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Analysis of acoustic emission patterns for monitoring of rock slope deformation mechanisms

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ABSTRACT

Acoustic emission (AE) is generated in soil and rock materials by rearrangement of particles during displacement or increasing damage in the microstructure preceding a collapse; therefore AE is appropriate for estimation of slope degradation. To overcome the high attenuation that characterise geological materials and thus to be able to monitor AE activity, a system that makes use of a waveguide to transmit AE waves from a deforming zone to a piezoelectric transducer was developed. The system quantifies acoustic activity as Ring Down Count (RDC) rates. In soil applications RDC rates have been correlated with the rate of deformation, whereas the recent application to rock slopes requires new interpretation strategies. In order to develop new strategies the system was installed at two rock slope trial sites in Italy and Austria. RDC rates from these sites, which have been measured over 5 and 1.5 years respectively, are analysed and clear and recurring trends are identified. The comparison of AE trends with response from a series of traditional instruments available at the sites allows correlation with changes in external slope loading and internal stress changes. AE signatures from the large rock slope in Italy have been identified as generated in response to variations in the groundwater level and snow loading. At the slope in Austria, AE signatures include the detachment of small boulders from the slope surface caused by the succession of freeze-thaw cycles during winter time. The work reported in this paper is contributing to the development of AE monitoring and interpretation strategies for rock slopes. The longer-term aim is to identify approaching failures and derive rules for setting thresholds that can be used to give warning of rock slope failures in time to enable action to be taken.

1. Introduction

Acoustic emission (AE) is the phenomenon of radiation of sub-audible stress waves produced by any material undergoing irreversible changes in its structure due to rapid energy release. These waves have typically frequencies higher than 20 kHz. In soil AE is generated by inter-particle friction (Koerner et al., 1975) and in rock materials it is generated by nucleation and propagation of new fractures and/or displacement along existing discontinuities (Hardy, 2003); hence AE is suitable to be used as a measure of deformation or degradation preceding a slope failure.

As AE radiates from the source and travels through the material, the amplitude of such waves tends to attenuate due to many factors including geometric spreading, internal friction, scattering and mode conversion (Hardy, 2003). Geological materials are characterised by high attenuation, which means that only relatively small volumes can be investigated. Koerner et al. (1981) provides attenuation ranges for soil >10 dB/cm and for intact rock in the order 10^{-1} to 10^{-3} dB/cm for frequencies of about 20 kHz. To partially overcome signal attenuation problems and to monitor larger volumes of the material, bars or tubes composed of a low attenuation solid such as steel (<10^{-4} dB/cm), referred to as waveguides, have been used in geotechnics and many other monitoring fields. The purpose of waveguides is to create a preferential low attenuation path to direct AE signals to AE sensors (Chichibu et al., 1989; Dixon et al., 2003; Shiotani and Ohtsu, 1999).

In order to monitor AE trends generated within a deforming fine grained soil slope with high attenuation, Dixon et al. (2003) conceived a system which makes use of an active waveguide to generate a stronger AE signal and transfer this to a piezoelectric transducer. Laboratory testing and field trials (Dixon et al., 2014; Smith and Dixon, 2014; Smith et al., 2014) demonstrated that an increase in deformation of a soil body (e.g. slope) results in an increase of AE activity, providing also an empirical coefficient of proportionality that links AE rates monitored with an increasing rate of deformation (velocity).

The prospect of using the system to forecast failure of rock slopes has been recently considered. Slopes composed of rocks characterised by brittle behaviour have the potential to fail catastrophically (e.g. Nichol et al., 2002) and monitoring of pre-failure deformation with classical geotechnical instruments is challenging as collapse develop very rapidly

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(i.e. very small displacement magnitude prior to large scale and rapid collapse). However, the deformation process that leads to nucleation and propagation of fractures releases acoustic stress waves, which are therefore suitable to be used as an indicator of incipient failure.

Therefore, to effectively use the system for the monitoring of rock slopes it has to be considered that not only do rock slopes show significantly different behaviour in terms of strength criteria and failure modes compared to soils, they also include discontinuities and can be much more permeable to rainfall. This means that very different AE trends are recorded. To be able to recognise trends in the AE information that are generated by slope degradation, which could ultimately lead to collapse, it is essential to understand the acoustic rock mass response to internal and external excitations. Therefore, the approach developed is to identify AE signatures for all the processes able to generate acoustic trends (e.g. temperature-related, seepage within rock fractures, groundwater level changes, seismicity, deformation, etc.) and differentiate between those that are descriptive of an ongoing deformation/degradation process and those that do not carry any useful information and can be considered as "noise".

This paper deals with recurring AE patterns detected at two trial sites, examining relations with parameters measured using traditional geotechnical instrumentation and discussing hypothesis about the possible generating processes.

2. The monitoring system

Acoustic emission in this study was detected using a sensor system attached to a waveguide. The system was originally developed for the detection of AE activity generated by deformation of slopes formed in fine grained soils (i.e. soils with dominance of silt or clay fractions) (Dixon and Spriggs, 2007; Dixon et al., 2003; Spriggs, 2004).

Acoustic emission is measured by means of a piezoelectric transducer mounted on a steel waveguide (Fig. 1). The primary function of the waveguide is to direct AE waves to the transducer located at ground level. As discussed above, high frequency waves travelling along the steel tube attenuate much less than in a fine-grained soil or a discontinuous rock medium. The waveguide is installed in a borehole, which ideally should reach the stable stratum below any shear surfaces or potential shear surfaces that may form within a soil slope or across any critical discontinuities that may lead to failure in a rock slope.

In soil applications, the gap between the waveguide and the borehole is backfilled with gravel or coarse sand. This makes the system "active" as the gravel/sand acts as a wave generator when the host soil moves (Dixon et al., 2014, 2003). The reason for introducing the generator lies in the poor acoustic properties of the host material as fine soils generate very low AE levels that are challenging to detect due to high attenuation. Adding a noisy backfill ensures that AE activity generated is sufficiently high to be transferred to the waveguide without being dissipated along the path. In rocks, the energy of generated AE is orders of magnitude greater than AE in soils and attenuation of AE is lower than in soils. Therefore, grouting the waveguide into the rock is sufficient for the stress waves generated by the deforming rock mass to be transferred from the rock to the steel tube. This is considered to be a passive system, as the grout surrounding the waveguide is not expected to be the primary source of generated AE in detected deformation events.

AE generated by deformation mechanisms on one or more discontinuities that intersect the waveguide, or in its vicinity, is transmitted by the waveguide to the piezoelectric transducer clamped at the free end (Fig. 1), which converts mechanical signal to electronic signal. The transducer is coupled with silicone gel to allow better wave transmission. A transducer with sensitivity to frequencies >20 kHz is used to limit the recording of low frequencies from environmental background noise (e.g. generated by wind, traffic and anthropic activities).

The electronic signal is subsequently processed by a computing device called a sensor node. The sensor node amplifies the signal and applies a band-pass filter that removes frequencies lower than 20 kHz and higher than 30 kHz. The lower limit is to remove background noise and the upper to restrict AE to a range that can be readily processed in this battery-powered device (i.e. higher processing rates require increased power). Ring Down Count (RDC) rates are then determined counting the number of times the signal exceeds a predetermined voltage threshold within a pre-set period of time (Fig. 2). The threshold voltage is used to remove the lower amplitude background and spurious noise, hence it needs to be set sufficiently high so that no RDC are recorded during periods of time when there are no rock deformations occurring (i.e. during periods of good weather). The user can select a value for the voltage threshold in the range 0.05–0.49 V; for the studies reported in this paper it was set at 0.25 V. The sampling frequency choice is between 1 and 60 min. Typically, time periods of 15 min are a good compromise in order to maximise memory storage capacity and yet provide the benefit of high temporal resolution monitoring. At the end of each monitoring period, the sensor compares the number of RDC counts with up to four pre-determined alarm threshold values of RDC rate. The sensor node is capable of sending an alert SMS with the corresponding warning status to an assigned responsible person as soon as one of the thresholds is exceeded. In soil slope applications the four warning statuses available are very slow, slow, moderate and rapid displacement rates, each corresponding to a user defined RDC rate.

The reported study is part of ongoing research to develop strategies for data interpretation in order to relate AE activity to the initial stages of rock slope collapse. The analysis of recurring AE patterns is a

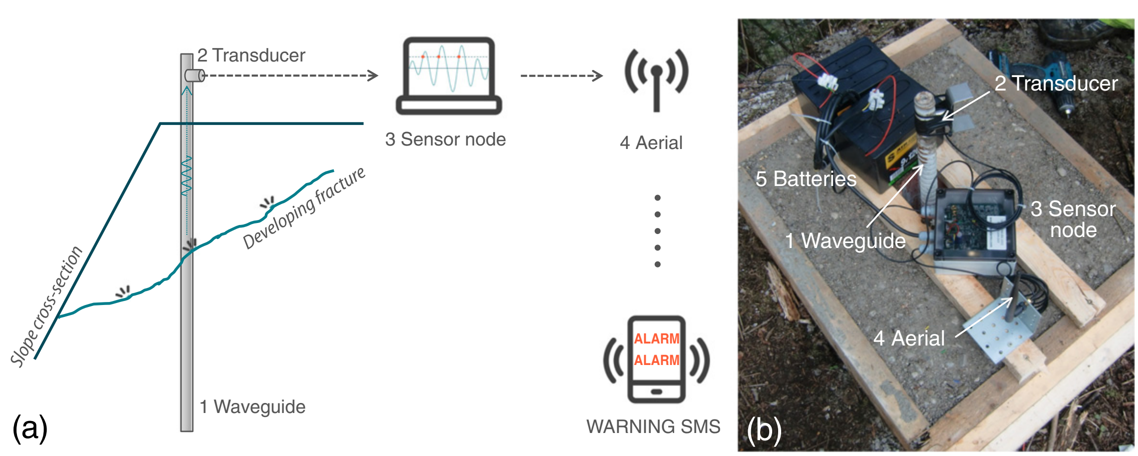

Fig. 1. (a) Simplified concept schematic of the AE monitoring system installed within a rock slope; (b) installation at one of the sites. As AE travels along the waveguide (1), it is measured by a piezoelectric transducer placed at the free end of the waveguide (2) and subsequently processed by a sensor node (3). In case an alarm is triggered, a warning SMS is sent through an aerial (4). The system is battery operated (5). All the equipment is protected with a weatherproof cover (after Codeglia et al., 2015).