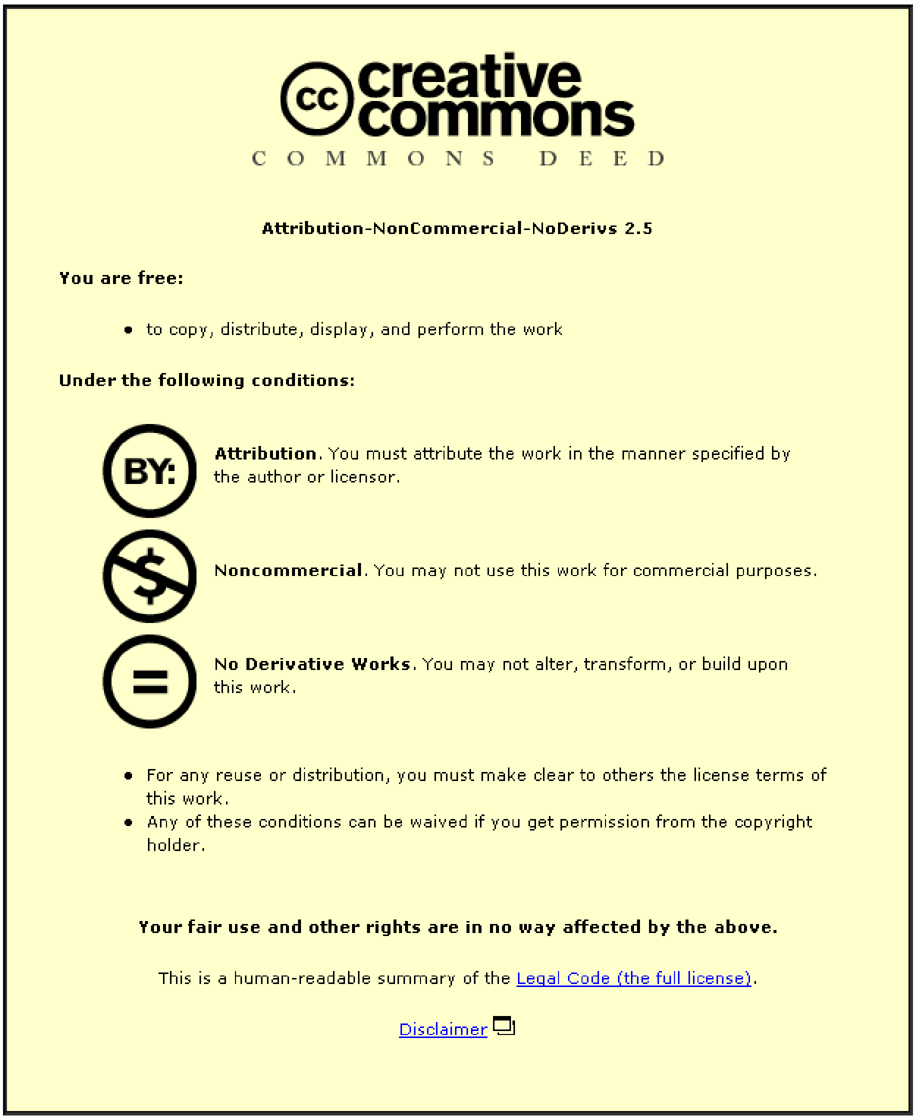

Landslide hazard evaluation by means of several monitoring techniques, including an acoustic emission sensor

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ABSTRACT: At Passo della Morte in the Italian Eastern Alps a geomorphological survey has identified potential instability of the valley side slope that could result in a debris/rock avalanche, which would threaten the Tagliamento River. A nationally important road passes through a tunnel 130 m long behind the potentially unstable slope. The stratum comprises a sequence of Limestone layers, dipping in the slope direction towards the river. Although currently there is no clear evidence of movement, the geological setting indicates a predisposition to instability that could involve a large landslide and extremely fast deformations can be foreseen. To appraise the physical characteristics of the rock mass and to provide an early warning of instability, monitoring instrumentation has been installed and monitored since late 2010. Extensometers, MEMS, TDR cables, a vertical inclinometer, a seismic station to monitor Limestone rock mass deformation generated micro-tremors and an acoustic emission (AE) monitoring system have been installed. The instruments are connected to real-time recording and transmitting units. The paper describes the geological setting and associated potential modes of instability. It details the design of the instrument installations and presents results obtained to date. In particular, the novel acoustic emission monitoring approach is described including sensor design, method of operation and comparison of the measured AE response with the deformation measurements and detected micro-tremor trends. Initial results indicate a strong response of the acoustic sensors to rainfall events. No significant rock mass deformations have been detected at depth within the slope to date, although a surface extensometer has shown widening of a bedding tension crack. Upgrading of the instrumentation system is ongoing and it is planned to continue monitoring for the foreseeable future.

1 INTRODUCTION

Monitoring, together with field survey, is a fundamental observation methodology to analyze potential hazards and damage, and to collect ancillary data (Corsini 2008). Large-scale rock fall frequency is lower than other types of landslides but the damage that can be caused is severe. For risk reduction purposes these kinds of phenomena are extremely complex and therefore “almost impossible” to stabilize with structural countermeasures, however it is possible to act to reduce the vulnerability to such events. When it is not feasible to move infrastructure from the run out path, it can be appropriate to use monitoring systems to implement alert networks that can potentially raise an alarm if failure is indicated.

However, it is technically difficult to monitor large scale rock falls because large numbers of rock fractures are hard to study as it is difficult to identify the critical monitoring locations, and the brittle strength of fractures further complicates design of an appropriate monitoring strategy.

Therefore, the development of new monitoring techniques and different approaches in assessing monitoring data is necessary; for example new sensors that can cover large volumes of the rock mass would be very useful. Moreover, redundancy and variability in monitoring techniques could help in better interpreting recorded data and clarifying the significance of trends that otherwise could be discarded through concerns over their precision.

For large rock falls or for rock slides in general there is a lack of monitoring data available in the literature to help guide and select the optimum methods to assess the time to failure (Fujisawa 2000). However, this is possible when the rupture mechanism is creep controlled through the analysis of deformation rates (Saito 1965, Fukuzono 1985).

The paper deals with two related phenomena (Figure 1); one developed in the past as a rock avalanche which caused a temporary 20 meters deep damming of the Tagliamento River Valley, the other represents a potential landslide due to the structural setting of the slope that shows signs of instability with different mechanism of slope evolution possible. As a result of geological and topographical similarity it can be assumed that the potential slope failure phenomenon might evolve in the same way as the previous event. This hypothesis is further supported by the fact that the rock slope is no longer confined on either the right or left sides. It is believed that the slope currently represents a considerable threat as a failure would result in the valley being dammed to a considerable depth. Assessment identified that a monitoring system was needed to evaluate the state of slope deformation activity and to assess the related hazard. Moreover, it was anticipated that it could also be used as a warning/alarm system, since such processes are generally characterized by a rapid evolution.

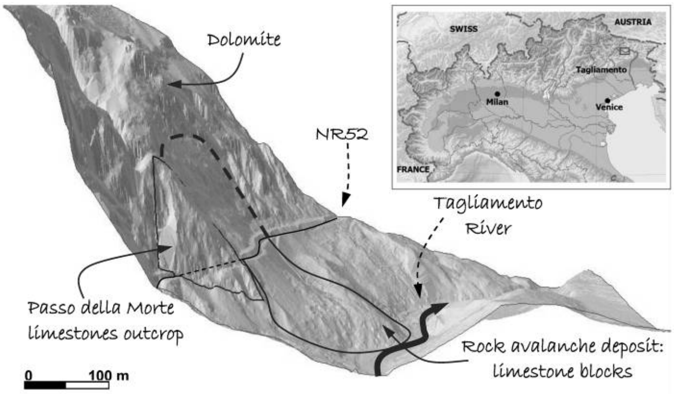

Figure 1. Area of investigation at Passo della Morte and 3D representation of the slope with the landslides highlighted.

2 PHYSICAL SETTING

The left flank of the Tagliamento River Valley, east of Forni di Sotto along the National Road 52 (Figure 1), is affected by several hill-slope processes, characterized by a range of typologies and different state of activity (Marcato 2007). These phenomena were mainly caused by debuttressing due to a melting glacier, which occupied the valley until approximately 10,000 years ago. The landslide blocks at this site influence operation of two road tunnels and they have the potential to impact on the Tagliamento River through valley damming. The potentially unstable slope is formed from Limestone (Calcari scuri stratificati - lower Carnian), with Dolomite (Dolomia dello Schlern - upper Ladinian) forming the underlying bedrock (Figure 1).

The Limestone rock mass is approximately 130 m wide and 250 m high (i.e. from 900 m to 650 m a.s.l.), below 650 m a.s.l. the slope is covered by debris deposits. The Limestone mass is densely stratified, with layers of variable thickness, but rarely more than 0.5 m thick, with strongly wavy or planar bedding planes. In some cases the Limestone alternates with marl, more or less calcareous, of varying thickness, from a few millimeters to 0.25 m. The dip direction of the layers coincides with the slope, with layers inclined at 73° towards the River. The rock mass is divided into numerous blocks of very variable size, that are isolated by a dense system of discontinuities and random fractures (not attributed to particular systems) and small faults. The sub-vertical attitude of the strata, combined with common openings between layers (some several centimeters in width) and the weak properties of the inter-bedded material, allows easy infiltration of water into the rock mass during rainfall and creates ideal conditions for slope failures to occur.

From the structural point of view it is possible to identify in the Limestone rock mass two distinct zones. These are shown in Figure 2 where they are divided by the dashed line.

- Zone A has planar and slightly irregular layers, the bedding planes are substantially closed or rarely open a few millimeters and fill material is absent.
- Zone B is characterized by open bedding planes, or partially open, that are planar to undulating and have marl in-filling. In the upper part of the zone, associated with small folds, the Limestone layers have a shallower slope angle.

Figure 2. Limestone rock mass, Zone A is described as a compact rock mass while Zone B is characterized by open bedding discontinuities. The dashed line marks the boundary between Zones A and B and coincides with a poor Rock Quality Design (RQD <25%) band, two metres wide.

There are two possible scenarios for slope evolution: single rock fall events involving blocks in the order of 1 m^3, or a failure controlled by the Limestone bedding and orthogonal joint system with the event involving the entire or a part of the Limestone rock mass (Codeglia 2011). In this latter case the rupture mechanisms could occur through Zone A, sliding along the contact between Limestone and Dolomite involving the entire Limestone rock mass (700,000 m^3), or Zone B could collapse due to buckling of the Limestone layers (500,000 m^3).

3 MONITORING SYSTEM

Generally it is considered difficult to monitor the displacement of a landslide generated in a rock mass, due to its rigid nature. Therefore it is necessary to make measurements at critical points within the rock mass of a wide range of physical parameters. It is also preferable to design redundancy into the monitoring system so that multiple and different measurements can be used to support interpretation and increase data reliability. In Passo della Morte the geo-mechanical survey and slope morphology were used to design a monitoring system, including selection of sensor type and location, that could be used to identify and quantify the rock mass behavior and its activity. The surveys, instrumentation system design and installation were carried out by IRPI under the assignment of Regional Civil Protection Agency.

Four boreholes were drilled in the rock mass, three of them sub-horizontal (S1, S2 and S3) and one vertical (I22) at locations shown in Figure 3. They have been designed to investigate and then monitor the extent of the Limestone rock mass, taking into account the geological features and in particular the dip direction of the strata. The most important features monitored are:

- The contact between massive Dolomite bedrock and stratified Limestone
- The boundary between Zones A and B
- Bedding planes within the Limestone, with particular interest in those infilled by marls or with special features (e.g. slickensided surfaces).

The monitoring devices installed in the slope are listed in Table 1 and their locations are shown in Figures 3 and 4.

RDQ analysis was performed on the core retrieved from borehole S1 and this information was used to locate the anchor point for extensometer EXT1 within competent intact rock and to ensure monitoring takes place of the “poor” rock mass band within the Limestone. Three extensometers were installed in borehole S1 in order to understand which zones of the rock mass are involved in the landslide mechanism and hence to locate the primary shear plane that controls stability. Two MEMS type accelerometers were also installed in borehole 1 to provide additional information to the extensometer data trend. Core analysis also provided an opportunity to observe the type of fracturing affecting the rock mass, joint surface morphology and their condition. For example, interlayer marls when stresses reveal evidence of movement through the formation of graphite. Projection of the borehole S1 core analysis in the west rock mass face (Figure 4) supported the geomechanical survey and selection of the optimum type and location of sensors. High precision (± 0.01 mm) wire extensometers (EXT4, EXT5 and EXT6) were installed across open bedding planes in areas of poor rock quality (Figure 4).

Table 1. Type, reference name and location of sensors

LOCATION	INSTRUMENT INSTALLED		ID
Borehole I22	*Inclinometer tube (100 m)*		*I22*
	Piezometric sensor		*P22*
Borehole S1	*3- borehole based extensometers*	*75 m*	*EXT1*
		37 m	*EXT2*
		23 m	*EXT3*
	MEMS type accelerometers	*75 m*	*MEMS1*
		23 m	*MEMS2*
Borehole S2	*TDR cable (50 m)*	*Φ 22mm*	*TDR2*
		Φ 41mm	*TDR2bis*
	Steel waveguide (50 m) + acoustic emission sensor	*AEWG1*	
Borehole S3	*TDR cable (30 m)*	*Φ 22mm*	*TDR3*
		Φ41mm	*TDR3bis*
	Steel waveguide (30 m) + acoustic emission sensor	*AEWG2*	
Outside, west rock mass face	*Extensometers*		*EXT4*
			EXT5
			EXT6
	Temperature sensor		

Boreholes S1, S2 and S3 were drilled from within the NR52 road tunnel (Figure 3). S2 and S3 were each instrumented with two TDR cables, with different diameters, and 50 mm diameter steel waveguides for acoustic emission monitoring (see Section 4). Borehole S2 penetrates the contact between the Limestone and Dolomite bedrock and S3 traverses the layers of Limestone located between the tunnel and outer face of the slope. The extensometers, TRD cables and waveguides were grouted in the boreholes using a cement and fine sand grout mix. Boreholes S1, S2 and I22 and associated instruments were formed/installed in November/December 2010 and S3 in September 2011. A seismic station (SS) was also installed in December 2010 and is located adjacent to the inclinometer borehole (Figure 3). This sensor (Mark L-4C 1.0 Hz seismometer) was set with a sampling frequency of 200 Hz and was designed, installed and operated by University of Trieste to measure micro-tremors generated by rock falls and deformations within the Limestone rock mass. It forms part of the regional seismic monitoring network. A weather station records temperature and precipitation for the site.

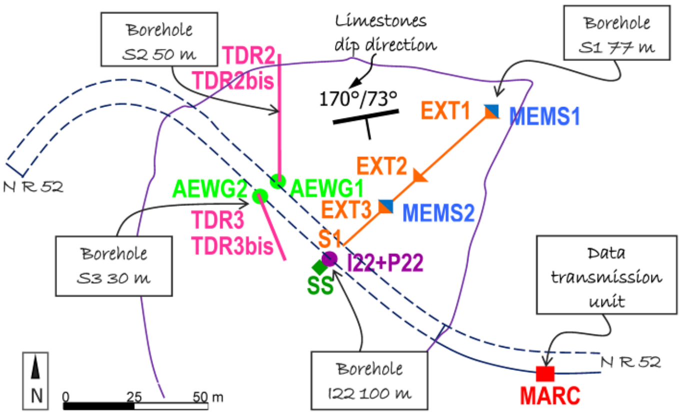

Figure 3. Plan view of the monitoring system layout.

Figure 4. Projected RQD analysis from the S1 core on the west rock mass face, location of external extensometers and indicative location of inclinometer casing, wave- guides and TDR cables.

4 ACOUSTIC EMISSION MONITORING

4.1 *Introduction*

Materials undergoing deformation generate acoustic stress waves (also known as acoustic emission (AE) and sub-audible noise). Studies of AE aim to use the capture and measurement of the signal to determine the extent of material deformation. In soil, AE is generated from inter-particle friction and in rock by fracture propagation and displacement along discontinuities (*microseismic* and *rock noise)*. Acoustic emission can be detected using suitable transducers to provide information on the presence and location of straining.

Acoustic emission monitoring is not a new technique. It has been described in standard texts on geotechnical instrumentation (e.g. Dunnicliff 1988) and on landslide investigation (e.g. Schuster & Krizek 1978), although considerable scepticism exists regarding practicality of the technique. Stability of soil and rock slopes has been studied using AE techniques for over 60 years by international researchers (e.g. Koerner *et al.* 1981, Shiotani & Ohtsu 1999). International research has demonstrated that AE is generated during soil and rock slope movements and that AE monitoring is capable of detecting pre-failure deformations earlier than traditional instrumentation. A limitation of the previous studies is that they did not establish a method to quantify slope deformation rates using measured acoustic emission

4.2 *AE relationships with mechanism and rate of slope failure*

Dixon *et al.* (2003) and Dixon & Spriggs (2007) report research to develop a quantitative relationship between AE and slope deformation behaviour focusing on soil slopes, and Cheon *et al.* (2011) report research to develop an interpretation method for rock slopes. Dixon *et al.* (2003) describe an approach using AE monitoring of active waveguides. Deformation of the slope results in straining of the active waveguide system (steel tube with granular backfill surround) leading to generation of AE. Dixon & Spriggs (2007) detail a laboratory investigation to develop AE processing and interpretation strategies that can be used to produce relationships between AE and soil slope deformation rates.

This research demonstrated for the first time that AE monitoring can be used to give both an early indication of slope instability and also quantification of slope movement rates. Quantification of AE is achieved by calculating AE rates and relating these directly to rates of deformation for a given design of active wave guide. Derived displacement rates are accurate to an order of magnitude, which is in line with current practice for classifying slope movements. The system is also sensitive to changes in displacement rate. Cheon *et al.* (2011) developed a procedure for establishing fracture types and damage levels for cut rock slopes using a calibrated active waveguide installed in a grouted borehole.

4.3 *AE monitoring technique*

A key element of the AE approach is the use of high monitoring frequencies (i.e. 20 to 30 kHz). Filters are used to focus AE detection within this high frequency range to eliminate environmental noise such as generated by wind, traffic, humans and construction activities. However, these relatively high frequencies attenuate rapidly in soils and fractured rock. This is the reason that waveguides are typically employed in slope monitoring studies. AE generated within the body of the slope can be transmitted to the surface by a steel waveguide. In quiet soils (e.g. clays) the annulus between the borehole wall and the steel waveguide is filled with ‘noisy’ granular soil (e.g. sand or gravel). This ‘active’ waveguide generates detectable AE when the slope deforms. In rock slopes AE waveguides are typically grouted into the borehole. Deformation of both the rock mass and the grout generate AE of sufficient strength to propagate tens of metres along the waveguide to the sensor.

Historically a key limitation on the use of AE sensors has been the cost and complexity of monitoring instrumentation and the need for a secure instrument house and mains electricity. This limitation has now been removed through the design of a unitary battery operated real-time acoustic emission slope displacement rate sensor called Slope ALARMS (Dixon & Spriggs 2011). This comprises a piezoelectric transducer, pre-amplifier, filters, signal processing, data storage and power supply. A version incorporating wireless communication of data has also been designed. Research sensors based on this design have been produced by the British Geological Survey in collaboration with Loughborough University. These sensors are being used in a number of proof-of concept trials (e.g. Dixon *et al.* 2010) including at Passo della Morte.

The piezoelectric transducer is placed on the waveguide (Figure 5), and the sensor and waveguide are enclosed in a cover to eliminate the possibility of anything coming into contact with the waveguide. The battery is charged by a solar panel.

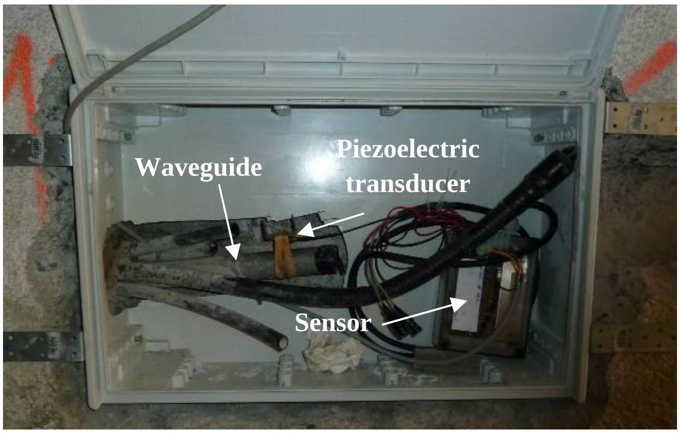

Figure 5. Piezoelectric transducer and AE sensor located on waveguide AEWG2, borehole S3.

5 RESULTS OF MONITORING

Monitoring commenced in December 2010 and it will continue for the foreseeable future. This paper focuses on measurements of AE, deformation from the extensometers, seismic activity and precipitation. The AE and seismic readings are recorded every 15 minutes, the extensometers every 30 minutes and precipitation every 60 minutes. Measured AE rates are the number of times in each 15 minute period that the detected signal exceeds a pre-determined threshold (traditionally called ring down counts – RDC). The seismic data has been analysed to produce an equivalent measure (Zoppè 2011).

During the monitoring period to date only EXT4 has measured deformations. This extensometer is located on the slope surface across a bedding plane crack (Figure 4). Total deformations of 3 mm, comprised from several events, have been measured over the period July to September 2011. Each episode of movement is associated with a rainfall event, although typically deformations occur a few hours after peak rainfall occurs. Figure 6 shows time series for rainfall, cumulative AE and cumulative EXT4 deformations. None of the deformation events generated detectable AE in borehole S2. This is not unexpected due to the large distance between waveguide AEWG1 and the slope surface, and the fact that no deformations were recorded in borehole S1 extensometers concurrently with EXT4, thus indicating that general deformation of the Limestone mass did not occur. Borehole S3 and instruments TDR3, TDR3bis and waveguide AEWG2 have been located specifically to monitor the outer layers of Limestone involved in the deformation behaviour measured by EXT4. However, monitoring commenced after the events described above had occurred.

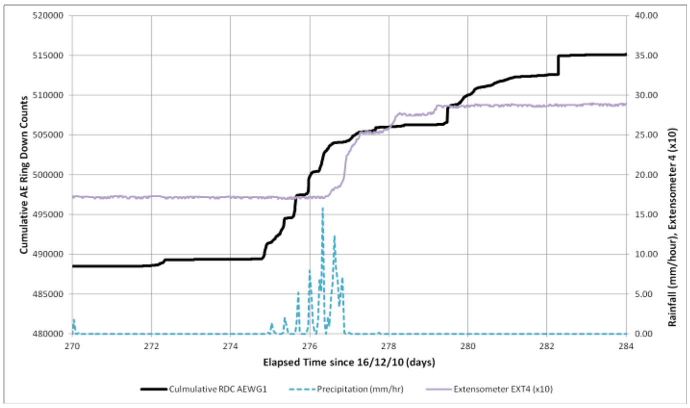

Figure 6. Example rainfall, cumulative AE (AEWG1) and cumulative displacement (EXT4).

There is a strong correlation between rainfall and AE measured using AEWG1. Figure 7 compares rainfall and AE rates for a 1 1/2 day period in May 2011. This is a typical response, with peak AE rates lagging one to two hours behind the peak rainfall rate. This lag is thought to be due to the time required for rainfall to flow into the rock mass through discontinuities. It is currently not clear whether measured AE is generated directly by this groundwater flow or by stress increases, and hence strains, resulting from build-up of pore water pressures within the rock mass. Although the borehole extensometers have not indicated deformations during these rainfall events it is still possible that AE monitoring to detected very low strains as it is a more sensitive technique. Further monitoring is required to establish the mechanism generating the AE as concurrent measurement of rock mass deformation is required to establish the signature of deformation generated AE events. There are a small number of clear AE events that cannot be attributed to rainfall but the mechanism causing these is currently unknown.

Micro-seismic events are also directly related to rainfall but with less lag between peak rainfall and generated seismic activity. This is logical because the seismic sensor is located a few metres from the slope surface in a side gallery of the tunnel, and hence it is close to rain/slope surface processes. There is evidence that seismic activity is in part generated by small scale rock falls and surface movement of loose material triggered by rainfall. For some rainfall events there is a good correlation between AE and seismic events but in many instances the correlation is poor with instances of strong AE with minimal seismic events and vice versa.

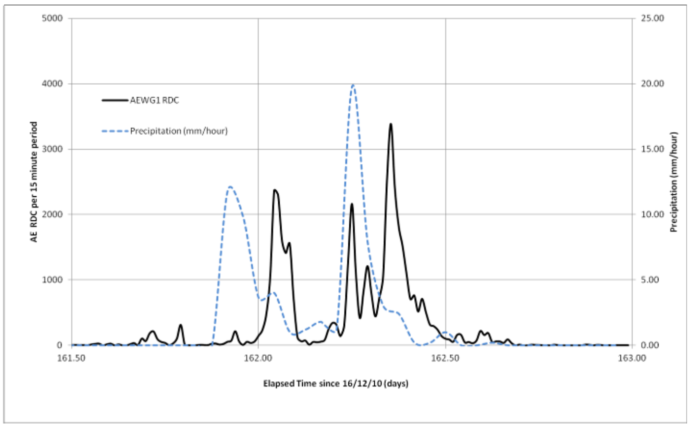

Figure 7. Example relationship between rainfall and AE rates.

6 CONCLUSIONS

Potential instability of the valley side slope at Passo della Morte has been identified involving a sequence of steeply dipping Limestone layers. To appraise the physical characteristics of the rock mass and to provide an early warning of instability, instrumentation has been installed and monitored since late 2010. Extensometers, MEMS, TDR cables, a vertical inclinometer, a micro-seismic station and an AE monitoring system have been installed. To date, the only deformations measured are 3 mm of bedding plane crack widening on the slope surface. This was not detected by the other instruments, including the AE waveguide, as they are located away from the crack location. New instruments were installed in September 2011 to investigate this part of the rock mass. There is a strong relationship between AE and rainfall. The mechanism generating the AE is unknown and continued monitoring is required to investigate this further. Seismic and AE measurements are correlated at times but also differ for significant periods. This is likely to be because the seismic measurements are able to detect slope surface processes while the AE system is monitoring the rock mass around the waveguide. Monitoring will continue for the foreseeable future.

7 ACKNOWLEDGEMENTS

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