Long-term monitoring of Austrian railway tunnels – A next step forward

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ABSTRACT: At the large infrastructure projects of the Austrian Federal Railways OeBB in the Alpine region geotechnical structures with different characteristics are encountered. Especially fault zones associated with high overburden are a great challenge during tunnelling, often resulting in large deformation of the rock-support system. On the other hand support for tunnels in swelling ground has to be designed to an expected swelling pressure during the life time of a tunnel. The goal is to apply robust, reliable and durable monitoring systems for observing such geotechnical structures during a service life of the tunnels of 150 years. The benefit is to early detect unfavourable tendencies of the system behaviour and the planning of measures in terms of predictive maintenance accordingly in due time. Finally this ensures high availability of the tunnels during operation. The paper presents the implementation of long-term monitoring via the projects Koralm Tunnel, Granitztal Tunnel and the Semmering Base Tunnel.

Keywords: long-term monitoring, OeBB railway tunnel, ground pressure, fibre optic sensing, vibrating wire strain sensors, automatic data acquisition.

1 INTRODUCTION

Fault zones associated with high overburden are a great challenge during tunnelling and often result in large deformations of the rock-support system. On the other hand the potential of swelling ground is another problem. Although the support is designed due to the expected ground pressure uncertainties in terms of the further development of loads acting on the tunnel during its operation and lifetime still remains. This is where the strategy of the Austrian Federal Railways OeBB starts to apply long-term observation of a tunnel in selected sections in weak rocks or fault zones. The main goal is to identify unfavourable tendencies in the displacement characteristic as well as the development of stresses in the tunnel lining. Based on the respective geotechnical situation targeted measures in the sense of predictive maintenance can be planned in due time. This ensures to reduce operational restrictions to a minimum and the highest possible tunnel availability. In order to achieve this ambitious goal, appropriate monitoring concepts and methods for the observation of the inner lining are already developed and implemented. In the following aspects of long-term monitoring are outlined via the projects Koralm Tunnel (KAT), Granitztal Tunnel (GTT) and the Semmering Base Tunnel (SBT). Successful long-term monitoring installations required the involvement of all stakeholders at an early stage. During the planning phase, the position of the monitoring equipment has to be aligned with the location of other tunnel infrastructure like conductor rails, handrails, emergency lights etc. Otherwise, measurements may not be possible, e.g. levelling staff cannot be setup due to handrail, or sensors may be destroyed for instances by drillings for the conductor rail mounting. Furthermore, a close collaboration with the tunnel design engineer can utilize synergies, like using communication cables also for the transfer of sensing data. During the construction, an ongoing coordination with the construction company is required to minimize interference of sensor installations with the construction process and to guarantee a high sensor survival rate.

2 REQUIREMENTS FOR LONG-TERM MEASUREMENTS

To ensure measurements in the long term the requirements for instruments installed in monitoring sections during the lifetime of a tunnel are higher compared to those used in the relatively short time span during tunneling. Long lasting durability, robustness and high reliability of the gained data during the overall observation period are some of the key issues (EN ISO 18674-1).

Long-term monitoring does not only require a careful selection of sensors, but also the consideration of a redundancy of the measuring methods and the implementation of a parallel quality management. The installation of the systems during the concreting phase of the inner shell and before the installation of the electromechanical equipment requires special precautions such as the clear marking of cable routes, sensor positions and detailed documentation. The redundancy is achieved by using two completely different and independent measuring methods: On the one hand the use of fiber optic sensors and on the other hand the installation of strain transducers based on the vibrating wire technique. The parallel execution and operation of a sensor arrangement similar to a monitoring section at the Institute of Geodesy at the TU Graz/Austria under laboratory conditions as well as the application of defined deformations is part of the quality management.

3 MONITORING LAYOUT

The monitoring layout consists of a combination of embedded sensors and surface mounted observation points. Rigid movements, settlements, tilting and convergences can be detected with geodetic techniques. These measurements have to cover also areas which are assumed to be stable. Figure 1 displays a typical monitoring section where the inner lining blocks n-1, n, n+1 are suspected to experience long term deformations, whereas the blocks n-3 and n+3 are outside the deformation area and are assumed to be long-term stable.

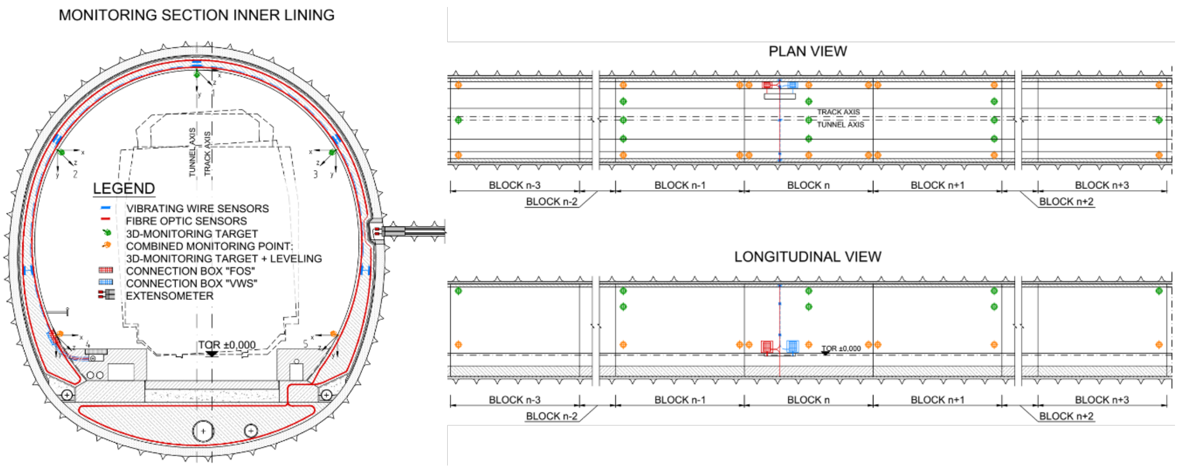

Figure 1. Typical geodetic and strain monitoring sections for long-term monitoring.

4 MEASURING SYSTEMS AND METHODS

4.1 Strain monitoring with geotechnical sensors

Along the Koralm Tunnel, Granitztal Tunnel and Semmering Base Tunnel projects more than 60 measuring cross-sections will be equipped, mainly with strain sensors, in individual cases with joint- and pore water pressure sensors as well as extensometers.

Each monitoring section contains five pairs of vibrating sensors (VWS) for strain measurements. These sensors are fixed on the innermost and outer wire mesh layer, see Figure 2 right, in such a way that they can detect strains in the circumferential direction (Radoncic et al. 2015). The arrangement of the transducers in pairs is important to be able to evaluate bending moments later from the calculated normal forces. The sensor type used is a GEOKON 4200-7 with an increased measuring range of 10,000 µm/m. This high measuring range was chosen in order to take into account sensor stresses and associated zero-point shifts during the concreting process. Nevertheless, a repeatability of the measurements of < 5 um/m is to be expected.

Each measuring point is equipped with a thermistor to detect temperature and, if necessary, compensate for temperature influences on the measurement series.

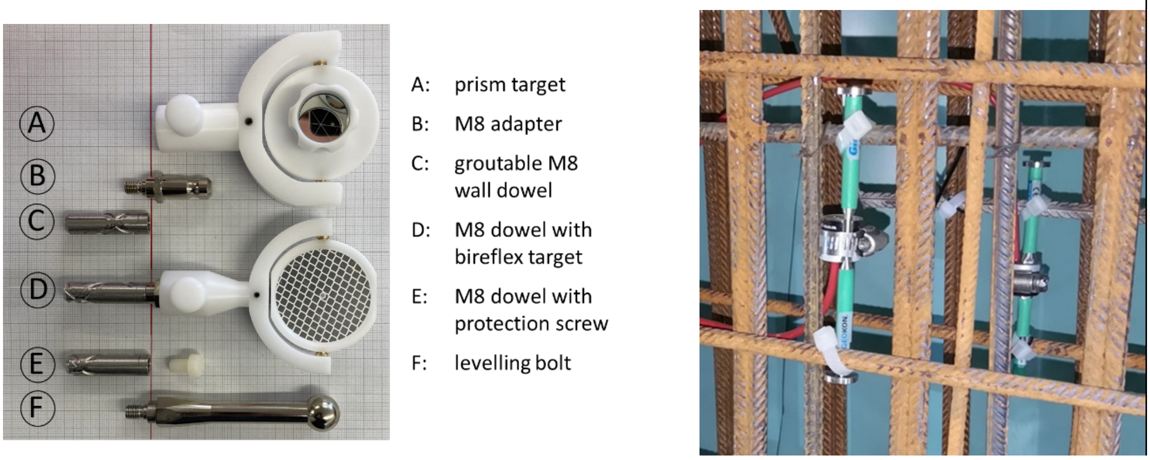

Figure 2. Components of a 3D monitoring point (left), strain sensors installed pairwise on the inner and outer wire mesh layer (right).

To record displacements in the rock in selected areas monitoring sections with multifold extensometers are integrated into the long-term monitoring program. These instruments were already installed during tunneling. For long-term monitoring, the measuring heads will be revised and equipped with water-tight vibrating wire displacement transducers. The entire assembly remains outside the sealing foil, protected in a foamed box. Only one cable per extensometer location is led through the foil to the data logger.

The rod lengths of the extensometers are between 3 and 15 m. For the observations with the 50 mm displacement transducers an accuracy of +/- 0.05 mm is expected.

4.2 Strain monitoring with DFOS strain sensors

Distributed fibre optic sensors (DFOS) enable the measurement of strain along the entire fibre length with spatial resolutions of 0.5 m or better over several tens of kilometers (Monsberger and Lienhart 2021, Monsberger et al. 2022). The measurement instrument, called interrogator, couples light into a glass fibre, analysis the backscattered signal and can be far away from the measurement position (e.g. outside of the tunnel). Sensing cables are installed at the individual cross sections. These cables have a glass fibre core, which is usually protected by metal tubes and a structured cable surfaces ensures well bonding with concrete (Monsberger and Lienhart 2021). In order to separate longitudinal strain from curvature changes it is recommended to embed the cable in different depths of the lining. Furthermore, fibre optic strain sensing is always cross sensitive to temperature changes. A common approach to derive strain is to numerically correct the temperature influence with a separate temperature cable where the fibre is loose and hence does not experience any strain change.

4.3 Deformation monitoring with geodetic techniques

The target and marking equipment were specially developed to meet the requirements for long-term monitoring (see Figure 2 left). The measuring points can be equipped with 3D targets (bireflex targets or prisms) as well as with levelling pins, whereas the point identity is the same for all systems. The wall plugs with diameter of 12 mm and length 45 mm are made of stainless steel. They are glued or grouted into D=14 mm drill holes. The manufacturing accuracy of all parts is 0.1 mm to allow replacement of target components without connection measurement. It should be noted that the targets are dismantled between measurement campaigns.

The inner lining blocks, which are suspected to experience long-time deformations are equipped with leveling points on each corner in the lower sidewall area, in order to get information about tilting of the blocks. At the beginning, the end and in the middle of the area of interest, the inner lining blocks feature monitoring cross sections with five 3D monitoring targets, evenly distributed in circumferential direction (Figure 1).

4.4 Data acquisition and data forwarding

In a high-speed tunnel, significant electromagnetic interferences in the measuring circuits are to be expected. These disturbances are caused by high alternating current densities along the track and are also feed in by the power supply line which is cabled parallel to the traction current. This not only distort measured values, but can also destroy entire measuring circuits. Therefore, copper cabling along the tunnel axis was largely avoided. The sensor lines were laid as perpendicular as possible to the tunnel axis and connected as short as possible to the multiplexer of the data logger (see Figure 3). Furthermore, attention was paid to the potential separation of the sensor lines, the supply voltage and data transmission.

The applied multiplexers from Campbell Scientific are based on relays. This means that the measuring lines are galvanically isolated from the data logger outside of a measuring cycle. The supply side is protected by surge arresters, filters and a galvanically isolated power supply unit. Data transmission and communication with the data logger is done via a fiber-optic cable.

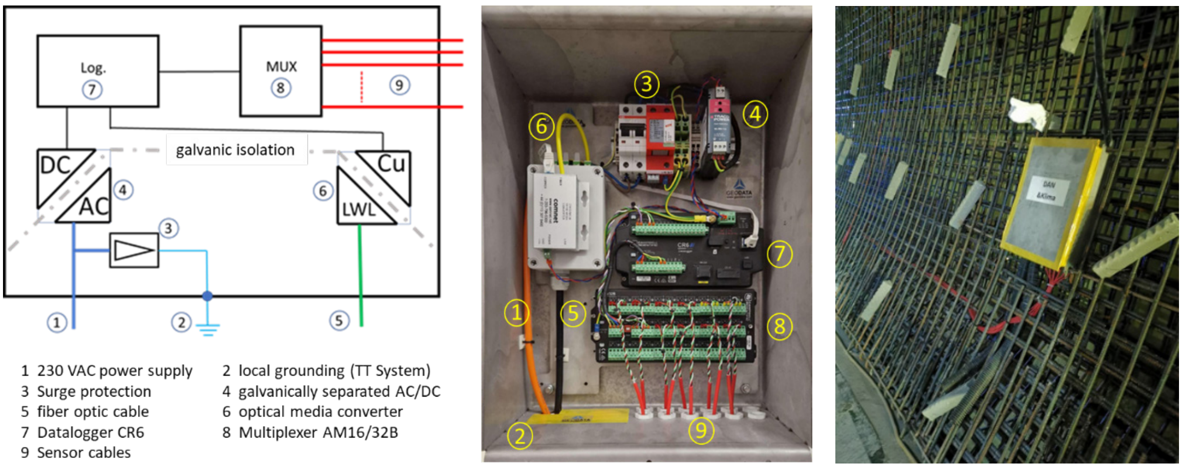

Figure 3. Concept for power supply, data logging and data transmission (left and middle), installed data logger in a formwork carriage (right).

5 MONITORING RESULTS

First measurements according to the presented concept already started. Figure 4 (left) shows the measured strain changes and development in a circumferential direction of one of the five monitoring sections of the Granitztal Tunnel equipped with fibre optics and strain sensor in an anhydrite section.

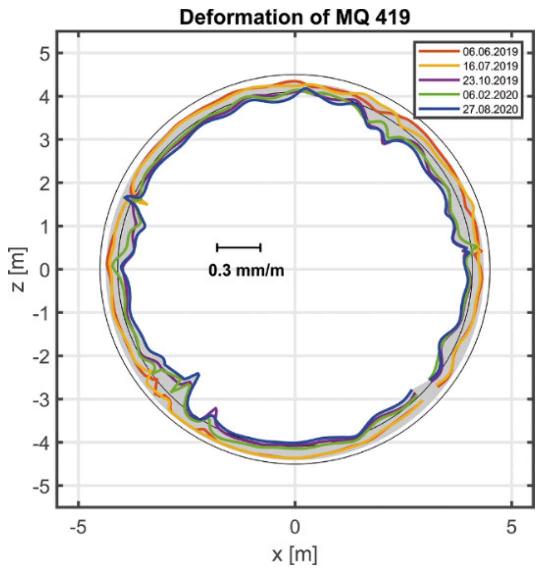

Figure 4. Example long-monitoring of strain development in the inner lining in an anhydrite section of the Granitztal Tunnel using fibre optics and strain sensors (left, Moritz et al. 2021). Future (right): Visualization of a region with high level of loading during operation of a tunnel caused by high strains (Hellmich et al. 2020).

6 CONCLUSION AND OUTLOOK

For the major infrastructure projects in Austria such as the Koralm Tunnel, the Granitztal Tunnel and the Semmering Base Tunnel, appropriate monitoring concepts for the future are already developed. This especially with regard to the expected long-term effects of geotechnical structures, such as weak rocks or fault zones on the inner lining.

The evaluation of the stress state of the tunnel shell shall be continued during the 150-year service life. These are the focus of a newly initiated research project with the aim of making hybrid methods applicable for in-situ concrete inner linings and for pre-cast concrete segmental linings (Hellmich et al. 2020, Scharf et al. 2023, Razgordanisharahi et al. 2023). In this way, in the future unfavourable developments in the stress state of such tunnel supports can be detected early and targeted measures in the sense of predictive maintenance can be planned in due time according to the geotechnical situation (see Figure 4 right).

For this purpose, target, warning and alarm values for the geotechnical long-term monitoring must already be specified in the maintenance planning – similar to the geotechnical safety management during the construction phase (Moritz et al. 2011, OeGG 2014).

Depending on the service life, economic aspects and risk assessments, measures to be derived amongst others from the long-term measurements have to be planned according to the respective maintenance strategy. Predictive planning based on reliable (monitoring) data can make a valuable contribution using the required resources in order to guarantee reliable structures over their life cycle economically and effectively. Such a procedure can reduce operational restrictions to a minimum and the highest possible tunnel availability can be guaranteed at OeBB-Infrastructure.

REFERENCES

EN ISO 18674-1; Geotechnical investigation and testing – Geotechnical monitoring by field instrumentation - Part 1: General rules (ISO 18674-1:2015).

Hellmich, C., Pichler, B., Heissenberger, R. & Moritz, B. 2020. 150 years reliable railway tunnels – Extending the hybrid method for the long-term safety assessment. *Geomechanics und Tunnelling* 13 (5), pp. 538–546, Ernst & Sohn: Berlin.

Monsberger, C.M., Bauer, P., Buchmayer, F. & Lienhart, W. 2022. Large-scale distributed fiber optic sensing network for short and long-term integrity monitoring of tunnel linings. *Journal of Civil Structural Health Monitoring* 12, pp. 1317–1327. DOI: 10.1007/s13349-022-00560-w.

Monsberger, C.M. & Lienhart, W. 2021. Distributed Fiber Optic Shape Sensing of Concrete Structures. *Sensors 2021*. DOI: 10.3390/s21186098.

Moritz, B., Koinig, J. & Vavrovsky, G.-M. 2011. Geotechnical safety management in tunnelling – an efficient way to prevent failure. *Geomechanics und Tunnelling* 4 (5), pp. 472-488, Ernst & Sohn: Berlin.

Moritz, B., Heissenberger, R., Schachinger, T., Lienhart, W. 2021. Long-term monitoring of railway tunnels. *Geomechanics and Tunnelling* 14 (1), pp. 35–46. DOI: 10.1002/geot.202000049.

OeGG Austrian Society for Geomechanics. 2014. *Geotechnical monitoring in conventional tunnelling*. In-house publisher: Salzburg.

Radoncic, N., Kern, M., Weissnar, M. & Moritz, B. 2015. Strain gauges in pre-cast concrete segments: working principle, evaluation and interpretation. *Geomechanics and Tunnelling* 8 (3), pp. 265–272, Ernst & Sohn: Berlin.

Razgordanisharahi, A., Scharf, R., Pichler, B., Sorgner, M., Höld, H., Pilgerstorfer, T., Moritz, B. & Hellmich, Chr. 2023. Data-driven analytical mechanics of segmented tunnel linings: ground reaction and load carrying behavior. In: *15th ISRM Congress 2023 & 72nd Geomechanics Colloquium*, Schubert & Kluckner (eds), Salzburg, Austria, October 9 - 14, 2023.

Scharf, R., Pichler, B., Heissenberger, R., Moritz, B. & Hellmich, Ch. 2023. Data and analytical mechanics: a new look on NATM tunnels. In *15th ISRM Congress 2023 & 72nd Geomechanics Colloquium*, Schubert & Kluckner (eds), Salzburg, Austria, October 9 - 14, 2023.