Geotechnical and geophysical investigation of a rock mass for the design check of an ornamental stone quarry

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ABSTRACT: The design of an open-pit quarry must continuously adapt to the real conditions of the excavation faces, to meet safety requirements and maximize the effectiveness of the operational process. The case study of an ornamental stone quarry characterized by great value and challenging excavation geometry is analyzed in this study. The exploited rock mass is characterized by a non-ubiquitous discontinuity distribution due to the presence of highly fractured bands, mainly parallel to the excavation faces. The discontinuity network needs to be analyzed to forecast the rock mass mechanical behavior during excavation. In this regard, the integration of geotechnical and geophysical surveys allows the rock mass to be studied from the surface to a considerable depth. Trace mapping on scaled digital images was combined with traditional geomechanical methods and GPR surveys, executed on the excavation faces, to assess the variability of discontinuity spacing and to characterize the fractured bands.

Keywords: open-pit quarry, spacing, digital images, GPR, fracture band.

1 INTRODUCTION

The stability of a potentially unstable rock mass is highly sensitive to the continuity of the fractures cutting it. Evaluation of the spacing and persistence of these fractures is generally based on surface geological observations and geomechanical analyses. This approach, however, suffers from the lack of information about the rock mass structure beneath the surface and a precise definition of the fractures properties. With respect to these issues, geophysical surveys could be helpful in obtaining information inside the rock volume and comparing them with the ones coming from the superficial geomechanical observations. This data integration is crucial to get a more comprehensive characterization of the state of fracturing of the rock mass. In consistent rock masses with high electrical resistive properties (i.e., massive rock formations usually present at excavation sites), Ground Penetrating Radar (GPR) is the most suitable technique to provide precise information about the near-surface structures and fracture setting. This is due to the potentially obtainable vertical and horizontal resolution, which depend on the rock characteristics and the frequency of the chosen antenna, the satisfactory penetration depth in resistive materials, to detect deeper fractures, and the low weight and versatility of the GPR equipment. Several literature examples on the application of GPR for fault and fracture mapping are available in the literature (e.g., Grodner, 2001; Lualdi and Zanzi, 2004; Porsani et al., 2006; Deparis et al., 2007; Poisson et al., 2009; Anterrieu et al., 2010).

2 MATERIAL AND METHODS

2.1 Case study

The Lorgino quarry, located in Crevoladossola (Verbano-Cusio-Ossola province, Italy), managed by Tosco Marmi s.r.l., is developed in a dolomite limestone unit, mostly composed of dolomites and saccharoid marbles of different colors, embedded within folded gneiss. A complex fold is recognizable and is related to the main foliation, generally following a 160/70 trend. Moreover, the rock mass is characterized by three different sets of joints, oriented parallelly (340-360/25-70) and orthogonally (240-275/80-85) to the main foliation. All three sets are involved in the stability of the rock faces of the quarry. Still, only the foliation and the first set of joints are of interest for this study, given that the excavation faces of the quarry are parallel to these discontinuities. These joints are not homogeneously distributed within the rock mass but tend to cluster around fractured bands. Excavation benches develop so that the front and back surfaces are almost parallel to the main foliation.

2.2 GPR Surveys

GPR surveys were performed in the northern corner of the quarry, along different excavation fronts (Figure 1), dragging the GPR antenna along the horizontal direction at the height of about 1.5 m from the bench floor. This allowed us to image the fracture setting inside the rock mass along a plane perpendicular to the excavation front and to analyze the inner structure of the fracture network. Given

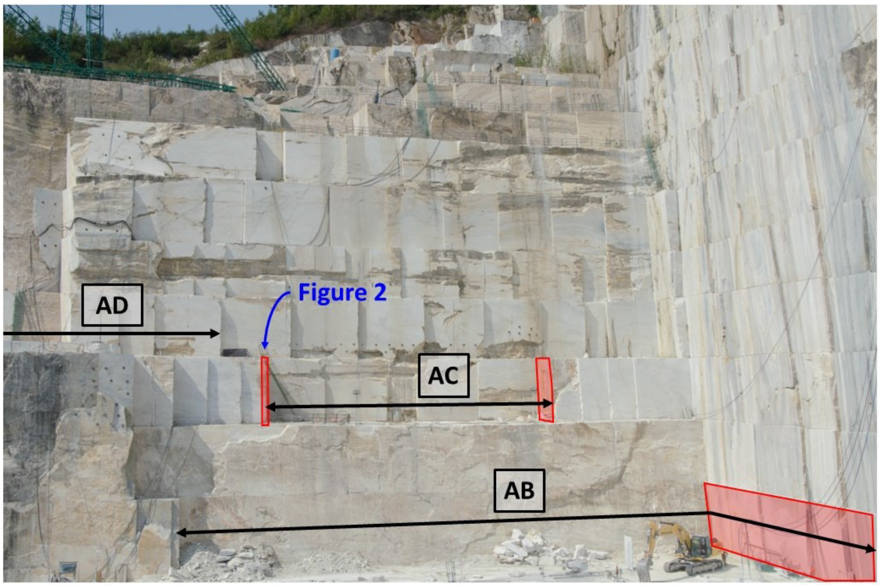

Figure 1. Location of executed GPR (black lines AB, AC, AD) and the geomechanical surveys (red squares).

the GPR acquisition direction, the main fractures imaged are the ones developed parallel to the excavation front, which are also the most prone to produce instable rock volumes.

GPR profiles were acquired with a 500-MHz GSSI antenna connected to an IDS K2 unit. A wheel encoder (IDS Survey Wheel Kit WHE50) was used to drag the antenna along the investigated direction and allow correct trace positioning. Raw radargrams acquired in the different sectors were processed in Reflexw (©Sandmeier geophysical research), with a common processing sequence, including:

1. Dewow, that is, high-pass filtering to remove electronic low-frequency noise.
2. Start time shift in correspondence with the main bang (i.e., air–ground reflection with the highest amplitude) to remove signal delay and retrieve a correct travel time in the subsurface.
3. Time cut at 200 ns to remove deeper noisy portions of the radargrams.
4. Background removal, that is, average trace subtraction to attenuate the horizontal clutter along the profiles.
5. Band-pass filtering in the 100-650 MHz range to attenuate noise outside the frequency band of interest.
6. Divergence compensation to recover the amplitude of the deepest reflections.
7. FK migration, to collapse diffractions and back-propagate the reflections to their real position.

The time-depth conversion was performed with a propagation velocity of 0.105 m/ns estimated on diffraction hyperbolas identifiable within the radargrams before the FK migration step. With the assumed velocity value, a vertical resolution of about 5 cm and an effective depth of investigation of about 10 m can be hypothesized, which allows for the reconstruction of the inner fracture network. All the acquired radargrams were interpreted employing the same approach: this allowed us to extract information on the spacing of single fracture planes and the spacing and thickness of the evidenced fractured bands. These data were then compared with those provided by traditional geomechanical surveys.

2.3 Geomechanical surveys

Two approaches were employed to reconstruct the spacing frequency distributions. At first, a traditional contact survey of the joints visible on the rock faces was carried out, selecting appropriate scan lines oriented both orthogonally and parallel to the main foliation. This was also done to have access to data from rock faces oriented accordingly to GPR data, so that a comparison could be drawn (Costantini et al., 2019).

Due to the observable variability of the joints' spacing and orientation over the significant vertical extension of the rock faces, the need to perform this kind of measurement at different heights was clear. This, though, was impossible because of the inaccessible nature of the upper portions of the quarry: therefore, a non-contact approach was employed, too. Pictures of the different faces of the quarry were taken: to minimize the distortion associated with the height of the rock faces, the pictures were shot at different elevations. Then, the pictures were scaled with reference to linear horizontal elements of known length; consequently, a composition of the photos was performed. At this point, all the discontinuities identifiable on the scaled pictures were traced: this step produced a digital map of the fracture and joint pattern. Lastly, many virtual horizontal scanlines were generated in different positions of the map, and spacing data were collected. The discontinuities were classified as simple joints when isolated, singular, or if always clearly distinguishable. Discontinuities whose traces were not always clearly distinguishable from each other or that were clustered were classified as fractured bands. Sectors of the rock face characterized by a significant degree of fracturing or high damage levels of the rock matrix were classified as fractured bands, too. An example of this process is portrayed in Figure 2 alongside the result of the GPR data.

It should be noted that these fractured bands do not have a defined geometry in terms of thickness and persistence, nor do they appear as frequently as the other joints on the analyzed rock faces: in many instances, only one band could be identified for each excavation surface. Fractured bands are generally characterized by large spacing, at least above 5 m but more likely beyond the tens of meters: therefore, for the limited extension of the surveyed area, it was not possible to collect a significant sample of spacing values.

3 RESULTS AND DISCUSSION

As visible in Figure 2 (left), below a shallow portion of altered material (yellow band), mainly related to excavation activity, some localized continuous reflections can be observed: these are most probably related to isolated fracture planes. Among these fractures, some appear with increased reflection amplitude (dark orange dashed lines) with respect to others (orange lines). The reflection amplitude of these fractures can be related both to their depth (deeper fractures are more attenuated than shallower ones) and also to the persistence and aperture of the fracture plane. Also, an evident alteration band, about 35 cm thick and composed of multiple scattered reflection events (pink band), is visible in the radar section and can be attributed to a deformation band or system of multiple joints. Similar results were obtained along other alignments. Particularly in almost all alignments, the presence of both isolated fractures and a continuous fractured band was evidenced.

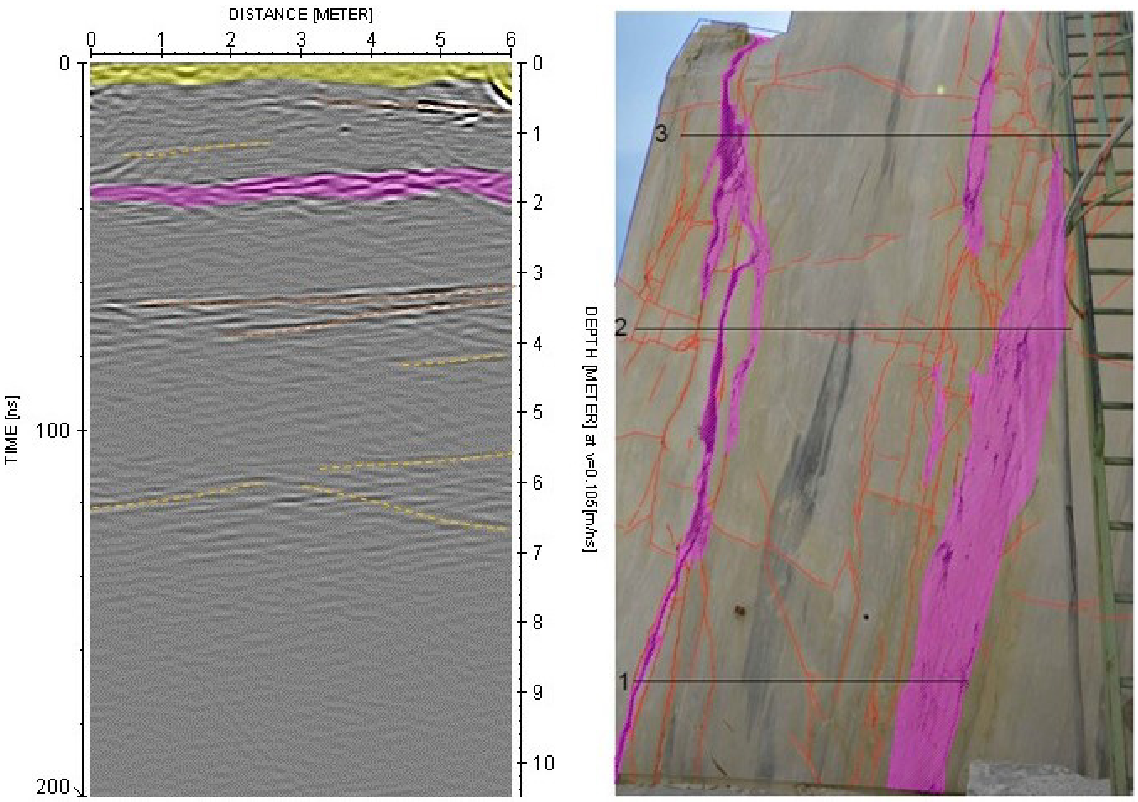

Figure 2. (left) Results of GPR surveys along a portion of the AC alignment, for location refer to Figure 1. (right) The corresponding rock face with joints mapped in orange and fracture bands in pink; the black lines are scanlines: for reference, scanline number 2 is approximately 2,5 m long.

The traditional contact method and the image analysis techniques employed on the rock faces of the quarry produced a significant number of spacing data: considering the orientation of the GPR data, which lay on a plane orthogonal to the analyzed rock face, the scanlines on the rock faces are oriented coherently with the GPR data; the scanlines are ranged between some meters up to approximately 10 m. The data gathered shows that the most common spacing values are smaller than 1,5 m, but maximum values reach up to approximately 6,5 m. This data describes the totality of discontinuities measured on the rock faces, not distinguishing single joints or fractures (in orange in Figure 2) from fracture bands (in pink in Figure 2). For these last, an average thickness was also estimated: with this respect both GPR and geomechanical surveys agree in attributing an average thickness of about 0,35 m. It should also be noted how the reflecting body identified by the GPR at approximately 2 m from the surface (Figure 2, on the left) matches the position of the large fractured band identified on the rock face (Figure 2, on the right).

The comparison between spacing data for single joints measured with GPR and geomechanical surveys is visible in the diagram of Figure 3: the spacing distribution obtained from the GPR surveys is almost perfectly aligned with that produced by the traditional contact surveys and the image processing.

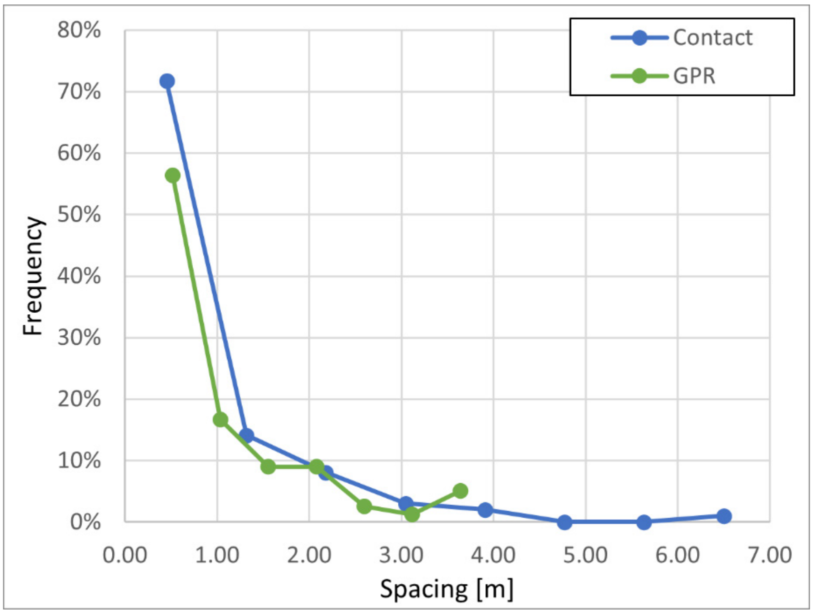

Figure 3. Comparison between the spacing measured on the rock faces (blue) and by GPR (green).

It should be noted that the data visible in Figure 3 describes the spacing frequency distribution of single joints only; fractured bands were accounted for separately. This was done because, in the analyzed area of the quarry, very little data regarding the fractured bands could be gathered, due to the limited extension of the surveyed surfaces. However, since the fractured bands appear to control, at least locally, the stability of the rock faces, they should be characterized as single objects and not as groups of discontinuities.

Table 1. Main features of discontinuities and fractured bands.

	Spacing		Persistence	
	Min [m]	Max [m]	Min [%]	Max [%]
Discontinuities	0.05	6.95	9	87
Fractured bands	1.05	9.35	17	67

Regarding the information on spacing of single discontinuities, the results obtained depict a quite significantly fractured rock mass, with most of the spacing values below 2 m. It is also true that the results described here must not be considered representative of the entire quarry: they highlight local problematic situations on which one should focus attention with regard to excavation safety and bench stability.

This is confirmed by the fact that the quarry is cultivated by extracting blocks of considerable size, which are usually not damaged beyond usefulness by the fractures within.

4 CONCLUDING REMARKS

Trace mapping on scaled digital images was combined with traditional geomechanical methods and GPR surveys, executed on the excavation faces, to assess the variability of discontinuity spacing and to characterize the fractured bands at an ornamental stone quarry excavation site. Results of the surveys report a very good correspondence of the data obtainable from the different adopted techniques. This result is promising with respect to a systematic integration of geomechanical and GPR surveys for rock mass characterization and excavation design. Geomechanical surveys offer indeed very high resolution and can be conducted along different alignments. Conversely GPR surveys allow increased investigation depth within the rock mass but reduced resolution and limited available alignments (i.e., only on excavation fronts). The two techniques are therefore complementary, and their integration could allow a more comprehensive and detailed characterization.

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