Remote monitoring of natural slopes: Combining use of Terrestrial Laser Scanning and innovative rockfall alert system

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Abstract. The article describes the first results of a research project aimed to digitalize the monitoring activities of natural rock masses. The project started with a geotechnical remote analysis on the high-definition 3D point cloud detected by a terrestrial laser scanner (TLS), and with the identification of principal discontinuities elements through 3D manual and automatic analysis of the fractures. The results of these survey campaigns have allowed identifying geometrical information of the blocks at risk, to perform a detachment risk assessment and an evaluation of the potential falling trajectories through the lumped mass methodology. The geotechnical monitoring of the rocky mass has seen the combined use of two techniques: the use of a terrestrial laser scanner (TLS) combined with Imaging Matching algorithms; and the implementation of an innovative smart warning system for detachment phenomenon realized by Maccaferri s.p.a., applied to rockfall barriers and drapery mesh, able to provide real-time status notifications and warning alerts. According to the first data analyses, both the proposed techniques can provide excellent monitoring of the rocky slopes, with low costs. The methodological approach proposed perfectly integrates with smart management of excavation sites and the infrastructure and can guarantee an extremely high level of health and safety.

1. Introduction
Ornamental stone quarries are, in many cases, built along mountain slopes, which exposes the quarry site, and consequently the operators, to potential phenomena of detachment of the most altered and superficial portions of the rock mass. For these reasons it is advisable that, in quarries where such circumstances occur, the stability problems of the rocky slopes are addressed and solved, using both the appropriate calculation and monitoring approaches and the most suitable technical tools for carrying out the interventions, whether they are active (preventive) or passive (protective).

The note, referring to some practical examples, identifies the phenomena of instability due to falling rocks and analyses the intervention and monitoring techniques for the prevention and protection of quarry sites.

2. Rock mass instability phenomena that cause rock falls
Rockfall is a dangerous process that can frequently occur in rock masses, following their progressive degradation. The phenomena of instability of rock masses that cause a rock fall are a threat to the workers of quarries and mines, and for this reason, the mitigation of such phenomena is a very important task. The factors that can trigger detachment phenomena on an excavation wall or a natural face are many due to natural processes such as rain, freeze-thaw cycles, earthquakes or sometimes caused by the interaction with excavation activities that alter the morphology of the slopes.

In the fall process, three zones are distinguished: one of detachment where the release of the boulders takes place and their free fall begins; the transition zone where the rocks slow down as a result of
bouncing or rolling; and the deposit zone where the boulders stop and accumulate. The behavior of the bodies in the transition area is due to the angle of inclination of the slope, which determines the mode of movement, this process is outlined in figure 1.

**Figure 1.** Rockfall process.

3. **Preventive and protective intervention techniques**

The possible preventive intervention techniques to control instability phenomena can be summarized in two different design approaches:

- elimination of the problem with the removal of the unstable portion through localized reclamation and scaling;
- stabilization of the area with suitable consolidation, control of surface and deep waters with drainage and regulation of running waters.

The possible protective intervention techniques are mainly aimed at intercepting, diverting or stopping the single elements or masses already in motion. Some of these interventions can be located upstream, to control the instability capable of interacting with the quarry, or downstream of the yards to protect man-made areas underlying the mining area, in general they are:

- the re-profiling of the slope, with the creation of intermediate berms or aprons that can act as accumulation areas for collapsed debris;
- the installation of rockfall nets, with different technologies for damping the kinetic energy of the blocks;
- the embankments obtained with blocks of rock, cliffs, reinforced earth.

The first models for the design of protective structures were based solely on the geometric characteristics of the slopes [1], with the passage of time full-scale tests were carried out to provide increasingly refined design schedules, up to the most sophisticated models 3D forecast numbers. In figure 2 a sizing scheme of the rockfall barrier is proposed as a function of the expected kinetic energy of impact [2].
4. Analysis of the danger and risk of falling rocks

In the context of a rockfall, the eventuality that an event of a given intensity (energy) or size (volume) occurs within a particular region is indicated as a rockfall hazard. The definition involves the concept of location (where an episode will occur), magnitude or intensity (amount of energy) and frequency (its repetition over time).

The concept of assessing the danger of falling rocks is combined with the concept of risk assessment, which is defined through three essential elements: danger, exposure of the elements at risk and their vulnerability.

The mapping / zoning of the risk of falling rocks or susceptibility leads to the drafting of a useful document for the preliminary assessment of adequate protective measures. There are some guidelines that define consistent criteria for combining probability of occurrence or susceptibility, and intensity in a map document, such as for example and Swiss guidelines [3], as shown in figure 3, which propose a matrix scheme that defines different danger zones, of different colors.

![Matrix scheme for the analysis of rockfall risk in Switzerland.](image)

**Figure 2.** Abacus for choosing the correct rockfall barrier according to the expected kinetic energy of impact [2].

**Figure 3.** Matrix scheme for the analysis of rockfall risk in Switzerland.
5. Safety control through geomechanical monitoring

In recent years, a digital innovation project has been developed, called Twin Marble Quarry, in which the mountain is transformed into a digital twin called Gemini where the geotechnical, management and industry 4.0 paradigms are summarized and managed in a holistic way.

In some marble quarries of the Apuan Alps, which have joined the project, attention was paid to the potential of the terrestrial laser scanner (TLS) in geotechnical problems, developing a workflow that would fully exploit the potential of the point cloud High definition 3D obtained from the survey with TLS, starting with the identification of the main families of discontinuities through a manual and automatic analysis of the point cloud.

The great improvement that the TLS has brought in the assessment of rockfall risk concerns the possibility of monitoring the detachment of blocks from the rocky slope between two or more eras.

This approach allows both the quantification of the magnitude and an estimate of the landslide frequency of a rock wall. Furthermore, from various observations conducted in the field and described in the literature [4], it emerged that an increase in landslide activity usually precedes the occurrence of larger events by a few months. Similarly, when this activity decreases, it can be deduced that the frequency of landslides stabilizes during a given period [5].

The geotechnical monitoring activity conducted through a terrestrial laser scanner (TLS), is based on Imaging Matching algorithms, thus allowing a systematic analysis of the changes in the spatial configuration in a given area with respect to an initial spatial configuration at time "zero".

The processing results are expressed as displacement vectors between two points (or common areas) or relative distances between two data sets. Furthermore, the monitoring of movements on rocky slopes is in a certain sense simpler than on earth slopes because the movements can be considered as transformations of rigid bodies.

In figure 4 you can see an example of data processing obtained by scanning with TLS of a rocky slope facing the quarry yard, where the displacements with respect to the initial reference reading were measured.

![Figure 4](image-url)
The standard deviation of the measurements can be quite high, depending on some factors such as the quality of the TLS data, the density of points, the existence of vegetation, the roughness of the relief, the quality of alignment between scans, relative positions or absolute of the TLS. From our first experiences, comparing consecutively acquired TLS data sets, it is possible to achieve values of 5 mm for close distances (within 150 m) and high point density.

Although in some cases the precursor movements may be of the same order of magnitude with respect to the instrumental errors, several authors have observed that the errors can be considerably reduced by taking into account the information of the neighboring points, i.e. by reducing the noise by filtering or averaging [6], [7], [8]. For example, it has been shown that it is possible to detect millimeter surface displacements in an outdoor experiment, even if single points had a higher standard deviation [8].

In addition, some HelloMac devices combined with main rockfall protection systems such as rockfall barriers, simple coatings, cortical reinforcements, etc. were also tested in collaboration with Officine Maccaferri Italia S.r.l.

These sensors are able to detect rockfall phenomena (such as deformations, detachments, impacts, etc.) coming from different directions and which may affect one or more parts of the protection systems.

Two examples of installation on rockfall barriers and drapery system are shown below in figure 5.

These devices have proved to be very versatile and ideal for many applications in the quarry, even on the steepest slopes, as they are able to communicate even in situations of limited or no network coverage, and powered by internal batteries that guarantee several years of autonomy.

Both the technologies described are optimized in combination with the Sensorium software platform developed by Studio Pandolfi, developed to manage and display data from monitoring systems, through its WEB pages the data are at any time available to the customer in graphic and tabular.

![Figure 5. Example of installation of the HelloMac device on a rockfall barriers and on a drapery system (Officine Maccaferri Italia S.r.l).](image)

6. Conclusions
The correct design of an ornamental stone quarry must involve multidisciplinary aspects, which must necessarily be coordinated by qualified technicians in the management and design of mining activities, in order to achieve adequate objectives in terms of safety, environmental impact and development of the quarrying site.

In the article, rockfall phenomena were analyzed, and intervention techniques for controlling rocky slopes were discussed. The above considerations also show that TLS technology represents an essential tool for managing rockfall risk, becoming a standard tool for the analysis of such phenomena in the coming years. Technology is also progressing, creating ever more precise devices of reduced size that can also be transported by drones. The huge amount of data will probably remain a problem as computers will have to be increasingly performing in order to process the greatest amount of data obtained with increasingly accurate TLS systems.

The real challenge will be to develop new methods to fully exploit the potential of TLS, perhaps capable of processing in real time and combined with early warning systems.
Furthermore, it is evident that an IT platform capable of collecting the readings of the classic geotechnical control and monitoring systems, with the most recent alert systems, is a tool with high potential and a precious support for quarry cultivation.

In conclusion, it can be stated that in order to develop an adequate project, it is necessary to deepen the knowledge of the geological, geostuctural and geomechanical conditions of the site, and to provide the most suitable intervention techniques (active or passive) for the control of the various problems always referring to the most up-to-date state of the art, which for rockfall protection technologies is still evolving.

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