Monitoring of preconvergence deformations in a road tunnel: data analysis and validation

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Abstract. Tunnels are complex constructions, generally built in difficult geological contexts. When dealing with underground structures, the study of ground deformations is a key aspect to consider in order to guarantee safety during the tunnel excavation and construction quality. One of the main aspects to investigate is related to the development of preconvergence phenomena in the advance core, i.e. deformations involving the volume of rock mass ahead of the tunnel face. This paper presents the application of a new monitoring tool specifically developed to measure preconvergence effects during the excavation phases with a direct approach. The device, called PreConv Array, consists of a series of 3D MEMS (Micro Electro-Mechanical System) and temperature sensors. The system takes advantage of automated procedures for data acquisition, elaboration, and representation, thus achieving a near-real time monitoring of the ground differential vertical settlements ahead of the excavated face. Monitoring results reported in this paper are related to the installation of a PreConv Array during the excavation phases of a road tunnel located in Northern Italy. The collected data allowed to highlight the displacements of the tunnel crown in correspondence of each step of the excavation works. Moreover, the comparison with theoretical Longitudinal Deformation Profiles (LDP) evidenced the good correspondence between PreConv data and the theoretical curves.

1. Introduction

During the realization of underground constructions, an in-depth knowledge of the rock mass behavior represents a crucial factor for the correct execution of the excavation works. In fact, the tunnel design process depends strongly on the structure interaction with the surrounding environment, both during its construction and the subsequent operational phase [1].

For this reason, monitoring instrumentation has progressively gained more and more importance in underground excavation processes. Following the principles introduced by the observational method [2], the monitoring activity should aim to obtain information on ground response, verify design parameters, identify any potential critical trend, and provide an overall control on the construction process [3-5]. In particular, automated monitoring systems presents a series of advantages that makes them an appropriate choice in these scenarios. These include the possibility to manage and control all instrumentation from remote, the removal of uncertainties related to manual operations, and the ability to achieve higher sampling frequencies [6,7].
When dealing with tunnels and underground works, ground deformation is one of the main parameters to take into account in order to understand the rock mass response to the excavation process. The analysis and control of the medium behavior in proximity of the advance core allows to obtain useful information to identify the arising of stability problems. As described in the ADECO-RS method [8], the deformation processes at the tunnel front include three components: the front extrusion, the tunnel cavity convergence, and the preconvergence deformations taking place ahead of the excavation face. All these elements are strictly related, and the monitoring of their evolution should be a primary task during the tunnel construction phase [9,10]. However, unlike extrusion and convergence, which can be measured with appropriate devices, the direct monitoring of preconvergence phenomena is possible only in rare conditions, usually by exploiting instrumentation installed on the surface above the tunnel crown [11]. The monitoring device described in this paper is intended to provide a new methodology to measure the occurrence of deformations ahead of the advance core with a direct approach, without having to resort to instrumentation installed outside the underground construction.

2. Materials and Methods
The functioning principle of the presented monitoring instrumentation derives from MUMS (Modular Underground Monitoring System) technology, developed by ASE S.r.l., a private company originally born as a spin-off of the University of Parma. This system was created for the development of an automated inclinometer, designed to replace manual measurement procedures, and has been used as a basis for the development of several other geotechnical monitoring devices, including buildings, geotechnical structures, and underground constructions [12,13]

2.1 PreConv Array
PreConv Array is an innovative instrument designed to measure the preconvergence deformations during tunnels excavation. It consists of a chain of synthetic resin sensors, called PreConv Links, located at predefined distances. Each node of the Array is linked by a quadrupole electrical cable and a fiberglass rod to preserve the correct alignment and distance between each Link [14]. The MEMS (Micro Electro-Mechanical System) sensor integrated in each node measures the ground differential vertical settlements induced by the different excavation stages in the tunnel crown.

As the excavation works advance, the PreConv Array returns deformations data both ahead and behind the tunnel face. In fact, once the advance core passes one of the embedded sensors, the Link can still be used to measure convergence effects in the already excavated portion of the tunnel. Moreover, the instrumentation can continue the monitoring activity also after the construction phase, detecting displacements in the tunnel crown during the operational phase.

![Figure 1. PreConv Link components.](image-url)
while the $Y$ axis is orthogonally directed with respect to the previous one, giving information on the node roll. Finally, the $Z$ axis is directed downward, parallel to the gravity vector. Each node has its segment of relevance and calculation point (Figure 2) starting from the middle point between the considered node and the previous one, terminating in the middle point between the considered node and the following one. According to this configuration, the displacement elaboration follows a calculation direction that starts from the anchor until the last calculation point of the Array.

![Segment of relevance of PreConv Link $i$](image)

**Figure 2.** Segment of relevance and calculation point definition.

The entire monitoring process is fully automated and takes advantage of Internet of Things (IoT) technologies for improved communication and interaction between each component of the system, resulting in an integrated procedure that includes monitoring data acquisition, elaboration, storage, and representation [15]. Thanks to this approach, it is possible to achieve high sampling frequencies and obtain a considerable amount of information concerning the monitored element. Moreover, the large number of available data allows for the implementation of self-check algorithms and statistical analyses to assess the dataset quality and improve its reliability.

The PreConv Array is designed for quick installation and deployment, with different configurations depending on the excavation methodology employed (table 1). Moreover, the automated data sampling is designed to be carried out without interfering with excavation works.

**Table 1.** PreConv Array installation techniques according to different tunnel excavation methods.

| Tunnel excavation method | Possible installation technique |
|--------------------------|---------------------------------|
| Conventional tunnel excavation (preconfinement intervention not required) | Sub-horizontal borehole above tunnel crown |
|                          | Sub-horizontal drilling after a pilot tunnel realization |
|                          | Guided perforation above tunnel crown |
| Conventional tunnel excavation (preconfinement intervention required as umbrellas) | Instrument installation inside pipe used for jet-grouting preconfinement |
| Tunnel Boring Machine (TBM) | Sub-horizontal borehole above tunnel crown |
| TBM from vertical shafts | Horizontal borehole above tunnel crown |

The case study presented in this paper regards a deep tunnel located in the north of Italy, connecting two important valleys. The mountain features a high presence of glacial deposit, while the bedrock presents mainly quartz phyllite. The north entrance of the tunnel is excavated inside melted deposits, which have been previously studied and characterized by laboratory tests together with on-site surveys.
3. Results and Discussion

The PreConv Array was installed horizontally inside melted deposits to identify the preconvergence displacements induced by the excavation works ahead of the tunnel face, and to monitor the converging deformations after the tunnel face passage. The tool was located at 180 m from the north entrance for a length of 18 meters, with 18 sensors spaced 1 meter one from each other.

The zero reference for the displacement evaluation, located before CP 18, was defined few hours before the start of the excavation activity on the first day of monitoring activity. The reference value was chosen taking into account the injection influence and the induced vibration that could generate anomalous displacements. The PreConv Array collected data with a 10-minute sampling frequency, sending them every hour automatically to the elaboration centre.

Local vertical displacements occurred during initial excavation phases (Figure 3) showed an inflection point near the tunnel face, involving nodes located behind the tunnel face (i.e. CP 18 and CP 17) and sensors installed in the rock mass ahead of the excavation front (from CP 16 to CP 13). This behaviour indicates that calculation points behind the tunnel face started to converge radially, while the nodes located ahead of the tunnel face showed the expected preconvergence deformation.

During the excavation works advancement, data displayed a similar trend, with downward movements evidenced by sensors located in the tunnel section already excavated. Figure 4, referring to a front progression of +8.75 m from the starting point, provides an example of this behaviour. In this phase, the tool measured a cumulative displacement of -2.8 mm in correspondence of CP 12, while CP 11 indicated an upward local displacement. This is probably caused by a vertical settlement acting before the PreConv Link 11, which determined a counterclockwise rotation of the node. CP 10 evidenced a preconvergence deformation of +1.5 mm.

![Excavation works +2.50 m](image)

**Figure 3.** a) Vertical local displacements and b) cumulative displacements evaluated from zero reference. Excavation front position: +2.50 m.
Starting from the following excavation phase, corresponding to a front advancement of +10.00 m, the PreConv Array started to display a noticeable increase of the vertical displacements magnitude. In particular, in this specific step, the maximum evaluated local displacement amounts to -28.8 mm for CP8 (Figure 5). Following stages displayed deformations within the same order of magnitude, underlining a change in the rock mass response with respect to the one characterizing the first period of the monitoring activity. In the example reported in Figure 6, referring to a front advancement of +13.75 m, it is possible to observe a local convergence displacement of -13.8 mm in PC6, located behind the excavation face.

After reaching progressive +15.00 m of advance, works were stopped to prepare the next excavation field. Forepoles were installed and cemented from this section for a total length of 18 meters. The last considered excavation step was at +17.50 m, where the tunnel face was exactly under the CP1. Recorded displacements showed an increase of convergence settlement on CP3 of -2.7 mm. The cumulative displacements from the reference date amount to a total of -35 mm (Figure 6). Moreover, monitoring data show a displacement ratio much higher moving from CP9 to CP1 if compared to the previous calculation points. These values are an indication of possible changes in the mechanical behaviour of the surrounding ground once the excavation works reached CP9 (+10.00 m).
Figure 6. a) Vertical local displacements and b) cumulative displacements evaluated from zero reference. Excavation front position: +13.75 m.

Figure 7. a) Vertical local displacements and b) cumulative displacements evaluated from zero reference. Excavation front position: +17.50 m.

Moreover, a comparison with theoretical curves was carried out, considering the Longitudinal Displacement Profiles (LDP) proposed by Hoek [16] and Panet [17] to verify the displacement data highlighted by PreConv Array. Theoretical curves indicate that the maximum displacement occurs at a distance of approximately 8 tunnel radii behind the tunnel face, while the radial deformation is zero once a distance of 4 tunnel radii is reached ahead of the tunnel face [16]. The following equations were used to define the LDP curves, referring respectively to Hoek (1) and Panet (2) formulations.

$$\frac{u_r}{u_{r,\text{max}}} = 0.25 + 0.75\left(1 - \left(\frac{0.75}{0.75 + x/R}\right)^2\right)$$  \hspace{1cm} (1)

$$\frac{u_r}{u_{r,\text{max}}} = \left(1 + \exp\left(-\frac{x}{1.10}\right)^{-1.7}\right)$$  \hspace{1cm} (2)

To provide a correct data interpretation, it is necessary to underline some aspects:
• For this comparison, displacements obtained through the PreConv Array are considered in their absolute value, based on the assumption that every displacement is a vertical settlement.

• Each calculation point position was considered fixed, thus evaluating and cumulating its recorded displacements at a different distance from the tunnel face, depending on the excavation phases.

Figure 8 displays two examples of the comparison between the theoretical trend and PreConv Array data, referring to two PreConv Links located in different part of the Array. Overall, monitoring data provided a good correspondence with LDP curves, both for convergence deformation (corresponding to a positive $x/r$ value), and for radial displacements measured ahead of the excavation face (represented by $x/r < 0$). Moreover, since every presented calculation point did not display further displacements after the tunnel passage, it is possible to assume that the surrounding ground is stable.

**Figure 8.** Comparison between theoretical LDP curves and monitoring data sampled by (a) PreConv Link 2 and (b) PreConv Link 13.

4. Conclusions

The monitoring activity of ground deformations is one of the most important aspect to take into account during the realization of underground constructions. Acquiring information regarding the rock mass behavior is fundamental to identify stability issues during the works executions, and can provide useful details to help the project designer during the construction phase (e.g. advance ratio assessment, support systems definition, construction site safety, etc.).

The device presented in this paper, named PreConv Array, was developed to measure preconvergence deformations acting on the rock mass during the tunnel excavation. The entire monitoring system is fully automated and allow to acquire data with high sampling frequencies to provide an accurate description of the structure interaction with the surrounding environment. A PreConv Array was installed in a pilot site located in Northern Italy, in order to identify deformation ahead of the advance core. The monitoring tool was composed of 18 nodes 1-meter spaced, for a total length of 18 meters.

The instrumentation was able to identify both convergence and preconvergence effects, depending on the excavation front position. Moreover, the high sampling frequency allowed to follow the deformations evolution during the different stages of the excavation process.

In the initial phases, monitoring data showed a radial convergence in the already excavated part of the tunnel, with sensors located ahead of the advance core following a preconverging trend. Once the excavation works reached a distance of 10 meters from the first node, CP 8 evidenced a significant increment in vertical displacements, indicating a change in the mechanical response of the surrounding ground from this point onwards. Finally, monitored data were validated through a comparison with
Longitudinal Displacement Profiles (LDP) curves, showing an overall good correspondence with theoretical trends.

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