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A microseismic-based procedure for the detection of rock slope instabilities

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A B S T R A C T

The accumulation and spatial location of damage can lead to the progressive formation of macroscale discontinuities and the possible collapse of portions of rock slopes. Since rock fracturing is accompanied by the generation and transmission of elastic waves that travel through the affected material, an analysis procedure that is able to interpret data, recorded by means of a microseismic monitoring system, has been developed. The procedure is made up of three main parts: the identification and grouping of similar events, the hypocenter location of grouped events and the cross-analysis of the spatial distribution of the source events with the structural setting of the investigated area.

The application of this methodology to a dataset recorded by a monitoring system installed on the Matterhorn mountain has pointed out that this approach can contribute to recognizing areas subjected to a common rupture mechanism, which can concern one single fracture or a set of neighboring fractures. If signals that are generated over time from a certain area have a waveform with similar characteristics, the rupture mechanism that causes the signals is the same. At this regard, a good knowledge of the local structural setting of the slope and of the characteristics of some documented rockfall events can contribute in supporting the above statement and help focus on areas where failures are kinematically possible.

1. Introduction

It is generally accepted that most solids emit low-level seismic signals when they are stressed or deformed. In the geotechnical field, this phenomenon is generally referred to as acoustic emission (AE), at the laboratory sample scale, or micro-seismicity (MS), at the rock massive scale.

When a rock fractures, it produces AE/MS signals that transmit through the rock as elastic waves. The installation of MS systems, which monitor self-generated acoustic signals that occur within the ground, is therefore being adopted more and more to monitor the stability of underground structures, such as mines, tunnels, natural gas and petroleum storage caverns, for example [1–5], as well as to evaluate rock damage, for example [6–10], and predict slope failures, for example [11–18].

The identification and location of the state of damage of rock under various physical conditions is very important; in fact, the accumulation of damage and its spatial location can lead to the progressive formation of macroscale discontinuities, and the possible collapse of portions of a rock slope [19].

Since the study of the AE/MS signals can provide information about the size, location and strain mechanisms of an AE/MS event, as well as the properties of the medium through which acoustic waves travel, it can contribute to rock failure prediction.

The main approaches to the analysis of AE/MS data and to their correlation with rock fracturing processes can be grouped in the following three categories.

The first and most common approach consists of the simple counting of the number of AE/MS events prior to failure. The analysis of this information can contribute to the comprehension of the possible correlation between the AE/MS rate and the inelastic strain rate and, when coupled to damage mechanics models, to the determination of how damage accumulates during loading and to the prediction of failure, for example [20,21].

The second class of investigation concerns the location of hypocenters of AE/MS source events. This technique requires precise knowledge of the arrival time data of AE/MS signals recorded over an array of sensors. The analysis of spatial and temporal variations of the hypocenter of recorded events can help to improve the understanding of the progression of microcrack growth and the clustering that lead to rock failure [20].

The third category involves a full waveform data analysis. One aspect of this approach concerns the determination of fault plane solutions of AE/MS source events from the first motion data. These studies can show that, in addition to pure tensile and slipping

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events, a significant number of more complex type events occur in the period leading up to fault nucleation [22,23].

This paper describes a procedure that can be used for the analysis and interpretation of microseismic events that are naturally generated inside rock slopes and which are recorded by means of a microseismic array. This procedure combines the concept of waveform data analysis and hypocenter location.

In particular, the method aims at evidencing how microseismic recordings can be used to recognize areas where ruptures can be organized along a fracture or along neighboring fractures. The contribution in this direction is made possible by the identification of signals that arrive at different time periods from a common area and are characterized by similar waveform characteristics.

Signals produced in a certain area have similar waveforms over time, if the rupture mechanism that causes the signals is the same.

A cross-analysis between similar signal information and data on the local structural setting of the slope can contribute to recognizing the phenomena that can point out a change in the internal stress and setting of a slope, and which can be precursory to the collapse of portions of rock slopes, especially when an increment in the number of signals with similar characteristics is observed.

The potentiality of the method is illustrated through its application to a dataset recorded by means of a microseismic monitoring system installed on the Matterhorn mountain. This site was selected due to the wide interest it has received because of the large number of rockfall events that have affected the Matterhorn area over the last few years. The extreme conditions that characterize the investigated site (i.e. 4478 m a.s.l.) make quite unique the availability of a continuous recording period lasting 6-months, like that presented in the paper, almost unique. In fact, after this fortunate experience, the system was frequently affected by damage, which made further long periods of recordings impossible.

The terms “cold season” and “warm season” have been adopted here according to climatological definitions. The cold season lasts from October until the end of March, and the warm season lasts from April until September. Warm and cold periods can be observed within both the warm and the cold seasons.

The available data refer to November 1, 2007–April 7, 2008, and, as a consequence, they concern the cold season, when no people were present in the area. The absence of human activity offers the advantage of having undisturbed MS recordings but, on the other hand, this made the direct observation of new rockfall events impossible. However, thank to the good knowledge of the structural setting of the slope in the investigated area and of the size, spatial distribution and characteristics of some rockfall events documented during summer time, the crossing of the above data with microseismic results made the interpretation of the nature and origin of the collected data possible.

Furthermore, a correlation with rock temperature recordings, at a depth of 55 cm, showed that, for the analyzed period, the temperature curve can be divided into 4 periods, with a succession of cold and warm periods, and that most of the microseismic activity occurred during the transition from warm to cold periods. The cold periods, which were characterized by a continuous and more rapid temperature decrease in time, had the highest average daily number of events. No concentration of events occurred when the rock temperature increased (i.e. during the transition from cold to warm periods). Similar behavior was observed by Gruner [24], who treated a set of 800 events from both a historical and rock-mechanical point of view. A detailed analysis of the above aspects can be found in [25].

2. Signal analysis procedure

Microearthquakes that occur in a given area rarely occur as single and isolated events. In this regard, a misinterpretation can occur when microearthquakes are considered as individual features, instead of comparing signals recorded over a long period of time among them. Methods that are used to recover the correct information, by investigating signal relations, may be divided into two classes: time-domain methods and frequency-domain methods [26]. Cross-correlation analysis belongs to the former type, while spectral analysis (or spectrum analysis) belongs to the latter.

The cross-correlation, Γ_{xy}, of two signals, $x(t)$ and $y(t)$, in time (t) domain results in

$$\Gamma_{xy}(\tau) = \lim_{T\to\infty}\frac{1}{T}\int_0^T x(t)y(t-\tau)d\tau \to \Gamma_{xy}(\tau) = \lim_{T\to\infty}\int_o^T x(t)y(t-\tau)dt \quad (1)$$

and exhibits a maximum when the two signals are similar, where T is the time period and τ is the time lag between the two signals.

The slowness and need of interpolation of the cross-correlation computation, as well as the eventual need of a priori knowledge of the signal frequencies, have made the spectral version of the cross-correlation computation (spectral analysis) a more appealing method for signal processing. This procedure allows one to identify a frequency (f) domain representation of a time domain signal using a Fourier transform of the cross-correlation function.

In short, the cross-spectrum, γ_{xy}, quantifies the energy that is common to both the $x(t)$ and $y(t)$ signals. The cross-spectrum normalized by the smoothed auto-spectra of the $x(t)$ and $y(t)$ signals is the coherency, $C^{\approx}{}_{xy}(f)$. Its value is minimal when the $x(t)$ and $y(t)$ signals are uncorrelated, while it increases up to unity in the case of a perfect correlation between the two signals [23]:

$$\overset{\approx}{C}_{xy}(f) = \frac{\overline{\gamma_{xy}(f)}}{(\overline{\gamma_{xx}(f)})^{0.5}(\overline{\gamma_{yy}(f)})^{0.5}} \quad (2)$$

where $\overline{\gamma_{xy}(f)}$ is the smoothed cross-spectrum of the $x(t)$ and $y(t)$ signals, while $\overline{\gamma_{xx}(f)}$ and $\overline{\gamma_{yy}(f)}$ are the smoothed auto-spectrum of the $x(t)$ and $y(t)$ signals, respectively.

The relation between signals recorded at two different points of a monitoring network, but caused by the same source, is always linear and stationary, that is, it is a function of the characteristics of the medium in which the wave has propagated. However, signals recorded at different times at the same point of a network are only related to each other through a linear and stationary relation, if they originate from the same source or from similar sources.

The above-described approach has here been applied to data recorded by a microseismic monitoring network, installed on the Matterhorn peak, in order to investigate whether multiplet events had occurred in the studied area. A multiplet and a doublet are a set and a pair of similar-appearing events, respectively.

According to the above-described aspects, each multiplet can indicate an area in which the signals are characterized by common rupture mechanisms. In this context, the use of techniques for hypocenter location can contribute to determining the spatial distribution of the hypocenters. If the hypocenters are aligned along an almost planar surface, a particularly active discontinuity can be identified; if they are rather scattered, they can indicate concomitant rupture along a set of discontinuities. These hypotheses can be confirmed through an analysis of the morphostructural setting and of the evolution of slope processes in the investigated area.

The NonLinLoc open-source set of programs have been used to locate the hypocenters (http://alomax.free.fr/nlloc/). The original version of NonLinLoc allows a probabilistic, non-linear, global search of an earthquake location to be made. As a consequence, the application to microseismic networks, which are generally small, has dictated the necessity of modifying and adapting the program.

The Vel2Grid program in the NonLinLoc package is the pre-processor that is devoted to velocity model computation. It allows