Listening for Landslides: Method, Measurements and the Peace River Case Study

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ABSTRACT
Landslides cause many thousands of fatalities each year all over the globe 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 cost effective instrumentation that can provide an early warning of slope instability to enable evacuation of vulnerable people and timely repair and maintenance of critical infrastructure. An approach that uses detection and quantification of acoustic emission (AE) generated as a slope deforms has been developed through research and performance demonstrated in multiple field trials. This paper will describe the measurement system and the approach developed to quantify slope displacement rates. Measurements from long-running field trials in the UK will be shown to demonstrate performance of the method. Finally, the paper will introduce a case study at Peace River, Alberta, where the AE monitoring system is being used to monitor stability of a slope that threatens continued operation of a major highway. Initial AE readings will be presented and compared to surveys of an adjacent inclinometer casing. The influence of precipitation on generated AE and performance of the system during sustained low temperatures will be discussed.

1 INTRODUCTION

1.1 Slope monitoring

Every instrument or monitoring technique implemented on a geotechnical engineering project should be selected and placed to assist with answering a specific question: if there is no question, there should be no instrumentation (Dunnicliff 1988).

Reasons for instrumenting and monitoring a landslide include: to provide early warning of movement and of failure; to provide information for input into analysis and remediation design; to monitor landslide behaviour in response to and through construction; to verify the stability of a landslide subsequent to remediation; and to monitor the condition of infrastructure (in terms of serviceability and ultimate limit states) that have the potential to be affected by slope instability (Dunnicliff 1988; Machan & Beckstrand 2012).

Examples of important parameters to monitor are: shear surface depths; direction and rate of mass movement; and pore water pressures, be they positive or negative (i.e. suction), along a slip surface or potential slip surface as this informs of transient changes to effective stress and therefore the stability of the slope. The total magnitude of deformation is also of interest as a few millimetres of displacement can impact on the serviceability limit state of adjacent buildings and infrastructure. Additionally, soils with strain softening characteristics can exhibit a reduction in strength subsequent to the mobilization of peak strength in response to very small deformations, at which point high magnitude deformations can occur at low stresses (Skempton 1964).

The cost of remediation subsequent to landslide failure is very high compared to the cost of corrective measures and repairs prior to collapse; this highlights the importance of slope stability monitoring (Pilot 1984). Subsequent to the identification of questions that need to be answered, a cost-benefit analysis is usually performed during the design of the monitoring programme. Slope monitoring costs range from inexpensive and short term to costly and long term (Kane & Beck 2000). The labour costs associated with manual readings of instruments is high and is preferentially mitigated by the use of Automated Data Acquisition Systems (ADAS) (Machan & Beckstrand 2012).

There are many different techniques and types of instrumentation commonly used in landslide monitoring. No single technique or instrument can provide sufficient information about a landslide, and therefore various combinations are usually used. Each technique or instrument has associated capital (i.e. product and installation) and operating (e.g. labour and power) costs, along with varying degrees of performance. The performance of instrumentation is often measured in terms of accuracy and precision, spatial and temporal resolutions, sensitivity, and reliability.

Surface deformation monitoring methods investigate the change in shape of the ground surface and can provide measurements of the direction and rate of slope movement, and often provide high spatial resolution. Examples of such surface monitoring methods include: photogrammetry (aerial and terrestrial); remote sensing (e.g. InSAR and LiDAR); surveys of pegs using Total Stations or GPS; and fibre optics. Each of these techniques provides high spatial resolution but often low temporal resolution (with the exception of fibre optics) due to the time and cost required to conduct each survey and process the data. Each technique also provides varying levels of accuracy.

Subsurface deformation monitoring methods provide the information necessary for stability assessment and remediation design; one critical parameter being the depth to the shear surface(s). Sub-surface instruments often yield high levels of accuracy, although with relatively low spatial resolution as the instrument informs only of the soil surrounding the borehole in which it is installed. The traditional manually read inclinometer is the most commonly used instrument for sub-surface deformation monitoring; it is an interval monitoring instrument and offers relatively low temporal resolution as measurements can only be taken when the casing is manually surveyed. The advent of in-place inclinometers overcame this problem as the probe can be installed at the shear surface depth (once the depth has been determined from manual surveys) and can log data continuously with high temporal resolution, however; the cost of such instrumentation is high. This is the same for the ShapeAccelArray (SAA) which can very accurately, continuously, and with high temporal resolution monitor three-dimensional displacements using MEMS sensors that are installed at regular intervals along the depth of a borehole. In-place inclinometers and SAAs can also provide remote real-time information if connected to a communication system, however; all of this is expensive and usually requires monthly payments to a service provider.

There is a clear need for affordable instrumentation that can provide continuous, remote, real-time information with high temporal resolution on slope movements for use in the protection of people and infrastructure by practitioners.

1.2 Landslide movements and early warning

Leroueil (2001) defined four stages of slope movement and these are depicted in Figure 1: pre-failure; onset of failure; post-failure; and reactivation. It can be seen that the displacement rate (or velocity) vs. time relationship for both first-time failures and reactivations are expected to increase exponentially with time until a peak velocity is reached, and then subsequently decay exponentially until movement ceases and equilibrium is regained. In reactivated landslides the shear surface is already at or close to residual strength and therefore no further strain softening (i.e. loss of strength) can take place and small low velocity movements generally occur (Hutchinson 1988; Leroueil 2001). During first-time failure the velocity of the sliding mass is expected to progress over several orders of magnitude; from the gradual development of a defined failure surface at low velocities, to the subsequent strength loss during brittle failure at high velocities. The order of magnitude slope displacement rate classifications initially developed in Transportation Research Board (1978) and later modified by Cruden & Varnes (1996), and Anderson & Holcombe (2013, p92) are shown in Figure 2. The velocity scale varies over several orders of magnitude, from millimetres per year to metres per second.

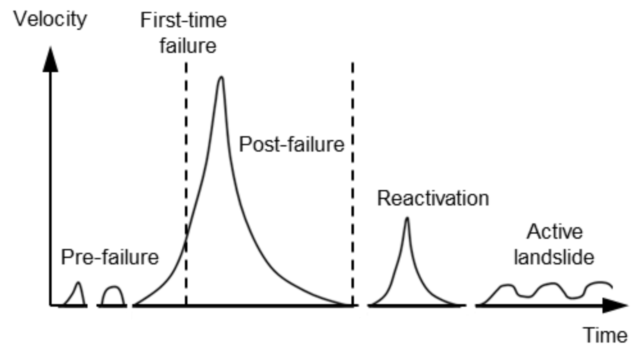

Figure 1. Stages of landslide movement after Leroueil (2001)

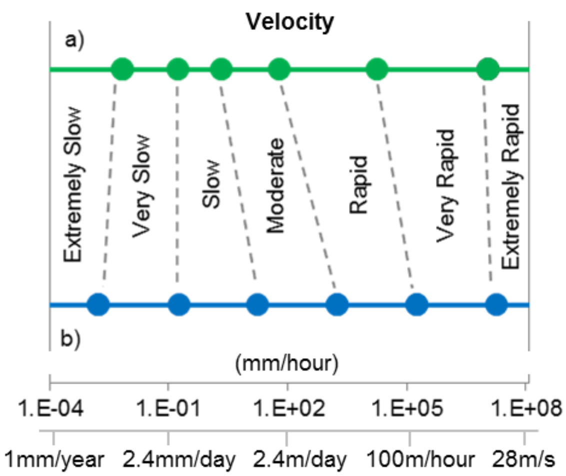

Figure 2. Landslide velocity scale after a) Transportation Research Board (1978) and b) Anderson & Holcombe (2013, p92)

It is important that early warning systems used to detect such catastrophic first-time failures have heightened sensitivity and can detect accelerations of movement as early as possible. The time lag between the approach of failure being detected and communicated to full failure taking place needs to be as great as possible in order to enable evacuation of vulnerable people and timely repair and maintenance of critical infrastructure. An early warning system must also be robust so that false alarms are not generated as this undermines confidence, it should allow the mode of failure to be identified and the rates and magnitude of movement should be indicated so that the likelihood and significance of failure events can be determined.

Current 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) based on detecting and quantifying acoustic emission generated by deforming soil slopes has been developed and trialled using unitary battery operated sensors.

This paper will describe the acoustic emission measurement system and the approach developed to quantify slope displacement rates. Measurements from long-running field trials in the UK will be shown to demonstrate performance of the method. Finally, the paper will introduce a case study at Peace River, Alberta, where the AE monitoring system is being used to monitor stability of a slope that threatens continued operation of a major highway.

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 (also termed 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 in geotechnical applications. It has been described in standard texts on geotechnical instrumentation (e.g. Dunnicliff 1988) and on landslide investigation (e.g. Schuster & Krizek 1978). 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 has 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 soil AE research (e.g. Fujiwara et al. 1999, Shiotani & Ohtsu 1999), and in Switzerland (e.g. Michlmayr et al. 2013). 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. The low magnitude signals and high attenuation attributed to the quiet cohesive soils that are found within many slopes necessitates the introduction of sources of increased AE activity, and a waveguide to transport the signal. The 'active' waveguide is installed in a borehole that penetrates stable stratum below any shear surface or potential shear surface that may form beneath the slope. It comprises a metal waveguide rod or tube that provides a low resistance path for AE signals to travel from the source to the sensor at the ground surface. The annulus surrounding the waveguide is backfilled with granular 'noisy' soil. When the host soil slope deforms, the column of granular soil also deforms and this induces relatively high levels of AE that can propagate along the waveguide. The AE produced from this system does not relate directly to the stress state of the host soil slope, however, through calibration of the system it is possible to relate AE behaviour of the soil column with deformations of the ground. AE in the active waveguide system is induced by a variety of mechanisms: straining of the steel tube directly (i.e. in bending); shearing at the interface between the backfill and the waveguide; and compression and shear within the backfill material (i.e. inter-particle friction).

Dixon et al. (2003) describe the AE monitoring case study of a coastal slope at Cowden, north-east England. The slope was formed of 20 m high cliffs of stiff glacial till and was experiencing rotational sliding due to erosion of the toe. The project comprised the installation of a variety of waveguides and inclinometers, both of which were read at intervals. Each reading from the active waveguide took the form of sampling the AE signal envelope for a 3 minute period, from which the area under the signal was determined (i.e. a measure of AE energy). Figure 3 shows the time series of measurements; the active waveguide comprised a steel tube with gravel backfill. Note that the onset of movement occurred prior to the first readings being taken, however; the displacement- and AE energy-time series show similar behaviour and demonstrates the potential for the AE technique to detect changes in displacement rate during first-time failure.

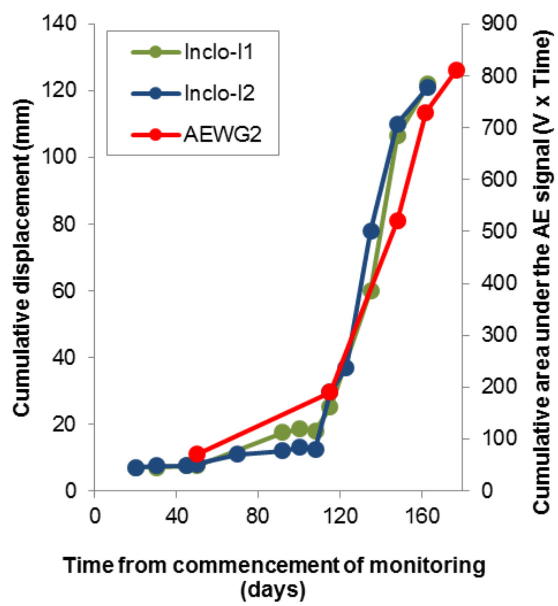

Figure 3. Cumulative displacement- and AE energy- time series from the Cowden monitoring experiment after Dixon et al. (2003)

Dixon & Spriggs (2007) found that by applying displacement rates that were separated by orders of magnitude (i.e. slow, moderate and rapid as in Figure 2) to active waveguide models in the laboratory, the magnitude of AE rates generated were also separated by orders of magnitude, and proportional to the displacement rate applied. This research demonstrated for the first time that AE monitoring can be used to give quantification of slope movement rates.

3 THE SLOPE ALARMS SYSTEM

Historically, a key limitation on the use of the AE technique has been the cost and complexity of the monitoring instrumentation and the need for secure instrument housing and mains electricity. In order to make AE slope monitoring relevant for a range of applications and accessible to users, it became apparent that a simpler low cost system is required. This limitation has now been removed through the conception 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. Various parameters can be determined from the AE waveform and a selection of these is shown in Figure 4. In order to reduce the amount of processing power and storage capacity required from a battery operated sensor, the decision was made to record ring down counts (RDC). RDC are the number of times the signal amplitude crosses a programmable threshold level within a predetermined time period. Previous research has shown that changes in strain rates results in proportional changes in AE rates; a notable work being Dixon & Spriggs (2007). Research sensors based on this design and incorporating wireless communication have been designed and produced by the British Geological Survey (BGS) in collaboration with Loughborough University and they are being used in a number of proof-of concept trials in the UK, Italy, Austria and Canada.

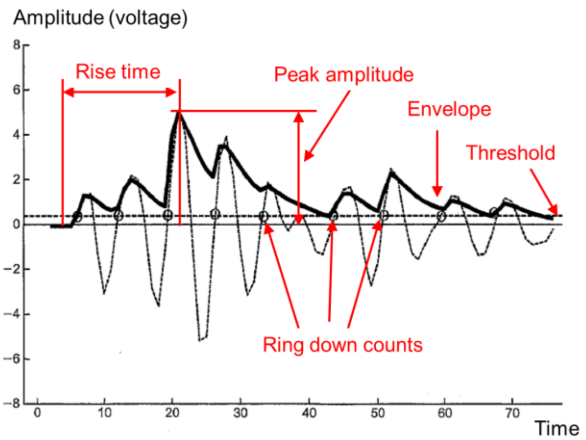

Figure 4. Example AE event waveform with typical parameters defined after Dixon et al. (2003)

The AE sensor is located on the active waveguide, which comprises a steel tube installed in a gravel filled borehole constructed into a potentially unstable soil slope (Figure 5). In real-time, generated AE are detected by the transducer and recorded by the sensor at pre-defined time intervals. Measured AE rates are the number of times in each time period (i.e. 15, 30 or 60 minutes) that the detected signal exceeds a programmed voltage threshold.

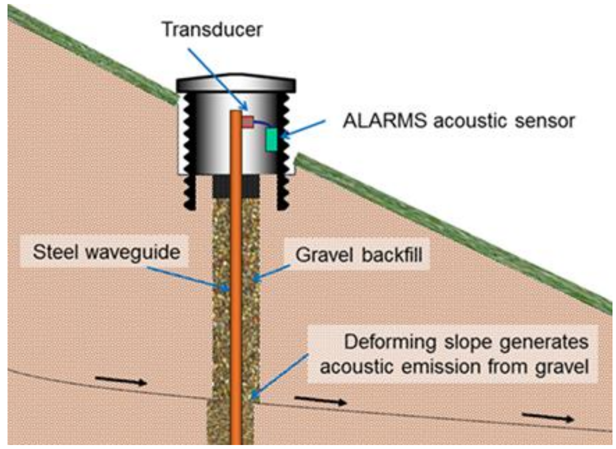

Figure 5. Schematic of an active waveguide installed through a slope with an ALARMS sensor at the ground surface

A key design aspect of the Slope ALARMS AE approach is the use of filters to focus AE detection within the frequency range of 20-30 kHz to eliminate environmental noise such as generated by wind, traffic, humans and construction activities. Recorded AE rates are compared to pre-determined trigger/action values. If a trigger value is exceeded, an alert message is communicated to a nominated person(s) to enable relevant action to be taken.

3.1 Hollin Hill field trial of Slope ALARMS

The landslide complex at Hollin Hill (described in Dixon et al. (2014a)) is characterized by shallow rotational failures at the top of the slope that feed into translational lobes of flowing material further down slope. Two of these translational lobes of flowing material were instrumented with active waveguides and Slope ALARMS sensors, along with adjacent inclinometer casings to provide sub-surface deformation measurements.

A deformation event that occurred at the reactivated landslide at Hollin Hill is shown in Figure 6. The plot in Figure 6 shows two inclinometer readings with roughly 3mm of shear surface displacement occurring between them. The triggering rainfall event can be seen prior to the sudden increase in AE rates, which is interpreted to indicate the onset of movement. The AE rate (RDC/hour) rapidly increases towards a peak value and then slowly decreases, giving a bell shaped log-normal curve. This signature shape of the AE rate-time curve is characteristic of reactivated slope deformations that have occurred at Hollin Hill and at other sites. Such reactivated slope kinematics are explained by an initial acceleration of the slide mass due to increasing pore water pressures on the shear plane, and hence reducing shear strength and stability, and a peak velocity is approached. This is followed by a deceleration of movements as pore water pressures dissipate and due to mobilisation of shear resistance internally in the slide mass and through remoulding at the landslide toe. The shape of the AE rate-time curve for the deformation event is analogous to a velocity profile. Leroueil (2001) presented a conceptual velocity-time profile for the 'reactivation stage' of slope movements that possessed the shape of a normal distribution (shown in Figure 1). The event shown in Figure 6 is analogous to such behaviour.

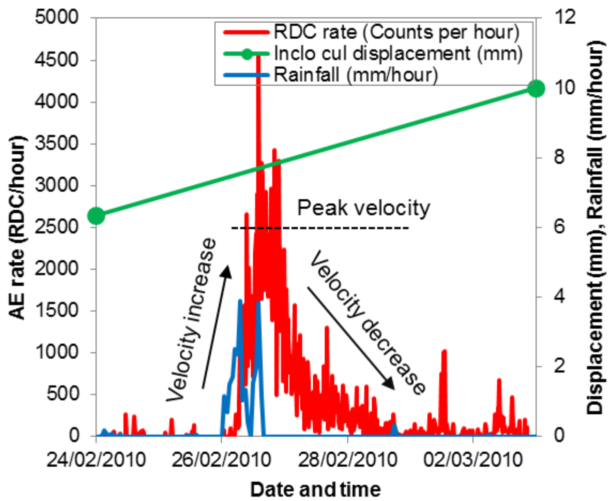

Figure 6. Reactivated landslide deformation event AE signature after Dixon et al. (2012)

The rate of landslide displacement governs the rate of straining of the active waveguide, and therefore the AE rates (RDC/hour) that are generated. Analysis of the AE time series is based on the premise that output AE rates are proportional to the velocity of landslide movement. An example calibration relationship can be seen in Figure 7 and written as a function in Equation 1; such a relationship allows the velocity of movement to be determined through monitoring AE rates.

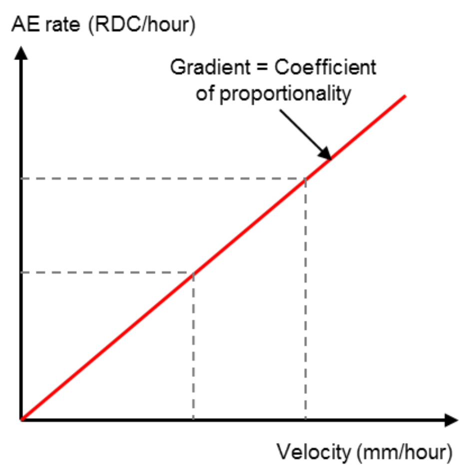

Figure 7. Calibration AE rate-Velocity relationship for active waveguide and Slope ALARMS system after Dixon et al. (2014a)

$$\text{Velocity} = (1/C_p) \times \text{AE rate} \quad [1]$$

The gradient of the relationship, or coefficient of proportionality (C_p), is a function of many 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 that influences the magnitude of AE signal attenuation as it is transmitted from the shear zone to ground surface by the waveguide; 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. As the majority of these factors are different for each system installation (sensor and active waveguide), each installation currently requires individual calibration. This method can be used to derive displacement rates accurate to an order of magnitude, which is in line with current practice for classifying slope movements (i.e. slow, moderate, rapid as defined in Transportation Research Board (1978)).

Dixon et al. (2014a) and Dixon et al. (2014b) both detail and use the AE rate-velocity relationship that has been described above. The relationship shown in Figure 7 and Equation 1 can be determined subsequent to a deformation event by equating the area under the AE event log-normal bell shaped curve to the magnitude of displacement that was measured by adjacent deformation monitoring instrumentation for the same period. The total event displacement can be distributed proportionately to each trapezoidal integrand under the curve. This will allow the velocity over each trapezoid under the curve to be determined from the displacement/time relation. This enables a velocity-time curve that is proportional to the AE rate-time curve to be produced for the displacement event; an example taken from Dixon et al. (2014a) can be seen in Figure 8.

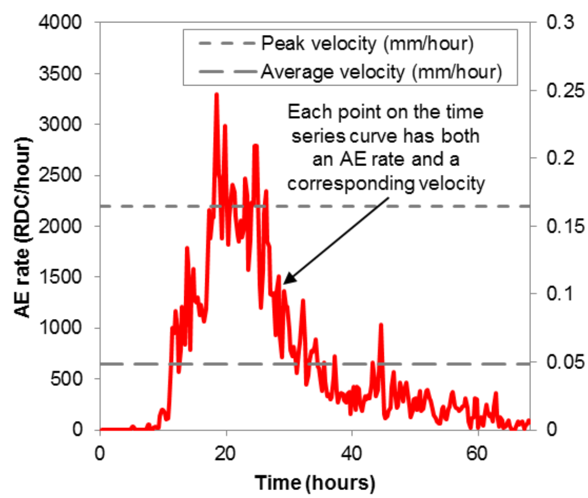

Figure 8. AE rate- and derived velocity- time relationship for reactivation event at Hollin Hill after Dixon et al. (2014a)

The sporadic nature of the AE rate data is due to slip-stick deformations taking place between the gravel particles within the backfill as interlock is overcome and regained. Indeed it would be assumed that the velocity-time profile of the slope movement would be a smoother curve of moving averaged values. Interrogation of the velocity profile for the event in Figure 8 yields an event duration of roughly 60 hours, with a peak velocity of 0.16mm/hour and an average velocity of 0.05mm/hour. This event would be classified as 'very slow' according to Transportation Research Board (1978). The systems apparent sensitivity at relatively small displacement rates indicates that the technique is suitable for detection of changes in relative slope stability in response to destabilising (e.g. climate related) and stabilising (e.g. remediation) events, and as an early warning system.

Figure 9 illustrates how the AE data can be used to produce continuous cumulative deformation data based on the calibration example in Figure 7 using Equation 1. The velocity-time profile produced from the AE data was used to determine the cumulative displacement throughout the deformation event. Displacement-time relationships for slope movement patterns are reported to exhibit similar 'S' shaped curves (e.g. Petley et al. 2005). This approach provides temporal resolution for the cumulative inclinometer data and demonstrates the potential of continuous AE monitoring using technology such as Slope ALARMS sensors to deliver continuous deformation rate information, as an alternative to traditional in-place inclinometers. This information can also be delivered remotely in real-time through the communication system.

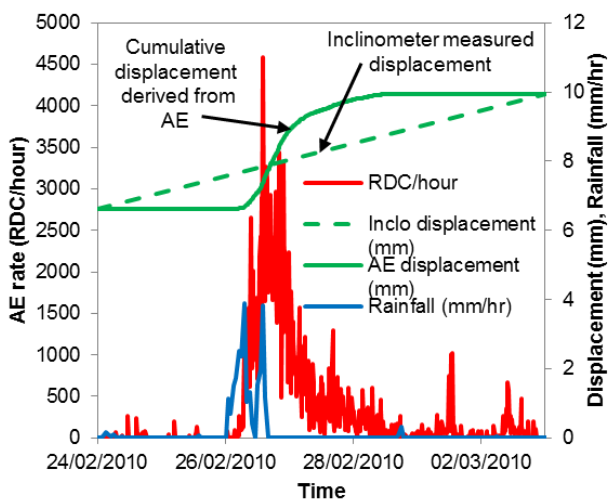

Figure 9. Derivation of cumulative displacement from AE measurements after Dixon et al. (2014a)

4 THE PEACE RIVER CASE STUDY

4.1 Introduction

The Peace River region is one of the most historically active landslide sites in Western Canada and there has been extensive landslide activity since deglaciation (Morgan et al. 2012). The common types of slope failure in the Peace River region area are translational and rotational failures, with many of these landslides impacting on road and rail lines near the town of Peace River.

The surface morphology in the area is a result of Holocene erosion and the late Wisconsin glacial event. This has led to extensive formation of colluvial deposits, which are comprised primarily of lacustrine clay (Davies et al. 2005). Lacustrine clay has relatively low strength and is responsible for many of the slope stability problems in the Peace River region, including slope failures at the Michelin site (Davies et al. 2005). The locations of the lacustrine clay layers which act as potential failure planes can be seen in Figure 10.

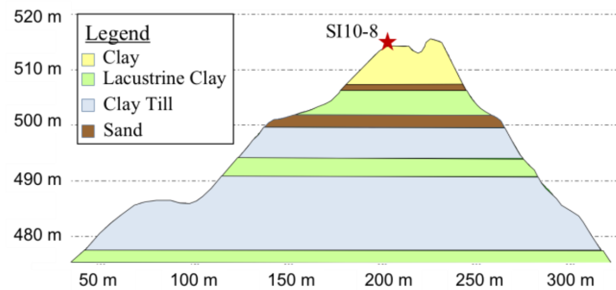

Figure 10. Cross Section of Michelin Landslide at Inclinometer SI10-8 (Section A in Figure 11) with simplified soil layers from Borehole Log 10-8

4.2 The Michelin landslide

Michelin is one of six sites located along Highway 744 which are currently being monitored for slope instability by Thurber Engineering Ltd. on behalf of Alberta Transportation. The Michelin site covers 200 m of highway between chainage 57.7 km and 57.9 km. Currently there are a series of 1 m to 4 m high scarps and several small slides on the site. These slides are located down slope of a concrete pile wall which was constructed in 1997 as part of a stabilisation attempt (Thurber 2009). The location of the Michelin landslide site along Highway 744 can be seen in Figure 11.

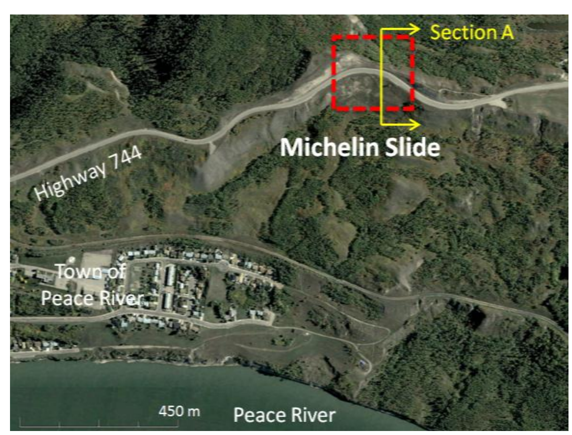

Figure 11. Location of Michelin landslide along Highway 744, the placement of the cross section in Figure 10 is shown as Section A

Initial problems were observed at the Michelin site in 1988, four years after the construction of the highway. Between 1988 and 1992 slope stabilization was attempted by installing cement stabilised stone columns along the length of the site. However, the slope remained unstable and slide activity during 1992 caused settlement to occur along the outer 1/3 of the columns. Due to the continued movement of the slope, inclinometers were initially installed in 1992. In 1997 a 50 m wide slide occurred at chainage 57.8 km requiring further remediation using a combination of a shear key, a toe berm and light weight fill (shredded tires). Since 1999, when the last stabilization effort was completed, some settlement and cracking has been noted as well as continued movements measured at depth by the inclinometers (Thurber 2009).

4.3 Queen's-Loughborough research

Queen's University and Loughborough University are trialling two emerging landslide monitoring technologies at the Peace River site; AE monitoring (Slope ALARMS), and unmanned aerial photogrammetry (unmanned aerial vehicle – UAV).

Aerial photogrammetry utilizes high resolution images taken by an unmanned aerial vehicle (UAV) to generate high-density point cloud data and orthorectified images. These images are used to quantify and visually document the evolution of a landslide. The use of UAV images has been used for a similar field study of the sensitive clay landslide at Mud Creek in Ottawa. However, due to the brittle nature of the sensitive clay it is very difficult to capture images of pre-failure deformations. Instead, images tend to be either "pre-failure" or "post-failure." The field study at Peace River, which has less sensitive soil, will allow for the currently used image analysis techniques to be further developed in order to more precisely quantify the rate of ongoing landslide movements from visual images.

The first North American field trial of Slope ALARMS is also being conducted at Peace River. This field study will allow the Slope ALARMS system to be trialled in a new field environment, and specifically test performance throughout sustained low temperatures.

Peace River was selected as a research site as there have been a large number of historical landslides in the area. Many translational failures have occurred along Highway 744 in the past, including a large failure in May of 2013. This failure resulted in the road being closed for several months. Since Highway 744 is one of only two access routes to the east side of Peace River, closure of the road severely impacts on transportation. In addition, the highway is located upslope of the CN railway and downslope of a gas pipe line. The risk associated with slope movements impacting on the operation of this infrastructure has triggered Thurber Engineering Ltd.'s monitoring programme; the site is monitored using inclinometers, piezometers and periodic visual inspection. These already installed instruments provide a reference for the AE measurements and aerial photographs. Peace River is also ideal for testing landslide deformation technology since it is currently undergoing continuous movement as opposed to large sudden failures. The site is also ideal for testing the use of aerial images to measure slope displacement due to the lack of large trees, which impede image correlation.

4.4 The monitoring programme

Currently there are seven slope inclinometers and six piezometers installed at the Michelin landslide site. The instrumentation location plan can be seen in Figure 12. The location of the Slope ALRAMS waveguide and the closest inclinometer (SI10-8) are highlighted. Readings from the inclinometers and piezometers are taken twice a year unless large displacements are measured; necessitating more frequent readings.

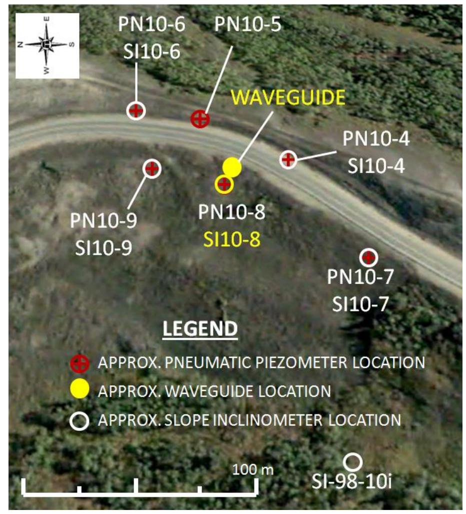

Figure 12. Instrumentation location plan at the Michelin slide, the location of the Slope ALARMS waveguide and the closest inclinometer (SI10-8) are shown in yellow

4.5 AE instrumentation installation

An active waveguide was installed in a 150 mm diameter borehole that penetrated to a depth of 21 m below ground level. The waveguide was installed in the centre of the borehole and comprised 3 m lengths of 38 mm diameter steel pipe connected with screw threaded couplings. The annulus around the steel tube was backfilled with 10 mm subrounded washed pea gravel. The pea gravel backfill filled the annulus from the base of the borehole to 11.9 m below ground level and hydrated bentonite grout chips filled the annulus up to 8.8 m below ground level. The depth of the shear surface was determined to be at roughly 16 m from an already installed inclinometer casing adjacent to the active waveguide (Figure 13).

As the AE is predominantly generated in the zone of shearing, the 'active' section (gravel backfill) of the waveguide only needed to cover a zone at the slip surface to function successfully. The bentonite grout plug was used to seal against the ingress of surface water that can potentially generate AE unrelated to slope movements and therefore contaminate the data set. Borehole spoil was used to fill the remaining annulus around the waveguide to the ground surface. The tube extends 0.3 m above ground level and is encased in a secure protective chamber. A unitary AE sensor is located inside the protective cover. A piezoelectric transducer is coupled to the waveguide and linked to the sensor via a cable. The AE sensor is powered by air alkaline batteries (Figure 14).

Cumulative AE ring down counts are recorded and time stamped for each monitoring period. Monitoring commenced at this site in July 2013 and has been continuous since. A recording period of 30 minutes and a voltage threshold level of 0.25v were used. The data was downloaded from the sensor manually during site visits at which the inclinometer casing was also surveyed. However, a wireless coordinator unit has been installed 30 m away and this will provide remote access to the sensors enabling remote downloading of the AE data. It will also provide a facility for real-time communication to mobile phone via automated text messages of AE rates based on pre-set thresholds being exceeded.

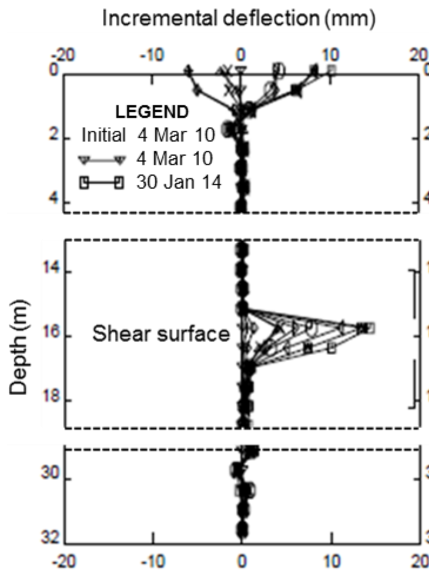

Figure 13. Inclinometer (SI10-8) report showing the depth of the shear surface

Figure 14. Waveguide with piezoelectric transducer attached, AE sensor, and batteries inside surface cover

4.6 Initial time series of AE measurements

Figure 15 shows cumulative RDC, cumulative displacement (from SI10-8) and cumulative precipitation for the initial monitoring period. Of note are the steep increases in the cumulative RDC record (i.e. the 'S' shaped curves). These show periods of increased AE rates followed by reduced AE rates, and can define periods of slope movement as described in section 3.2. A sample event (Event A) which was preceded by a period of precipitation (snow) has been selected and is shown in Figure 16 at a larger scale.

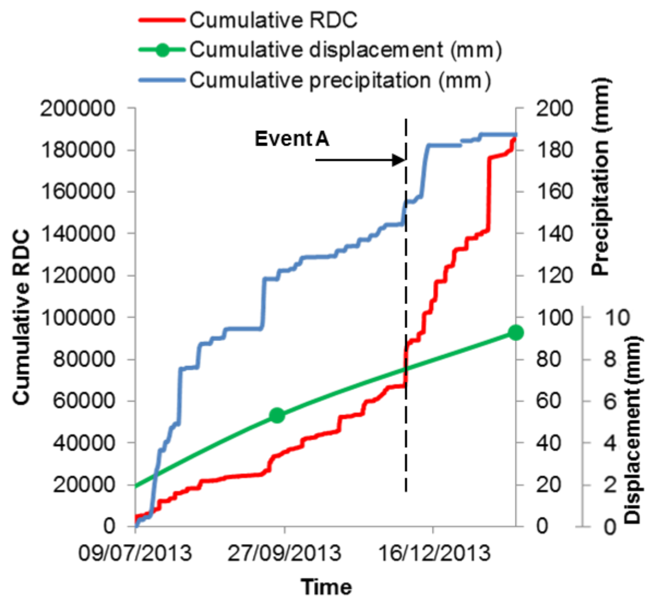

Figure 15. Cumulative RDC-, displacement- and precipitation- time, with Event A highlighted

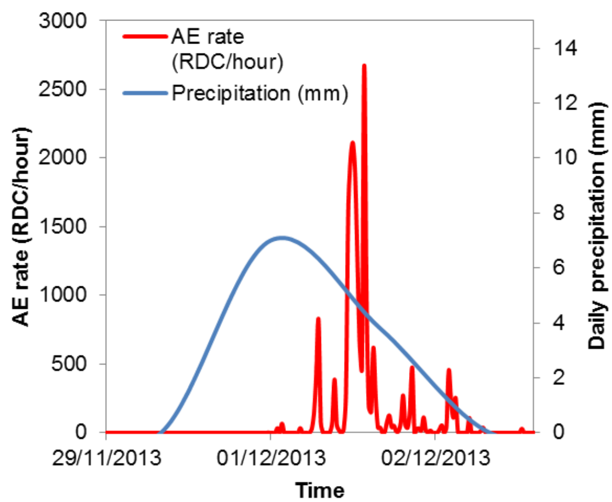

Figure 16. AE rate- and precipitation- time for Event A

It can be seen that the AE generation is triggered by preceding precipitation. The AE rate (RDC/hour) rapidly increases towards a peak and then decreases, and the curve exhibits a similar shape to the deformation events described in section 3.2. The increased AE rates in Event A were sustained for 1.5 days indicating they were generated in response to a period of slope movement. However, as continuous measurements of slope deformation were not available it is an assumption at this time that Event A was generated by sub-surface straining of the active waveguide in response to slope movement. Another hypothesis is that seepage effects are superimposed on the AE time series, and the elevated levels of AE activity in Event A could be in response to seepage through the active waveguide gravel column; either via groundwater flow through relatively permeable stratum, or infiltration from the ground surface.

Figure 17 shows cumulative RDC and daily mean temperature for the initial monitoring period. It was important to investigate the influence of the sustained low temperatures on the performance of the AE system. A sample event (Event B) which occurred during a period of changing temperature (a change of several degrees C, above and below zero) has been selected and is shown in Figure 18 at a larger scale.

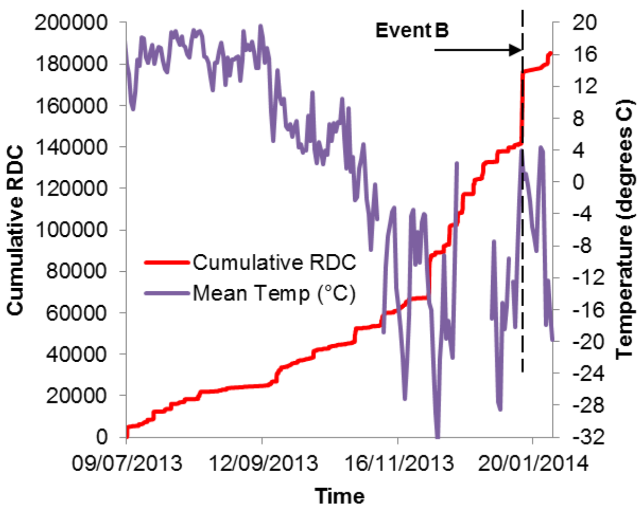

Figure 17. Cumulative RDC- and temperature- time, with Event B highlighted

The increased levels of AE activity in Event B are hypothesised to be caused by temperature changes, causing for example; physical expansion and contraction of the surface cover and/or near surface soil inducing AE within the frequency range that the sensor monitors. There is a strong possibility that many of the AE events detected after the temperature dropped below freezing could be caused by the cycles of extreme temperature changes.

The fact that the adjacent inclinometer recorded shear surface displacements during the period of monitoring suggests that the sensor has detected AE generated by sub-surface straining of the active waveguide in response to slope movement, and periods of slope movement are contained in the cumulative RDC record. However, the influence of AE generated by seepage and temperature effects also seems to be superimposed on the cumulative RDC record. The challenge is to differentiate between the AE signatures of these different events in order to filter out seepage and temperature effects from the AE time series, and ultimately determine the displacement-time behaviour of the slope with relatively high temporal resolution. This is currently being investigated. Of note is the fact that the AE system continued to operate throughout sustained sub-zero temperatures, as low as -30 degrees C.

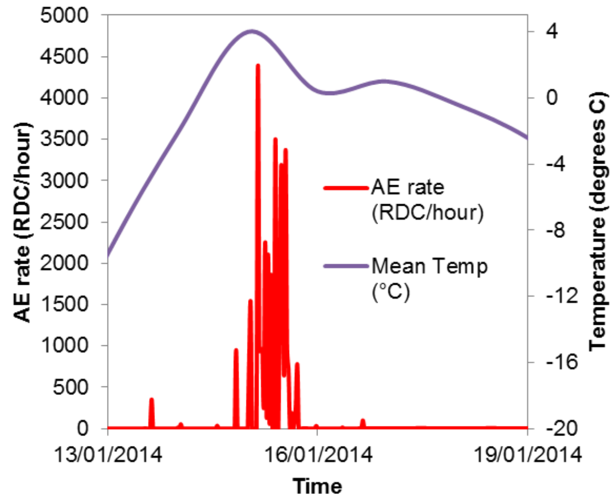

Figure 18. AE rate- and temperature- time for Event B

5 SUMMARY AND FUTURE WORK

The paper summarises 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 AE rates 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. Operation of a unitary AE sensor is detailed in the paper, which can be used to provide relatively low cost continuous real-time slope monitoring. The AE sensor is being trialled on an active landslide at Peace River, Alberta, Canada. Performance is being compared to traditional inclinometer slope displacement measurements, and will be compared to aerial photogrammetry (UAV) in the near future.

The initial period of monitoring at Peace River has shown that there are potentially three types of AE signatures, generated in response to; slope movement, seepage, and temperature changes. The current challenge is to differentiate between the AE signatures of these different sources in order to filter out seepage and temperature effects from the AE time series, and ultimately determine the displacement-time behaviour of the slope with relatively high temporal resolution. The system has been shown to continue to operate during sustained sub-zero temperatures, as low as -30 degrees C.

Field trials of the Slope ALARMS monitoring approach at Peace River and other sites are on-going and validation against continuous deformation data is expected in the near future.

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