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Analysis of Acoustic Emission patterns for monitoring of rock slope deformation mechanisms

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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 (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 pre-determined 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 0.05-0.49V; for the studies reported in this paper it was set at 0.25V. The sampling frequency choice is between 1 and 60 min. Typically, time periods of 15 minutes 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 necessary step to acquire the understanding and knowledge that can lead to development of appropriate criteria for setting thresholds (or, if needed, design a different threshold system) that can provide an early warning of incipient failures. Therefore, alarm thresholds for rock slopes, equivalent to those for soil, have not been determined at this stage.

The system works continuously and in near real-time providing high temporal resolution information. Processing power was optimised in order for sensors to work on batteries without maintenance for more than one year, which makes the system suitable to be installed at remote sites. The system uses a simple processing approach such as counting of the number of times the signal amplitude exceeds a static threshold (Ring Down Counting) to minimise power consumption and maximise memory storage. Clearly this comes at the cost of limiting the system capabilities. The recording of whole waveforms (or Short Time Average/Long Time Average ratio triggered recording), for example, could provide increased information, including the possibility to locate the AE source along the waveguide using the difference in arrival time of different wave modes (e.g. Maji et al., 1997). This not only would require increased power but also significantly increased sensor processing capacity and a memory capable of storing the enormous amount of data recorded. This would require a sensor connected to a mains power supply and much bulkier equipment, which is often impracticable when working at remote sites. Sites that have restricted access (e.g. due to geographical position, adverse conditions such as snow cover for prolonged periods, etc.) are often monitored with low sensitivity or low temporal resolution systems (e.g. remote sensing, manual-reading inclinometer, etc.) as other automated systems are too power demanding or too expensive. These traditional methods seldom provide real-time information for use in early warning of instability. Therefore, there is a clear need for high sensitivity, continuous and near-real time systems that can provide information on the state of slope stability.

3. The Passo della Morte (PdM) trial site

Passo della Morte trial site is situated in North-Eastern Italy, about 3 km east from Forni di Sotto [Lat 46.3978, Lon 12.7026] on the left flank of Tagliamento River valley. Coordinates are given in decimal degrees and refer to WGS84 Web Mercator projection. The AE monitoring system at Passo della Morte was set up in stages starting in summer 2010. The site (Fig. 3) consists of an unstable rock mass, as indicated by the history of failures, in stratified limestone (Calcari scuri stratificati – lower Carnian). This is steeply lying (typical dip angle 73°) on massive dolomite (Dolomia dello Schlern – upper Ladinian), which forms the stable underlying bedrock. Passo della Morte road tunnel crosses the limestone rock mass for its entire width (Fig. 3b), at a constant altitude of 720 m a.s.l. with only shallow cover (0-15 m) on the side towards the slope.

At this site geological and geomorphological surveys, supported by remote sensing techniques such as Terrestrial Laser Scanning (TLS) and Infra-Red Thermography (IRT) (Teza et al., 2015), were carried out in order to identify the critical joints and weak zones of the rock mass. These studies were used to select the most appropriate location for each of the monitoring instruments installed on site.

3.1 Monitoring system

Three horizontal waveguides were inserted in boreholes drilled through the steeply dipping limestone layers from within the road tunnel. The three 146 mm diameter boreholes were designed with specific functions in mind: AEWG1 penetrates for 50 m into the rock away from the slope, reaching the stable stratum of dolomite in the last 12 m; AEWG2 (30 m) and AEWG3 (10 m) penetrate the limestone slabs between the tunnel and the slope surface to monitor activity of open discontinuities filled with marl that can be observed daylighting on the slope face. Waveguides inserted and grouted in the boreholes are 50 mm diameter steel tubes, in singular lengths of 3 metres screwed together with connectors to reach the desired total length. Each waveguide was equipped with a sensor at different times: AEWG1 has been in place since 16/12/2010, AEWG2 since 27/09/2011 and AEWG3 since 12/10/2012.

Other than the three AE sensors, several other monitoring instruments are installed at the site. Five Time Domain Reflectometry (TDR) cables of various diameters (22 or 41 mm), a three point rod extensometer, an inclinometer, piezometric sensor, two MEMS accelerometers, a down-hole accelerometer and a seismometer have been installed to monitor displacements of strategic sections and other physical quantities (groundwater level, seismic motion) within the rock mass. Additionally, three crackmeters and three GPS benchmarks monitor displacement of key points on the surface. Figure 3 shows the location of the instruments and their designation. Data recorded since April 2011 has been made available by CNR-IRPI for comparison with AE RDC trends. Rainfall data are available since December 2010 and snowfall data since January 2012. Although AE data are collected on site per 15 min periods, they are aggregated here in hourly data to allow easier comparison with other data types recorded once per hour.

3.2 Interpretation from AE

AE events at the Passo della Morte site can be visually subdivided in three categories based on different AE event-patterns: type A, type B and type C (Fig.4). Events are defined as periods of measured AE activity that can be one or more monitoring periods bounded by periods of zero or lower than 10 RDC/hour within one hour monitoring period. These patterns are recognised on all three waveguides, although with slightly different AE rate levels.

Type A pattern events are common throughout the data series, occurring during both dry and rainfall periods. AEWG1 typically has measured counts in the range 100-400 RDC/hour, which last for one or very few 1-hour monitoring periods. AEWG2 Type A events are in the same order of count rate as AEWG1 but they can last for several consecutive 1-hour monitoring periods. AEWG3 event rates are higher, about 300-1000 RDC/hour and generally last for a single 1-hour monitoring period and are more frequent than AEWG1 events. Rarely these events are recorded by all the waveguides simultaneously, which leads to the hypothesis that such events are generated by local mechanisms (e.g. deformation on a discontinuity or local ground water flow) generating low energy AE that cannot propagate to more than one waveguide.

Type B pattern events usually last for a few days and are recorded primarily by one sensor while the other two show lower RDC/hour rates. These types of events can show a sharp increase in RDC/hour rate at the beginning, or they can gently rise to a peak RDC/hour rate, but in both cases the rates typically decrease gradually. They are mainly associated with changes in the groundwater level, which is discussed in Section 3.2.1. However, some do not correlate to particular rainfall events and occur when the piezometric level does not change. The generating mechanism for these events is to date unclear.

Type C pattern events can reach 140,000 RDC/hour on waveguide AEWG1, 100,000 on AEWG2 and almost 200,000 RDC/hour on AEWG3 within a single 1-hour monitoring period, which give them a very sharp peaky shape. Comparison with snowfall data suggest that they could be generated by snow loading on the surface of the slope. Details are given in Section 3.2.2.

To be able to reach a better understanding of the acoustic trends recorded, all the possible causes that can generate acoustic emission have to be taken into account, therefore, earthquakes have been considered as a possible source as Passo della Morte is in an active seismic zone. As a rock mass shakes under the effect of the peak ground acceleration (PGA) cracks can grow or small displacements can take place, hence releasing energy in the form of high frequency waves (AE). Further discussion is reported in Section 3.2.3.

Although longer waveguides intersect more discontinuities, it is difficult to establish a proportional relationship between tube length and RDC/hour. In fact not all discontinuities *might be active at the same time and the level of activity depends on the generating process, as it will be clearer from the discussion of data. Also, the intrinsic attenuation of the waveguide must be taken into account, which, although lower than the rock medium surrounding the waveguide, is still capable of damping the acoustic emission generated at a long distance from the sensor. Therefore, some events can be recorded by one sensor and not by the other sensors, regardless of the waveguide length.*

3.2.1 Groundwater pressure variation

Acoustic emission events in the order of some thousands of RDC/hour are related to variations in the groundwater level following periods of intense rainfall, which are common in particular during autumn time in the area. The delay between rainfall and rise in the groundwater level is in the order of about twelve hours. No RDC are normally recorded during this period of time, meaning that rainfall seepage through fractures between the rock slope surface and groundwater does not induce AE response (this is clearly visible in the example given in Fig. 5a). AE response is simultaneous with the increase in the groundwater level.

AEWG1 is sensitive to these events, consistently recording distinct RDC/hour rates when variation in the ground water level (i.e. pore water pressures) occurs. As can be seen in the piezometric level vs AE rates plots in Fig. 5b, the RDC/hour and water level rise are generally proportional (although with occasional higher AE spikes): water level increases of 1 to 2 m induce 1,000-5,000 RDC/hour, increases bigger than 5 m induce AE rates in the order of 5,000-30,000 RDC/hour with occasional spikes reaching 60,000 counts. There seems to be also proportionality in terms of distributions with time (i.e. sharp increase at the beginning of an event followed by a gentle decrease as the water level equilibrates to the long-term level). AEWG2 shows a similar response, although not as pronounced. Only increases in water level > 5 m correlate with increased AE activity. Counts are in the order of 1,000-1,500 RDC/hour. AEWG 3 shows higher AE rates for these types of events with rates recoded in the range 5,000-15,000 RDC/hour, they appear to be sharp and spiky (i.e. RDC/hour is generated over a small number of monitoring periods) but the counts are not proportional to the variation in groundwater level (Fig. 5b).

Changes in water pressures due to an increase or decrease of water level induce rearrangement of stresses within the rock mass, which results in micro-deformation and consequent AE stress release. This deformation is a non-linear process and develops in steps of instant energy release (i.e. slip – stick behaviour). The release intensity depends on the energy previously accumulated and hence it is expected that the relationship between piezometric level change and AE rates will not be proportional in some cases.

The different response of the three waveguides to the same generating mechanism is explained by their location: AEWG1 penetrates deep into the rock mass crossing multiple bedding planes and the contact between the limestone and dolomite, whereas AEWG2 and AEWG3 are located near to the slope face and thus monitor a relatively superficial portion of the rock mass.

3.2.2 Snow load

Type C pattern events are mainly observed during winter time. These events can be described as "spiky" as they are high counts which last for short periods of time, just one to three monitoring periods (i.e. one to three hours). The spikes can be grouped in clusters over periods of some days or be more sporadic. AEWG3 seems to be particularly sensitive to the production of this type of events showing RDC/hour rates that are approximately double of those recorded from AEWG1 and AEWG2 in the same monitoring period. This type of event was initially observed and discussed by Codeglia et al. (2015) where a dependence to low temperature and correlation with displacements recorded by extensometers EXT4 and EXT5 was hypothesised, but the causes were uncertain. Recently, snow data series have been acquired from the closest available snow-gauge placed in the vicinity of Malga Cjampiuz [Lat 46.3505, Lon 12.6790]. When interpreting snow data versus other parameters such as temperature it is important to take into account that the snow-gauge is located 5.5 km SW from Passo della Morte at an altitude of 1710 m a.s.l., which is about 1000 m higher than Passo della Morte at tunnel level, where the temperature sensor (TEMP) is located. Therefore, snow events recorded by the gauge might have not taken place at PdM site. For this reason, only events that meet the following two conditions are considered as actual snowfall events occurring at Passo della Morte: a) an increase in the snow-gauge plot can be observed and b) the temperature at PdM is around zero (as can be seen in Fig. 6). Assuming that at higher altitudes temperatures are generally lower, if condition a) is verified but condition b) is not, a snowfall event has probably taken place at the snow-gauge altitudes, but not at PdM where temperatures are higher and hence precipitation is expected as rain. Also, a period of constant temperature is considered as an indicator of thick cloud cover, which could indicate conditions for snow precipitation. It is generally accepted (e.g. Rossow and Lacis, 1990; Rossow and Zhang, 1995) that cloud cover reflects part of the sun light spectrum resulting in reduced earth heating during the day, and retaining earth's warmth from escaping into space at night, hence influencing the fluctuation of air temperature. Fluctuation will thus be minimal in case of clouds cover during winter time as temperatures are already generally low.

As can be observed in Fig. 6, in correspondence with periods for which all the conditions for snowfall are verified, the high-rate spiky AE events are present. This suggests that the snow cover could be responsible for generating such AE activity. The hypothesis here is that the snow accumulating on the slope produces a pressure on the surface of the sub-vertical limestone slabs. This additional vertical stress could make the slabs moving vertically, generating a differential micro-displacement between adjacent layers. This mechanism of deformation is aided by the marl infilling of the bedding planes between the limestone layers, which have very poor strength properties. The interaction between the limestone units could generate the AE behaviour recorded.

Paterson (1994) suggests snow density values between about 100 kg/m^3 for light new snow immediately after falling and 400 kg/m^3 for wind packed snow, including in this range are intermediate values which refer to damp and settled snow. Taking an average snow density value of 200 kg/m^3, the stress increase for every 0.1 m of snow depth would be in the order of 0.2 kN/m^2. Considering that at the site a single snow fall event can easily reach 0.5-1 m, this means that an additional stress of 1-2 kN/m^2 can be applied to the surface of the slope in a few hours.

Displacements measured by extensometers EXT4 and EXT5 placed across cracks daylighting on the slope are available during some periods of time that match with snowfall events. These displacement could be interpreted as being generated by the snow pressures but, due to the exposed location of the devices, at this stage it can't be excluded that the displacements recorded are due to snow accumulated on top of the extensometers.

3.2.3 Earthquakes

Northeast Italy is a seismically active area. Earthquakes are one of the main triggers for landslides, but even when the motion is not strong enough to induce a collapse, the shaking can result in internal deformation of the rock mass (e.g. relative deformation of units and fracture formation) contributing to slope degradation.

Acoustic emission rates recorded by the sensors after earthquake occurrences have been verified: for this purpose earthquake records were obtained from the Italian National Institute of Oceanography and Experimental Geophysics seismic network (CRS-OGS, 2016) for the period 17/12/2010 – 10/01/2016. Data are filtered to exclude duplicate events with matching date, time and magnitude values. As an initial analysis, only earthquakes that occurred within a radius of 20 km from Passo della Morte and with local magnitude $M_L \geq 2.5$ are considered as those representing the highest energy events occurred in the surroundings since the sensors were installed. As RDC values are reported at the end of one-hour monitoring periods, RDC values taken into account for every earthquake refer to the following rounded up hour (e.g. earthquake time 16:05:01 corresponds to RDC recorded at 17:00:00).

Twenty-three events have been identified: local magnitude M_L values are in range 2.5-3.8, with five events exceeding $M_L = 3$. The minimum epicentre distance from the site is 3.8 km and maximum is 19.5 km. The general response from the three waveguides is RDC/hour = 0 (i.e. there are no detected RDC/hour generated by the seismic event), in very few cases RDC/hour < 50, with one single episode reaching 3,813; 77 and 1,798 RDC/hour counts on waveguides AEWG1, AEWG2 and AEWG3 respectively. However, further comparison with the other available parameters measured in the same time period allow a conclusion that these counts are due to rock mass response to increasing groundwater level and not the concurrent seismic event.

The analysis clearly concludes that there is no acoustic emission response to the earthquakes recorded to date. The result is in line with Zoppè (2015) who calculates the theoretical peak ground acceleration (PGA) at Passo della Morte based on the strongest earthquakes ($M_L > 4.5$) recorded in the last 30 years within 100 km from the site: the eight earthquakes identified by Zoppè (2015) (M_L in range 5.4-6.3, distances 32-77 km) give PGA values between 0.005-0.050 g, which are too low to induce rock slope collapse.

Considering that the expected PGA for the area is 0.225-0.250 g with 10% probability of exceedance in 50 years as per the "Seismic hazard map of the Italian territory" (OPCM 3519, 2006) it can't be excluded that strong earthquakes closer to the site could take place and induce fracturing of the rock mass in the future.

4. The Grossreifling (SART) trial site

Grossreifling trial site is situated in Styria, Austria about 1.5 km north of Grossreifling [Lat 47.6739, Lon 14.7099] on the left bank of Enns River, which is one of the largest Austrian tributaries of the Danube River. The site consists of a steep conglomerate slope that threatens a section of the railway line St. Valentin-Tarvisio at km 91,400. The Grossreifling trial site was set up in April 2014 as a complementary component of the Sentinel for Alpine Railway Traffic (SART) project. SART is a pilot project that aims to improve safety of alpine railways through reducing the risk of damage to tracks and trains due to rock falls, and to provide a cost saving alternative to expensive dynamic rock fall barriers. The system takes advantage of a dual approach: early warning of imminent rock falls, given by acoustic emission generated within the rock constituting the slope, and detection of rock fall occurrence, provided by a light static catch fence instrumented with movement sensors that give information about the debris that detaches from the slope and impacts the fence. The two subsystems share a common control centre, which issues warnings and alarms to the rail traffic operator, providing information to allow action, specifically slow down or stop the railway traffic (although this control function is not implemented in the pilot phase).

4.1 Monitoring system

At Grossreifling two horizontal waveguides (H108L and H209R) and one vertical waveguide (VE10U) were installed. Figure 7 shows the slope instrumented and the location of waveguides and detection fence. The waveguides are formed using 32 mm threaded self-drilling tubes. These differ from the 50 mm smooth tubes usually installed at other sites (e.g. Passo della Morte). The self-drilling type of tubes is quite common in slope surface stabilisation applications but their use as waveguides is innovative. As there is no need to pre-drill a borehole of bigger diameter, the time and cost for installation was greatly reduced. The annulus between the tube and borehole wall is filled by pumping grout through the hollow stem to the drill bit thus backfilling the annulus between tube and borehole wall towards the slope surface. The downside of this installation approach is that in rock it is not possible to reach a great depth, as bars are relatively thin and the drilling equipment is light to make it manoeuvrable. After about 10 m the thin tubes struggle to transmit the power needed to the drill bit for progression into the rock mass. From a preliminary study conducted in the laboratory on 3 m tube lengths, there is little difference (for slope monitoring purposes) in AE propagation within the waveguide between threaded and smooth bars. However, attention should be paid when mounting the piezoelectric transducer. Experiments showed that the best coupling between transducer and waveguide is given when the transducer is mounted on a flattened thread (i.e. produced by filing), increasing the area of contact.

The study slope is 70 m high, the top being at 505 m a.s.l. and the bottom at 435 m a.s.l., where the rail line is located. Waveguides H108L and H209R are installed horizontally in the conglomerate at altitudes of about 487 m a.s.l. and 486 m a.s.l., respectively, and penetrate into the rock mass for 3 m. They are installed about 5 m apart diverging at an angle of about 45°. It is important to note that H209R is installed into loose debris for about a third of its length (1 m), while H108L is located in the conglomerate for its full length. Waveguide VE10U is composed of 4 bars of 3 m connected using screwed couplings to form a total length of 12 m and penetrates the conglomerate from near the top of the slope (500 m a.s.l.). Its bottom is therefore about 1 to 2 m higher in terms of altitude with respect to the two horizontal waveguides. From a plan perspective waveguide VE10U is located in between the other two.

To allow comparison between the three waveguides, piezoelectric transducers (Physical Acoustics R3alpha) and voltage threshold (0.25V) settings are the same for all sensor nodes. All three sensors were calibrated in the laboratory prior to installation and found to give the same response to standard calibration tests. Other data available at this site for comparison are records (date and time) of events hitting the detection fence, along with photos from the cameras triggered by movement sensors installed on the fence.

Recently, data has become available from a nearby weather station. This is located in Mooslandl, about 4.5 km SE from the site in a straight line, along the Enns River valley.

Hourly rainfall and temperature measurements are available since 01/04/2014. At Grossreifling a rain gauge and temperature sensor were installed at the beginning of the project but they have been subject to power faults on numerous occasions and hence did not provide continuous reliable time series. However, a comparison of the Grossreifling and Mooslandl data sets for periods of overlap has been useful to determine that the Mooslandl rainfall is representative of the weather in Grossreifling and suitable for comparison with AE recorded at the site.

4.2 Interpretation of measured AE

The period of time considered for data analysis in this paper is from 29/08/2014 to 31/12/2015. AE records actually started on 11/04/2014 but gaps in H108L and H209R covers allowed water to leak and drip onto the free end of the waveguide, generating RDC/hour trends. The covers were re-sealed on 28/08/2014.

Events at Grossreifling cannot be generally subdivided into categories depending on RDC/hour rates as AE response is very different for each waveguide for the reasons detailed below:

H108L shows RDC/hour rates that in general are lower by more than one order of magnitude compared to the other two waveguides. Rates are generally below 4000 RDC/hour with only five single (i.e. 1 hour) periods exceeding this value, with a maximum number of counts recorded being about 26,000 RDC/hour. AE activity recorded by waveguide H209R is orders of magnitude higher than the adjacent H108L: rates are generally about 100,000 RDC/hour with a few events exceeding this. About four events are just below the maximum counts recorded of 550,000 RDC/hour.

VE10U also has measured counts about 100,000 RDC/hour and also events distribution with time very similar to H209R. The main difference is the highest number of counts recorded with VE10U reaching close to 750,000 RDC/hour on two occasions.

It is important to note that the five biggest events during the monitoring period are recorded by all the three waveguides, although with different rates. Although rates are significantly different for the three waveguides due to their specific locations and ground conditions, it has been possible to identify two categories of events that are, with different response rates, present in all three datasets: events related to rainfall, discussed in Section 4.2.1, and events related to freeze-thaw cycles, discussed in Section 4.2.2.

4.2.1 Rainfall

From the time series of measurements it is clear that part of the AE activity is generated by rainfall events. In particular, the response of sensors H209R and VE10U is instantaneous (see below) and RDC/hour levels are high, generating the peak values discussed above. AE rates with time are similar in shape to rainfall trends as can be seen in the example provided in Fig. 8a. AE and rainfall rates are proportional (Fig. 8b), although the relationship is not always consistent. Both waveguides show AE rates generated by rainfall that are typically in the region of 20,000 to 50,000 counts per hour, lasting for the entire duration of the rainfall event and in some cases continuing after rainfall ceases. In Fig. 8a a major event is reported in May 2015, showing very high sustained counts well above 100,000 RDC/hour. These occasional high count events last for a single monitoring period (i.e. they are occur within an 1-hour monitoring period). Comparison with rainfall data also shows that in general there is no delay between rainfall and generated AE, or at least the delay is restricted to the 1 hour time resolution of measurements. This suggests that the AE is generated by almost immediate infiltration of rainfall into the near surface high permeable stratum, which is slope talus for H209R and vegetated soil for VE10U.

It is interesting to observe that all waveguides show, throughout the dataset, some AE rate peaks that are relatively higher (i.e. a larger ratio of rainfall rate to AE response of slope). An example is shown in Fig. 8a around 14/05/2015. As these atypical peaks are not caused by an increase in the rain rate, it can be interpreted that AE is generated by other deformation mechanisms and superimposed on top of the AE activity generated by the flow of water. Rainfall triggered deformation of the slope material would be a potential mechanism generating AE. These require further investigation.

H108L shows a sporadic and weaker response to rainfall, although the major rainfall events generate increased AE levels but an order of magnitude less than compared to the other two sensors. H108L response to rainfall is normally in the range of 500-1000 RDC/hour. This weaker response is a result of H108L being installed within intact rock at a location with no superficial soil surface deposits.

4.2.2 Freeze-thaw

Low AE rates lasting only a few monitoring periods are recorded during winter time when the temperature drops below zero at night and rises above zero during the day. As can be observed in Fig. 9, rates are in the order of 500-1,500 RDC/hour for waveguide H108L. Waveguide H209R shows slightly higher rates, about 2,000 counts per hour and waveguide VE10U shows higher counts of 3,000-5,000. However, VE10U has greater variability; in some periods events don't exceed 1,000 RDC/hour and at some time no AE is measured. H108L and H209R AE events are consistently recorded during the warmest hours of the day, whereas VE10U AE is generally measured at night. This could be explained considering the waveguides locations; H108L and H209R are much closer to the rock mass face and probably are subject to the effect of the slope surface defrosting during the warmer hours of the day. Fluctuations of the rock face temperature around zero degrees Celsius can induce movement on discontinuities and the detachment of small boulders from the surface. This later mechanism is confirmed by photographs taken in winter of the slope and detection fence. These are taken automatically triggered when debris impact the fence. Counts are recorded by all the waveguides simultaneously when a prolonged period of temperatures higher than zero follows a cold period (i.e. with temperatures sub-zero for a number of days).

5. Conclusions

This paper details an approach for monitoring the stability of rock slopes using measurement of acoustic emission generated by deformation mechanisms. The system comprises a steel waveguide with grout surround located in the rock mass, with AE measured using a piezoelectric transducer coupled to a sensor that conditions the signal to remove background noise and quantifies activity as ring down count rates. Although relationships between AE and slope displacement rates are now established for soil slopes, this novel application to monitoring of rock slopes means that new interpretation strategies are required. Time series of AE recorded at two rock slopes in Italy and Austria have been compared with responses of a range of traditional instruments. Potential drivers of rock mass deformation mechanisms have been considered systematically (i.e. rainfall, snow, temperature fluctuations and seismic activity). Clear and repeatable AE trends have been measured and associated with changes in external slope loading and internal stress changes.

At Passo della Morte, Italy, clear and consistent AE trends have been measured as the rock mass responds to variations in the groundwater level, which alters stress conditions in the steeply bedded limestone. In addition, AE are also generated in response to snow loading on the slope and the hypothesis is that the vertical stress increase results in differential micro-displacements between the limestone layers. The distribution and magnitude of AE rates from these two mechanisms can be differentiated. Confidence in the interpretation of the links between destabilising factors (e.g. snow loading and ground water level) is provided by the multiple events recorded, consistent behaviour and simultaneous measurement of AE on multiple waveguides. It has been shown that to date there is no link between seismic activity from local events up to magnitude $M_L = 3.8$ and AE recorded by the system, although generation of AE linked to shaking of the rock mass cannot be discounted for future earthquake events.

At the Grossreifling, Austria, rain seepage into the near surface slope talus and top soil has been found to generate high rates of AE. However, the correlation between rainfall and AE rates are not consistent and it is hypothesised that rain triggered mechanisms of slope instability could be indicated by elevated AE. When the slope is subjected to freeze-thaw temperature cycles, AE rates have been detected that are linked to observed detachment of small boulders from the slope surface.

The two case studies presented demonstrate that AE monitoring using grouted waveguides can be used to detect and differentiate a range of rock slope deformation mechanisms. Work is continuing in order to establish correlations between AE rates and deformations, and propose relationships that can be used to interpret AE for classes of slopes. This is challenging as detected AE rates are linked to the specific location of the waveguide in the rock mass relative to the deformation mechanisms. Large scale failure events have not occurred at either site during the monitoring periods. Therefore, the ability of AE measurements to detect deterioration of rock slope stability towards failure, and hence be used to provide an early warning, is not yet proven. However, the sensitivity of measured AE to relatively small scale and/or localised changes to rock mass loading and stress state, give confidence that a large scale event can be detected using AE as stability deteriorates. Monitoring is continuing at both sites to extend the data sets and with the expectation that significant failure events will occur.

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