Field trial of an acoustic emission early warning system for slope instability

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ABSTRACT: Slope failures world-wide cause many thousands of deaths each year and damage built environment infrastructure costing billions of pounds to repair, resulting in thousands of people being made homeless and the breakdown of basic services such as water supply and transport. There is a clear need for low cost instrumentation that can provide an early warning of slope instability to enable evacuation of vulnerable people and timely repair and maintenance of critical infrastructure. Current instrumentation systems are either too expensive for wide scale use or have technical limitations. An approach, Assessment of Landslides using Acoustic Real-time Monitoring Systems (ALARMS), has been developed and demonstrated through research. An approach developed using measurement of acoustic emission generated during the onset of slope failure to provide quantitative information on slope displacement is described. Sensor operation, deployment strategy, laboratory validation and field performance is considered. The paper presents the results of a field trial of acoustic sensors on an active landslide at Hollin Hill, North Yorkshire, and introduces additional on-going trials in the UK and Italy. Real-time monitoring of acoustic emission generated by the deforming slope has been compared to traditional inclinometer slope displacement measurements. Analysis of the results of the field trial has established that there is a direct relationship between AE and displacement rate trends triggered by rainfall events. Slope deformation events have a characteristic 'S' shaped cumulative AE vs. time relationship indicating initial acceleration followed by deceleration of the slide body.

1 INTRODUCTION

Slope failures world-wide cause many thousands of deaths each year and damage built environment infrastructure, costing billions of pounds to repair, resulting in thousands of people being made homeless and the breakdown of basic services such as water supply and transport. The large majority of deaths from slope failures occur in countries located in tropical regions (e.g. South East Asia and Central America), triggered by extreme rainfall, and in earthquake prone regions. The United Nations International Strategy for Disaster Risk Reduction (UN-ISDR) through the Hyogo Framework for Action 2005-2015 Building the Resilience of Nations and Communities to Disasters (adopted at the UN Conference on Disaster Reduction, Japan 2005) has produced a five point action plan. The second element of this plan is *Identify, assess and monitor disaster risks and enhance early warning*. Specific gaps and challenges identified include the need to develop early warning systems whose warnings are timely and understandable to those at risk.

In western countries, fatality rates are lower, however the impact on performance of infrastructure and cost of repair is high. In the UK, fatalities from slope failures are rare, but the current cost of unstable slope management is known to be considerable, although not quantified. Instability of both natural and constructed slopes presently has a significant impact on the built environment and infrastructure in the UK with many tens of thousands of people living with slope instability (e.g. Ventnor, Lyme Regis and parts of London and Edinburgh). Tens of thousands of kilometres of transport links and utilities are located in areas susceptible to failure of natural slopes. In addition, there are 20,000km of earthworks (i.e. cuttings and embankment) the failure of which has a major detrimental effect on the UK's infrastructure as demonstrated by the disruption of road and rail networks resulting from the many slope failures that occurred during periods of high precipitation in the last decade. There is growing concern that global change, in the form of climate change and increased population concentrated in urban areas, will result in a rise in the number and magnitude of slope failures causing fatalities, particularly in developing countries. In developed countries, climate change and the ageing infrastructure is anticipated to lead to increasing frequency of slope failures causing disruption to services and increased cost of maintenance).

The need for low cost instrumentation that can be used to provide an early warning of slope instability to enable evacuation of vulnerable people and timely repair and maintenance of critical infrastructure is self evident. Current systems are either too expensive for wide scale use or have technical limitations. An approach based on acoustic emission real-time monitoring of soil slopes is described. This paper extends Dixon *et al.* (2010) which introduced the approach and presented results from the first few months of monitoring at the Hollin Hill landslide using Slope ALARMS sensors. It presents the extended monitoring programme for this site and briefly introduces a number of other sites where Slope ALARMS sensors are being trialled.

2 ACOUSTIC EMISSION MONITORING OF SOIL SLOPES

Materials undergoing deformation generate acoustic stress waves (also known as acoustic emission (AE) and sub-audible noise). Studies of AE aim to use the capture and measurement of the signal to determine the extent of material deformation. In soil, AE is generated from inter-particle friction and in rock by fracture propagation and displacement along discontinuities (*microseismic* and *rock noise).* Acoustic emission can be detected using suitable transducers to provide information on the presence and location of straining.

Acoustic emission monitoring is not a new technique. It has been described in standard texts on geotechnical instrumentation (e.g. Dunnicliff 1988) and on landslide investigation (e.g. Schuster & Krizek 1978), although considerable scepticism exists regarding practicality of the technique. Stability of soil and rock slopes has been studied using AE techniques for over 50 years by international researchers, although the low energy and high attenuation of AE in soil hindered production of a viable field system. The most significant contribution in the area of AE behaviour of soil has been made by Koerner *et al.* (1981) who carried out extensive laboratory and field studies of both fundamental AE characteristics of soil and field applications. This work demonstrated that deforming soil produces detectable AE and that the levels of emissions are directly related to the stress state of the soil. More recently, a number of researchers in Japan have been active in acoustic emission research (e.g. Shiotani & Ohtsu 1999). This body of international research has demonstrated that acoustic emission is generated during soil slope movements and that AE monitoring is capable of detecting pre-failure deformations earlier than traditional instrumentation. However, interpretation of acoustic emission data has previously been only qualitative.

Dixon *et al.* (2003) and Dixon & Spriggs (2007) report research to develop a quantitative solution to this problem. Dixon *et al.* (2003) describe an approach using AE monitoring of active waveguides. Deformation of the soil body results in straining of the active waveguide system (steel tube with granular backfill surround) leading to generation of AE. Figure 1 shows a schematic of the measurement system. Initial field trials demonstrated that slope deformations can be detected using active waveguides and AE monitoring detected pre-failure ground movements before traditional direct deformation measurements. Dixon & Spriggs (2007) developed AE processing and interpretation strategies to produce relationships between AE and slope deformation rates. This research demonstrated for the first time that AE monitoring can be used to give both an early indication of slope instability and also quantification of slope movement rates. Quantification of AE is derived from calculating AE event/count rates and these can be related to rates of deformation for a given design of active waveguide. The system is also sensitive to changes in displacement rate, making the technique suitable for detection of changes in relative slope stability in response to destabilising (e.g. climate related) and stabilising (e.g. remediation) events.

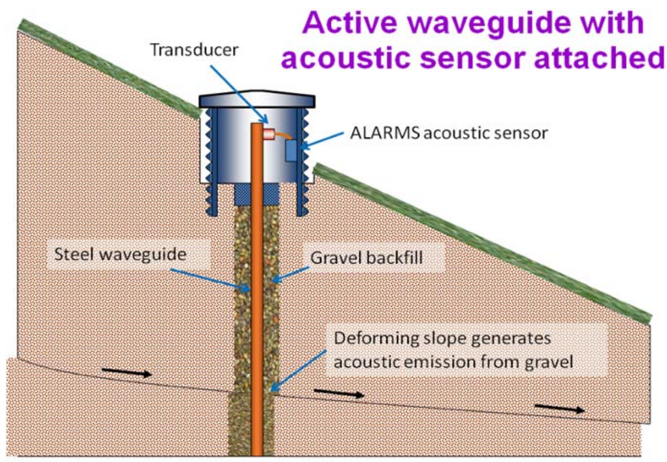

Figure 1. Schematic of the AE monitoring system, including active waveguide.

The monitoring strategy and instrumentation developed by Dixon & Spriggs (2007) was trialled in a test embankment. The PC based real-time AE soil slope monitoring instrumentation was trialled by continuous monitoring using nine waveguides for periods up to several months at a time. Monitoring demonstrated the robustness of the measuring system (i.e. minimal false alarms).

Historically a key limitation on the use of the AE technique has been the cost and complexity of monitoring instrumentation and the need for a secure instrument house and mains electricity. In order to make AE slope monitoring relevant for a range of applications and accessible to users in both developed and developing regions of the world, it became apparent that a simpler low cost system is required. This limitation has now been removed through the design of a unitary battery operated real-time acoustic emission slope displacement rate sensor called Slope ALARMS (Dixon & Spriggs 2011). This comprises a piezoelectric transducer, pre-amplifier, filters, signal processing, data storage and power supply. A version incorporating wireless communication of data has also been designed. Research sensors based on this design have been produced by the British Geological Survey in collaboration with Loughborough University. These sensors are being used in a number of proof-of concept trials as described below.

The AE sensor is located on an active waveguide, which comprises a steel tube installed in a gravel filled borehole constructed into a potentially unstable soil slope. The waveguide length can be many tens of metres long, with the length dictated by the need to intersect potential shear surfaces that may form beneath the slope. Acoustic emission are generated as the straining soil slope deforms the gravel backfill in the borehole and are transmitted to the ground surface by the steel waveguide. In real-time, generated AE are recorded at pre-defined time intervals. Measured AE rates are the number of times in each time minute period (i.e. 15, 30 or 60 minutes) that the detected signal exceeds a pre-determined threshold (traditionally called ring down counts – RDC). Derived displacement rates are accurate to an order of magnitude, which is in line with current practice for classifying slope movements.

A key element of the AE approach is the use of high monitoring frequencies (i.e. 20 to 30 kHz). Filters are used to focus AE detection within this high frequency range to eliminate environmental noise such as generated by wind, traffic, humans and construction activities. However, these relatively high frequencies attenuate rapidly in soils and fractured rock. This is the reason that waveguides are typically employed in slope monitoring studies. AE generated within the body of the slope can be transmitted to the surface by the steel waveguide. Recorded AE rates are compared to pre-determined trigger/action values. If the trigger values are exceeded, an alert message that includes the derived displacement rates is communicated to a nominated person(s) to enable relevant action to be taken.

3 HOLLIN HILL FIELD TRIAL OF AE SENSOR

3.1 *Introduction*

In order for any new instrumentation to be accepted by users there is a need to compare performance against traditional well established techniques, which for slope monitoring is inclinometer based systems. This is required to demonstrate the AE instrument is robust and can operate in the field environment, that it is capable of detecting deformation rates commonly measured using inclinometers and that there are benefits in using the new AE technique, such as improved performance (i.e. sensitivity) and reduced cost. A slope early warning system should provide sufficient warning to enable action to be taken (i.e. implement an emergency plan), it must be robust so that false alarms are not generated as this undermines confidence and also provide information on rates and magnitude of movement so that likelihood and significance of failure events can be determined. In addition, it should allow the mode of failure to be identified so that the significance of a failure event can be assessed. A field trial is currently in progress to compare unitary AE sensor performance against inclinometer measurements. An active landslide at Hollin Hill (Figure 2) was selected for the trial as in recent years slope deformations have occur during the winter months and there was confidence that measurable slope deformations would be experienced during the monitoring period. The British Geological Survey (BGS) has developed and installed at this site a permanent geophysical and geotechnical monitoring system to assess the suitability of resistivity and self-potential (SP) methods for investigating and monitoring spatial and temporal behaviour (Chambers *et al.* 2008).

3.2 *Site geology and hydrogeology*

The Hollin Hill research site [SE 6807 6883] lies 11 km to the west of Malton, North Yorkshire, UK, occupying an elevation of between 55 and 100 mAOD. The site is located on a south facing valley side with a slope of approximately 12^{o}. The bedrock geology, from the base to top of slope, comprises the Lias Group Redcar Mudstone Formation (RMF), Staithes Sandstone and Cleveland Ironstone Formation (SSF), and Whitby Mudstone Formation (WMF), which are overlain at the top of the hill by the Dogger Sandstone Formation (DF). The bedrock is relatively flat lying with a gentle dip to the north. Slope failure at the site is occurring in the weathered WMF, which is highly prone to landsliding. The landslide is characterized by shallow rotational failures at the top of the slope that feed into larger-scale slowly moving lobes of slumped material (Figure 2); the rotational features and active lobes extend approximately 150 m down the slope from the top of the hill, and extend laterally more than 1 km along the valley side. In recent years, movement of the lobes has been in the order of tens of centimetres per annum. Movement typically occurs in the winter months (i.e. January and February) when the slope is at its wettest. During this period water can be observed accumulating in the basins caused by rotational slips towards the top of the slope, and can be seen emerging from the toe of the lobes. Drainage from the site also occurs along a spring line at the base of the SSF, where groundwater appears to be running off the surface of the less permeable underlying RMF. Recently installed piezometers have revealed elevated pore pressures at the failure planes within the slipped WMF and at the interface between the slipped WMF material and the underlying SSF.

3.3 *Installation of AE waveguides and inclinometer casings*

Three pairs of active waveguides and inclinometer casings have been installed through two of the lobes (Figures 2 and 3). The waveguides were installed in 130mm diameter holes to depths of 5.7 m below ground level. The waveguides comprise two 3.0 metre lengths of 50 mm diameter 3mm thick steel tubing connected with screw threaded couplings. The annulus around the steel tubing, which is located in the centre of the borehole, is backfilled with angular 5 to 10 mm gravel. This is placed in nominally 0.25 metre high lifts, each compacted before addition of the next lift. The top 0.3 metres of the borehole is backfilled with a bentonite grout plug to seal against the ingress of surface water. The steel tube extends 0.3 metres above ground level and is encased in a secure protective chamber (Figure 3). Inclinometer casings were installed approximately 1.0 metre from the waveguides with keyways orientated along the slope dip and strike directions. The inclinometer casings penetrate to a depth of 6 metres below ground level and the annulus around the casing is grouted using medium stiffness cement bentonite

grout. Secure covers are constructed over each casing.

Figure 2. Aerial photograph of the Hollin Hill research site with the extent of the landslide lobes defined and the waveguides/inclinometer instrument locations marked (© UKP/Getmapping Licence No. UKP2008/01)

Figure 3. A view looking up the slope of the middle lobe with Cluster 1 acoustic waveguide protective cover and adjacent inclinometer casing in the foreground and Cluster 2 next to the small tree. BGS resistivity instrumentation compound and solar power array is at the top of the photograph.

Figure 4. Acoustic emission sensor and battery

3.4 *AE sensor*

A unitary AE sensor is located inside the protective cover (Figure 4). A piezoelectric transducer is attached to the waveguide and linked to the sensor via a cable. The AE sensor is powered by a battery, which is re-charged by a solar panel (Figure 3). Monitoring is continuous.

Cumulative AE ring down counts are recorded and time stamped for each 15 minute period. Monitoring commenced on 15th December 2009 at Cluster 2 and has been continuous apart from short periods due to battery failure. Monitoring at Clusters 1 and 3 commenced in February 2010 and continued until December 2010 when the sensors were removed for use on other sites (see Section 4). Initially, the data was downloaded from the sensors manually during weekly site visits to survey the inclinometer casings. However, a wireless coordinator unit was located in the BGS resistivity compound in summer 2010 which provided remote access to the sensors enabling remote downloading of the AE data. It also provided a facility for real-time communication via automated text messages of AE rates based on preset thresholds being exceeded.

3.5 *Deformation history*

Ideally, assessment of the AE sensors should be made by comparing the time history of AE measurements with a continuous time history of deformation measurements. Unfortunately in place inclinometers required to obtain continuous deformations are expensive and could not be afforded for this study. This high cost is the motivation for developing Slope ALARMS as it is anticipated that the sensors could provide a cheaper real-time monitoring alternative. The inclinometer casings were surveyed during site visits. During the first part of 2010 the readings were made weekly in an attempt to define periods of slope movement as precisely as possible. The reading frequency was extended during periods when slope movements were unlikely to occur due to relatively drier weather.

The inclinometer surveys show that the shear plane is relatively shallow at 1.5 metres below ground level. A number of deformation events can be clearly identified in early 2010, however there are no indications of slope deformations since this time, including during the 2010/11 winter months. This is a result of the unusual dry conditions during this extended period.

3.6 *Acoustic emission history*

Figure 5 shows cumulative AE for Cluster 2, rainfall per hour and the cumulative inclinometer displacements at a depth of 1 metre. Of note are the steep rises in AE, labeled Events 1 and 2, which follow intensive periods of rainfall. These increased rates of generated AE are located in periods of slope deformation indicated by the inclinometer measurements. It is concluded that these increased rates of AE events, and other similar events recorded at the three clusters, are generated by slope deformations, and hence that AE can be used as a measure of the timing and rate of slope displacement. As continuous measurements of deformation were not available, it is an assumption at this time that the steps in cumulative AE give the timing of the slope movements. However, the existence and timing of these events adds weight to the assumption. For example, measurements at Clusters 1 and 2 give AE events at exactly the same time, which is expected as they are located on the same lobe of the landslide. This hypothesis is being tested at other sites where continuous slope deformations are being measured using in-place inclinometers (Section 4).

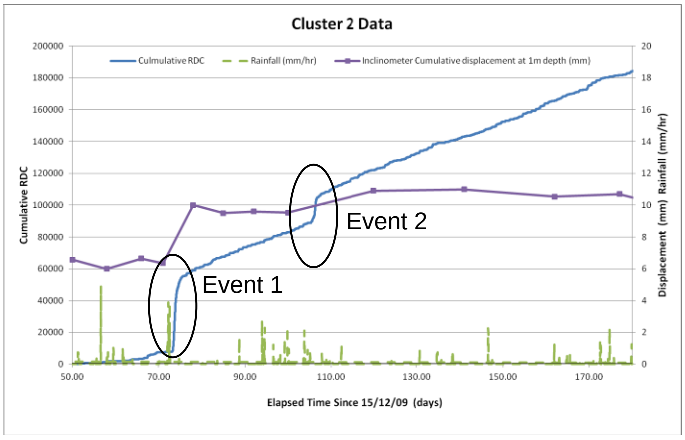

Figure 5. Cumulative AE and cumulative displacements for Cluster 2 and hourly rainfall

3.7 *Deformation event AE signature*

Figure 6 shows Event 1 at a larger scale. It can be seen that the start of AE generation is about 30 hours after the preceding rainfall event commenced. The AE rate rapidly increases, denoted by the slope of the cumulative AE vs. time relationship, and then slowly decreases, giving an 'S' shaped curve. This shape is produced by all of the AE events that are believed to be generated by slope deformations.

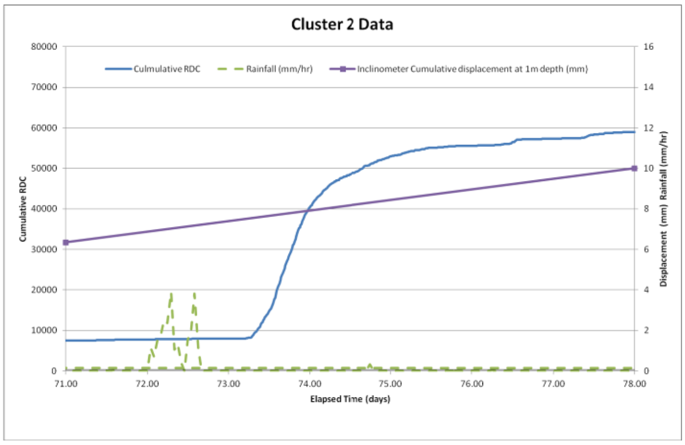

Figure 6. Cumulative AE for event 1, Cluster 2

The AE ring down count rate per hour for Event 1 is shown in Figure 7. The bell shaped relationship is produced by the 'S' shaped cumulative AE measurements and is typical of the events monitored. For this event the RDC relationship is log normal but in some of the other events it is closer to a normal distribution.

Monitoring will be continued at Hollin Hill over the 2011/12 winter period in order to record additional AE events, as it is anticipated that further slope movements will occur,

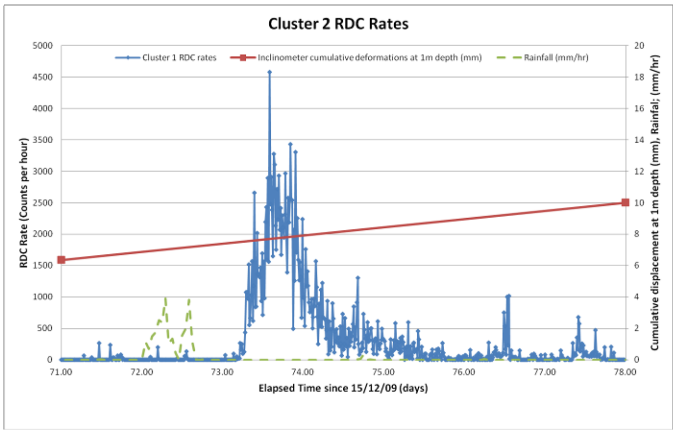

Figure 7. AE ring down count rate for event 1, Cluster 2

4 ADDITIONAL FIELD TRIALS

Field trials of the Slope ALARMS sensors are currently in progress at three sites in addition to Hollin Hill. These sites are: a cutting slope failure on the UK rail network where AE is being compared to output from an in-place continuously monitored inclinometer; a coastal landslide where re-activation threatens access to 30 properties; and a large rock slope in the Eastern Italian Alps where AE monitoring is being compared to a range of deformation monitoring methods (Dixon *et al.* 2012). All of these sites, plus a landslide in a natural slope adjacent to a major highway that will be instrumented before the end of 2011, will be monitored for the foreseeable future.

5 SUMMARY

The paper introduces the concept of using acoustic emission monitoring to assess stability of soil slopes. International research over the past 50 years has demonstrated that deforming soil slopes generate detectable AE and that rates of AE are proportional to displacement rates. Previous research by the Authors has developed a monitoring system using active waveguides and an associated processing procedure that employs quantified AE rates to measure slope displacement rates. Design of a unitary AE sensor is detailed in the paper. This is a relatively low cost real-time slope monitoring system. The AE sensor is being trialled on an active landslide at Hollin Hill, North Yorkshire, UK, where performance is being compared to traditional inclinometer slope displacement measurements. Results indicate that there is a direct relationship between AE and displacements. Increased AE rates following rainfall events are believed to indicate slope displacements. Slope deformation events have a characteristic 'S' shaped cumulative AE vs. time relationship indicating initial rapid acceleration followed by deceleration of the slide body. Field trials of the Slope ALARMS sensors at Hollin Hill and other sites are ongoing and a more detailed interpretation will be possible at the end of the 2011/12 winter period.

6 ACKNOWLEDGEMENTS

We would like extend our sincerest gratitude to Steve and Josie Gibson (the Hollin Hill landowners) for their involvement and cooperation in the research. This paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

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