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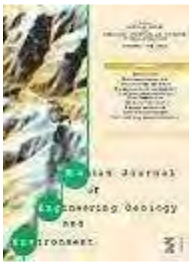
Original:

Lanciano, C., Vanneschi, C., Tufarolo, E., Salvini, R. (2021). Distributed optical fiber sensors and terrestrial laser scanner surveys for the monitoring of an underground marble quarry. ITALIAN JOURNAL OF ENGINEERING GEOLOGY AND ENVIRONMENT, 1(1), 117-125 [10.4408/IJEGE.2021-01.S-11].

Published:

DOI: http://doi.org/10.4408/IJEGE.2021-01.S-11

Italian Journal of Engineering Geology and Environment



Associazione Italiana di Geologia Applicata ed Ambientale

AIGA 2021 - VII National Congress

23-24 September 2021 - LECCO (Italy)

Proceedings

https://ijege.ceri.uniroma1.it/

https://www.aigaa.org/gga20.asp

DOI: 10.4408/IJEGE.2021-01.S-11

DISTRIBUTED OPTICAL FIBER SENSORS AND TERRESTRIAL LASER SCANNER SURVEYS FOR THE MONITORING OF AN UNDERGROUND MARBLE QUARRY

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EXTENDED ABSTRACT

Negli ultimi decenni la tecnologia in fibra ottica, nata negli anni Settanta nel campo delle telecomunicazioni, ha conosciuto una forte evoluzione. Uno spin-off di questa tecnologia è rappresentato dalle applicazioni di sensoristica, oggigiorno sempre più utilizzate per il monitoraggio strutturale e per applicazioni in campo geo-ingegneristico. In questo lavoro viene presentato un sistema sperimentale per il monitoraggio di una cava di marmo in sotterraneo situata nelle Alpi Apuane (Toscana, Italia). Il sistema è costituito da Sensori Distribuiti in Fibra Ottica (*Distributed Optical Fiber Sensors* - DOFS) basati sullo Shift di Frequenza di Brillouin (*Brillouin Frequency Shift* - BFS). Questo tipo di sensori offre diversi vantaggi, quali dimensioni e peso ridotti, stabilità a lungo termine, immunità ai disturbi elettromagnetici, e, soprattutto, la capacità di monitorare le variazioni dei parametri fisici con continuità spaziale lungo la fibra.

La cava oggetto di studio è la Cava del Piastraio di Sotto, sita presso Levigliani di Stazzema (Provincia di Lucca), dove si estraggono le varietà merceologiche di marmo denominate Arabescato e Statuario Corchia. La cava, situata sul versante sud-ovest del Monte Corchia ad un'altitudine variabile tra circa 1200 e 1400 m s.l.m., si sviluppa nel sottosuolo su più livelli. In questo lavoro viene studiato il primo livello, che si sviluppa in direzione N-S per circa 150 m di lunghezza e 40 m di larghezza. In particolare, nell'ampia camera meridionale sono stati scelti due pilastri di dimensione media 10x10x15 m caratterizzati dalla presenza di vari sistemi di discontinuità. Al fine di soddisfare la necessità di svolgere le attività minerarie in condizioni di sicurezza, la cava risulta essere idonea per il monitoraggio mediante DOFS e tecnologie geomatiche. Per ottenere informazioni sulla stabilità di due pilastri, sono stati installati sulle due strutture portanti 250 metri lineari di DOFS e, tramite un'apposita unità di controllo (centralina di misura OSD-1), sono state effettuate misure multitemporali di BFS da cui è stato possibile risalire ai valori di deformazione (strain) e temperatura. In particolare, sono state applicate due diverse tecniche di misura: la *Brillouin Optical Time Domain Analysis* (BOTDA), basata sullo *scattering* stimolato di Brillouin, e *Brillouin Optical Time Domain Reflectometry* (BOTDR), basata sullo *scattering* spontaneo di Brillouin.

Inoltre, sono stati eseguiti rilievi con Laser Scanner Terrestre (T*errestrial Laser Scanning* - TLS), coadiuvati da rilievi GNSS (*Global Navigation Satellite System*) e rilievi topografici tradizionali mediante Stazione Totale (*Total Station* - TS) con l'obiettivo di: i) identificare le discontinuità sulle pareti rocciose della cava non misurabili con metodi geologici tradizionali a causa di condizioni di inaccessibilità (i.e. altezza dei pilasti), ii) georeferenziare la traccia del cavo sensore in fibra ottica e, iii) localizzare eventuali fenomeni di deformazione evidenziati dall'analisi dei dati DOFS. In particolare, sono stati effettuati rilievi GNSS differenziali mediante ricevitori geodetici a doppia frequenza e rilievi con TS finalizzati all'aggancio delle diverse scansioni laser e alla georeferenziazione di tutti i dati misurati, inclusa la traccia 3D del cavo sensore in fibra ottica. I dati GNSS e TS sono stati elaborati utilizzando i *software* Leica™ Geo Office 8.4 e ConVergo; il primo ha consentito il *post-processing* dei punti misurati (punto di origine delle misure effettuate con la TS, punto scelto come direzione zero e *target* di riferimento per le scansioni laser) utilizzando i dati di contemporanee registrazioni effettuate dalle stazioni permanenti ubicate in prossimità dell'area di studio; con il secondo, invece, l'informazione di quota è stata trasferita dall'ellissoide WGS84 al livello del mare. I dati TLS, invece, sono stati elaborati in ambiente Trimble® Realworks.

I risultati ottenuti in questo lavoro sono prodotti geomatici, ovvero il modello 3D texturizzato (di tipo mesh) dei pilastri analizzati e il DEM (*Digital Elevation Model*) e l'ortofoto della cava, e i risultati del sistema di monitoraggio DOFS, ovvero i profili di BFS, strain e variazione di temperatura.

Nonostante le difficoltà incontrate, legate sia alle condizioni di lavoro che alle rigide temperature invernali, il sistema è riuscito a funzionare bene e a rilevare valori di deformazione e temperatura precisi e affidabili che sono sempre rientrati nelle tolleranze di sicurezza. L'integrazione di un sistema di monitoraggio DOFS con le tecnologie geomatiche ha offerto la possibilità di gettare le basi per l'implementazione di un sistema di monitoraggio in tempo reale volto a tutelare la sicurezza dei lavoratori dai rischi legati a possibili crolli di roccia, soprattutto nei siti sotterranei, dove le vie di fuga sono molto limitate.

Questa ricerca è stata finanziata dalla Regione Toscana nell'ambito del progetto denominato "Monitoraggio in tempo reale delle pareti di cava mediante utilizzo di fibre ottiche – CAV_OTT" (POR FESR 2014-2020) realizzato tra aprile 2017 e febbraio 2019.

ABSTRACT

The sensing applications nowadays are always more used for structural and engineering-geological applications. In this work, an experimental monitoring system of an underground marble quarry, located in the Apuan Alps (Tuscany, Italy) is presented.

The system is composed by Distributed Optical Fiber Sensors (DOFS) based on Brillouin Frequency Shift (BFS).

By using a control unit, multitemporal data of strain and temperature were measured thanks to the installation of 250 linear meters of DOFS placed around two pillars.

Terrestrial Laser Scanning (TLS) surveys, aided by GNSS (Global Navigation Satellite System) and TS (Total Station) measurements, were executed with the aim of: i) identifying physically inaccessible rock joints (i.e. height of the pillars), ii) georeferencing the DOFS and, iii) locating any strain phenomenon. The integration of a DOFS monitoring system with geomatic technologies has given the possibility to initialize a real-time monitoring system aimed at protecting the safety of the workers from possible rocky wall collapses.

The results obtained in this work are the texturized 3D model of the analyzed pillars, the DEM and the orthophoto of the quarry, and the profiles of BFS, strain and temperature variation. This research was funded by Tuscany Region (Italy) though the POR FESR 2014-2020 plan.

***Keywords**: Distributed Optical Fiber Sensors, Terrestrial Laser Scanning, strain and temperature monitoring, underground marble quarry*

INTRODUCTION

In the last decades, underground excavation activities in the Apuan Alps marble district of Tuscany Region (Italy) have become a method alternative and safer than traditional open-pit exploitation. This happens not only when the underground excavation is suggested by the characteristics of the rock mass, but also in respect of environmental reasons, which over time have become increasingly important (Oggeri & Oreste, 2015), and for the introduction of regional regulations.

Furthermore, underground exploitation could be preferable in economic terms and in the cases where surface operations are not technically feasible (Oggeri, 2000).

Several elements must be taken into consideration when an underground excavation is preferred: i) workers safety, ii) structural conditions of the rock mass, iii) excavation technology, iv) commercial characteristics of the extracted raw material in terms of color, grain size, workability, etc., v) environmental sustainability and vi) economic yield compared to open-pit cultivation methods. In terms of safety and commercial yield, the stability of excavation walls must be guaranteed over the long term and all the necessary systems of remediation and monitoring must be adopted. Generally, at depth (underground excavations) the rock mass has fewer joints than at surface (open pit); nevertheless, main fragile tectonics elements and joints are still present and rigid movements of rock wedges may occur starting from the walls or from the tunnel roofs. The experience in excavation activities can provide useful indications about the monitoring of the walls and the stress condition of the rock mass (Cravero & Iachibino, 1997).

However, the definition of safety conditions for workers in underground sites must be based on data derived from the precise monitoring of excavation, trying to predict the possible failures by adopting appropriate analysis techniques.

This approach describes the design line of underground excavations such as tunnels, deep mines, or large civil structures (Bieniawsky, 1984; Brady & Brown, 2006; Barla *et alii*, 1986).

The case study presented in this work refers to the "Piastraio di Sotto"quarry (Fig. 1), located in the Levigliani District of Stazzema Municipality (Lucca Province, IT). The extraction site is part of a large plicative structure of the Apuan Alps resulting from an intense and complex tectonic evolution attributable to the compressive phase D1 and subsequently affected by the relaxing phase D2 (Carmignani & Kligfield, 1990). The structure is a non-cylindrical isoclinal fold, commonly defined as "sheath folds" (Sanderson, 1973), identified in the reference geological map as the Orto di Donna - Altissimo Mount – Corchia Mount – Puntato syncline. This complex geological structure is characterized by a kilometric extension of theaxial plane that affects the entire western Apuan area, from north to south, for at least 20 km (Fig. 2).

The area of Corchia Mount represents an example of polyphased tectonics, object of investigations since the late 1800s (Lotti, 1881; Zaccagna, 1932), because it presents the matter of the Apuan Alps "double vergency" highly discussed and studied also by the first researchers. This structural interpretation, which many authors still consider valid today, unifies the Corchia Mount and the nearby Arni valley. Only a few decades ago this area has been interpreted as resulting from the interference between the large late folds and the isoclinal structures generated by the collisional D1 phase (Carmignani & Giglia, 1979).

The structural analysis (Carmignani *et alii*, 1993) highlights that the synform including the Corchia Mount does not maintain a horizontal axial direction but tends to dip towards the south in correspondence of the Corchia Mount, and towards the north near Puntato, where it breaks up into a distinct fold.

The geological relationships, in terms of dip directions, also highlight the presence of two anticlines that match the Corchia Mount syncline; they correspond to the anticline of Campanile-Fociomboli and, more to the south, that of Mosceta,

Fig. 1 - Location of the "Piastraio di Sotto" quarry in the territory of the Tuscany Region (a); Perspective view of the two monitored pillars (b), here the scale bar is indicative only

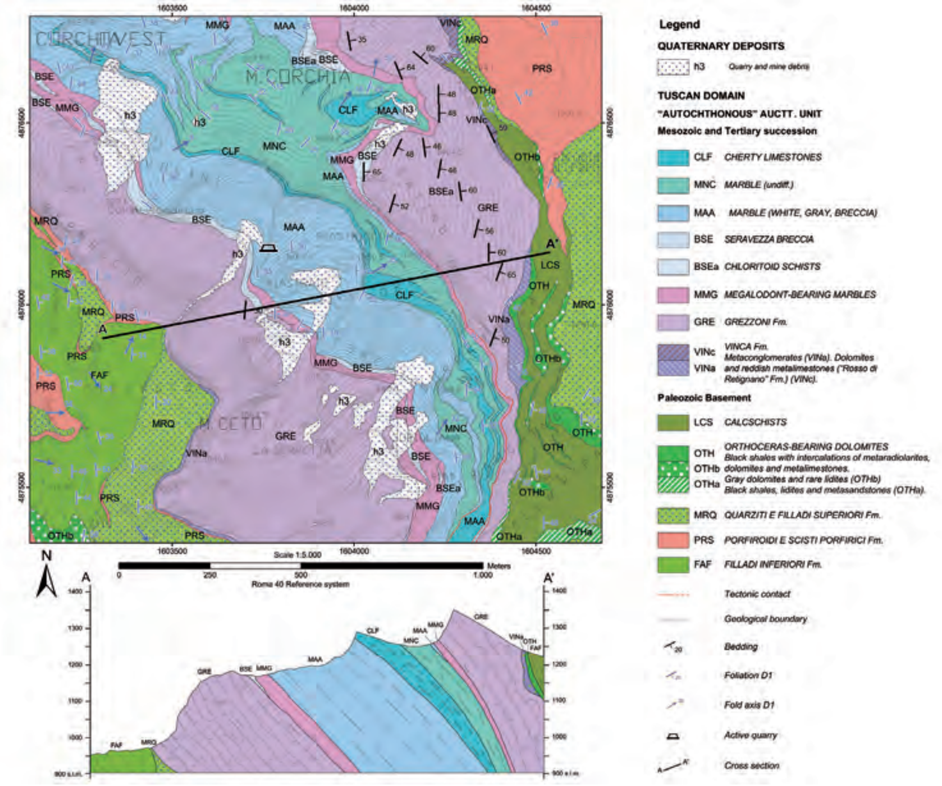

Fig. 2 - Geological map of the area and interpretative cross section

both attributable to a complex structural framework of sheath folding.

The marbles of the Corchia Mount are cultivated in four quarries called “Piastriccioni”, “Tavolini A”, “Tavolini B”, “Borra Larga” and “Piastraio di Sotto”. In particular, the latter is an active underground marble quarry where the “Arabescato” and the “Statuario Corchia” varieties are extracted. The quarry, located in the southwestern side of the Corchia Mount at an altitude varying between 1200 and 1400 m a.s.l., develops in underground through several levels. The higher level, which develops mainly in the north-south direction for about 150 m in length and an average width of 40 m, is that presented in this work. Two pillars 10x10 m large and 15 m high, shown in Fig. 1 and characterized by the presence of various joint systems, were chosen in the large southern quarry chamber for being monitored by using DOFS and geomatic technologies.

In the recent past, no detachments of rock blocks have been registered even if the stability analyses of the walls, that have been carried out in the CAV_OTT project, demonstrated that the probability of failure for kinematics related to planar and wedge sliding and toppling are very high both in in static and dynamic conditions. It should be noted, however, that the quarry has already been secured by means of bolts and reinforcements (Fig. 3).

Fig. 3 - Underground areas with installed reinforcement bolts

MATERIALS AND METHODS

Terrestrial Laser Scanning

The geometry of the quarry chambers and, particularly, of the two pillars object of the DOFS monitoring, was reproduced thanks to a TLS survey which was executed by using a Trimble® TX8 device (Fig. 4). The instrument technology bases on the time-of-flight measuring method in a way to improve productivity in the field with an acquisition speed up to 1,000,000 points/s; the TLS reaches a measurement range of 340 m with a linear distance error of ± 2 mm up to 100 m.

The 3D point clouds derived from the scans were later used to rebuild the exact geometry of the pillars and to draw the location of the DOFS; in case of possible movements of the rock mass, this will allow to exactly know the position of the microstrain recorded by the fiber sensor installed on them.

To reconstruct the morphology of the area under study, nr. 8 scans were executed from different positions on the quarry floor. Once identified the area to be observed, the instrument automatically starts scanning, acquiring the geometric information and the intensity of the reflected signal in a rapid time (about 10 minutes for a 360° scan in azimuth and 317° in zenith).

Fig. 4 - TLS at work in the “Piastraio di Sotto” quarry. Detail of the TLS during data acquisition (left). TLS and black and white targets, in background, used for data registration and georeferencing (right)

The result, immediately viewable on the device screen, is a three-dimensional point cloud that faithfully represents the geometry of the investigated area. At the end of each scan, the instrument was replaced, on the tripod placed in the scanning position, by a Nodal Ninja Ultimate R1 bracket, on which a Nikon™ D7100 digital camera, with a Sigma 8 mm f/3.5 fish-eye lens, was mounted. In this way, it was possible to acquire a certain number of high-quality photos to be later aligned to the three-dimensional point cloud. Trimble® Realworks software was used for the TLS data processing; it allows to view, explore, and edit the collected 3D point clouds. In this case, the alignment of the different scans was carried out, initially, by using an auto-registration tool of the software which bases on fitting planes. Later, the so-called “target-based registration” was used to georeference the whole cloud using the coordinates of black and white targets placed all around the study area. The world coordinates of the targets came from a topographic survey described in the next paragraph.

Afterwards, the point cloud was cleaned (unwanted scanned objects such as, operating machines, electrical cables, people, etc. were deleted from the data) and simplified to make the management easier without losing detail and accuracy. Finally, the panoramic photos from the fish-eye lens were aligned to the point cloud, in such a way to give the RGB cloud from which a textured model, the DEM and the orthophoto were created using Trimble® Realworks.

GNSS and TS surveys GNSS and TS surveys

With the aim of georeferencing the data with a millimetric accuracy, a Differential GNSS (DGNSS) survey was carried out by using two Leica^{TM} GS15 dual frequency geodetic receivers (Fig. 5). They have been operating in static mode, acquiring the signals transmitted by the satellite constellation continuously, for more than two hours, and recording the data at time intervals of 5 seconds. Object of the DGNSS survey were the point of origin of the topographic measurements done using the TS, and that chosen as its "zero direction".

Fig. 5 - Dual frequency geodetic receivers operating in static modality in the areas facing the "Piastraio di Sotto" quarry entrance

The TS survey, necessary for georeferencing the TLS data, was carried out using a Leica^{TM} Nova MS50 Multi-Station. Black and white targets (Fig. 6) were positioned onthe quarry floor (and at different heights) and measured by the TS.

Fig. 6 - Example of the black and white targets positioned inside the quarry

The TS survey included the GNSS pointschosen as origin of the topographic measurements and as "zero direction" because, thanks to the contemporary knowledge of their terrain coordinates (UTM32N reference system from GNSS post-processing), all the black and white targets were roto-translated and georeferenced.

The post-processing of the GNSS and topographical data was performed using Leica^{TM} Geo Office 8.4 and ConveRgo software. The first code allowed the post-processing of the points measured by the GNSS survey, using the data of permanent stations located near the study area, and the 3D roto-translation of the black and white target coordinates. ConveRgo software allowed to change the altitude of the points from ellipsoidal to orthometric, transferring the elevation information from the WGS84 ellipsoid to the sea level.

DOFS installation and setup

Data were recorded by using the OSD-1 system, a control unit provided by the company Optosensing S.r.l, which allows obtaining BFS, temperature and strain values (Lanciano & Salvini, 2020). In particular, the OSD-1 system can send the logs directly to a centralized enterprise-type database. Logs provide distance from the source and microstrain values that were archived into the database in a georeferenced mode.

When designing the sensor cable arrangement for the strain measurement, the 3D geometry of the pillars was recreated and used, together with the photos, for planning the DOFS installation. The position of the optical fiber was designed trying to intercept as many rock mass discontinuities as possible. The sensor cable, 250 linear meters long, was installed following two phases: a pre-installation, by using a witness wire, and the effective installation. Both were carried out thanks to the quarry technicians. A mechanical basket (Fig. 7) was used to position the DOFS at the desired heights. The sensor cable was finally placed on a layer of a special adhesive resin (Lanciano & Salvini, 2020) and secured to metal plugs.

The cable was then covered with glue to improve adherence to the surface and to protect DOFS from meteoric disturbances and dust.

The optical fiber sensor from the inside out is composed by

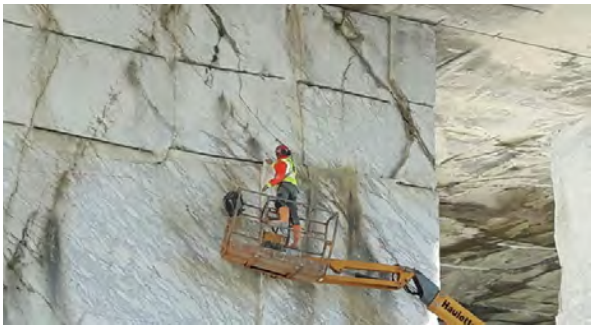

Fig. 7 - Quarryman at work during the phase of DOFS installation

i) a glass fiber with a total diameter of 125 µm, ii) a primary polyamide coating which brings the diameter to 250 µm and iii) a polyvinyl chloride (PVC) coating which brings the final diameter to 900 µm (LANCIANO & SALVINI, 2020).

DOFS installation includes a cable for the temperature compensation which contains the fiber and a gel suitable for promoting heat exchange; it is arranged parallel to that for measuring the strain but with the fiber not rigidly bound. The temperature measured by this second fiber is that resulting from the external temperature (air) and the temperature of the rock where the fiber rests. The purpose of the temperature compensation, carried out in the proximity of the fiber that measures the deformation, is to eliminate the local effects of temperature from the strain.

The data acquisition was carried out by the BOTDA (Brillouin Optical Time Domain Analysis) method, based on the stimulated Brillouin scattering (BARRIAS *et alii*, 2016; MINARDO *et alii*, 2018), which, using additional incident light, enhances the amount of scattering. All the first measurements were taken through the BOTDA technique.

Subsequently, as the sensor cable broke due to the contact with the roughness of the rock mass, the consecutive measurements were acquired in BOTDR (Brillouin Optical Time-Domain Reflectometry) mode which is based on the spontaneous Brillouin scattering. This methodology makes it possible to acquire data even in the presence of a break in the sensor cable: the BOTDR measurements were performed by injecting light first from the START side, and then from the END side of the measurement fiber, so as to be able to reconstruct the entire profile and compare it with the reference one acquired in BOTDA mode.

RESULTS AND DISCUSSION

Output from the geomatic surveys

Important and useful geomatic products were obtained from the georeferenced RGB point cloud; namely, the texturized 3D model of the pillars to be monitored by DOFS (Fig. 8), the DEM (Fig. 9) of the inner part of the quarry and the orthophoto (Fig. 10).

Fig. 8 - Perspective view of the texturized 3D model (mesh type) of the pillars; thered polyline represents the DOFS installed on the column sides

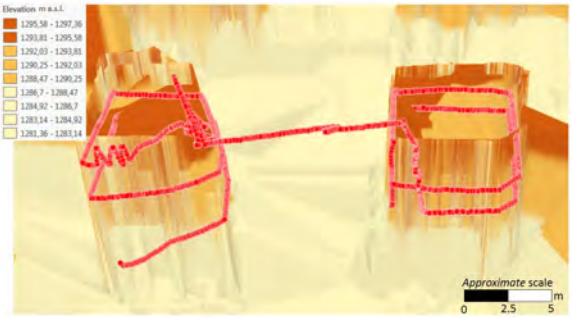

Fig. 9 - Perspective view of the DEM (TIN format – Triangulated Irregular Network); the red polyline represents the DOFS installed on the column sides

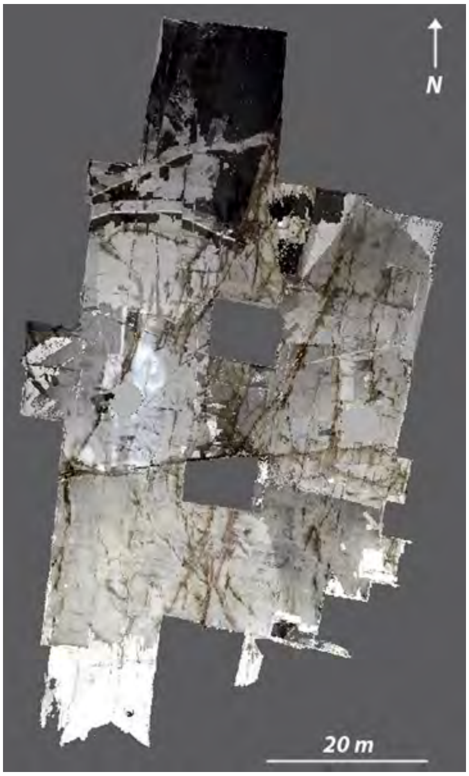

Fig. 10 - Orthophoto of the internal chambers of the quarry (2D planar view of the floor)

Results from DOFS monitoring

Four multitemporal DOFS measurements were carried out at the investigated quarry during the time span of ten months (Fig. 11). The first measurement, performed on January 23, 2018, is of the BOTDA type while the following three, respectively dated June 20, September 20, and October 11, 2018, are of the BOTDR type.

Unfortunately, none further surveys were carried out because, in the period between November 2018 and February 2019, the extraction site was closed due to adverse winter weather conditions.

Data in Fig. 11 shows how the measurements extend over a length equal to, approximately, 450 m; the first part, from the 0 distance up to 220 m, was set up from the central unit to the pillars but is not used for monitoring the fiber strain; instead, it is used for the temperature compensation.

For a distance greater than 220 m, a bigger variability of the BFS in noticeable in Fig. 11 because of the strain actions on the fiber. The substantial overlap between the zero-profile, measured in BOTDA mode, with the subsequent ones acquired in BOTDR mode is appreciable.

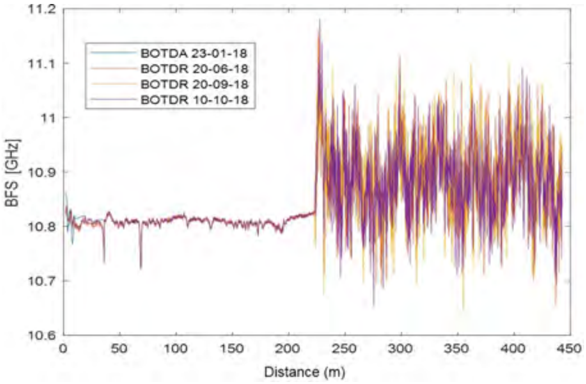

Fig. 11 - BFS profiles acquired at the quarry in both BOTDA and BOTDR modes

Starting from the BFS data presented in Fig. 11, the trend of the strain along the fiber was computed. To obtain this result, data from the first survey (i.e., January 23, 2018) was considered as reference and the BFS profile measured on that date was subtracted from all subsequent profiles. Fig. 12 shows the strain profiles thus obtained. To obtain a clearer visualization, the low frequency component of the strain values was amplified using a moving average filter over 51 points (corresponding to about 10 m of cable); the result of such operation is shown in Fig. 13. The difference between the first measurement and the next ones is due to the presence of deformation actions that act on the fiber following the installation and gluing procedure. The variation of the strain between -400 and +400 με can be related to physical-mechanical properties of the sensors, instability of the fiber glued to the walls, remaining temperature fluctuations along the cable (few °C may imply up to 100 με).

From the statistical analysis of data, a standard deviation value of 140 με of each strain profile suggested the choice of an alarm threshold for deformations five times greater than the standard deviation itself (Burr *et alii*, 2013); the alarm was then set to 700 με. The stress value corresponding to this alarm threshold, calculated as shown in Lanciano & Salvini (2020), is equal to 63 MPa (σ_{calc}). The compressive strength (σ_u) of the marble, on the other hand, has been estimated from laboratory tests equal to 117,6 MPa.

As $\sigma_{calc} < \sigma_u$, the alarm threshold value of 700 με was considered as suitable and precautionary for the strains of the analyzed structures (Fig. 12). Looking at the graph of Fig.13, it is possible to notice that this threshold value was never reached in any position throughout the monitoring period.

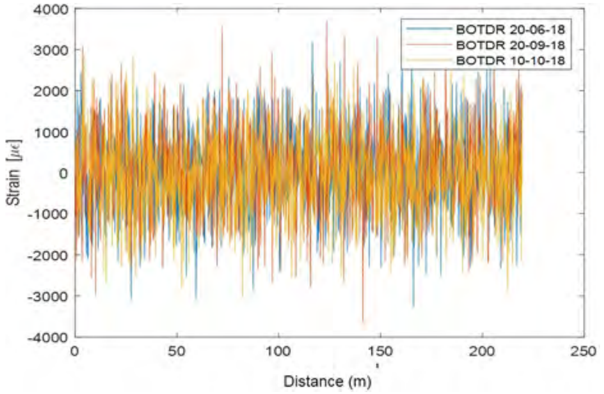

Fig. 12 - Strain profiles as computed in respect to the first measured data with BOTDA

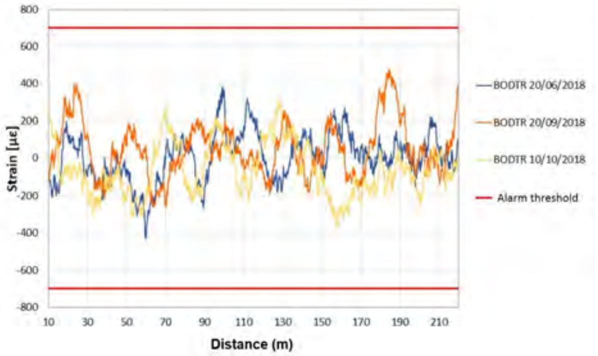

Fig. 13 - Filtered strain profiles and alarm thresholds (red lines)

The profiles of temperature variation (Fig. 14) were obtained starting from the data shown in Fig. 11 and related to the first 220 m. The obtained temperature data fluctuates between about [-8, +8] °C and do not seem to be significantly affected by natural seasonal variations: it is, in fact, an underground site where average temperatures are generally constant and low.

This is quite different from the results from Lanciano & Salvini (2020) that refer to an open pit where temperature variations cause significant deformation on the marbles. The displacement values, there, are characterized by a decrease at the beginning of the warm season and by an increase with the arrival of the cold season because of thermoclasty, a particular behaviour of the marble most likely related to the anisotropy of calcite mineral, which tends to expand and contract in directions constrained by crystallographic axes (Salvini *et alii*, 2015; Bonazza *et alii*, 2009; Malaga-Starzec *et alii*, 2002; Siegesmund *et alii*, 2000).

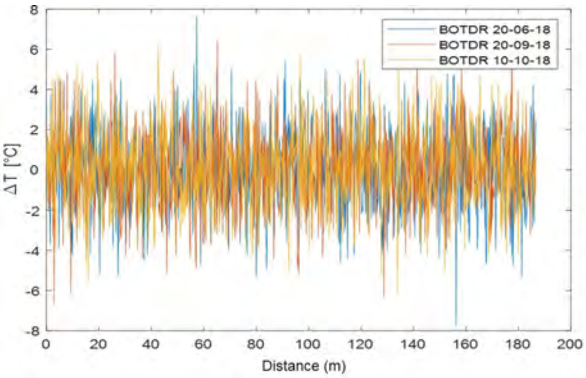

Fig. 14 - Profiles of temperature variation

CONCLUSION

This paper has shown the phases of design, implementation and analysis of an innovative monitoring system consisting of DOFS and geomatic technologies aimed at monitoring two pillars of an underground marble extraction site in the Apuan Alps. Four DOFS measurements, of both BOTDA and BOTDR type, allowed to obtain three strain profiles which showed stability conditions of the pillars. In fact, the alarm threshold was never reached in any of the three profiles. In terms of back-analysis, in the period of interest, it can be said that no rock collapses or significant strains were detected. The temperature data does not seem to be significantly affected by natural seasonal variations probably since the quarry is underground where average temperatures are always quite low and constant.

A critical lack of the work concerns the closure of the extraction site in the winter months, due to adverse weather conditions, which prevented the possibility of carrying out further DOFS surveys. Despite these practical problems, the optical fiber came out as a tool able to return reliable results even in an unfriendly environment such as an underground marble extraction site and to supply the desired measurements; in fact, from the BFS values the corresponding strain and temperature values were calculated. Therefore, although there is no direct comparison term, the evaluation of the effectiveness of the experimental monitoring system, with reference to the ability to acquire strain and underground temperature data, is undoubtedly positive.

In the future, given that the fibers are already installed on the quarry walls, the pursuance of data acquisition activities could offer the possibility of analyzing much more consistent strain and temperature datasets that could be used to develop real-time monitoring systems aimed at protecting the health of the workers and, in the medium-long term, planning of the mining activities.

ACKNOWLEDGEMENTS

This research was funded by Tuscany Region (Italy) though the POR FESR 2014-2020 plan within the project named “Real-time monitoring of quarry walls using fiber optic sensors – CAV_OTT”.

The authors would like to thank Poli D. (Cooperativa Levigliani), Gardenato M. (Studio Rocgeo S.a.s.), Mirabile M. (Optosensing S.r.l.), Zeni L. (University of Campania) and Carmignani L. (University of Siena) for their support of this research.

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Received February 2021 - Accepted June 2021