An acoustic emission slope displacement rate sensor: Comparisons with established instrumentation

An acoustic emission slope displacement rate sensor: Comparisons with established instrumentation

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What it can do

The following are lessons learned from extensive laboratory experiments and field trials of the Acoustic Emission (AE) slope monitoring system:

- It provides information on slope displacement rates continuously and in real-time.
- It is sensitive to small displacements and very slow displacement rates.
- It is able to inform operators in real-time that a slope is accelerating (or decelerating) with quantification of changes in rates of movement.
- It continues to operate at larger displacements (at >500 mm of shear surface displacement) than other subsurface instruments.
- Inclinometer casings and standpipe piezometer pipes can be retrofitted with the AE system and converted into continuous real-time displacement rate sensors.
- Quantification of displacement rates from detected AE is independent of host slope soil.
- One sensor at a site can inform timing of site inspections and trigger manual readings of inclinometer casings.
- All sensor elements are located at ground level for ease of maintenance and reuse.
- Sensor costs are lower than current continuously read in-place inclinometer systems.
- Low-cost materials are installed in the borehole and are easily reproducible (comparable installation cost to inclinometer casings).

How it works

Acoustic Emission

AE are high-frequency stress waves that propagate through materials surrounding the generation source. In soil, AE is generated by inter-particle friction and in rock by fracture propagation and displacement along discontinuities. Hence, the detection of AE is an indication of deformation.

System overview

The active waveguide (Figure 1) is installed in a borehole that penetrates existing or anticipated shear surfaces beneath a slope. It comprises a metal waveguide tube with a granular backfill soil surround. When the host slope deforms, the active waveguide deforms, generating AE that can propagate along the waveguide. A transducer coupled to the waveguide at the ground surface converts the AE to an electrical signal, which is processed by the AE sensor. The AE sensor amplifies the signal and attenuates frequencies outside of the 20 to 30 kHz range, removing low frequency (<20 kHz) environmental background noise (e.g. traffic and construction activity). The sensor records the number of times the waveform crosses a pre-programmed voltage threshold level within pre-set time intervals; ring-down counts (RDC) per unit time (AE rates). The developed AE monitoring system is called Slope ALARMS (Assessment of Landslides using Acoustic Real-time Monitoring Systems).

Interpretation of AE

An increasing rate of displacement generates an increasing number of particle-particle/particle-waveguide interactions in the active waveguide. Each interaction generates a transient AE event, which combine and propagate along the waveguide where they are monitored at the ground surface. Hence, AE rates produced and measured by the system are proportional to the velocity of slope movement. The coefficient of proportionality is a measure of the systems sensitivity (i.e. the magnitude of AE rates produced in response to an applied velocity) and is dependent on a number of variables related to the AE measurement system, such as: the sensor sensitivity controlled by signal amplification and voltage threshold; the depth to the shear surface, which influences the magnitude of AE signal attenuation as it is transmitted from the shear zone to the ground surface by the waveguide; and active waveguide properties such as the tube geometry and backfill properties. The magnitude of AE rate responses produced by each measurement system will depend on these factors, in addition to the rate of slope displacement.

Warning messages

AE rates recorded in each monitoring interval are compared to threshold levels, which are derived for the order of magnitude slope displacement rate classifications (e.g. Cruden and Varnes 1996); ‘slow’ (e.g. 1 mm/hour), ‘moderate’ (e.g. 100 mm/hour) and ‘rapid’ (e.g. 10,000 mm/hour). If a sensor detects RDC within a set time period that exceeds a trigger warning level, the sensor transfers this to the communication system through a wireless network link. The communication system subsequently sends an SMS message to responsible persons so that relevant action can be taken (e.g. send a suitably qualified person to inspect the slope, stop traffic or other relevant action). The absence of generated SMS messages means that slope displacement rates are lower than the minimum threshold set. Automatically generated daily health SMS messages provide information on the status of the system, demonstrating it is operational. The system therefore provides continuous real-time information on slope displacement rates with high temporal resolution (i.e. monitoring periods are typically 15 or 30 minutes). Figure 2 shows an operation schematic of the AE early warning system.

Installation

Active waveguides are typically installed in 130 mm diameter boreholes, although smaller diameter boreholes can be used (e.g. down to 50mm as detailed below). A minimum depth of approximately 2 m below existing or anticipated shear surface(s) is advisable. The waveguide typically comprises lengths of 50 mm diameter 3 mm thick steel tubing connected with screw threaded couplings. The annulus around the steel tubing is backfilled with compacted angular 5-10 mm gravel. The top 0.3 m of the borehole is backfilled with a bentonite grout plug to seal against the ingress of surface water. The steel tube extends 0.3 m above ground level and is encased in a secure protective chamber. The AE sensor is located inside the protective cover. A piezoelectric transducer is attached to the waveguide and linked to the sensor via a cable. Waveguides can also be installed in inclinometer casings as detailed below.

Proof that it works

Comparisons with ShapeAccelArray (SAA) measurements

SAAs installed at Hollin Hill, a shallow reactivated landslide in North Yorkshire, UK, have allowed the comparison of continuous AE with continuous subsurface displacement measurements. A series of reactivated slope movements occurred in response to periods of rainfall that produced transient elevations in pore water pressure along the shallow shear surface (1.5 m deep) in January 2014 (Figure 3). These comparisons confirm that AE rates generated by the system are directly proportional to the rate of displacement.

Retrofitting inclinometer casings

Retrofitting inclinometer casings with the AE system has two key benefits: the provision of continuous real-time information on slope movements; and continued operation beyond displacements that would normally be sufficient to render inclinometer casings unusable (i.e. not allow the torpedo probe to pass the shear surface). To trial this approach, an inclinometer casing was retrofitted with an AE system at the Hollin Hill landslide; results from this trial for a period of movement are shown in Figure 4, which demonstrate that inclinometer casings retrofitted with active waveguides can provide continuous information on slope displacements. As the inclinometer casing diameter is only 70 mm, waveguide tubing with smaller diameter (25 mm diameter and 2 mm wall thickness) and sand backfill (sub-angular 0.6-2 mm) were employed. Active waveguides retrofitted inside 50 mm diameter standpipe casings have also been shown to work effectively.

Further information

Multiple references to publications about AE monitoring of slopes can be found at www.slopealarms.com, including further details of the system, laboratory studies and detailed case study information. Slope ALARMS sensors can be purchased from Loughborough University along with associated technical support and organisations interested in collaborating to further commercialise Slope ALARMS are invited to discuss opportunities with the authors (full contact details are given at www.slopealarms.com). A very low cost version of the sensor has been developed for use in low and middle income countries to help protect vulnerable communities, field trials are in progress and details will be available in the next 12 months. Other sources of AE monitoring systems and services are:

- www.tuv.com
- www.mistrasgroup.com
- www.physicalacoustics.com

However, it should be noted that these do not currently have equipment optimised for continuous slope monitoring in remote locations or experience of such applications.

Summary

For soil slopes, the field evidence from multiple long-term trials, supported by controlled laboratory studies, prove conclusively that AE rates measured using an active waveguide system are proportional to slope displacement rates. AE rates can show when the slope is stable, accelerating or decelerating. Therefore, when employed with user defined thresholds, AE monitoring can provide a warning of instability. In addition, the AE monitoring technique has been shown sensitive to small magnitudes of movement and very slow slope displacement rates, which means that it can provide early information on the occurrence of slope movements and changes in the rates of these movements. This information is automatically communicated in real-time to nominated parties so that appropriate actions can be taken. Monitoring of AE has been in progress at example sites for over five years with very few false alarm events, giving confidence in the robustness of the approach.

AE monitoring of rock slopes employing grouted waveguides is showing potential to provide information on rock mass displacement mechanisms. Research is on-going to establish AE signatures that can be used to warn of instability as increasing AE rates could be related to accelerating damage events at the micro-scale as precursors of a macroscopic brittle failure.

Acknowledgements

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Reference

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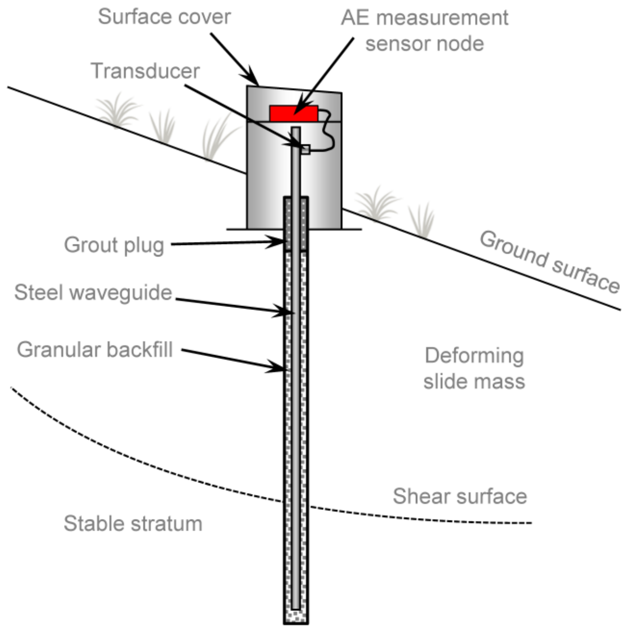

Figure 1. Schematic of an active waveguide installed through a slope with an AE monitoring sensor connected at the ground surface.

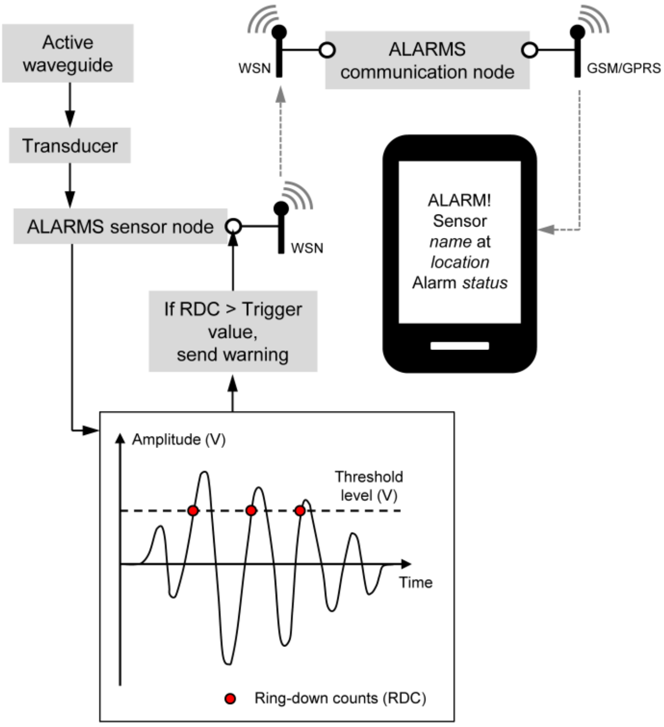

Figure 2. Schematic of operation of the AE monitoring and communication system

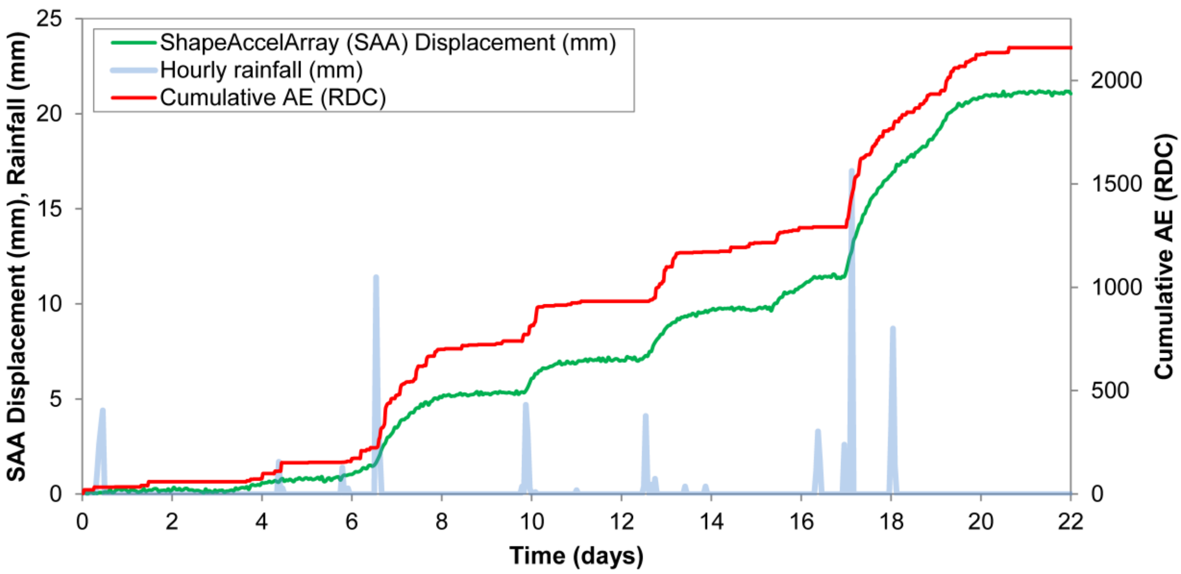

Figure 3. Time series for reactivated slope movements at Hollin Hill landslide: Rainfall, cumulative AE and cumulative SAA displacement

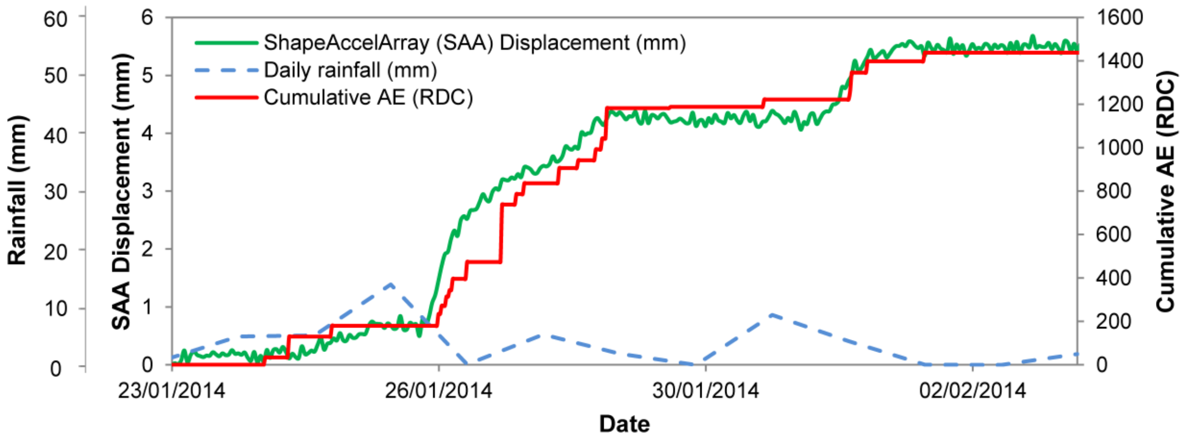

Figure 4. SAA measured displacement, retrofitted inclinometer AE and rainfall time series for a period of reactivated slope movements at Hollin Hill