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Strategies for rock slope failure early warning using acoustic emission monitoring

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Abstract. Research over the last two decades has led to development of a system for soil slopes monitoring based on the concept of measuring Acoustic Emission (AE). A feature of the system is the use of waveguides installed within unstable soil slopes. It has been demonstrated that the AE measured through this technique are proportional to soil displacement rate. Attention has now been focused on the prospect of using the system within rock materials. The different nature of the slope material to be monitored and its setting means that different acoustic trends are measured, and development of new approaches for their interpretation are required. A total of six sensors have been installed in two pilot sites, firstly in Italy, for monitoring of a stratified limestone slope which can threaten a nationally important road, and secondly in Austria, for monitoring of a conglomerate slope that can endanger a section of the local railway. In this paper an outline of the two trial sites is given and AE data collected are compared with other physical measurements (i.e. rainfall and temperature) and traditional geotechnical instrumentation, to give an overview of recurring AE trends. These include clear AE signatures generated by stress changes linked to increased ground water levels and high energy events generated by freeze-thaw of the rock mass.

1. Introduction

Landslides cause thousands of fatalities every year, and there is an expectation for this number to grow in the coming years [1]. Global incidence of landslides is rising dramatically as a response to increased climate variability and frequency of extreme weather conditions. At the same time, expanding urbanization, uncontrolled land-use and environmental degradation are increasing the size of vulnerable areas. All these factors result in greater exposure of population, infrastructures and economic activities to landslide risk. It is therefore clear that monitoring techniques able to foresee imminent landslides and provide an early warning are essential in order to undertake actions that lead to risk reduction and disaster prevention.

Research over the last two decades [2] has led to development of a system for early warning of soil slopes instability based on the concept of measuring Acoustic Emission (AE). The AE is measured by a piezoelectric transducer sensor installed on a waveguide. The waveguide is a pipe placed into a borehole drilled within an unstable soil slope and has the specific function to transmit AE waves generated by the mass movement to the sensor. Laboratory tests and field trials have demonstrated [3–5] that detected AE trends are proportional to the rate of deformation (velocity) of the unstable slope. As the system is capable of sending alarms when AE rates exceed a certain level, it is suitable to be used as an early warning of soil slopes instabilities. The monitoring technique developed is called Slope ALARMS (Assessment of Landslides Using Acoustic Real-time Monitoring Systems).

Recently, attention has been focused on the prospect of using the system within rock materials. The different nature of rock, its setting and the different failure modes mean that different acoustic trends are measured. Their interpretation requires development of new strategies comprehending how a specific rock mass system acoustically responds to various external and internal excitations (e.g. temperature, groundwater level changes, seismicity, deformation) and identifying possible sources of noise (e.g. water seepage) in order to discern trends in the AE information that can provide an early warning of collapse. This paper provides a first overview of recurring AE trend patterns detected, considers these in relation to measurements from traditional geotechnical instrumentation installed at the sites and discusses possible associated causes.

2. Acoustic Emission (AE) monitoring of rock slopes

Materials undergoing deformation generate transient sub-audible stress waves due to rapid release of energy, which radiates from the source and propagate through the material. These waves have typically frequencies higher than 20 kHz and are called Acoustic Emission (AE). Monitoring the evolution of AE in a material gives information on the degradation of the material itself. In rocks, AE is generated at different scales by propagation of new fractures and/or displacement along existing discontinuities [6]. Therefore, detection of AE is an indicator of deformation within a rock mass. Increasing AE rates cannot be directly related to an increasing rate of deformation, they could rather be related to accelerating damage events at the micro-scale as forerunners of a macroscopic brittle failure. Evidence of accelerating patterns prior to collapse has been widely found at the laboratory sample scale (e.g. [7]) and precursory event trends are known also at the slope scale [6,8].

Acoustic Emission is measured by means of a system (Figure 1) that consists of three segments: detection, analysis and communication. The detection segment comprises a steel pipe, also called waveguide, and a piezoelectric transducer. The primary function of the waveguide is to increase the zone of influence of the transducer to high frequency waves (i.e. high frequency waves travelling in steel attenuate much less than in 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 slope. In rock slopes the waveguide is grouted into the borehole in order to provide continuity for stress waves to propagate from the rock mass to the steel tube. This is considered to be a passive system, as the grout is not expected to be the primary source of generated AE in a deformation event. In soil slopes a noisy granular backfill is used to generate AE (i.e. an active system). AE waves generated across the waveguide, or in its vicinity, are conveyed by the steel bar to the piezoelectric transducer mounted at the free end of the bar (Figure 1), which converts mechanical signal to electronic signal. The use of a high-pass transducer (i.e. very low sensitivity to low frequencies) ensures that low frequencies, which are generally generated by wind, traffic, anthropic activities and therefore considered background noise, are not recorded.

The electronic signal is subsequently analysed by a sensor (analysis segment of the system), which is actually a computing device with limited functions. The sensor amplifies the signal and applies the band-pass filter that removes frequencies lower than 20 kHz and higher than 30 kHz. Ring Down Counts (RDC) rates are subsequently determined counting the number of times the signal exceeds a pre-determined voltage threshold (Figure 2) within a pre-set period of time, typically set at 15 minutes. For each monitoring period, the sensor compares RDC rates with 4 pre-set alarm thresholds of increasing RDC orders of magnitude.

As soon as one of the thresholds is exceeded, the sensor sends an alert SMS to an assigned person with the corresponding warning status stamped on it (communication segment). The four warning status available are Very slow rate, Slow rate, Moderate rate and Rapid rate, which were selected for describing soil slope movement rates. Alarm thresholds have still not been determined for rock slopes. It is part of the ongoing research to derive relationships between AE rates and level of damage within the rock in order to be able to identify the appropriate criteria for setting threshold levels for early warning purposes. The system works continuously and in real-time providing high temporal resolution information. Power consumption has been optimised in order to work on batteries without maintenance for more than one year, which makes the system suitable to be installed at remote sites.

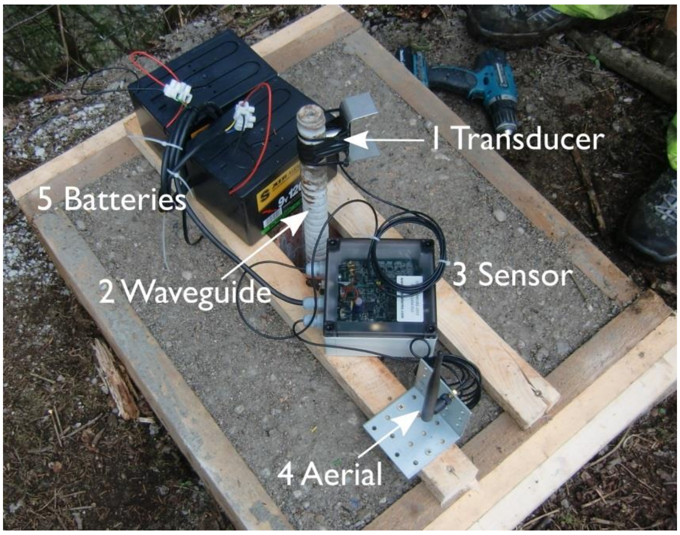

Figure 1. AE monitoring system installation within a slope. AE is measured by a piezoelectric transducer (1) placed at the free end of the waveguide (2) and processed by the sensor (3). In case an alarm is triggered, the information is sent through an aerial (4). The system is battery operated (5). All the equipment is protected with a weatherproof cover.

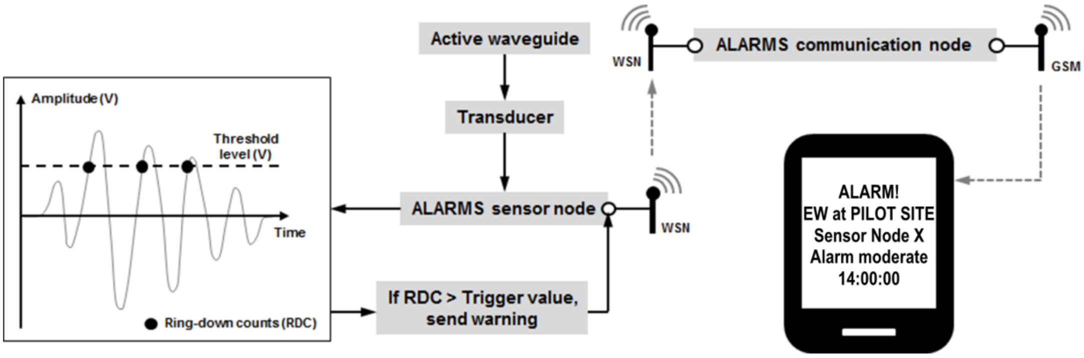

Figure 2. Schematic of operation of the AE monitoring for soil slopes including sensor node and communication system, after [9,10]. In rock slopes the active waveguide is replaced by a grouted passive waveguide.

The distinction between stable/unstable strata to install the waveguide through is not always clear. For example, in intensely fractured rock slopes the rupture surface could develop along one or many pre-existing discontinuities, which are hard to identify. Moreover, some types of rocks experience very small deformation prior to collapse, which makes it very challenging to identify a distinct rupture surface prior to failure without first installing monitoring instrumentation. Boreholes are often drilled across sets of discontinuities for which movements are likely to be expected but without penetrating a definite stable stratum. Also in the case of unstructured rock it is difficult to locate the stable zone, and it can be challenging to distinguish discontinuities that might lead to failure. In this case waveguides are located in areas with potential for instability or near areas that have already experienced failures.

At this point it is very important to highlight that detected AE are not only generated from deformation of discontinuities crossed by the waveguide (i.e. installed directly through them) but also by deformation mechanisms within a volume of rock surrounding the waveguide. Thus, the waveguide location precision is not essential; what is important is to assess the size of the monitored volume of rock surrounding the waveguide. The volume depends on the specific rock mass properties, i.e. attenuation of AE in the rock material [11], structural characteristics and particular grade of fracturing. All these elements affect the attenuation of the signal, which is a measure of the energy loss of wave propagation in a rock mass: the higher the attenuation, the shorter the distance that waves can travel and, thus, smaller the monitored volume surrounding the waveguide; and vice versa. Attenuation within the rock mass is not the only source of loss of energy. Some energy is also dispersed (reflected) as the AE propagates through interfaces between rock, grout and steel as every material has its specific acoustic characteristics.

In the interpretation of AE rates it is important to consider that recorded RDC are a function of a number of factors. Along with attenuation, due to various aspects mentioned above, the characteristics of the AE source (i.e. the magnitude of AE event generated by deformation of the rock mass) and settings of the monitoring equipment (i.e. sensitivity of the transducer, voltage threshold set in the sensor node) all affect the recorded RDC rates. Therefore, AE rates, trends of AE behaviour in time and comparisons between waveguides are relative measures of the deformation phenomena and can be used to provide information on deformation mechanisms rather than absolute values. In the following sections a description is provided of two monitoring sites where the Slope ALARMS system is installed.

3. Trial site 1: Passo della Morte (Northern Italy)

Passo della Morte trial site is situated in North-Eastern Italy, about 3 km east from Forni di Sotto [Latitude 46.398325, Longitude 12.701861] on the left flank of Tagliamento River valley. The AE monitoring system at Passo della Morte was set up in various stages since summer 2010. The site consists of an unstable rock mass in stratified limestone (Calcari scuri stratificati – lower Carnian), steeply lying on massive dolomite (Dolomia dello Schlern – upper Ladinian), which forms the stable underlying bedrock (Figure 3). The limestone outcrop is about 130 m wide and 250 m high, occupying elevations between 650 and 900 m above sea level (a.s.l.). It is relevant to highlight that the Passo della Morte tunnel crosses the limestone rock mass for its entire width, at a constant altitude of 720 m a.s.l. with only shallow cover (0-15 m) on the side towards the slope. The rock mass is throughout its volume divided into blocks with a range of sizes that are mainly isolated from the bedding and three other discontinuity sets, along with several random fractures and small faults.

Two possible slope evolution scenarios have been anticipated [12]: progressive detachment of blocks in the order of 1to 10 m^3 or failure controlled by the bedding involving a part (less than 500,000 m^3) or the entire slope (up to 650,000 m^3). In the latter case it has been demonstrated [13] that the falling material could reach the base of the slope forming a temporary valley obstruction about 20 m high and 200 m long. The instability endangers operation of the National Road 52 but it represents also a considerable threat for settlements and strategic elements, such as bridges, located downstream along the valley if valley damming and sudden release of the accumulated water occurred. Other relevant research studies regarding this site include [14,15].

3.1. *Monitoring system*

At this site three horizontal waveguides were inserted in boreholes drilled through the steep limestone layers from within the road tunnel (Figure 3). The three 146 mm diameter boreholes were designed with specific functions in mind: AEWG1penetrates 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 wide openings filled with marl that can be observed daylighting on the slope face. Waveguides inserted and grouted in the boreholes are 50 mm diameter steel pipes, in singular lengths of 3 meters screwed together with connectors to reach the desired total length. The waveguides were equipped with three sensors 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 (Figure 3). 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. Three crackmeters and three GPS benchmarks monitor displacement of key points on the surface. Data recorded since April 2011 has been made available by CNR-IRPI for comparison with RDC trends. Rainfall data are available since December 2010.

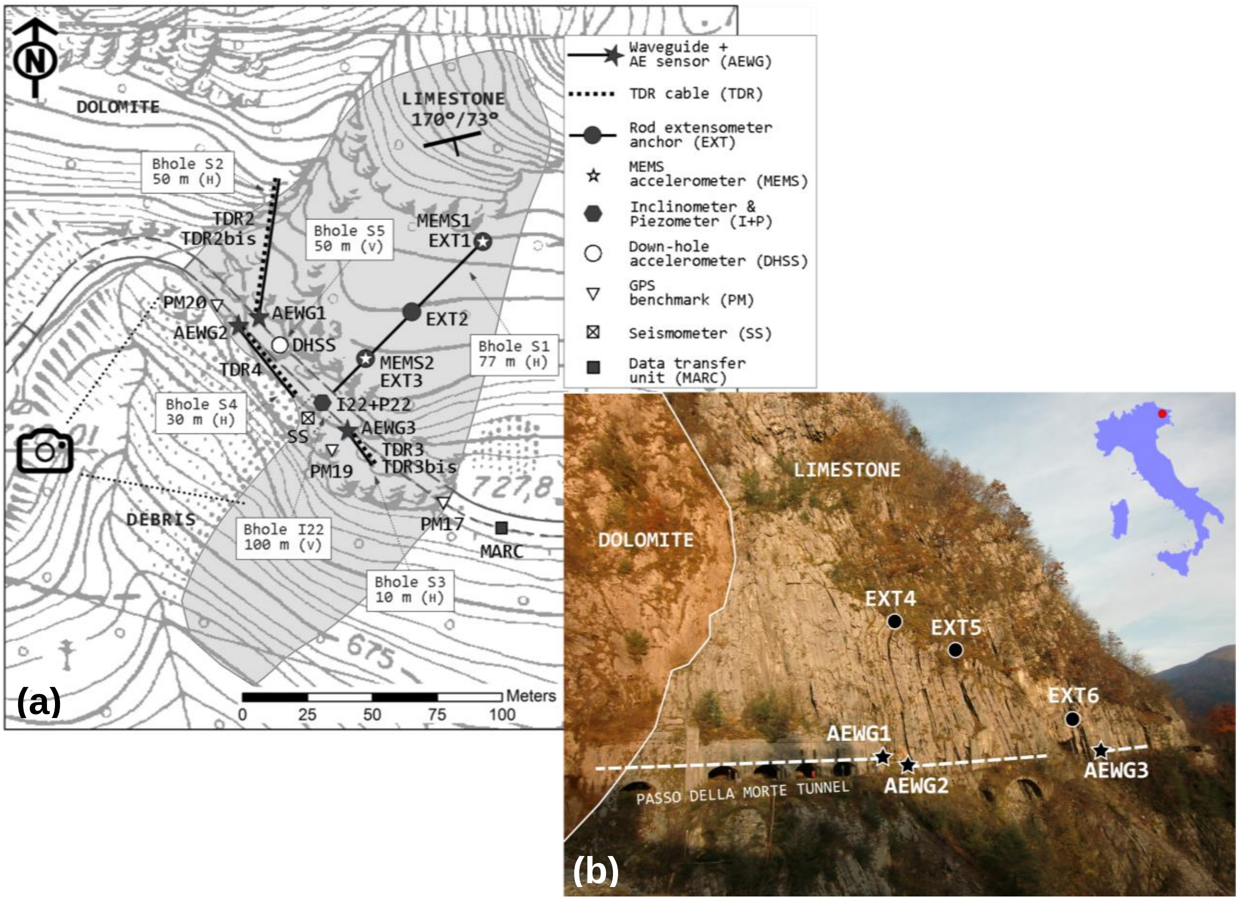

Figure 3. Passo della Morte (Italy): (a) schematic of the unstable limestone rock mass and position of waveguides (AEWG1, 2, 3), along with TDR cables, extensometers, MEMS accelerometers, an inclinometer, piezometer, a down-hole accelerometer and a seismograph station; (b) west rock mass face with projection of the waveguide positions and locations of crackmeters (EXT4, 5, 6) [16].

3.2. AE trends

AE events at Passo della Morte site can be subdivided in three categories based on different AE rate levels: low (<1,000 RDC/hour), medium (1,000-10,000 RDC/hour) and high (10,000-100,000 RDC/hour) rate events. Low AE rate events are rather common throughout the data series. They occur both during rainfall events and during dry periods and their duration is from hours to a few days, with occasional spikes of 400-800 counts per hour that are several times higher than the average 50-100 counts per hour. These events are often recorded by all the three sensors (AEWG1, AEWG2 and AEWG3) although they show different numbers of counts (RDC). Medium AE rate events usually last for a few days and are recorded in particular from one sensor while the other two are silent or show lower activity levels. They don't seem to be associated with particular rainfall events and occur when the piezometric level does not change. These types of events can show a sharp increase at the beginning, or they can gently rise to a peak AE rate, but in both cases the rates usually decrease gradually. High AE rate events are discussed in the following paragraph, as a hypothesis on their genesis can be made.

3.2.1. High AE rate events. Very high energy events are observed in the data series. They are extremely high counts which last generally for one monitoring period (i.e. 1 hour in the example), and certainly for not more than three consecutive monitoring periods. These spiky events can be isolated or grouped in clusters within a few days. Another distinctive trait of such events is that they are recorded simultaneously by all the three sensors, although AEWG3 consistently records acoustic rates higher by about one order of magnitude compared with AEWG1 and AEWG2. The example provided in Figure 4 shows five clusters of spiky events. AEWG3 reaches almost 100,000 counts per hour while the other two sensors barely exceed 10,000 counts per hour at the same time (thus they are hidden in Figure 4 by the AEWG3 data).

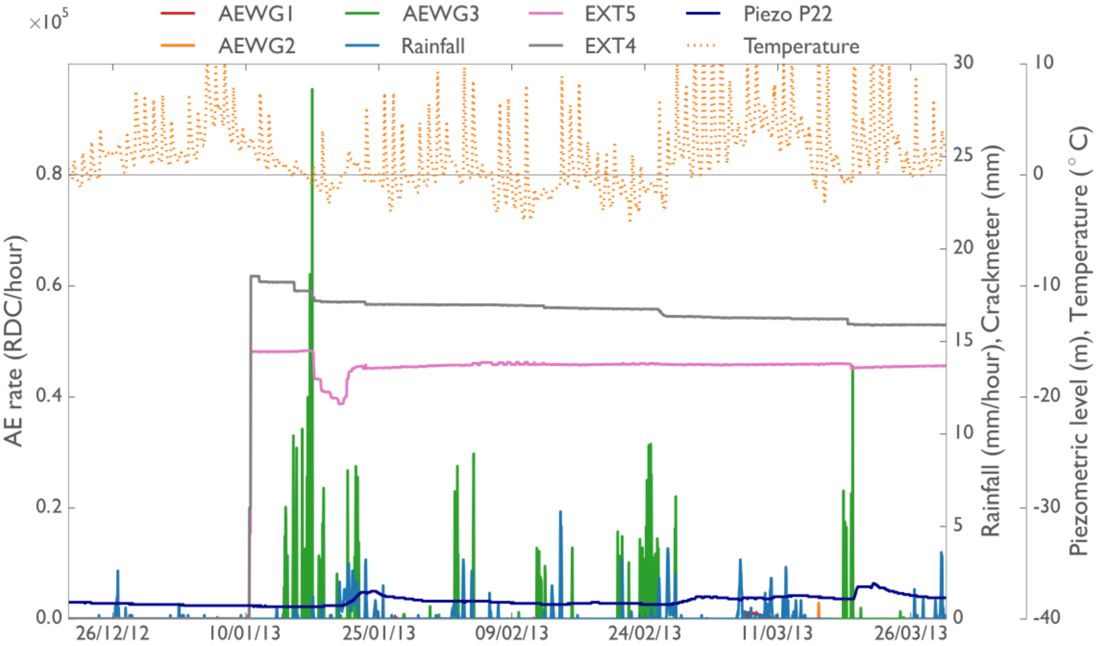

Figure 4. High AE rate events. EXT4, EXT5 were not operating until 10/01/2013. Piezometric level is referred to the well-head placed in the tunnel at an altitude of 720 m a.s.l..

Rainfall and changes in ground water level do not seem to be critical for the appearance of such high RDC trends: in Figure 4 rainfall rarely reaches 5 mm/hour and the piezometric level change is not remarkable (about 2 m). Considering the temperature, there seems to be a relation between RDC and temperatures dropping below 0°C and, apparently, these spiky type of events are less frequent later in the year when the temperatures rise, and they reappear in Jan-Mar 2014 and Jan-Feb 2015. Therefore, the trends could be generated by water freezing into discontinuities surrounding the waveguide. This doesn't explain though why trends are recorded by all the three sensors, although with different orders of magnitude, in the same monitoring period (1 hour) considering that the temperatures stay low for several days.

Other interesting observations regard the crackmeters EXT4 and EXT5, which monitor two of the key discontinuities where they daylight on the slope (see Figure 3 for their location). They experienced operating problems in late 2012 but started to work correctly again on 10/01/2013. The crackmeters work in compression because the limestone slabs tend to tilt backwards (i.e. towards the stable dolomite) in that part of the slope. Figure 4 shows a possible good correlation between displacements recorded by the crackmeters and RDC rates, although this is not always consistent. Some clusters are in fact not linked to any measured displacement, but they could be generated by fractures that are not monitored, and a few displacement events do not seem to match any RDC clusters. Causes for these spiky types of events are still unknown but it appears clear that effects of low temperatures and displacements need to be further investigated, possibly as a combined and/or related effect.

3.2.2. Trends due to changes in groundwater level. A category of events is attributed to changes in water pressure within the rock mass due to variations of piezometric level (Figure 5). It can be observed that a delay of several hours occurs between the start of a rainfall event and the rise of water level, but AE recorded is simultaneous with the water level change. AE rates tend to accelerate when the water table rises and to decelerate, more or less sharply, when it drops. Hence the AE trend follows the stress changes within the rock structure. This behaviour is particularly evident during very intense rainfall events that are typical of the area in the autumn season. They can last for days and induce large variations in the piezometric level (i.e. tens of meters).

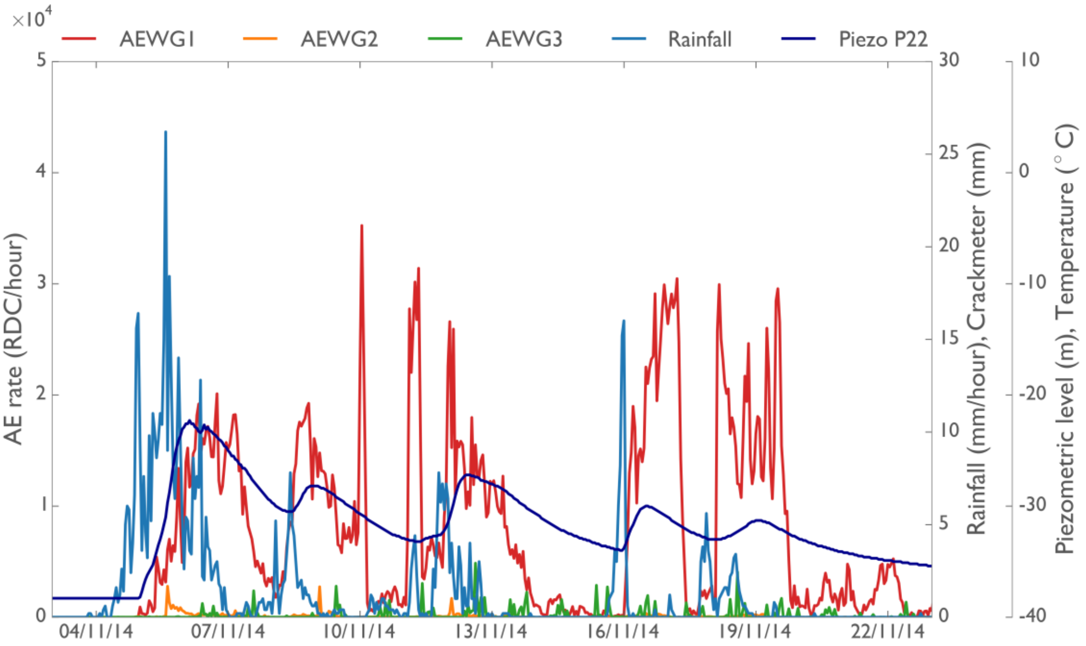

Figure 5. AE rate (RDC/hour) in response to changes in water pressure within the rock mass. Rainfall (mm/h) and piezometric level (m) are also indicated.

For the example shown in Figure 5, the first rainfall event starts at 00:00 on 04/11/2014 after a quiet and dry period; the piezometric level is initially -39 m from the tunnel level, 720 m a.s.l.. As the ground water table response begins at 00:00 on 05/11/2014, the RDC accelerating trends are recorded by waveguide AEWG1. During the previous 24 hours no AE activity is recorded by any of the sensors, although it was raining intensively. This latter observation is of great importance because it excludes the possibility that AE recorded is generated by rainfall seepage within discontinuities or by water flowing onto the waveguide. If this was the case AE would have been recorded earlier. The same behaviour can be observed for the consecutive rainfall events in Figure 5, although RDC doesn't start from zero as there is an overlapping effect of previous events. The groundwater table reaches its maximum (-22 m) at 03:00 on 06/11/2014, which is 17 m higher than the beginning, and after a few hours it starts to decline. AE in this phase remains relatively high because of the continuous water pressure variation (firstly increasing and then decreasing). Finally, AE rates decrease, but do not reach zero because a new rainfall event takes place.

Looking at the whole time series in Figure 5 it is noticeable that AE response follows the change in water level but is not proportional to it and shows occasional spikes. The reason for this is that AE is not generated by the water itself but as a secondary effect. In other words, the rearrangement of stress within the rock mass, which is caused by varied conditions in the water pressure, results in microdeformations in the rock mass, thus the acoustic stress release. This deformation is a non-linear process and develops in consequent steps of instant energy release and the release intensity depends on the energy previously accumulated.

4. Trial site 2: Grossreifling (Austria)

Grossreifling trial site is situated in Styria, Austria about 1.5 km north of Grossreifling [Latitude 47.673932, Longitude 14.709952] 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 (Figure 6). 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 increase the safety of alpine railways through reducing the risk of damage to tracks and trains due to rock falls, and providing a cost saving alternative to expensive dynamic rock fall barriers. The system takes advantage of a dual approach: early warning of imminent rockfalls, 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 (Figure 6). The two subsystems share a common control centre, which issues warnings and alarms to the rail traffic operator, providing enough information to take action, specifically slow down or stop the railway traffic (although this control function is not implemented in the pilot phase).

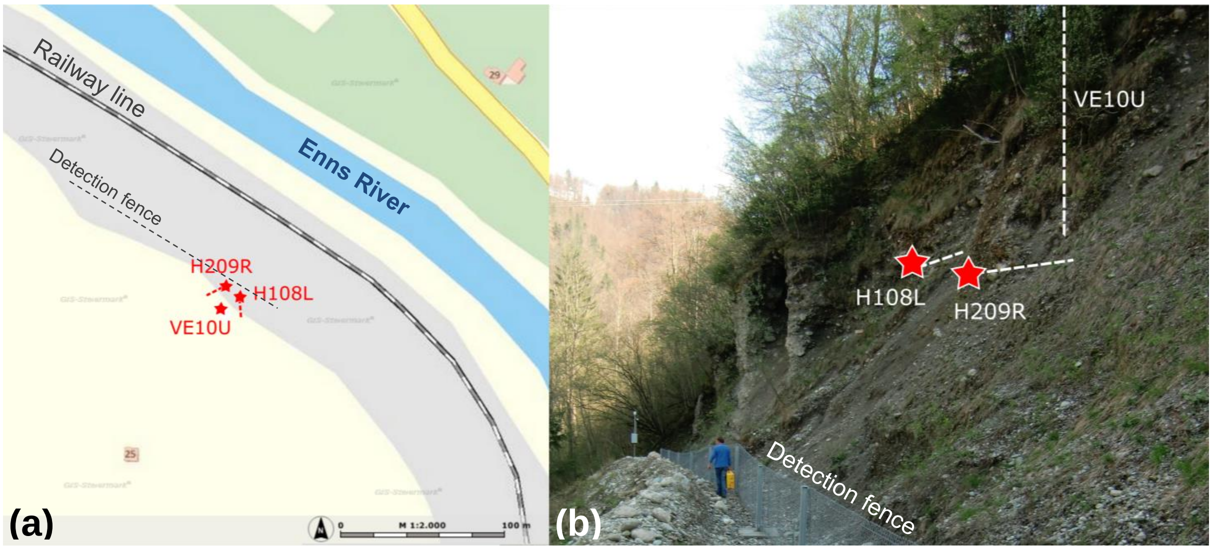

Figure 6. Grossreifling (Austria): (a) site layout map with plan view of the three waveguides (map from gis.steiermark.at); (b) image of the conglomerate slope with projection of the three waveguides and location of the detection fence.

The study slope is about 70 m high, from 435 to 505 m a.s.l.. The conglomerate outcrops only in the upper 15 m of the slope and is almost vertical, with local overhangs. Below this altitude the rock is hidden by debris falling from the top of the slope and accumulating with an angle of about 40°. Considering the geomorphology of the area it can be thought that the conglomerate forms the entire slope, from the top to the bottom. The top of the slope is also covered by 80-100 cm of vegetative soil. Clasts composing the rock are polygenic, with a dominant carbonate fraction, and high degree of roundness. It is possible, though difficult, to recognise a structure organised in flat layers of about 1-1.5 m, not always distinctly separated, which sometimes show a gradation inside them. The granular size range is in general very wide, from sand to boulders, but the percentage combination of grain sizes is variable from layer to layer. The grade of cementation is also irregular, but it does not necessarily follow the layer structure mentioned above. Some highly cemented zones are interposed with very poorly cemented ones, which can also include loose material. Size and distribution of the grains as well as the cementation degree affects the permeability; water seepage and formation of ice stalactites have been observed in winter coming from permeable zones. This suggests that water circulation has preferential routes inside the rock mass. Permeable and poorly cemented zones are probably more weathered due to the washout operated by the flowing water.

4.1. Monitoring system

At Grossreifling two horizontal waveguides (H108L and H209R) and one vertical waveguide (VE10U) were installed (Figure 6). 32 mm threaded self-drilling rods were used as waveguides, which differs from the 50 mm smooth pipes usually installed at other sites. The self-drilling type of rods 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 for installation is greatly reduced as well as the overall cost. The annulus between the rod and borehole wall is filled by pumping grout through the hollow stem to the drill bit thus backfilling 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 quite thin and after about 10 m they 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 rod 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.

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 from one another diverging of an angle of about 45° as they enter into the rock mass. It is important to note that H209R is installed into loose debris for about 0.8 to 1 m. Waveguide VE10U is composed of 4 bars of 3 m each screwed together for a total length of 12 m and penetrates the conglomerate from the top of the slope (500 m a.s.l.). Its bottom is therefore about 1 to 2 m higher in terms of altitude than the two horizontal waveguides and, from a plan perspective; waveguide VE10U is located in between them.

To allow comparison between the three waveguides, piezoelectric transducers and voltage threshold settings are the same for all of them. Other data available at this site for comparison are rainfall, temperature and the record (date and time) of events that hit the fence, along with photos from the cameras triggered by movement sensors installed on the fence. Unfortunately, the rainfall gauge and temperature sensor placed at the top of the slope experienced many power failures losing long periods of data and the measurement frequency has not been constant and regular throughout the year (ranging from about 15 to 70 min), which is not ideal for comparison with AE data collected every 15 minutes. Therefore, rainfall and temperature data have recently been requested from a nearby weather station, but they are still in the process of being obtained.

4.2. AE trends

AE trends recorded by H209R and VE10U sensors are, throughout the data series, consistently higher, by about one order of magnitude, than AE trends recorded by H108L. RDC for the first two sensors are generally in the order of 30,000 to 40,000 counts per hour, with a few occasional spikes that can broadly exceed 100,000 counts per hour. RDC recorded by sensor H108L are normally about 1,000 to 2,000 counts per hour, with few spikes that reach 5,000 counts per hour.

Looking at the whole data series it appears that H209R and VE10U have a high response to rainfall events, and looking closely also at H108L, AE seems to have a relationship with the rainfall, although with a different order of magnitude (Figure 7). The problems with the site rainfall records mentioned above do not make it possible, at this stage, to determine whether there is a delay or not between rainfall and generated AE. This is particularly important because three scenarios are possible: (1) no delay, meaning that AE is generated by direct infiltration of water within the near surface permeable stratum, which is debris for H209R and vegetative soil for VE10U, and if a proportionality is found, this effect can be removed from the data series (this behaviour is not expected for waveguide H108L as it is entirely grouted in rock and also protected from direct rainfall by overhanging conglomerate); (2) delay in the order of 1 hour, AE could be generated by water flowing within the rock mass discontinuities/porosity and the delay is due to the time for infiltration; (3) delay of several hours, due to the time for the water to elevate groundwater pressures and hence generate stress changes within the rock mass. During January 2015 some low level AE trends (400-500 RDC/hour) are recorded by one or all waveguides around 10am-3pm. It is likely that these trends are generated by the slope surface defrosting when temperatures rise during the hours of maximum solar gain; unfortunately rainfall events cannot be excluded as there are no rainfall data available for the period. At this stage further interpretation is not possible until more reliable rainfall and temperature are available.

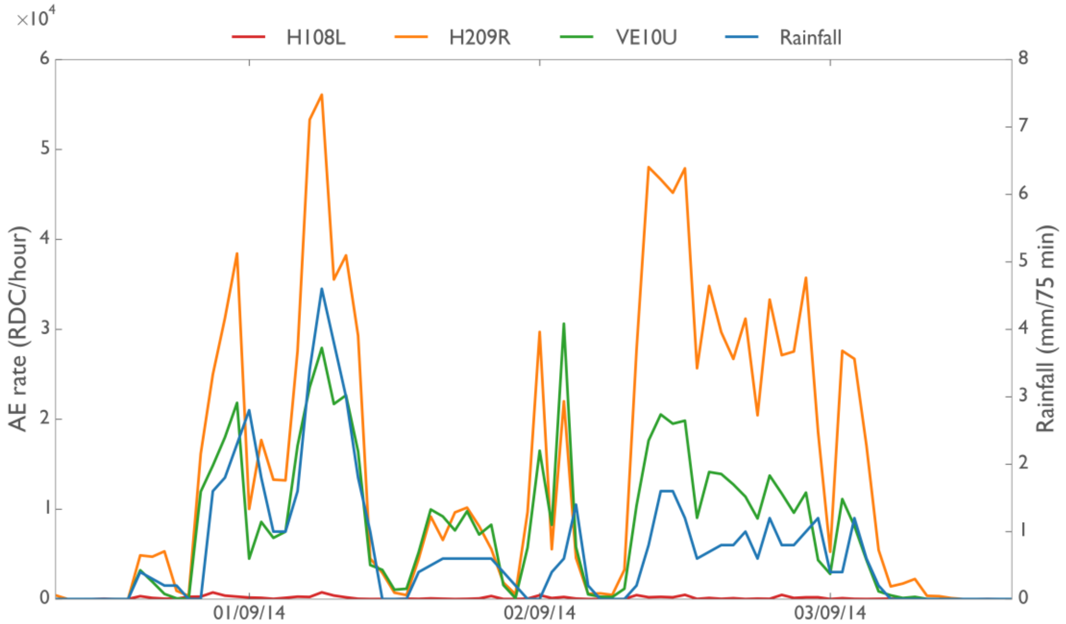

Figure 7. RDC rates in response to rainfall events. RDC values are given every 60 minutes while rainfall monitoring frequency is about 75 min. This is responsible for the plotted rainfall being shifted and hence appearing to arrive after the AE, which is not the case. It is clear that sensors H209R and VE10U with sections in loose material have a much greater response to rainfall than H108L.

5. Summary

A system for monitoring rock slope stability through Acoustic Emission (AE) has been described in this paper using grouted passive wave guides, and details of installations at two trial sites is presented along with an overview of recurring trends associated with deformation mechanisms. Interpretation of two recurring types of events at Passo della Morte (Italy) have been presented: a very high RDC rate event and AE RDC events that follow the evolution of the groundwater level. For the first event type a possible correlation with the movement of discontinuities monitored by EXT4 and EXT5 have been observed, but also temperatures below 0°C could have an influence. In the second type there is a clear response to changes in stress and resulting deformations due to the variation of the water level within the rock mass.

At the Grossreifling site in Austria, interpretation is limited by the lack of reliable rainfall data. However, it is possible to qualitatively identify dependence between rainfall events and AE trends, and low AE trends are possibly generated by thawing of the frozen slope surface during daylight hours in winter.

Field measurements at the two sites and analysis of data series will continue and, in combination with field and laboratory experiments, they will be used for further interpretation of AE generated by deformation mechanisms and consequently to derive relationships between AE and deformation. The ultimate purpose is to identify initial stages of collapse and to develop criteria for setting thresholds that can provide an early warning of the imminent collapse to allow useful action to be taken.

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