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1 **Analysis of Acoustic Emission patterns for monitoring**
2 **of rock slope deformation mechanisms**

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8 **1. Introduction**

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

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

27 In order to monitor AE trends generated within a deforming fine grained soil slope with high
28 attenuation, Dixon et al. (2003) conceived a system which makes use of an active waveguide
29 to generate a stronger AE signal and transfer this to a piezoelectric transducer. Laboratory
30 testing and field trials (Dixon et al., 2014; Smith and Dixon, 2014; Smith et al., 2014)

31 demonstrated that an increase in deformation of a soil body (e.g. slope) results in an
32 increase of AE activity, providing also an empirical coefficient of proportionality that links AE
33 rates monitored with an increasing rate of deformation (velocity).

34 The prospect of using the system to forecast failure of rock slopes has been recently
35 considered. Slopes composed of rocks characterised by brittle behaviour have the potential
36 to fail catastrophically (e.g. Nichol et al., 2002) and monitoring of pre-failure deformation
37 with classical geotechnical instruments is challenging as collapse develop very rapidly
38 (i.e. very small displacement magnitude prior to large scale and rapid collapse). However,
39 the deformation process that leads to nucleation and propagation of fractures releases
40 acoustic stress waves, which are therefore suitable to be used as an indicator of incipient
41 failure.

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

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

57 **2. The monitoring system**

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

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

69 In soil applications, the gap between the waveguide and the borehole is backfilled with
70 gravel or coarse sand. This makes the system "active" as the gravel/sand acts as a wave
71 generator when the host soil moves (Dixon et al., 2014, 2003). The reason for introducing
72 the generator lies in the poor acoustic properties of the host material as fine soils generate
73 very low AE levels that are challenging to detect due to high attenuation. Adding a noisy
74 backfill ensures that AE activity generated is sufficiently high to be transferred to the
75 waveguide without being dissipated along the path. In rocks, the energy of generated AE is

76 orders of magnitude greater than AE in soils and attenuation of AE is lower than in soils.
77 Therefore, grouting the waveguide into the rock is sufficient for the stress waves generated
78 by the deforming rock mass to be transferred from the rock to the steel tube. This is
79 considered to be a passive system, as the grout surrounding the waveguide is not expected
80 to be the primary source of generated AE in detected deformation events.

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

87 The electronic signal is subsequently processed by a computing device called a sensor node.
88 The sensor node amplifies the signal and applies a band-pass filter that removes frequencies
89 lower than 20 kHz and higher than 30 kHz. The lower limit is to remove background noise
90 and the upper to restrict AE to a range that can be readily processed in this battery-powered
91 device (i.e. higher processing rates require increased power). Ring Down Count (RDC) rates
92 are then determined counting the number of times the signal exceeds a pre-determined
93 voltage threshold within a pre-set period of time (Fig. 2). The threshold voltage is used to
94 remove the lower amplitude background and spurious noise, hence it needs to be set
95 sufficiently high so that no RDC are recorded during periods of time when there are no rock
96 deformations occurring (i.e. during periods of good weather). The user can select a value for
97 the voltage threshold in the range 0.05-0.49V; for the studies reported in this paper it was
98 set at 0.25V. The sampling frequency choice is between 1 and 60 min. Typically, time

99 periods of 15 minutes are a good compromise in order to maximise memory storage
100 capacity and yet provide the benefit of high temporal resolution monitoring. At the end of
101 each monitoring period, the sensor compares the number of RDC counts with up to four
102 pre-determined alarm threshold values of RDC rate. The sensor node is capable of sending
103 an alert SMS with the corresponding warning status to an assigned responsible person as
104 soon as one of the thresholds is exceeded. In soil slope applications the four warning
105 statuses available are Very slow, Slow, Moderate and Rapid displacement rates, each
106 corresponding to a user defined RDC rate.

107 The reported study is part of ongoing research to develop strategies for data interpretation
108 in order to relate AE activity to the initial stages of rock slope collapse. The analysis of
109 recurring AE patterns is a necessary step to acquire the understanding and knowledge that
110 can lead to development of appropriate criteria for setting thresholds (or, if needed, design
111 a different threshold system) that can provide an early warning of incipient failures.
112 Therefore, alarm thresholds for rock slopes, equivalent to those for soil, have not been
113 determined at this stage.

114 The system works continuously and in near real-time providing high temporal resolution
115 information. Processing power was optimised in order for sensors to work on batteries
116 without maintenance for more than one year, which makes the system suitable to be
117 installed at remote sites. The system uses a simple processing approach such as counting of
118 the number of times the signal amplitude exceeds a static threshold (Ring Down Counting)
119 to minimise power consumption and maximise memory storage. Clearly this comes at the
120 cost of limiting the system capabilities. The recording of whole waveforms (or Short Time
121 Average/Long Time Average ratio triggered recording), for example, could provide increased

122 information, including the possibility to locate the AE source along the waveguide using the
123 difference in arrival time of different wave modes (e.g. Maji et al., 1997). This not only
124 would require increased power but also significantly increased sensor processing capacity
125 and a memory capable of storing the enormous amount of data recorded. This would
126 require a sensor connected to a mains power supply and much bulkier equipment, which is
127 often impracticable when working at remote sites. Sites that have restricted access (e.g. due
128 to geographical position, adverse conditions such as snow cover for prolonged periods, etc.)
129 are often monitored with low sensitivity or low temporal resolution systems (e.g. remote
130 sensing, manual-reading inclinometer, etc.) as other automated systems are too power
131 demanding or too expensive. These traditional methods seldom provide real-time
132 information for use in early warning of instability. Therefore, there is a clear need for high
133 sensitivity, continuous and near-real time systems that can provide information on the state
134 of slope stability.

135 **3. The Passo della Morte (PdM) trial site**

136 Passo della Morte trial site is situated in North-Eastern Italy, about 3 km east from Forni di
137 Sotto [Lat 46.3978, Lon 12.7026] on the left flank of Tagliamento River valley. Coordinates
138 are given in decimal degrees and refer to WGS84 Web Mercator projection. The AE
139 monitoring system at Passo della Morte was set up in stages starting in summer 2010. The
140 site (Fig. 3) consists of an unstable rock mass, as indicated by the history of failures, in
141 stratified limestone (Calcari scuri stratificati – lower Carnian). This is steeply lying (typical dip
142 angle 73°) on massive dolomite (Dolomia dello Schlern – upper Ladinian), which forms the
143 stable underlying bedrock. Passo della Morte road tunnel crosses the limestone rock mass

144 for its entire width (Fig. 3b), at a constant altitude of 720 m a.s.l. with only shallow cover (0-
145 15 m) on the side towards the slope.

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

151 *3.1 Monitoring system*

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

162 Other than the three AE sensors, several other monitoring instruments are installed at the
163 site. Five Time Domain Reflectometry (TDR) cables of various diameters (22 or 41 mm), a
164 three point rod extensometer, an inclinometer, piezometric sensor, two MEMS
165 accelerometers, a down-hole accelerometer and a seismometer have been installed to

166 monitor displacements of strategic sections and other physical quantities (groundwater
167 level, seismic motion) within the rock mass. Additionally, three crackmeters and three GPS
168 benchmarks monitor displacement of key points on the surface. Figure 3 shows the location
169 of the instruments and their designation. Data recorded since April 2011 has been made
170 available by CNR-IRPI for comparison with AE RDC trends. Rainfall data are available since
171 December 2010 and snowfall data since January 2012. Although AE data are collected on
172 site per 15 min periods, they are aggregated here in hourly data to allow easier comparison
173 with other data types recorded once per hour.

174 *3.2 Interpretation from AE*

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

181 Type A pattern events are common throughout the data series, occurring during both dry
182 and rainfall periods. AEWG1 typically has measured counts in the range 100-400 RDC/hour,
183 which last for one or very few 1-hour monitoring periods. AEWG2 Type A events are in the
184 same order of count rate as AEWG1 but they can last for several consecutive 1-hour
185 monitoring periods. AEWG3 event rates are higher, about 300-1000 RDC/hour and generally
186 last for a single 1-hour monitoring period and are more frequent than AEWG1 events. Rarely
187 these events are recorded by all the waveguides simultaneously, which leads to the
188 hypothesis that such events are generated by local mechanisms (e.g. deformation on a

189 discontinuity or local ground water flow) generating low energy AE that cannot propagate to
190 more than one waveguide.

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

198 Type C pattern events can reach 140,000 RDC/hour on waveguide AEWG1, 100,000 on
199 AEWG2 and almost 200,000 RDC/hour on AEWG3 within a single 1-hour monitoring period,
200 which give them a very sharp peaky shape. Comparison with snowfall data suggest that they
201 could be generated by snow loading on the surface of the slope. Details are given in Section
202 3.2.2.

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

209 *Although longer waveguides intersect more discontinuities, it is difficult to establish a*
210 *proportional relationship between tube length and RDC/hour. In fact not all discontinuities*

211 *might be active at the same time and the level of activity depends on the generating process,*
212 *as it will be clearer from the discussion of data. Also, the intrinsic attenuation of the*
213 *waveguide must be taken into account, which, although lower than the rock medium*
214 *surrounding the waveguide, is still capable of damping the acoustic emission generated at a*
215 *long distance from the sensor. Therefore, some events can be recorded by one sensor and*
216 *not by the other sensors, regardless of the waveguide length.*

217 *3.2.1 Groundwater pressure variation*

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

226 AEWG1 is sensitive to these events, consistently recording distinct RDC/hour rates when
227 variation in the ground water level (i.e. pore water pressures) occurs. As can be seen in the
228 piezometric level vs AE rates plots in Fig. 5b, the RDC/hour and water level rise are generally
229 proportional (although with occasional higher AE spikes): water level increases of 1 to 2 m
230 induce 1,000-5,000 RDC/hour, increases bigger than 5 m induce AE rates in the order of
231 5,000-30,000 RDC/hour with occasional spikes reaching 60,000 counts. There seems to be
232 also proportionality in terms of distributions with time (i.e. sharp increase at the beginning
233 of an event followed by a gentle decrease as the water level equilibrates to the long-term

234 level). AEWG2 shows a similar response, although not as pronounced. Only increases in
235 water level > 5 m correlate with increased AE activity. Counts are in the order of 1,000-1,500
236 RDC/hour. AEWG 3 shows higher AE rates for these types of events with rates recorded in
237 the range 5,000-15,000 RDC/hour, they appear to be sharp and spiky (i.e. RDC/hour is
238 generated over a small number of monitoring periods) but the counts are not proportional
239 to the variation in groundwater level (Fig. 5b).

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

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

251 *3.2.2 Snow load*

252 Type C pattern events are mainly observed during winter time. These events can be
253 described as "spiky" as they are high counts which last for short periods of time, just one to
254 three monitoring periods (i.e. one to three hours). The spikes can be grouped in clusters
255 over periods of some days or be more sporadic. AEWG3 seems to be particularly sensitive to

256 the production of this type of events showing RDC/hour rates that are approximately double
257 of those recorded from AEWG1 and AEWG2 in the same monitoring period. This type of
258 event was initially observed and discussed by Codeglia et al. (2015) where a dependence to
259 low temperature and correlation with displacements recorded by extensometers EXT4 and
260 EXT5 was hypothesised, but the causes were uncertain. Recently, snow data series have
261 been acquired from the closest available snow-gauge placed in the vicinity of Malga
262 Cjampiuiz [Lat 46.3505, Lon 12.6790]. When interpreting snow data versus other parameters
263 such as temperature it is important to take into account that the snow-gauge is located 5.5
264 km SW from Passo della Morte at an altitude of 1710 m a.s.l., which is about 1000 m higher
265 than Passo della Morte at tunnel level, where the temperature sensor (TEMP) is located.
266 Therefore, snow events recorded by the gauge might have not taken place at PdM site. For
267 this reason, only events that meet the following two conditions are considered as actual
268 snowfall events occurring at Passo della Morte: a) an increase in the snow-gauge plot can be
269 observed and b) the temperature at PdM is around zero (as can be seen in Fig. 6). Assuming
270 that at higher altitudes temperatures are generally lower, if condition a) is verified but
271 condition b) is not, a snowfall event has probably taken place at the snow-gauge altitudes,
272 but not at PdM where temperatures are higher and hence precipitation is expected as rain.
273 Also, a period of constant temperature is considered as an indicator of thick cloud cover,
274 which could indicate conditions for snow precipitation. It is generally accepted (e.g. Rossow
275 and Lacis, 1990; Rossow and Zhang, 1995) that cloud cover reflects part of the sun light
276 spectrum resulting in reduced earth heating during the day, and retaining earth's warmth
277 from escaping into space at night, hence influencing the fluctuation of air temperature.
278 Fluctuation will thus be minimal in case of clouds cover during winter time as temperatures
279 are already generally low.

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

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

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

301 *3.2.3 Earthquakes*

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

306 Acoustic emission rates recorded by the sensors after earthquake occurrences have been
307 verified: for this purpose earthquake records were obtained from the Italian National
308 Institute of Oceanography and Experimental Geophysics seismic network (CRS-OGS, 2016)
309 for the period 17/12/2010 – 10/01/2016. Data are filtered to exclude duplicate events with
310 matching date, time and magnitude values. As an initial analysis, only earthquakes that
311 occurred within a radius of 20 km from Passo della Morte and with local magnitude $M_L \geq 2.5$
312 are considered as those representing the highest energy events occurred in the
313 surroundings since the sensors were installed. As RDC values are reported at the end of one-
314 hour monitoring periods, RDC values taken into account for every earthquake refer to the
315 following rounded up hour (e.g. earthquake time 16:05:01 corresponds to RDC recorded at
316 17:00:00).

317 Twenty-three events have been identified: local magnitude M_L values are in range 2.5-3.8,
318 with five events exceeding $M_L = 3$. The minimum epicentre distance from the site is 3.8 km
319 and maximum is 19.5 km. The general response from the three waveguides is RDC/hour = 0
320 (i.e. there are no detected RDC/hour generated by the seismic event), in very few cases
321 RDC/hour < 50, with one single episode reaching 3,813; 77 and 1,798 RDC/hour counts on
322 waveguides AEWG1, AEWG2 and AEWG3 respectively. However, further comparison with
323 the other available parameters measured in the same time period allow a conclusion that

324 these counts are due to rock mass response to increasing groundwater level and not the
325 concurrent seismic event.

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

332 Considering that the expected PGA for the area is 0.225-0.250 g with 10% probability of
333 exceedance in 50 years as per the "Seismic hazard map of the Italian territory" (OPCM 3519,
334 2006) it can't be excluded that strong earthquakes closer to the site could take place and
335 induce fracturing of the rock mass in the future.

336 **4. The Grossreifling (SART) trial site**

337 Grossreifling trial site is situated in Styria, Austria about 1.5 km north of Grossreifling
338 [Lat 47.6739, Lon 14.7099] on the left bank of Enns River, which is one of the largest
339 Austrian tributaries of the Danube River. The site consists of a steep conglomerate slope
340 that threatens a section of the railway line St. Valentin-Tarvisio at km 91,400. The
341 Grossreifling trial site was set up in April 2014 as a complementary component of the
342 Sentinel for Alpine Railway Traffic (SART) project. SART is a pilot project that aims to
343 improve safety of alpine railways through reducing the risk of damage to tracks and trains
344 due to rock falls, and to provide a cost saving alternative to expensive dynamic rock fall
345 barriers. The system takes advantage of a dual approach: early warning of imminent rock

346 falls, given by acoustic emission generated within the rock constituting the slope, and
347 detection of rock fall occurrence, provided by a light static catch fence instrumented with
348 movement sensors that give information about the debris that detaches from the slope and
349 impacts the fence. The two subsystems share a common control centre, which issues
350 warnings and alarms to the rail traffic operator, providing information to allow action,
351 specifically slow down or stop the railway traffic (although this control function is not
352 implemented in the pilot phase).

353 *4.1 Monitoring system*

354 At Grossreifling two horizontal waveguides (H108L and H209R) and one vertical waveguide
355 (VE10U) were installed. Figure 7 shows the slope instrumented and the location of
356 waveguides and detection fence. The waveguides are formed using 32 mm threaded self-
357 drilling tubes. These differ from the 50 mm smooth tubes usually installed at other sites (e.g.
358 Passo della Morte). The self-drilling type of tubes is quite common in slope surface
359 stabilisation applications but their use as waveguides is innovative. As there is no need to
360 pre-drill a borehole of bigger diameter, the time and cost for installation was greatly
361 reduced. The annulus between the tube and borehole wall is filled by pumping grout
362 through the hollow stem to the drill bit thus backfilling the annulus between tube and
363 borehole wall towards the slope surface. The downside of this installation approach is that
364 in rock it is not possible to reach a great depth, as bars are relatively thin and the drilling
365 equipment is light to make it manoeuvrable. After about 10 m the thin tubes struggle to
366 transmit the power needed to the drill bit for progression into the rock mass. From a
367 preliminary study conducted in the laboratory on 3 m tube lengths, there is little difference
368 (for slope monitoring purposes) in AE propagation within the waveguide between threaded

369 and smooth bars. However, attention should be paid when mounting the piezoelectric
370 transducer. Experiments showed that the best coupling between transducer and waveguide
371 is given when the transducer is mounted on a flattened thread (i.e. produced by filing),
372 increasing the area of contact.

373 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.,
374 where the rail line is located. Waveguides H108L and H209R are installed horizontally in the
375 conglomerate at altitudes of about 487 m a.s.l. and 486 m a.s.l., respectively, and penetrate
376 into the rock mass for 3 m. They are installed about 5 m apart diverging at an angle of about
377 45°. It is important to note that H209R is installed into loose debris for about a third of its
378 length (1 m), while H108L is located in the conglomerate for its full length. Waveguide
379 VE10U is composed of 4 bars of 3 m connected using screwed couplings to form a total
380 length of 12 m and penetrates the conglomerate from near the top of the slope
381 (500 m a.s.l.). Its bottom is therefore about 1 to 2 m higher in terms of altitude with respect
382 to the two horizontal waveguides. From a plan perspective waveguide VE10U is located in
383 between the other two.

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

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

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

399 *4.2 Interpretation of measured AE*

400 The period of time considered for data analysis in this paper is from 29/08/2014 to
401 31/12/2015. AE records actually started on 11/04/2014 but gaps in H108L and H209R covers
402 allowed water to leak and drip onto the free end of the waveguide, generating RDC/hour
403 trends. The covers were re-sealed on 28/08/2014.

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

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

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

417 It is important to note that the five biggest events during the monitoring period are
418 recorded by all the three waveguides, although with different rates. Although rates are
419 significantly different for the three waveguides due to their specific locations and ground
420 conditions, it has been possible to identify two categories of events that are, with different
421 response rates, present in all three datasets: events related to rainfall, discussed in Section
422 4.2.1, and events related to freeze-thaw cycles, discussed in Section 4.2.2.

423 *4.2.1 Rainfall*

424 From the time series of measurements it is clear that part of the AE activity is generated by
425 rainfall events. In particular, the response of sensors H209R and VE10U is instantaneous
426 (see below) and RDC/hour levels are high, generating the peak values discussed above. AE
427 rates with time are similar in shape to rainfall trends as can be seen in the example provided
428 in Fig. 8a. AE and rainfall rates are proportional (Fig. 8b), although the relationship is not
429 always consistent. Both waveguides show AE rates generated by rainfall that are typically in
430 the region of 20,000 to 50,000 counts per hour, lasting for the entire duration of the rainfall
431 event and in some cases continuing after rainfall ceases. In Fig. 8a a major event is reported
432 in May 2015, showing very high sustained counts well above 100,000 RDC/hour. These
433 occasional high count events last for a single monitoring period (i.e. they are occur within an
434 1-hour monitoring period). Comparison with rainfall data also shows that in general there is
435 no delay between rainfall and generated AE, or at least the delay is restricted to the 1 hour
436 time resolution of measurements. This suggests that the AE is generated by almost

437 immediate infiltration of rainfall into the near surface high permeable stratum, which is
438 slope talus for H209R and vegetated soil for VE10U.

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

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

451 *4.2.2 Freeze-thaw*

452 Low AE rates lasting only a few monitoring periods are recorded during winter time when
453 the temperature drops below zero at night and rises above zero during the day. As can be
454 observed in Fig. 9, rates are in the order of 500-1,500 RDC/hour for waveguide H108L.
455 Waveguide H209R shows slightly higher rates, about 2,000 counts per hour and waveguide
456 VE10U shows higher counts of 3,000-5,000. However, VE10U has greater variability; in some
457 periods events don't exceed 1,000 RDC/hour and at some time no AE is measured. H108L
458 and H209R AE events are consistently recorded during the warmest hours of the day,

459 whereas VE10U AE is generally measured at night. This could be explained considering the
460 waveguides locations; H108L and H209R are much closer to the rock mass face and probably
461 are subject to the effect of the slope surface defrosting during the warmer hours of the day.
462 Fluctuations of the rock face temperature around zero degrees Celsius can induce
463 movement on discontinuities and the detachment of small boulders from the surface. This
464 later mechanism is confirmed by photographs taken in winter of the slope and detection
465 fence. These are taken automatically triggered when debris impact the fence. Counts are
466 recorded by all the waveguides simultaneously when a prolonged period of temperatures
467 higher than zero follows a cold period (i.e. with temperatures sub-zero for a number of
468 days).

469 **5. Conclusions**

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

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

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

500 The two case studies presented demonstrate that AE monitoring using grouted waveguides
501 can be used to detect and differentiate a range of rock slope deformation mechanisms.
502 Work is continuing in order to establish correlations between AE rates and deformations,
503 and propose relationships that can be used to interpret AE for classes of slopes. This is
504 challenging as detected AE rates are linked to the specific location of the waveguide in the

505 rock mass relative to the deformation mechanisms. Large scale failure events have not
506 occurred at either site during the monitoring periods. Therefore, the ability of AE
507 measurements to detect deterioration of rock slope stability towards failure, and hence be
508 used to provide an early warning, is not yet proven. However, the sensitivity of measured AE
509 to relatively small scale and/or localised changes to rock mass loading and stress state, give
510 confidence that a large scale event can be detected using AE as stability deteriorates.
511 Monitoring is continuing at both sites to extend the data sets and with the expectation that
512 significant failure events will occur.

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