Listening for deterioration and failure: towards smart geotechnical infrastructure

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Global change is accelerating the rate of deterioration of geotechnical infrastructure systems. There is an urgent need for monitoring strategies that can be used to assess existing, ageing infrastructure through retrofitting sensors at discrete locations to detect and provide early warning of limit state failures. This paper describes a novel approach for smart geotechnical infrastructure that 'listens' to acoustic emission generated by geotechnical asset deterioration and failure. Acoustic emission rates generated by geotechnical systems have been proven to be proportional to deformation rates. It is becoming an accepted monitoring technology for geotechnical applications; however, challenges still exist to develop widely applicable interpretation strategies. This paper places acoustic emission geotechnical monitoring in a smart infrastructure context and presents the key factors influencing acoustic emission propagation and attenuation in buried structural elements; techniques for quantifying parameters; and interpretation frameworks for extracting information and knowledge on the deformation and strength behaviour of geotechnical infrastructure systems. Acoustic emission interpretation strategies for exemplar applications (e.g. slopes, pile foundations and buried pipelines) are developed and demonstrated through element- and large-scale experiments and field trials.

Notation

A	acoustic emission (AE) waveform amplitude
b -value	measure of the proportion of low- and high-magnitude events in an AE waveform
m	log-scale measure of the AE magnitude
N	number of AE events with a magnitude greater than m

1. Introduction

Infrastructure systems are fundamental for the functioning of society. Road and rail transport infrastructure, water distribution networks and power grids can be characterised as long-linear assets. Management and maintenance require understanding of the behaviour of these infrastructure systems and detection of changes that occur along their length due to complex deterioration mechanisms. Although globally there are ambitious programmes for delivering new infrastructure to improve the quality of life (WHO and Unicef JMP, 2015), many societies will rely for the foreseeable future on existing infrastructure. Much of this was designed and constructed many decades ago to meet very different user requirements (e.g. the UK railways constructed in the nineteenth century). Continued performance of this ageing infrastructure is critical to the quality of life of individuals and prosperity of nations. Wholesale replacement of heavily used infrastructure is both prohibitively expensive and impractical. Maintaining infrastructure assets requires a greater level of information than what is currently available to deliver improved decisions. This need is driving efforts to produce 'smart infrastructure' (ICE, 2016).

Rapid technological advances are being made in geotechnical condition monitoring. Distributed optical fibre strain sensing has

been developed with applications demonstrated in a range of geotechnical assets, including tunnel linings (e.g. Cheung *et al.*, 2010), pile foundations (e.g. Pelecanos *et al.*, 2017) and retaining walls (Mohamad *et al.*, 2011). Developments have also been made employing in-place inclinometer systems (e.g. ShapeAccelArray (Macciotta *et al.*, 2016)), wireless sensor networks (e.g. Hoult *et al.*, 2009), photogrammetry (e.g. Alhaddad *et al.*, 2018; Wheeler *et al.*, 2016) and electrical resistivity tomography geophysics (e.g. Uhlemann *et al.*, 2017).

Smart infrastructure can be defined as employing technologies such as connected sensors and big-data analytics integrated with physical infrastructure to deliver real-time monitoring of performance and state, leading to better decision-making and enhanced service (Weiss, 2009). Smart infrastructure has the potential to increase safety by implementing early-warning systems in critical operations and to allow a move from scheduled and reactive to predictive and proactive maintenance schemes. However, to realise delivery of smart infrastructure, three main challenges must be resolved as defined by Hartmann (2018). These challenges are driving extensive research worldwide.

- First, there is a need to deliver 'state awareness' (ICE, 2016) whereby sensors measure the real-time behaviour of a diverse range of infrastructure systems in response to environmental drivers (e.g. loading and weather) (Soga and Schooling, 2016).
- Second, data analytics are needed to process and extract information and useable knowledge from the big data generated by sensors (e.g. Bennetts *et al.*, 2018; Lau *et al.*, 2018).

- Third, decision-making methods need to be implemented that can combine information and knowledge extracted from multiple data sources to categorise asset states, predict future behaviour and hence provide early warning of failure and inform timing of interventions (e.g. maintenance or renewal).

A further overarching challenge in delivering smart infrastructure is the need to instrument both new and existing assets. While incorporating sensor systems in new-build infrastructure is achievable with minimal disruption and at a relatively low cost (Soga and Schooling, 2016), many of the existing technologies cannot easily be retrofitted along the many thousands of kilometres of existing, ageing infrastructure (e.g. buried pipes and earthwork slopes).

This paper addresses the need for an approach that can be used to retrofit sensors on existing infrastructure, in addition to new build, and which can monitor the state of an asset and detect deterioration mechanisms and their rate of change (ICE, 2016) so that early warnings of limit states can be delivered. The focus is on geotechnical systems in infrastructure (e.g. buried pipes, foundations). The approach uses the acoustic emission (AE) generated by deformation of assets to 'listen' for deterioration and failure. Figure 1 shows an illustration of the sensing concept applied to a buried pipeline. Differential ground movement causes soil deformation and relative deformation between the soil and pipe wall, which generates high-frequency noise (i.e. AE). This AE is transmitted into the pipeline where it propagates as guided waves to distributed monitoring sensors, which interpret the AE and send warnings to decision makers by way of telemetry.

All infrastructure is constructed in/on the ground. Stress cycles and deformation of the soil/structure system can lead to deterioration of asset performance. Global change is accelerating the rate of deterioration of geotechnical infrastructure systems through, for example, weather cycles with more significant extremes and increasing magnitude and increased frequency of user loading. This novel sensing approach employs distributed monitoring locations on asset elements (e.g. pipes, piles and

retaining walls). The assets then become an integral component of the measurement system as shown in Figure 1, allowing continuous measurements to be made along extended lengths of asset (e.g. hundreds of metres per sensor), which offers significant benefits over conventional monitoring approaches that provide localised information on deformations at discrete time intervals.

The paper places AE geotechnical monitoring in a smart infrastructure context, introduces the AE sensing approach and presents the key factors influencing AE propagation and attenuation in buried structural elements; techniques for quantifying AE parameters; and AE interpretation frameworks for extracting information and knowledge on the deformation and strength behaviour of geotechnical infrastructure systems. AE interpretation strategies for exemplar applications (e.g. slopes, pile foundations and buried pipelines) are developed and demonstrated through element- and large-scale experiments and field trials.

2. AE monitoring of geotechnical infrastructure systems

AE is becoming an accepted monitoring technology for geotechnical applications (e.g. Berg *et al.*, 2018; Dixon *et al.*, 2015a, 2015b; Mao *et al.*, 2018a, 2018b; Smith *et al.*, 2014, 2019a); however, challenges still exist to develop widely applicable AE interpretation strategies. AE are relatively high-frequency (i.e. typically non-audible) elastic stress waves that propagate through materials surrounding the generation source. AE is generated when a material undergoes irreversible changes in its internal structure – for example, as a result of crack formation or plastic deformation due to ageing, temperature gradients or external mechanical forces. AE has had successful application in a range of domains, typically to detect, locate and characterise damage – for example, structural health monitoring, quality control, system feedback and process monitoring (Beatie, 1983; Grosse and Ohtsu, 2008).

Successful application of AE monitoring in geotechnical engineering has been limited until recently because a series of key challenges needed to be addressed (Smith, 2015)

Figure 1. Illustration of the AE monitoring concept applied to buried pipelines

- the high level of attenuation that soil-generated AE experiences as it propagates through soil bodies in three dimensions
- the need to filter out background noise (e.g. generated by environmental noise, construction activity and traffic)
- the requirement for unitary portable technology that can monitor AE continuously for long durations in the field environment
- the need to develop strategies for interpreting and quantifying mechanical and hydromechanical behaviour from the measured AE.

An important difference between conventional applications for AE and those in geotechnical engineering is the distinction between transient and continuous AE. Mechanisms such as crack nucleation release AE rapidly over a short, defined time period, which is referred to as a transient event. In contrast, soil bodies are made up of large numbers of particles and each particle-scale interaction generates a transient event, which combine and form continuous AE.

Proportions of the energy dissipated during deformation of, and seepage of fluid through, soils are converted to heat and sound. The high-frequency (>10 kHz) component of this sound energy is AE. Dissipated energy in soil bodies and soil/structure systems predominantly occurs due to friction, damping (i.e. particle rearrangement) and damage (i.e. degradation at particle asperities and crushing). Hence, AE sensing is a valuable technique for monitoring energy dissipation in geotechnical systems due to, for example, stress changes and deformation. Increasing AE generation rates (i.e. increasing energy dissipation within the geotechnical system per unit time) can be used to detect, quantify and interpret accelerating deformation behaviour that accompanies progressive ground failure processes for use in early warning by decision makers.

Fundamental laboratory studies on the AE behaviour of soils carried out in the 1970s, 1980s and 1990s (e.g. Koerner *et al.*, 1976, 1978, 1981, 1984; Garga and Chichibu, 1990; Mitchell and Romeril, 1984; Shiotani and Ohtsu, 1999; Tanimoto and Nakamura, 1981; Tanimoto and Tanaka, 1986) led to the following qualitative conclusions: well-graded soils generate more AE than uniformly graded soils; angular particles generate more AE than rounded particles; AE amplitude increases with particle size; higher imposed stresses generates greater AE activity; and AE activity increases with imposed strain rate. Koerner *et al.* (1981) proposed the following qualitative guide for interpretation of AE generated from soils deforming against a steel structural element: (a) no AE indicates stability; (b) moderate levels of AE indicate marginal stability; and (c) high levels of AE indicate that the geotechnical system is unstable.

The purpose of AE research in geotechnical engineering over the past 60 years has been to quantify links between measured AE and strength and deformation behaviour to enable interpretation of

the field performance of geotechnical infrastructure systems, with a focus on slope stability monitoring. Recent advances have been made in the quantitative interpretation of mechanical behaviour from AE measurements using laboratory and field experiments. A significant recent advance has been quantification of relationships between measured AE and slope deformation behaviour, enabling early warning of accelerating slope movements and failure (Berg *et al.*, 2018; Dixon *et al.*, 2015a, 2015b, 2018; Michlmayr *et al.*, 2017; Smith and Dixon, 2015; Smith *et al.*, 2014, 2017a). Relationships between measured AE and pile load–displacement behaviour are being developed (Mao *et al.*, 2015, 2016, 2018a, 2018b). AE monitoring is also being used to quantify the deformation behaviour experienced by buried pipelines subjected to differential ground movements (Smith *et al.*, 2019a, 2019b, 2019c).

3. AE propagation and waveguides

AE attenuates significantly as it propagates in three dimensions through a soil body and hence low-attenuation propagation paths (i.e. waveguides) are required to measure AE generated at depth or large distances away from the monitoring sensors. Steel suffers significantly less attenuation than soil, by orders of magnitude, and therefore, steel elements are typically employed as waveguides. For example, AE sensors can be coupled to pre-existing structural elements, such as the outside wall of piles or pipelines, to measure soil–structure interaction-generated AE associated with ground movements along a length of the structure. In slope-stability-monitoring applications, exploiting pre-existing structural elements is not always possible, and so waveguide systems must be designed and installed. Figure 2 shows the active waveguide system that is used for slope stability monitoring where the granular backfill generates AE in response to slope movements.

AE transmitted into structural elements propagate as guided waves with a range of mode types (e.g. plane longitudinal, shear

Figure 2. Illustration of the active waveguide system used for AE monitoring of slope stability

and torsional and symmetric and asymmetric Lamb), which exhibit different propagation and attenuation characteristics (Heather-Smith *et al.*, 2018; Smith *et al.*, 2017b). The scale of the wavelength compared with the cross-sectional geometry (i.e. pipe wall thickness) governs which mode types propagate (Maji *et al.*, 1997; Smith *et al.*, 2017b). Attenuation of elastic stress waves occurs in materials due to mechanisms such as geometrical spreading, internal friction, scattering, diffraction and dispersion.

Buried structural elements will have both internal and external environments and, in the case of buried pipelines, joints at regular spacings. Boundaries with discontinuities in acoustic impedance increase attenuation (i.e. loss of AE energy) – for example, the changes in cross-section at joints and differences in material properties at interfaces with the internal (e.g. water, oil and gas) and external environments (i.e. soil). A framework for quantifying the magnitude of attenuation experienced by AE in buried structural elements has been developed using numerical simulations and large-scale experiments (e.g. Heather-Smith *et al.*, 2018; Smith *et al.*, 2017b). Example AE attenuation coefficients obtained experimentally by Smith *et al.* (2017b) for air–steel pipe–air and air–steel pipe–soil tri-layer systems in the 20–30 kHz frequency range were 0.2 and 2.8 dB/m, respectively, which means that AE can propagate many tens or even hundreds of metres from the generation source to the measurement point. Attenuation in steel pipes is on the order of 100 000 times lower than in soils. Development of an attenuation framework is enabling sensor spacings to be selected for a range of buried infrastructure applications. In addition, it also enables methodologies to be developed for source localisation by using the difference in arrival times between modes with known velocities to locate the position of the originating source along the length of the asset.

Source localisation methodologies are also being developed for AE propagating through soil bodies (e.g. Koseki, 2019; Mao *et al.*, 2019). However, while these advances have a role in element-scale laboratory testing, the significant levels of AE attenuation in soil bodies highlighted earlier mean that these approaches are impractical for field monitoring.

This body of research has identified several key variables that influence AE attenuation in buried structural elements. The attenuation magnitude is a function of the cross-sectional geometry, the properties of the joints (e.g. threaded or welded), the frequency content of the AE, the propagating mode type(s) and the density, Young's modulus and Poisson's ratio of the structural element, the internal environment and the external environment. In addition, consideration should be given to the depth-dependent nature of density, Young's modulus and Poisson's ratio in the external environment (i.e. soil).

4. AE measurement and quantification

The key, generic components of an AE measurement system include a piezoelectric transducer (e.g. the Mistras R3 α sensor is

widely used in geotechnical monitoring, which is sensitive over the frequency range 0–100 kHz and has a resonant frequency of 30 kHz) to convert the mechanical AE stress waves to voltage signals that can be conditioned and processed; bandpass filters and amplifiers to improve the signal-to-noise ratio; and analogue-to-digital converters to enable digital reconstruction of the waveform for storage and analysis. Filtering is an essential part of the AE measurement sequence. By removing low-frequency signals – for example, those below 20 kHz – false alarms are avoided, as extraneous noise is removed from the measurements (e.g. traffic and construction activity). Extensive field trials of slope stability monitoring using an AE measurement system that filters outside of the 20–30 kHz range have demonstrated that extraneous noise is removed (Dixon *et al.*, 2015a, 2015b, 2018; Smith *et al.*, 2014) and false alarms are not generated.

Figure 3 shows a series of time-domain methods for AE parameter quantification. Ring-down counts (RDCs) per unit time are the number of times that the AE waveform crosses a programmable threshold level within a predefined time interval and are a measure of signal energy. RDCs are widely used for continuous AE monitoring in geotechnical engineering because they can be computed in the hardware, removing the need for digital reconstruction of the full waveform and hence significantly reducing the processing and storage requirements for battery-operated field-based measurement devices. Moreover, monitoring RDCs improves extraneous noise removal; any noise (e.g. electronic) below the pre-set threshold level is ignored.

The area under the rectified AE waveform is referred to as the signal energy, and the root-mean square is a measure of the mean amplitude. Another useful AE parameter is the *b*-value, which can be obtained from the full AE waveform data (Pollock, 1973) and is a convenient way to describe the amplitude distribution in a single value. When the AE waveform is dominated by low-amplitude events, the *b*-value is large. As the proportion of higher amplitude events increases, indicating an increase in energy, the *b*-value reduces. The *b*-value is computed at intervals using the following equations

$$1. \quad \log N = c - bm$$

$$2. \quad m = \log A$$

where *A* is the amplitude; *m* is a log-scale measure termed 'magnitude'; *N* is the number of AE events with a magnitude greater than *m*; *c* is the point that the log *N*-against-*m* relationship intersects the *y*-axis; and the coefficient *b* (*b*-value) is the negative slope of the log *N*-against-*m* relationship. In addition, frequency-domain parameters are useful where critical mechanisms have characteristic or dominant frequencies (e.g. particle crushing (Section 5)).

Figure 3. Example AE waveform with a suite of AE quantification parameters superimposed

5. AE generated by soil bodies and soil/structure systems

Programmes of drained triaxial isotropic compression and shearing (axial compression) tests on sands and direct-shear testing of sand/steel plate interfaces (Smith and Dixon, 2019a, 2019b; Smith *et al.*, 2019b) have shown that AE generation is governed by the stress level, mobilised shear strength, strain (or deformation) rate and fabric evolution (e.g. volume change

behaviour). This research has also shown that AE activity is negligible until the current stress conditions (compression and/or shear) exceed the maximum that the system has experienced in the past; this behaviour is well established in AE monitoring of materials as the Kaiser effect. Figure 4 shows typical, idealised trends obtained from cycles of load–unload–reload triaxial isotropic compression (i.e. mean effective stress in Figure 4(a)) and shearing phases (deviator stress in Figure 4(b)) and

Figure 4. Illustrative, idealised AE trends from triaxial tests on dense sand (from Smith *et al.* (2019a, 2019c)): (a) isotropic load–unload–reload cycles of cell pressure; (b) load–unload–reload cycles of deviator stress

Figure 5. Illustrative, idealised AE trends from triaxial shearing tests on dense sand (from Smith *et al.* (2019a, 2019c)): (a) deviator stress plotted against shear strain; (b) volumetric strain plotted against shear strain; (c) AE rate plotted against shear strain; (d) b -value plotted against shear strain

demonstrates that AE can be used to detect when previous maximum stress states have been exceeded.

Deviator stress is the difference between the major and minor principal stresses acting on a soil body, which causes shear (or distortional) strain. The mean effective stress represents the average stress carried by the soil solids and causes volumetric strain.

Figure 5 presents exemplar, idealised trends obtained from a series of triaxial shearing tests performed by Smith and Dixon (2019a) on dense Leighton Buzzard sand. Figure 5 shows that AE rates generated by soil bodies in shearing increase with the stress level (e.g. analogous to different asset burial depths) and are proportional to the mobilised shear strength. Figure 5 also shows that AE measurements can be used to detect peak shear strength mobilisation. Exemplar trends derived from direct-shear tests of sand/steel plate interfaces performed by Smith *et al.* (2019b) are presented in Figure 6, which shows that AE rate and b -value measurements are proportional to the relative soil/structure shearing velocity, and hence, AE monitoring can be used to quantify the accelerating deformation behaviour in such geotechnical systems.

This body of research has identified several key variables that influence AE generation in soil bodies and soil/structure systems. For example, AE generation from deformation of a buried linear, cylindrical structural element (e.g. pipe or pile) is influenced by pipe circumference, soil properties and state, pipe interface surface properties, effective normal stress, mobilised shear strength and strain rate.

Research has demonstrated that deforming soils generate significant AE within the frequency range 10–100 kHz (e.g. Koerner *et al.*, 1981; Michlmayr and Or, 2014; Michlmayr *et al.*, 2013; Naderi-Boldaji *et al.*, 2017; Smith *et al.*, 2019a, 2019b). In addition, research by Lin *et al.* (2019) concluded that particle microcracking and crushing mechanisms generate higher-frequency AE (>100 kHz) than particle interaction mechanisms such as friction and rearrangement (typically <100 kHz).

Figure 6. Illustrative, idealised AE trends from direct-shear tests performed on sand/steel interfaces (from Smith *et al.* (2019b)): (a) AE rate plotted against shearing velocity; (b) b -value plotted against shearing velocity

Figure 7. Hollin Hill landslide: (a) site plan with instrumentation clusters highlighted (UK Ordnance Survey grid reference system); (b) cross-section through the eastern lobe at instrumentation cluster 3 with exaggerated SAA3 data showing the depth to the shear surface (cross-section axes in metres) (modified from Smith *et al.* (2014))

These recent research findings, in conjunction with the AE attenuation studies, are important, as they inform the design of AE-monitoring systems for field use including selection of optimum monitoring frequency, spacing of sensors, AE characteristics of soil states and trends required to extract information and knowledge of spatial and temporal behaviour.

6. Example applications of AE monitoring of geotechnical systems

6.1 Slope stability

Extensive field trials and large-scale laboratory experiments of AE monitoring using active waveguides (i.e. steel pipes installed in boreholes with noisy coarse-grained soil surround, Figure 2) installed in slopes have produced a significant body of evidence showing that generated AE rates are proportional to the rate of slope movement (Berg *et al.*, 2018; Dixon *et al.*, 2015a, 2015b, 2018; Smith and Dixon, 2015; Smith *et al.*, 2014, 2017a). As an example, continuous AE and displacement measurements were obtained from a reactivated landslide at Hollin Hill (Figure 7) in North Yorkshire, UK. The slope moves periodically due to transient elevations in pore-water pressures. The measurements presented in Figure 8 are taken from cluster 3; AEWG3 is the active waveguide (50 mm dia. steel tube with 3 mm wall thickness, nominal 10 mm angular gravel backfill), and SAA3 is the adjacent ShapeAccelArray in-place inclinometer system. The displacement measurements were recorded by SAA3 at the 1.5 m deep shear surface. Figure 8 shows highly comparable behaviour between cumulative AE and displacement trends for seven cycles of slope movement and evidence that AE rates are proportional to slope

Figure 8. SAA-measured shear surface displacement, cumulative AE (RDC) and hourly rainfall against time for a series of slide events at cluster 3 at Hollin Hill (modified from Smith *et al.* (2014))

displacement rates. AE rates and velocity are the time derivatives of cumulative AE and displacement, respectively (Smith *et al.*, 2014).

6.2 Pile foundations

Small-scale model pile penetration tests (Figure 9(a)) performed by Mao *et al.* (2018b) demonstrated that measured AE energy was proportional to mobilised penetration resistance. Figure 9(b) shows example results from this study, where a 40 mm dia. closed-ended pile was pushed into a test box filled with silica sand. The

Figure 9. (a) Schematic diagram of the pile-penetration-testing apparatus detailed in the paper by Mao *et al.* (2018b); (b) penetration, resistance and AE energy (per 10 s) measurements from a pile penetration test performed by Mao *et al.* (2018b) (modified from Mao *et al.* (2018b))

interpretation strategy proposed by Mao *et al.* (2018b) separated AE above and below 100 kHz, which enabled the evolution of particle breakage behaviour beneath the pile tip to be interpreted.

6.3 Buried pipelines

Results from a programme of differential ground movement experiments (Figure 10) performed on buried full-scale steel pipes at the Buried Infrastructure Research Facility at Queen's University, Canada, have established that pipe–soil interaction-generated AE contains information that can be used to interpret temporal mechanical behaviour (Smith *et al.*, 2019a, 2019c). The steel pipe had an outside diameter of 167 mm and a wall thickness of 4.5 mm and was instrumented with AE sensors, strain gauges, fibre-optic strain sensing and linear potentiometers. Deformation of the soil surface was measured using an automatic total station. The synthetic olivine sand was compacted in layers to a relative density of 85%. Example results from one test performed at a burial depth of 0.6 m are summarised here. Each test stage comprised 10 mm of differential floor displacement, giving a total floor displacement of 80 mm.

Figure 11 shows the AE and vertical downward pipe displacement measurements. The cumulative AE time series was comparable with the pipe displacement time series (Figure 11(a)). A distinct transition in response takes place in the cumulative AE against displacement relationship after stage 1 (Figure 11(b)). The insert

Figure 10. Schematic cross-section of the differential ground movement apparatus with a pipe burial depth of 0.6 m (modified from Smith *et al.* (2019a, 2019c))

in Figure 11(b) shows that AE activity initiated during stage 1 after approximately 6 mm of displacement, corresponding to the fault-rupture shear band intersecting the pipe elevation. A linear regression plotted through the AE rate against displacement rate relationship (Figure 11(c), average values plotted for each test stage) resulted in an R^2 value of 0.96. This establishes the capability of the AE approach to detect accelerating deformation behaviour of a pipe/soil system for use in early warning.

Figure 11. (a) Cumulative AE and pipe displacement time series; (b) cumulative AE plotted against pipe displacement; (c) AE rate plotted against pipe displacement rate (points represent average values for each test stage) (modified from Smith *et al.* (2019a, 2019c))

7. Extracting information and knowledge from AE for decision-making

Deteriorating geotechnical systems can experience accelerating deformations and strength reductions leading to serviceability and ultimate limit state failures. Detecting the early signs of these

processes will enable decision makers to undertake timely preventative measures, reducing damage and potentially saving lives. AE offers a relatively low-cost solution (i.e. an order of magnitude lower cost than that of in-place inclinometer systems) for retrofitting monitoring systems to existing, ageing assets

because widely spaced sensors can be employed at existing access points to provide continuous, remote and real-time information on deformation behaviour.

AE has become an accepted technology for slope stability monitoring as a result of the following challenges being overcome: (a) the significant attenuation of AE in soil bodies is addressed by use of waveguides (e.g. coupling sensors to pre-existing buried structural elements or installing bespoke waveguide systems); (b) false alarms due to extraneous noise are minimised through use of high monitoring frequencies (>10 kHz); (c) rapid advances in electronics and computing power mean that battery-operated AE measurement devices can be manufactured; and (d) strategies are being developed to identify, quantify and interpret characteristic mechanical behaviour from AE measurements. However, AE monitoring is yet to become an established practice in other geotechnical domains (e.g. pipelines, foundations, earth dams and retaining structures).

As an example, research has developed an AE landslide early-warning system, named Slope ALARMS, which is able to provide early detection of progressive failure and quantify slope displacement rates ranging from 0.0001 to more than 400 mm/h. Performance of the monitoring system has been demonstrated through extensive field trials and large-scale laboratory testing (Berg *et al.*, 2018; Dixon *et al.*, 2015a, 2015b, 2018; Smith and Dixon, 2015; Smith *et al.*, 2014, 2017a). Interpretation strategies for AE slope stability monitoring have been established (e.g. Smith *et al.*, 2017a). Figure 12 shows how slope displacement rates can be quantified from measured AE rates to provide early warning of accelerating slope movements. A universal

Figure 12. AE rate-velocity calibration relationships derived for a range of active waveguide backfills plotted on log scales with the standard landslide velocity scale (Cruden and Varnes, 1996) superimposed, demonstrating that generic relationships can be obtained for groups of backfills to determine AE rate warning trigger levels based on slope displacement rates (modified from Smith *et al.* (2017a))

relationship for a range of active waveguide backfill materials is presented, which can be used to quantify changes in displacement rates. The measurements shown in Figure 12 were obtained from a series of large-scale slope failure simulations performed by Smith *et al.* (2017a). The standard landslide velocity scale is superimposed to facilitate decision-making – for example, alerts are provided when slope movement progresses through ‘very slow’, ‘slow’ and ‘moderate’ thresholds. Accelerating trends whereby the slope progresses through successive displacement rate thresholds warn decision makers of incipient failure.

Smith and Dixon (2019a, 2019b) demonstrated the benefits of using AE to monitor the behaviour of soil bodies in element-scale laboratory experiments, and they proposed a framework to interpret the soil state, including mobilisation of peak shear strength, and to quantify rates of shear strain from AE measurements (Figure 13). This is particularly valuable for

Figure 13. Example use of AE for interpreting pre- and post-peak shear strength mobilisation and accelerating deformation behaviour in dense sand (modified from Smith and Dixon (2019a))

monitoring strain-softening geomaterials, where mobilisation of peak shear strength causes shear strains to localise into concentrated shear zones, whereupon an accelerating deformation behaviour ensues, as the soil mass is weaker under the same imposed boundary stresses; this ultimate limit state can have devastating consequences for people and infrastructure. This framework combines RDC and b -value measurements to interpret an enhanced level of information about the state and behaviour of the soil compared with monitoring RDC alone. However, challenges still exist to develop AE interpretation strategies that can be used by decision makers to assess the condition of a wider range of geotechnical assets and hence provide early warning of system failure.

Informed by practice in other smart infrastructure contexts, a conceptual framework for extracting information and knowledge from AE measurements for use in decision-making is presented in Figure 14. Upward progression in the triangle (Figure 14(a)) decreases the volume of AE data and increases its value. AE parameters (time- and/or frequency-domain) are quantified from the raw AE waveform data (Figures 14(b)–14(e)), and derived information is used as input into the interpretation and decision-making process (Figures 14(f) and 14(g)). Interpretation and decision-making can use time series analysis to deliver

information on rates of change (i.e. accelerating behaviour) or employ artificial intelligence algorithms, such as pattern recognition and deep learning (Figure 14(g)), trained to output asset condition information or alerts based on a suite of AE parameter inputs.

8. Summary

Geotechnical systems approaching limit states experience accelerating deformations and strength reductions. Detecting the early signs of these processes will enable decision makers to undertake timely preventative measures, reducing damage and saving lives. Smart infrastructure employs sensors and big-data analytics to deliver real-time monitoring of the state and performance of assets, leading to improved decision-making and enhanced service. This will allow a move from scheduled and reactive to predictive and proactive maintenance schemes.

This paper describes a novel approach for smart geotechnical infrastructure that listens to AE generated by geotechnical asset deterioration and failure. The AE approach addresses the need to retrofit sensors on existing infrastructure, in addition to new build, and which can monitor the state of an asset and detect deterioration mechanisms and their rate of change so that early warnings of limit states can be delivered.

Figure 14. A conceptual framework for extracting information and knowledge from AE measurements for use in decision-making: (a) progression from raw AE data to interpretation and decision-making (modified from Bowers *et al.* (2017)); (b) raw AE waveform; (c) joint time–frequency analysis; (d) AE energy; (e) cumulative RDCs; (f) time series analysis for rates of change; (g) deep learning

AE is becoming an accepted monitoring technology for geotechnical applications, and strategies are being developed to identify, quantify and interpret characteristic mechanical behaviour from AE measurements. Exemplar interpretation strategies developed using element- and large-scale experiments and field trials are presented in the paper. However, challenges still exist to develop widely applicable AE interpretation strategies that can be used by decision makers to deliver information on the condition of a range of geotechnical assets and hence provide early warning of system failure.

The experimental results and AE attenuation framework described are informing the design of AE-monitoring systems for field use including selection of the optimum monitoring frequency, spacing of sensors, AE characteristics of soil states and trends required to extract information and knowledge of spatial and temporal behaviour. The conceptual framework presented for extracting knowledge from AE measurements for use by decision makers illustrates how raw AE measurements can be used in time series analysis and/or artificial intelligence algorithms to interpret geotechnical system state and behaviour.

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