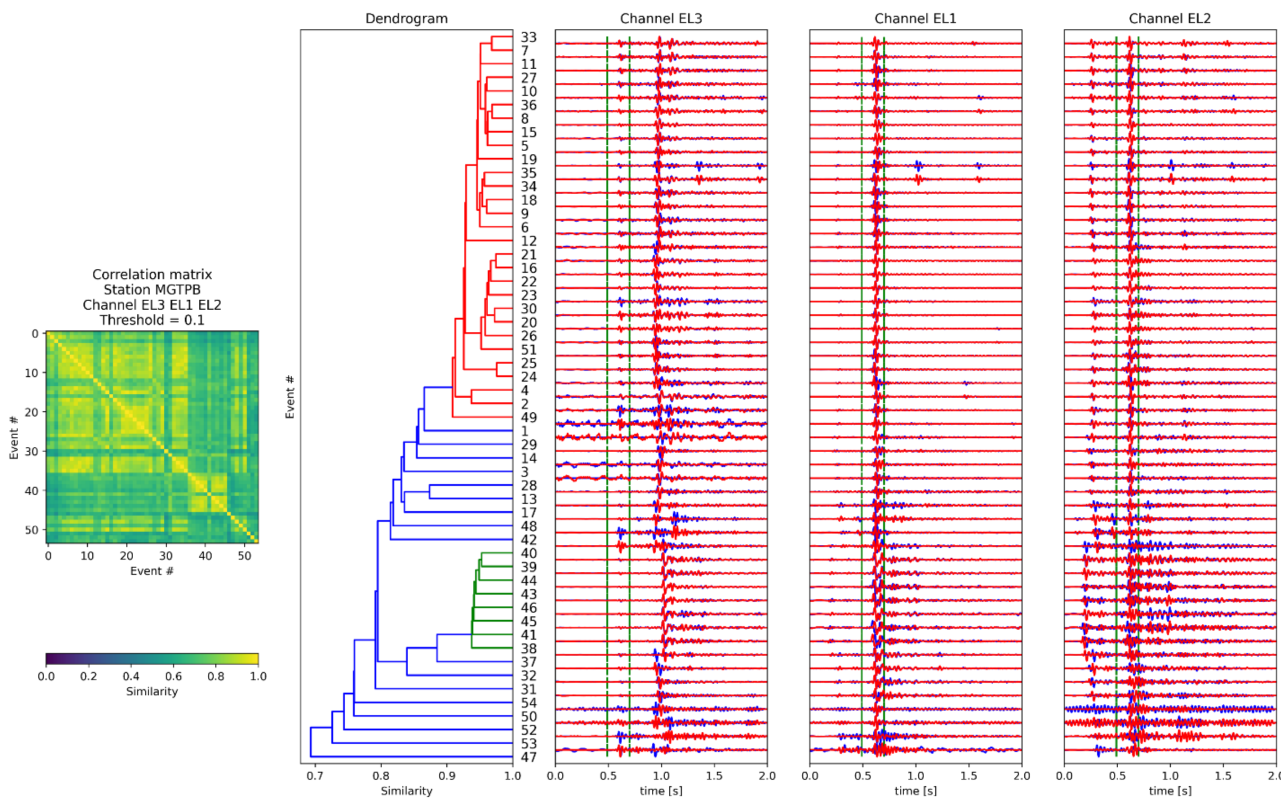

Figure 8: Representation of cluster and dendrogram analysis including correlation matrix.

4 CONCLUSION

The detection of seepage-induced internal erosion in soils, that is, the identification of particle transport provoked by a moving fluid within an earth structure, is a gap in infrastructure monitoring. There are established techniques capable of inferring the presence of fluids within soils (e.g.: geoelectric tomography) but fail to refer to particle transport. The use of AE as a technique to tackle this as well as other analogous themes is rather promising.

Given the necessity of integrating such a technique into a monitoring system in order to make it effectively implemented, the employment of a monitoring platform for this purpose is here propositioned.

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