Analysis of Microseismic Activity Within Unstable Rock Slopes

Diego Arosio, Laura Longoni, Monica Papini and Luigi Zanzi

Abstract This chapter illustrates the concept of passive seismics as a method for monitoring the propagation of cracks within a rock mass as a result of load stress or water freezing in view of the use of this technique for rockfall early warning. The methodology is still far from being a standard and consolidated technique. The research is making progress, but just a few real case studies are documented. They are shortly overviewed in the introduction. Then, an interesting field test where crack propagation was artificially triggered up to full rock detachment, while a small sensor network was active, is discussed to show the existence and the characteristics of precursory signals. It follows the illustration of the microseismic monitoring methodology through the description of the Mt. San Martino (Lecco, Italy) sensor network and the discussion of the preliminary results obtained during the initial months of activity. Apparently, the preliminary results show some correlation with rainfalls, but not with temperature. Microseismic spectra are mainly concentrated in the first 100 Hz. This probably means that the hypocentre distances from the sensors are quite longer than 10 m. Electromagnetic interferences are also observed as mentioned by other authors who have analyzed data sets from other microseismic networks installed in mountain regions. They are automatically discriminated from significant signals by a classification software which works on the time/frequency properties of these events. Hypocenter localization and clustering analysis of the significant events are the planned near-future activities.

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1 Introduction: Passive Seismics for Unstable Rock Slope Monitoring

Compared to other passive seismic applications such as earthquake monitoring or reservoir hydrofracturing monitoring, landslide and rockfall monitoring is at the very beginning. Earthquake monitoring has a very long tradition, the technology is consolidated, and the data interpretation is robust. Reservoir monitoring during hydrofracturing is a quite recent application, but remarkable advancements have been achieved in a very short time thanks to the enormous interest of the hydrocarbon industry. Besides, this application has one important advantage compared to landslides and rock slopes, i.e., the absence of environmental noise when the technique is applied with borehole sensor arrays. On the contrary, the limited funding of new initiatives in the civil protection sector and the peculiarities of the application of the passive seismic principle to unstable rock slope monitoring explain why this approach is still preliminary, why only a few examples of running monitoring projects exist, and why the expertise in the interpretation and use of rock slope seismic noise are still so poor.

One of the first examples which are well documented is the case of the Randa rockslide in the Swiss Alps (Spillman et al. 2007). The monitoring network was installed by ETH (Zurich) and has been active from 2002 to 2004. It consisted of twelve 3-axial sensors partly installed in boreholes and partly on the surface. The recorded microseismic activity was used to characterize the slope body. Hypocenter localization was performed by using a 3D velocity model created with a tomographic experiment.

The Aknes rock slope (Norway) is another example of microseismic monitoring. The network was installed by NORSAR (Blikra 2008, 2012) and has been active since 2005. Eight 3-axial geophones were installed. Data are systematically analyzed to perform event detection and classification. No localization is performed because a 3D velocity model is not available. The final objective is to monitor the risk of a big rockfall which might produce a tsunami since the unstable rock slope is facing a fjord.

More recent are the cases of Matterhorn (Swiss-Italian Alps) and Sechilienne (French Alps) monitoring networks. Both have been active since 2007. The Matterhorn network was installed by CNR (Amitrano et al. 2010) at very high altitude (about 3,830 m) close to the Carrel hut. It consists of five 3-axial high-frequency geophones installed in holes (3–5 m deep) and three 3-axial low-frequency geophones installed on surface. Because of altitude, the fractured rock slope is highly affected by freeze–thaw cycles which can represent a major cause of crack development and propagation. The Sechilienne network was installed by the Fourier

University of Grenoble (Helmstetter and Garambois 2010) and consists of three seismological stations that work in combination with three arrays of vertical sensors (one linear with 21 sensors and two circular with six sensors each). The network has been recording both internal cracks and rockfalls. Since 2009, a camera has been also installed to observe major rockfalls in order to correlate images and microseismic data in the attempt to calibrate the seismic interpretation in terms of falling rock volumes. Interesting correlations of microseismic events and rainfalls have been observed and studied at this site.

Another interesting case study is represented by the Heumoes slope monitoring network in the Vorarlberg Alps (Walter et al. 2012). It was made operative in 2009 by installing 3 seismic arrays, and in 2011, the system recorded an event produced by a major rockfall occurring at a distance of 5 km from the network. Extremely interesting is the fact that some hours in advance, the system also recorded some precursory events, partly produced by minor rockfalls and partly by fracture propagation.

Another case where a monitoring network had the chance to record precursory microseismic signals prior to an important rockfall is the Mesnil-Val study (Normandie, France). The network was installed on a coastal chalk cliff and consisted of two vertical stations in holes drilled on the top of the cliff (10 m deep) and three horizontal stations in holes drilled on the cliff face (6 m deep). Each station is composed by a geophone and an accelerometer to monitor a wide frequency up to 10 kHz. The network has been running from 2002 to 2004, and a major rockfall of about 1,000–2,000 m^3 occurred during the active period. Precursory signals were recorded since 15 h prior to the rockfall (Senfaute et al. 2009).

Inspired by these examples, we have been studying the problem of monitoring a limestone rock slope (Mt. San Martino) that is threatening the city of Lecco (northern Italy) where a campus of Politecnico di Milano University is located. Before installing a microseismic network and a meteorological station, we carried out some preliminary analysis. First, we set up some field tests on the typical limestones of the Prealpine region to explore its seismic properties such as velocity and absorption in order to predict the expected frequency range according to the sensor distance from the hypocenter (Arosio et al. 2009a). In that occasion, a comparison of the sensitivity of the different available technologies (MEMS accelerometers, piezoelectric transducers, geophones) was also accomplished. After that, we planned some laboratory and field tests aimed at studying the time–frequency characteristics of microseismic signals generated by crack propagation in the specific limestone rock which is typical of the Prealpine group of our selected rock slope. The objective of laboratory test was to reproduce the microseismic effects of freeze–thaw cycles on small rock samples (Arosio et al. 2013, 2014). The objective of the field test was to reproduce a gradual detachment of a small rock mass while monitoring the precursory microseismic signals with some piezo-accelerometers. The results of this test are summarized in the next section of this chapter, while Sects. 3 and 4, respectively, illustrate the microseismic network installed on the San Martino rock slope and the preliminary data analysis performed on the initial monitoring period.

2 Induced Crack Propagation Test

The objective of this test was to capture the signature of a typical crack that propagates in the rock face as a result of load stress or water freezing. The test was operated by soliciting the detachment of a small rock block (approximately 0.5 m^3) at the base of a limestone rock tower affected by a set of remarkable vertical fractures. This site was selected because of the proximity to the rock slope where the permanent monitoring network has been installed, sharing the same geological history. Thus, the results of this test should represent a good reference for the data analysis of the network records. Block failure was induced by means of a rectangular hydraulic jack inserted in an existing fracture; oil was manually pumped into the jack until complete block failure (actually, the block was completely detached but did not fall because it was held in place with a fastening system due to safety reasons). Three uniaxial piezoelectric accelerometers (Wilcoxon 799LF, sensitivity 500 mV/g, band 0.2–2,500 Hz) were deployed onto the rock surface at increasing distances from the hydraulic jack (Fig. 1) to collect microseismic signals generated by the forced fracture propagation. A 24-bit acquisition board continuously recorded signals with a sampling frequency of 5,120 Hz according to the band of the used transducers and in order to keep storage space to a minimum. Pressures as high as 0.45 MPa were reached and it took nearly 325 s to reach the block collapse. Sixty-nine events were detected during the experiment by the closest sensor, twenty-six events by the middle one, and just seven by the furthest sensor. More in

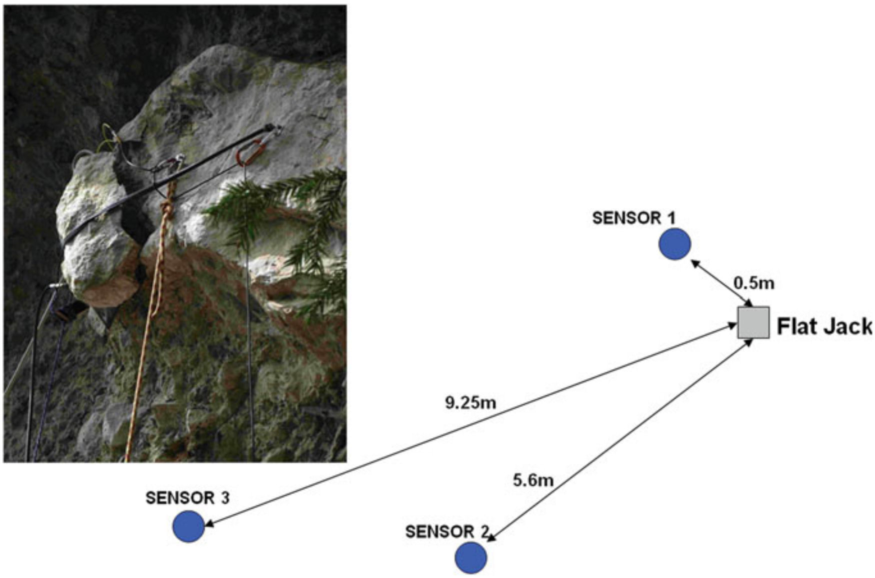

Fig. 1 Sensor positions and distances from the crack armed with the flat jack. The picture shows the rock block after full detachment and the ropes used to control the rockfall

detail, the furthest accelerometer was able to record meaningful signals just during the final burst sequence, when the strongest events were generated immediately before the ultimate collapse. As the two farthest accelerometers had similar orientation with respect to the source position, we also tried to estimate elastic wave attenuation by comparing the amplitude of the events detected by both sensors. We found an attenuation factor as high as 1.10 dB/m, which is in good agreement with other previous tests executed in another site but on the same type of limestone (Arosio et al. 2009a). By analyzing the events collected by the closest sensor, we observed wide bandwidth events with energy equally distributed in the whole frequency band of the recording system (Fig. 2 at the top). Thus, we cannot exclude that higher frequencies were also generated by the cracking phenomenon. However, a dramatic decrease of bandwidth is observed as soon as we move a few meters far

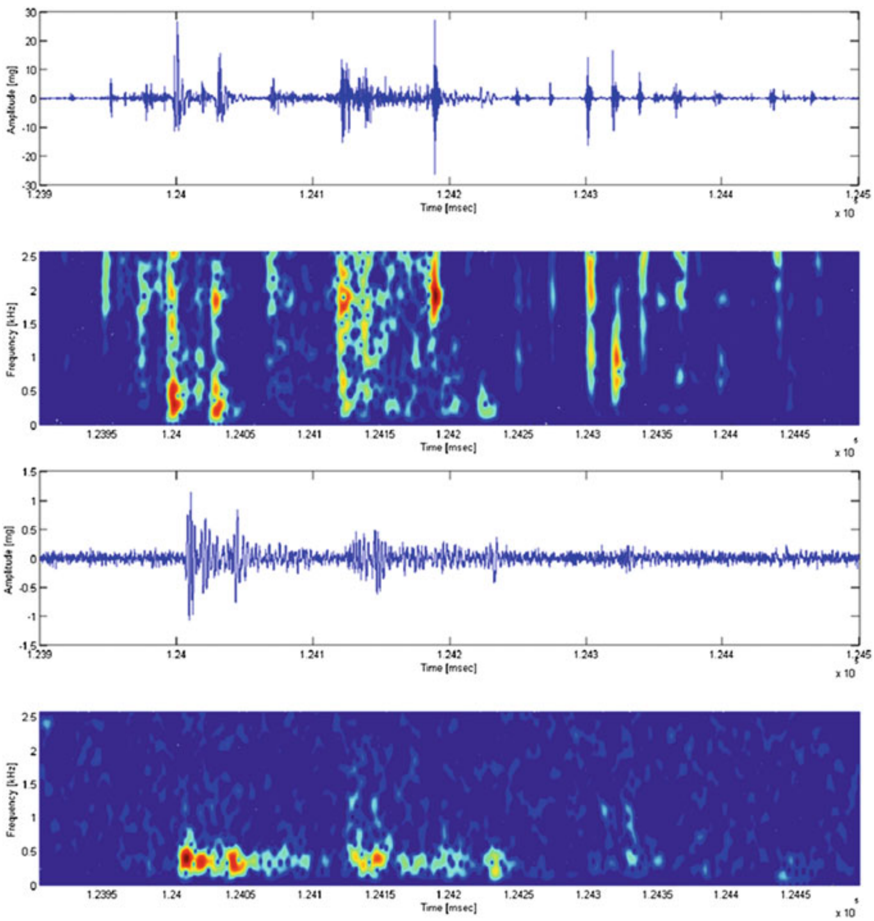

Fig. 2 Time–frequency representation of the final burst sequence recorded by the closest sensor (at the *top*) and the farthest sensor (at the *bottom*), respectively

from the crack position. Figure 2 (bottom) suggests that because of attenuation, an effective bandwidth of 500 Hz is sufficient to record most of the energy that travels at a distance of 10 m or more from the active crack.

In summary, this test indicated that a collapse is preannounced by an intense sequence of microseismic events with amplitude increasing as we approach the rockfall. Frequency spectra and attenuations observed at the different sensors suggest that a sampling frequency of 1 or 2 kHz is sufficient for a network of sensors with inter-distances in the order of a few tens of meters. Finally, the signatures of the events observed in this test will be a good reference for guiding the interpretation of the great amount of events recorded by the Mt. San Martino monitoring network.

3 Mt. San Martino Monitoring Network

Mt. San Martino is located at the end of the Lecco branch of the Como Lake (northern Italy). It is part of the Prealpi Lombarde and threatens the city of Lecco with the 300-m-high unstable rock face (Fig. 3). A major event occurred in 1969 caused 7 fatalities with a rockfall of about 15,000 m^3. The area that is currently monitored by the new microseismic network is close to the main scarp of the 1969 rockfall.

According to our preliminary test (Arosio et al. 2009a) carried out to compare the performances of different sensor technologies on the limestone rock of this Prealpi group, traditional sensors (i.e., geophones and piezoelectric transducers) are still remarkably superior to the low-cost MEMS accelerometers. Thus, we decided to install geophone sensors which can ensure in the required bandwidth (from a few Hz to 500 Hz) sensitivity comparable to that of piezo-transducers at a lower price.

Fig. 3 Mt. San Martino rock face threatening the city of Lecco (northern Italy)

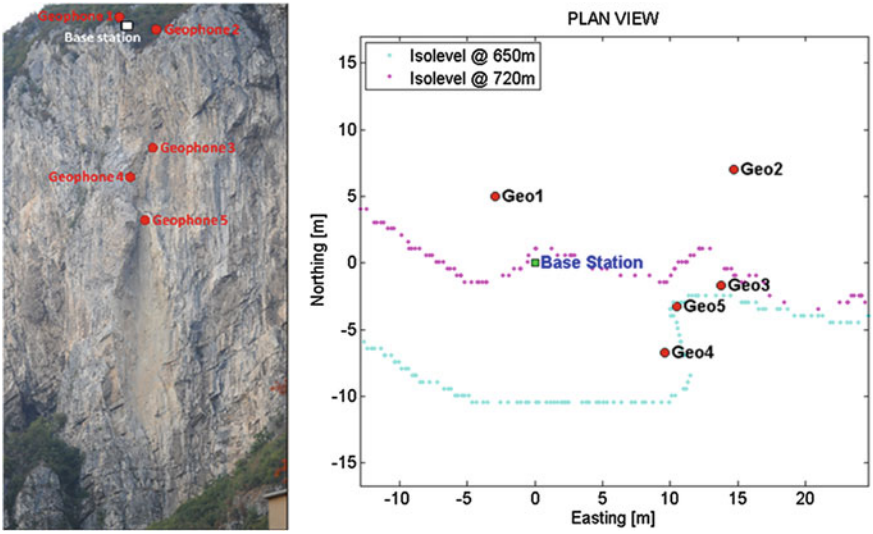

Fig. 4 Geophone positions on the rock slope (*left*) and plan view of the network geometry

The network consists of five 3-axial 28 Hz geophones plus a rain gauge and two temperature sensors (one for air temperature and one placed in a superficial fracture to check for freezing–thaw cycles).

Apart from three geophones installed in shallow holes onto the rock face, two geophones were deployed in vertical holes, 5 and 10 m deep, respectively, on the plateau above the rock face. The borehole sensors are important because they can provide data with higher signal-to-noise ratio (or sense weaker events) thanks to a quieter environment and improve the accuracy of source localization because of a better recording geometry (Arosio 2010). The network is extended more vertically than horizontally. The geophone position is illustrated in detail in Fig. 4. The elevation range, from the lowest to the highest geophone, approximately goes from 640 m to 720 m a.s.l.

The acquisition unit is equipped with an 18-channel 24-bit A/D conversion board and with a GPS receiver for correct network timing. Microseismic events are recorded when a selected short-time average/long-time average (STA/LTA) threshold is overcome by at least a single channel. Once a trigger occurs, the recorded event has a min–max duration range of 5–20 s with 2 s of pre- and post-trigger. Thus, multiple or prolonged events can be saved in a single records provided that they are not longer than 20 s. Sampling frequency for the microseismic events is 1 kHz, while meteorological parameters and the background seismic noise level are regularly collected at 10 s intervals. Other important parameters such as gain levels, threshold level, and filters were experimentally optimized during a preliminary calibration period in order to maximize the sensitivity of the network while trying to prevent the recording of non-significant noise events.

Power supply is provided by solar panels, and remote communication is granted by a dedicated radio link. Data are stored on a 2 GB CF card and daily transmitted to a central station located at the Lecco Campus of Politecnico di Milano.

4 Preliminary Data Analysis

The sensor network has been operating for more than one year, but data collection suffered from several power interruptions because of significant snowfall winter 2013–2014. In the first 7 months, the network recorded more than 5,000 events. We explored any possible correlation of these events with meteorological parameters. It seems that no correlation exists with temperature, but it is important to point out that the winter temperature was not particularly rigid, and according to temperature recorded by the sensor installed in a fracture, no freeze–thaw cycles occurred. Instead, a moderate correlation was observed with rainfalls. Figure 5 illustrates the cumulative number of events of the initial 7 months compared with the cumulative rainfall. Group of microseismic events is often observed after significant rainfalls but with a delay of a few days. This delay is longer in winter (4 or 5 days) and tends to reduce to 1 or 2 days toward summer. Interestingly, this sort of delayed correlation with rainfalls was also observed by Helmstetter and Garambois (2010).

A detailed analysis of time and frequency properties of our records shows that the events can be roughly classified with four types of signals: (a) single microseismic events, (b) multiple microseismic events, (c) spikes, and (d) noise, where only type (a) and (b) present properties that are quite similar to the expected type of events observed during the induced crack propagation test (Fig. 6). The amplitude spectra show that no significant energy is observed above 100 Hz, probably

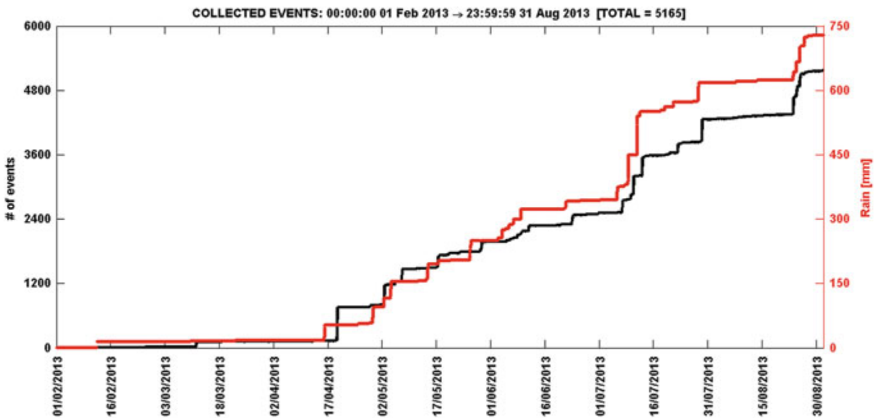

Fig. 5 Cumulative number of events in the initial 7 months of sensor network activity (*black line*) compared with cumulative rainfall (*red line*)

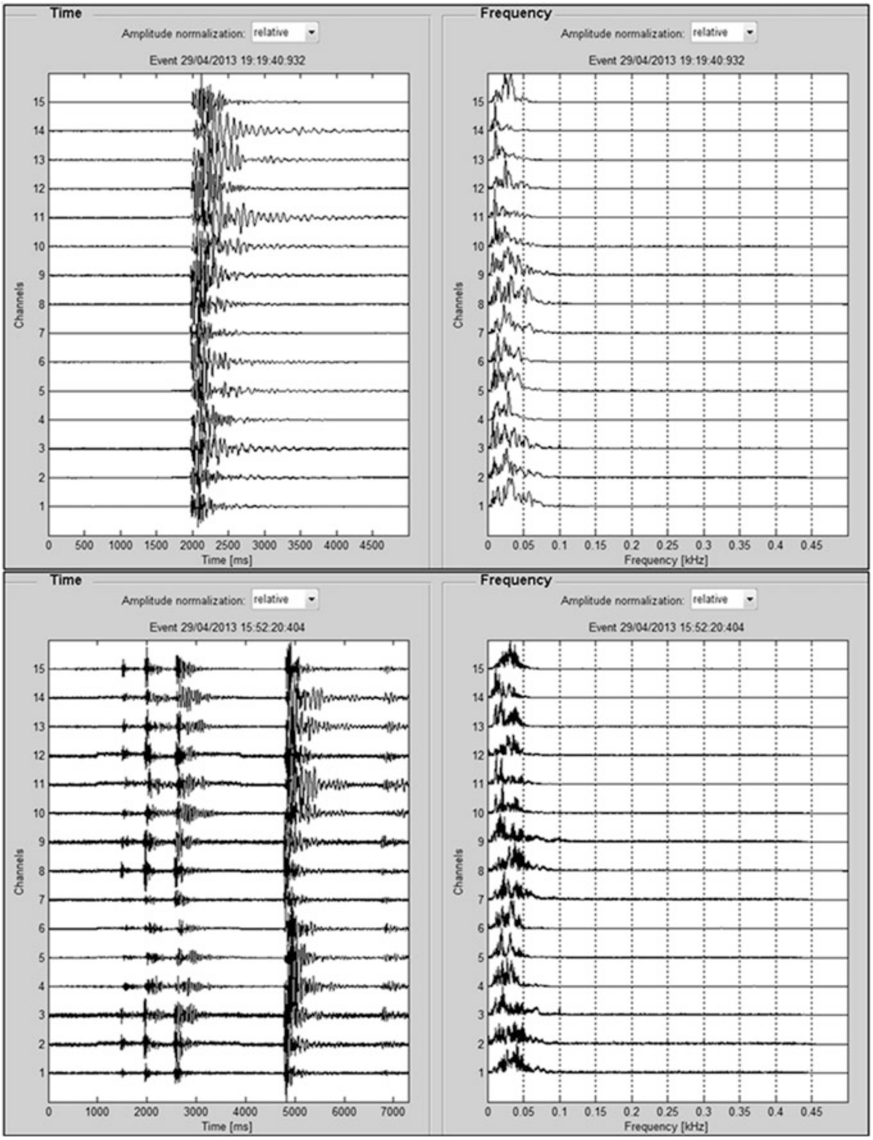

Fig. 6 Examples of time and frequency representation of significant single (at the *top*) and multiple (at the *bottom*) microseismic events

meaning that the hypocenters are quite farther than 10 m from the closest sensor. Figure 7 shows the typical signature of those events that we classify as spikes. The signature is unusually impulsive. The spectra span over the total available bandwidth (500 Hz) which probably means that the spectra were actually larger and were limited by the anti-alias filter of the acquisition board. It is hard to believe that

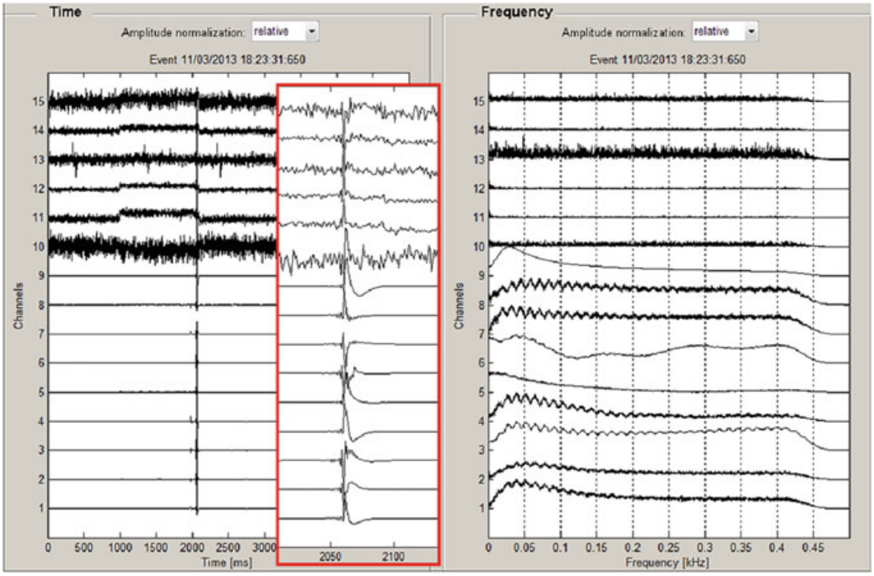

Fig. 7 Example of time and frequency representation of a spike event. In the *red box,* the timescale has been expanded around the spike

these events could be produced by crack propagation or other mechanical phenomena (e.g., micro-rockfalls). It is much more probable that these events result from electromagnetic interferences whose nature is still to be understood. The railway runs at the base of the rock face (i.e., at a distance of about 500 m), but no direct correlation has been demonstrated with the train timetable. Spikes occur during both day and night, while no trains are planned during the night and spikes are often distributed in groups that last for time intervals much longer than a train passage interval below the rock slope. Similarly, we did not find a correlation of spikes with local weather storms, but maybe the geographic area of our storm analysis should be expanded. A review of this correlation analysis is planned in order to consider a much larger geographic area. Thus, currently, we do not have any convincing explanation for these type (c) events. Again, it is interesting to note that a similar type of events was also noted by Spillmann et al. (2007). Finally, events of type (d), classified as noise, are records where an incoherent noisy signal lasts for the whole duration of the record on all the channels and occasionally hardly overtook the triggering threshold on one of the 15 channels. These noise events are possible because a very low STA/LTA threshold was selected to prevent any loss of significant events.

Given the large number of events (more than 5,000 in 7 months), we developed a software for automatic selection of significant events based on time and frequency characteristics of collected signals as well as on the number of sensors involved. As an example, we wanted to scrutinize from the 5,165 events recorded in the initial 7 months of monitoring all the events that excited more than three sensors simultaneously. A data set of 72 events was extracted. Among these, the software distinguished 20 spikes, 18 noise events, and 32 significant events (i.e., events of type (a) and (b)). Provided the SNR of the 32 selected events is high enough to allow a reliable traveltime picking, these events are those that could be submitted to a localization process to create a hypocenter distribution map from which to derive insights about the rock face internal fracturing process. As a matter of fact, four sensors represent the minimum setup needed to perform a 3D localization based on time difference of arrival (TDOA), see Hardy (2003) and Herath and Pathirana (2013). Figure 8 shows one of the 32 selected events as it was recorded by the five geophones. Raw data without any filtering or other processing are shown except local trace normalization. Data quality is good, and a fairly reliable traveltime picking can be performed on all the components of these geophones. From a rough analysis of the delays, it seems that the event reached the geophones in the following order: no. 4, no. 5, no. 3, no. 2, no. 1 so that the hypocenter is expected to be closer to the geophones installed on the rock face (no. 3, no. 4 and no. 5) rather than to the borehole geophones (no. 1 and no. 2). Actually, a critical issue in determining the hypocenter of the event is the velocity of the medium. Assuming a constant velocity medium, TDOA from two sensors confines the source location to a 3D hyperboloid and the intersection of three or more independent hyperboloids defines the hypocenter. Unfortunately, most authors who tried to perform 3D location of microseismic events generated by rock fracture propagation agree on saying that the

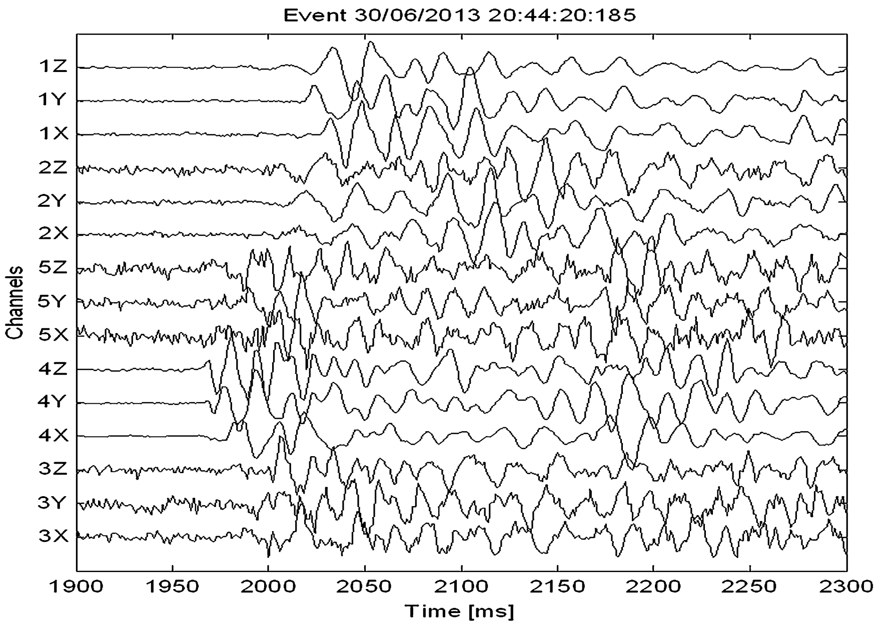

Fig. 8 Example of a single event detectable on all the components of the five 3-axial geophones

constant velocity assumption is too rough to obtain consistent results (Helmstetter and Garambois 2010; Spillmann et al. 2007). Thus, a more realistic velocity model is needed and the localization algorithm must incorporate a forward modelling software to calculate the signal trajectory through the fractured rock.

Another approach for 3D localization is the *coalescence* method (Drew et al. 2005) which helps handle data with bad SNR where traveltime picking becomes questionable, but which does not overcome the problem of the velocity field. This method consists of 3D focusing the recorded data in the supposed source position (Arosio et al. 2009b). Thus, a velocity field is still needed to apply the focusing operator. The hypocenter is found as the location where the highest amount of energy is collapsed by the algorithm. The method is widely applied to process microseismic data resulting from monitoring of reservoir hydrofracturing operations since the method can be applied automatically in order to get a real-time feedback for optimizing the proppant injection parameters. Compared to the TDOA algorithm where the result is exclusively determined by the traveltime delays, the coalescence method is also influenced by the energy observed by each sensor. Depending on the strategy that is applied to manage the energy received by the different sensors, the localization result may change. If no gain is applied, it is clear that the result will be mostly influenced by the sensors closer to the hypocentre, which are expected to receive much more energy than the farther receiver. Thus, energy in the coalescence method can work like a sort of weighting function applied to delay traveltimes. This is another possible advantage offered by the coalescence method compared to TDOA, although a sort of SNR-based weighting function could be also introduced in the TDOA process. In principle, a localization algorithm exclusively based on energy back-propagation analysis would be also applicable, provided that a reliable velocity field and an absorption field are assumed. As an example, by analyzing the energy collected by each geophone for the event illustrated in Fig. 8 (under the assumption of a constant absorption field), we found that the geophone closest to the hypocenter is still geophone no. 4 in full agreement with the TDOA indication, but the position for the other geophones do not match the order proposed by TDOA. Furthermore, the energy method also implies the necessity of neglecting the geophone coupling problem, i.e., the necessity to assume that the geophones are equally coupled or the necessity to calibrate the sensor network with specific experiments designed to estimate a coupling factor for each geophone. Given the difficulties associated with obtaining a good estimate of the absorption field and of the geophone coupling factor, it is hard to believe that a localization algorithm exclusively based on energy might compete with a TDOA or a coalescence method.

Currently, we do not have an opinion based on real data feedback between TDOA and coalescence methods because we still need to estimate a good velocity field for our unstable rock slope. To this aim, a tomographic experiment has been designed and will be performed before the next winter season.

Localization will be fundamental also for helping the classification of the significant events. As a matter of fact, among the 32 significant events of the initial 7 months, there might be events generated by a fracture propagation process but also events generated by a micro-rockfall (small stones hitting the rock face while falling down from the top of the rock face). Unfortunately, this occurrence is not improbable because the rock face, although quite vertical, is surmounted by a more gentle slope where rock debris accumulate and slide down especially during storms.

Thus, another priority for the near future is the classification of the significant events. To this aim, a database of the significant events is under construction. Any event is analyzed to extract a number of properties which include duration of the event, energy, SNR, bandwidth, spectral centroid, centroid variance, recording geophones, weather, and other parameters.

The goal is to complete this database as soon as a reliable velocity field is available with the localization of the events which excited more than four geophones and then to apply a clustering process to explore the possibility to get a clear discrimination at least between fracturing events and micro-rockfall events.

5 Conclusions

The way to an effective use of a microseismic monitoring sensor network for early warning of rockfall risk from an unstable rock slope is still quite long. According to our preliminary analysis of data collected on the Mt. San Martino rock face in Lecco (northern Italy), we can summarize the results as follows. Microseismic activity seems to have no correlation with temperature. However, this is a result which comes from a temperate winter during which according to our temperature sensors no freeze–thaw cycles occurred within the rock fractures. Instead, a moderate correlation exists with rainfalls although with a delay of some hours or a few days depending on the season (shorter delays in summer). No significant energy is observed above 100 Hz which probably means, according to our induced crack test, that the hypocenters are quite farther than 10 m from the closest sensor. Similarly to other microseismic monitoring networks installed on mountain regions, the Mt. San Martino network is also recording a great number of large bandwidth spikes, which we classified as electromagnetic interferences, whose nature is still under investigation.

Automatic discrimination software has been developed to extract significant events, and a database of significant event properties (e.g., duration, energy, SNR, bandwidth, spectral centroid, recording geophones, and weather) is under construction.

Several near-future activities are already planned: (a) a traveltime and attenuation tomographic experiment aimed at building a 3D velocity and absorption model, which according to most authors is absolutely needed to perform a consistent hypocenter localization of the events; (b) a classification process aimed at exploring how the significant events cluster according to their main properties and how the fracturing events can be discriminated from micro-rockfall events.

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