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Application of innovative monitoring tools for safety and alert procedures in road tunnels

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Abstract

Tunnels and underground structures are one of the most important components of road and railway networks, especially near urban areas. For this reason, it is particularly important to identify potentially hazardous conditions in order to guarantee the structure's durability and practicability. This paper presents a case study where a seismic event severely damaged a road tunnel located in Central Italy, impairing its accessibility and leading to its closure for safety reasons. Following the damage assessment, and given the importance of this specific structure, it was decided to perform a series of renovation works aimed to restore the tunnel's operability. In this context, an innovative automatic monitoring device, able to measure the structure deformation, was installed in a critical section of the road tunnel. This instrument, called Cir Array, is specifically designed for near-real time monitoring of convergence phenomena and localized deformations inside underground structures, obtaining accurate and reliable results during their operational phase. The instrumentation provided useful information about the structure's conditions, playing a major role into assessing the tunnel's accessibility and safety during the renovation works. Moreover, thanks to its automated and high frequency sampling process, it will allow the implementation of dedicated warning procedures related to the passage of the vehicles inside the tunnel.

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Keywords: Tunnel; Monitoring; Early Warning System; Innovative Technologies;

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Nomenclature

TBM	Tunnel Boring Machine
MUMS	Modular Underground Monitoring System
MEMS	Micro Electro-Mechanical System
UMTS	Universal Mobile Telecommunication System

1. Introduction

On October 30, 2016 at 07:40 a.m., a 6.5-magnitude earthquake hit Central Italy, becoming the most intense seismic event since the 1980 Irpinia earthquake (INGV, 2016). Among the large number of structures affected by the event, State Highway SS685 connecting Spoleto, Norcia and Arquata del Tronto experienced severe damages both to road surface and to additional structures (Galli et al., 2017). In particular, the earthquake heavily damaged the 4400-meters long San Benedetto road tunnel, which was realized to improve traffic on SS685, approximately 920 meters from the Norcia-side entrance. On-site surveys evidenced the presence of large cracks on the tunnel concrete covering layer and lifting of the road surface up to 24 cm (Fig. 1).

Fig. 1 - Details of the damaged road surface in the San Benedetto tunnel (after Galli et al., 2017)

Geological surveys performed after the seismic event highlighted the presence of several surface faults generated by the October 30th seismic event. This is a particularly rare occurrence, since these phenomena are typical of high-intensity earthquakes featuring at least Mw=6.0 (Galli and Galadini, 2001; Galli et al., 2017). Information acquired about deformations experienced by the structure, as observed during on-site inspections, led to the hypothesis that an active fault intercepted the tunnel's longitudinal section, generating shear strains in the upper concrete layer. Unfortunately, the presence of extremely dense vegetation near San Benedetto tunnel made it impossible to clearly identify the presence of surface faults near the structure in order to validate the hypothesis previously presented. (Galli et al., 2017).

2. Case study description

San Benedetto road tunnel is a single-track, four-lane tunnel featuring a circular section with a diameter of about 10 meters and a constant road gradient of 0.29%. The structure realization occurred in 1986 and started with the excavation of a pilot tunnel by using a Tunnel Boring Machine (TBM) with a diameter of 3.6 meters, followed by the main section completion thanks to rock blasting techniques (Micheli et al., 2017).

From a design point of view, the tunnel presents a preliminary lining composed by anchoring bolts, shotcrete and electro-welded meshes, while the final layer is composed by non-reinforced concrete. Moreover, it was decided to include a waterproofing layer between the linings due to significant ground water infiltrations. The intensity of this phenomenon decreased after the seismic event, probably due to the fractures generation that modified the groundwater flow (Micheli et al., 2018). The structure crosses rock masses mainly composed by carbonatic formations.

As can be observed in Fig. 1, major displacements interested mainly the road surface, while the structural stiffness of the concrete lining reduced the earthquake effects on the tunnel. The lack of an inverted arch in the tunnel's design can be considered as one of the principal causes of the significant deformations suffered by the structure. Fig. 2 reports the results obtained from a topographic survey performed on the road surface after the seismic event.

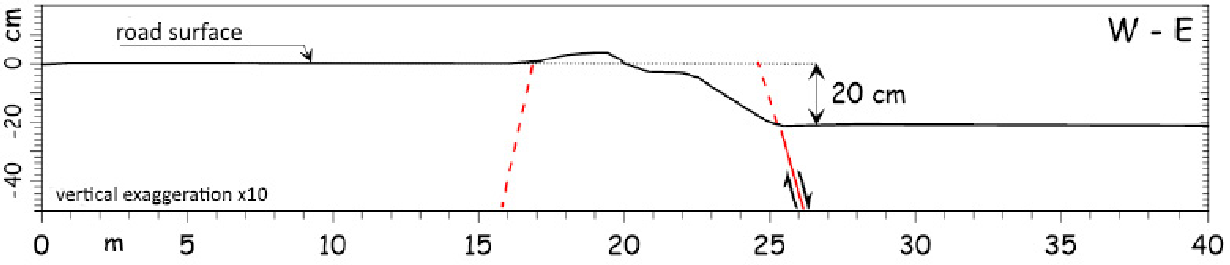

Fig. 2 - Road profile obtained from the topographic survey performed in the San Benedetto tunnel (modified after Galli et al., 2017)

Ultimately, significant damages suffered by the tunnel led to its closure for safety reasons. Given the relevance of the structure in the road network of the area, it was decided to perform a series of renovation works. In the initial stage, several test were scheduled to better understand the present context, including the stress state of the external lining and geometrical configuration of the elements composing the structure. The executive project was then realized according to these results. Renovation works included the strengthening of the structure by installing a concrete centering, composed by blocks able to dampen the effect of future seismic actions. Moreover, an innovative monitoring tool called Cir Array was installed in the damaged tunnel section, in order to measure the section convergence and deformations in underground excavations. Following renovation works completion, San Benedetto tunnel is nowadays functional and open to traffic.

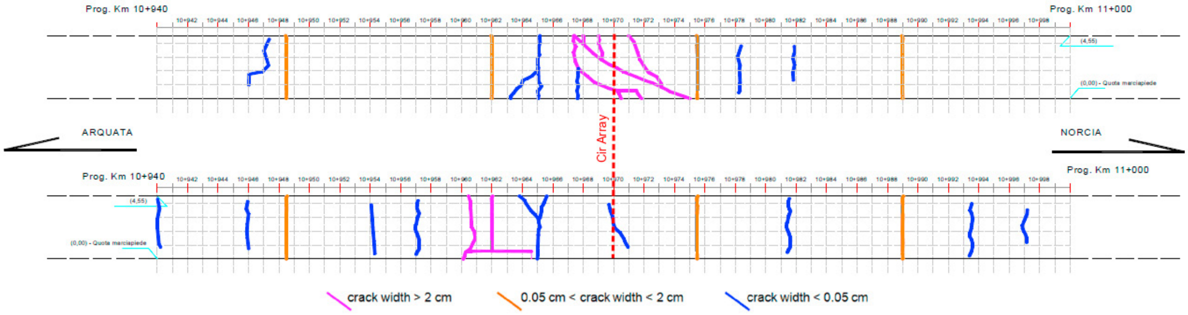

Fig. 3 - Location of the Cir Array tool installed in the tunnel, with details on the presence and entity of cracks in the surrounding area (modified after Micheli et al., 2017)

3. Materials and Methods

The instrumentation installed to monitor tunnel deformations is fully automated, and it is currently employed as a remote control tool during the operational phase of the structure. Moreover, it played an important role during renovation works in order to guarantee the underground excavation stability. The monitoring system can be defined as an integration of different components, in particular:

- Cir Array monitoring tool;
- Read-out unit;
- Data back-up and elaboration center;
- Dynamic and interactive visualization platform.

3.1. Cir Array

Cir Array is an innovative monitoring tool developed by ASE S.r.l. and based on MUMS technology (Modular Underground Monitoring System) (Segalini and Carini, 2013; Segalini et al., 2014). It is designed for near-real time monitoring of convergence phenomena and localized deformations taking place in a specific tunnel section. The instrumentation consists of a series of sensors embedded in epoxy resin nodes, called Links, connected by a fiberglass rod and an electrical cable. Links can be customized, according to the case, with different sensors able to record quantities such as displacements, water level variations and temperature. MUMS technology has been successfully applied to different case studies, including landslides (Segalini et al., 2019), tunnels (Carri et al., 2017) and geothermal fields (Tinti et al., 2018).

In particular, Cir Array is composed by a series of nodes (Tunnel Links) specifically developed for tunneling applications, equipping 3D Micro Electro-Mechanical Systems (MEMS). Starting from a fixed point, each Link provides its position in the space with respect to the previous sensor, thus returning the shape of the monitored section by cumulating the individual results evaluated in specific calculation points (Carri et al., 2017). For the case study presented in this paper, the installed tool consists of 37 Tunnel Links separated from each other by a distance of one meter, totaling 37 meters of extension (Fig. 4). Out of 37 nodes, 24 are placed on the upper part of the tunnel section, while the remaining 13 Links are installed on the invert arch. In this case, an aramid fiber cable replaces the fiberglass rod to connect different nodes.

The monitoring system was installed on April 2018 after the demolition of the lining damaged by the earthquake, and it was fixed directly to the rock mass thanks to specifically designed metal supports.

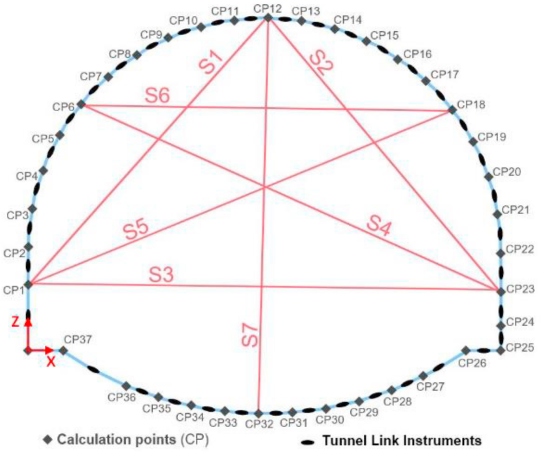

Fig. 4 - Cir Array composition as seen by looking at the monitored section in Norcia direction, including the position of seven convergence segments defined in the data elaboration phase

3.2. Read-out unit

The monitoring system here described relies on ASE801 Datalogger as a read-out unit. It allows to query each single Link with an appropriate sampling frequency customizable by the user. In the present case, from April 12, 2018 to July 05, 2018 the system was set to read the nodes position every 15 minutes, then it was modified to 1 hour after that date. ASE801 Datalogger is able also to store data on a SD Card as a local back up, sending them to the elaboration center thanks to UMTS technology.

1.1. Data back-up and elaboration

At the elaboration center, monitoring data sampled on-site and sent by the Datalogger are stored in a dedicated dynamic MySQL database featuring a daily multilevel back-up system. Raw data are converted in physical units with a proprietary software routine specifically developed for this purpose (see Carri et al., 2017 for further detail about calculation algorithms). Finally, elaborated data are saved in a separate section of the MySQL database. Fig. 5 reports a diagram summarizing the data management process, starting from the acquisition phase up to their elaboration.

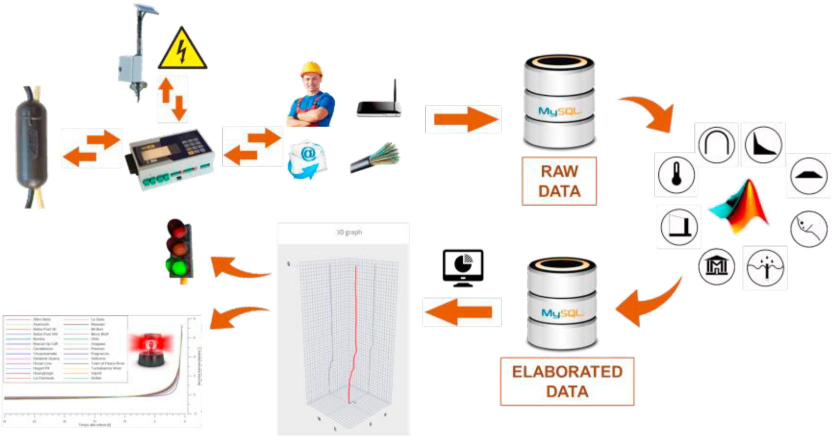

Fig. 5 - Schematic representation of the data management process for MUMS-based tools, including Cir Array instrumentation

3.3. Dynamic visualization platform

Finally, data representation takes place on a dedicated web-based platform with private access. It allows to visualize monitoring results referred to the entire time period or a specific time interval, which can be selected and magnified by the user. The platform includes also several tools able to identify different displacement levels and plot their evolution in time. An example of the web-based platform is reported in Fig. 6.

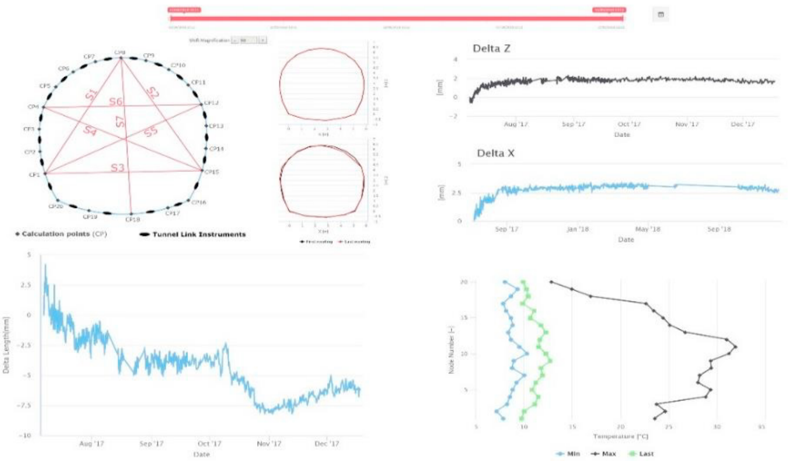

Fig. 6 - Web based platform developed by ASE s.r.l. for monitoring data visualization

4. Results

Available monitoring data refer to three different time intervals, which are described in Table 1. Issues related to on-site network problems are the main cause of data absence in the initial phase of the monitoring activity. Following these difficulties, probably caused by low telephone signal, it was decided to implement an optical fiber network to connect all the data loggers and devices on-site. Installation works started on September 15, 2018 and are still ongoing.

Table 1 - Monitoring time intervals

Time Interval	Initial Data [dd/MM/yyyy]	Final Date [dd/MM/yyyy]	Time Interval Duration [days]
1	12/04/2018	26/04/2018	14
2	07/06/2018	11/06/2018	4
3	05/07/2018	15/09/2018	71

Available monitoring data referred to time intervals previously presented were analyzed by taking into account the resultant value of displacements recorded both in X and Z direction for each single calculation point. In particular, maximum values of X and Z displacements were considered to compute the resultant movement by applying the following equation:

$$|S_{max\,C.P.}| = \sqrt{\left(X_{max\,C.P.}\right)^2 + \left(Z_{max\,C.P.}\right)^2} \qquad (1)$$

$S_{max\,C.P.}$ represents the resultant evaluated in the Calculation Point C.P., while $X_{max\,C.P.}$ and $Z_{max\,C.P.}$ are the maximum displacement values recorded in X and Z direction, respectively. The dataset analysis evidenced that 5 out of 37 Tunnel Links recorded a total displacement higher than 1 millimetre. In particular, Calculation Point 18 located in the inverse arch measured a resultant value of 2.3mm while on the upper part of the tunnel section, Calculation Point 18 recorded 2.0mm of displacement. Table 2 summarizes the results obtained from this elaboration.

Table 2 - Total displacement values over 1mm, with associated X and Z components

Calculation Point ID	X_{max} [mm]	Z_{max} [mm]	S_{max} [mm]
CP 14	-0.9	1.5	1.7
CP 18	-2.0	0.6	2.0
CP 20	1.0	1.0	1.4
CP 30	-2.3	0.4	2.3
CP 36	1.2	-0.5	1.3

Displacement data were useful also to analyze the repeatability of the installed instrumentation, allowing for a qualitative estimation of the impact of traffic on displacement measures. In fact, initially, San Benedetto tunnel was open only for four hours each day, hence it was possible to study the influence on the installed monitoring tool of vibrations induced by road traffic.

Results highlighted the stable behavior of Cir Array subjected to external actions, and recorded data evidenced that the effect of vehicles transit on the instrumentation is almost negligible. In particular, a repeatability test performed on 3432 data showed a standard deviation of the three acceleration components measured by MEMS sensors equal to 0.27 mg. Notably, the on-site results is better than the value obtained during laboratory tests, which showed a resultant value of 0.36 mg (Carri et al., 2017). This result is probably dependent of the improved installation procedure, since the original tested tool was installed on a more deformable setup with respect to concrete, leading to temperature-induced deformations.

5. Conclusions

The seismic event that involved several Central Italy regions on October 2016 caused significant damages to road infrastructures. Among those, the San Benedetto tunnel connecting Spoleto, Norcia and Arquata del Tronto suffered relevant damages, resulting in an uplifting of the road surface. Following the execution of several geological surveys in the area, it was decided to set up a monitoring system in order to study the structure's conditions. An automated tool called Cir Array, based on MUMS technology, was installed in order to monitor the tunnel's deformation without interfering with vehicles transit.

Since its installation date in April 2018, the instrumentation acquired a total of 3432 measures during its operating time period. Monitoring results underlined the structure's stability after the seismic event. However, some parts of the tunnel section experienced millimeter-sized displacements. In particular, the Node 30 located in the inverse arch displayed a total displacement value of 2.3mm, while Node 18 recorded a movement of 2.0 millimeter on the upper part of the tunnel section. Moreover, the monitoring activity proved quite useful to study the sensors behavior and particularly to identify possible interference caused by the ongoing traffic in the tunnel. Values obtained from the repeatability analysis were extremely positive, even surpassing results previously derived from laboratory tests.

Future developments of the presented case study includes mainly the continuation of monitoring activities in the tunnel, in order to evaluate the structure safety during the operational phase. The acquisition of new data would prove extremely important to implement new elaboration procedures based on statistical analyses to improve the tool reliability and accuracy. Moreover, by continuing the sampling process it would be possible to derive alert thresholds for early warning purposes.

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