Reinforced Earth Structures at Semmering Base Tunnel - Construction and Monitoring using Fiber Optic Strain Measurements

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ABSTRACT: Reinforced earth structures are extensively used at the disposal site Longsgraben of the new Semmering base tunnel. These structures were monitored during construction using the observational method according to Eurocode 7. Geodetic measurements to targets on the surface of the structure were regularly performed in selected cross sections. However, surface deformations give only limited information about the operation grade of geogrids due to the inhomogeneous strain distribution within the object. We present a fiber optic measurement concept for the reliable measurement of strain of geogrids within earth structures. The monitoring system was specifically developed for the Semmering project and uses distributed fiber optic sensing based on Brillouin scattering. About 2km of sensing cables were installed in the project area. Unique anchors were designed to reliably transfer deformations of the geogrids to the sensing cables. The stability of the anchors was verified in detailed laboratory investigations. The measured Brillouin frequency shifts are converted into strain values using calibration functions derived from laboratory experiments. Finally the measured internal and external deformations are compared to predicted deformations from the finite element analyses. We demonstrate that with the developed monitoring system internal deformations can be measured reliably and with high precision.

Keywords: New Semmering Base Tunnel, Fiber Optic Sensors, Brillouin backscattering

1 INTRODUCTION

The New Semmering Base Tunnel is one of the key projects of the current upgrade of the Austrian railway connection between Vienna, Graz and Klagenfurt (Gobiet, 2013). After completion the tunnel will have a length of 27.3km and will be part of the European TEN-T Core Network Corridor connecting the Baltic Sea to the Adriatic Sea.

Prior to tunnel excavation, various preparatory works had to be completed including the construction of a disposal site for 4.25 million m³ of excavated material. The disposal site is located in the so-called "Longsgraben", an uninhabited narrow valley close to one of the main access points for tunnel construction. At the disposal site reinforced earth structures with a length of more than 1.3km and heights of up to 25m were built. These retaining structures and ramps are located in steep mountainous terrain.

A systematic geotechnical monitoring process was performed during construction and after completion of the reinforced earth structures. Tensile forces in the geogrids were determined using internal strain measurements with fiber optic sensors. These measurements provide additional information about the complex behavior of reinforced earth structures in difficult terrain.

We present in this paper the reinforced earth structures constructed in Longsgraben valley. Furthermore, we discuss the development and installation of the fiber optic monitoring system. Finally, first measurement results are presented and compared to results of finite element analyses.

2 REINFORCED EARTH STRUCTURES IN LONGSGRABEN VALLEY

The disposal site for tunnel excavation material in Longsgraben valley covers an area of approximately 20 hectare and is located between 1.050m and 1.250m above sea level. During operation of the site, the valley will be refilled up to a height of 50m. Afterwards, the site will be covered with earth and afforested.

Prior to establishing the disposal site, the small mountain stream running at the valley floor had to be relocated to a new bed at the edge of the site, up to 50m above the valley bottom. Therefore, a reinforced earth structure with a length of 1.220m and a maximum height of 12m was constructed in the steep valley side, where the terrain slopes at an angle of 35° to 40°. A special challenge was the final section of the reinforced earth structure where the new stream bed is led back into the valley bottom in a steep slope (Figure 1-right). For maintenance, a road is situated along the new stream bed at the crown of the reinforced earth structure. The maintenance road can be reached via a reinforced earth ramp (Figure 1-left) with a maximum height of 25m and a length of 80m.

Figure 1. Reinforced earth structures at Longsgraben, Access ramp (left), installation of fiber optic sensing cable on the geogrid (center) and steep slope section (right)

The reinforced earth structures were designed with a slope angle of 60°. In the design process the fill material was specified by maximum grain size, grain size distribution and shear parameters. The requirements could be met by broken rock quarried on site. The geogrids were specified by the design value of tensile strength and their strain behavior. Due to the complex geometry of the structures and the inhomogeneous ground conditions it was necessary to apply bi-directional geogrids. The reinforced earth structures were constructed using Huesker Fortrac®-T geogrids.

Due to the complexity of the structures and the ground conditions the observational method according to Eurocode 7 was applied. Thus, a systematic geotechnical monitoring program was an essential part of the design. Geotechnical monitoring included weekly geodetic measurements in all critical cross sections of the structures. In addition, a fiber optic strain measurement system was installed in the steeply sloping segment of the new stream bed and in the access ramp.

Further details on design and construction of the reinforced earth structures and on the geotechnical monitoring are included in Schuller et al. (2014a, 2014b).

3 FIBER OPTIC MEASUREMENTS AT LONGSGRABEN

In this paper we concentrate on the measurements in the earth body to determine the operation grade of the geogrids. To investigate the behavior of the geogrids a sensing cable had to be embedded in the earth structure and work under harsh environmental conditions. Fiber optic sensors (FOS) are well suited for such applications. Successful geotechnical installations are described e.g. by Iten et al. (2009), Iten et al. (2012) or Hauswirth et al. (2011). Brückl et al. (2013) discuss a combination of established geodetic methods with integrated fiber optic sensors for the monitoring of landslides and demonstrate that the precise relative fiber optic measurements complement the absolute geodetic measurements.

3.1 *Fiber Optic Sensors for Geotechnical Applications*

FOS can be embedded into structures and have many advantages like insensitivity to electromagnetic disturbances compared to conventional sensors. Within the last 10 years many different types of sensors have been developed. These can be grouped into point sensors, quasi-distributed sensors and distributed sensors (Measures, 2001 p. 29). Examples for point sensors are interferometric systems based on Fabry-Perot interferometry (e.g. EFPI sensors) or low coherence interferometry (e.g. SOFO system). Quasi distributed systems are usually based on fiber bragg gratings (FBG). Distributed systems use the entire fiber as sensing element and are therefore best suited for large scale objects. Todays distributed fiber optic systems are based on Raman-, Rayleigh- or Brillouin backscattering.

Raman backscattering is used to measure the temperature distribution within earth structures and can be applied to detect water seepage in earth filled dams (ICOLD, 2012 p. 45). Rayleigh and Brillouin backscattering are sensitive to strain and temperature and therefore, with appropriate temperature compensation, these effects can be used to measure strain. Due to the large size of the object to be measured and the high number of monitoring sections it was decided to use a Brillouin backscattering system for this application.

Brillouin scattering occurs when light travelling in a single-mode optical fiber is reflected by the refractive index modulations produced by acoustic waves (e.g. Horiguchi et al., 1989; Nöther, 2010). This interaction is stimulated by a high power laser in Brillouin Optical Time Domain Reflectometry (BOTDR). BOTDA (Brillouin Optical Time Domain Analyzer) and BOFDA (Brillouin Optical Frequency Domain Analyzer) systems use a loop configuration where one end of the fiber is connected to a continuous wave pump laser and the other end to a laser which emits light pulses or amplitude modulated light waves. Thereby, a high operating range up to tenths of kilometers with spatial resolution of better than 1m can be achieved. However, the measurements cannot be performed if the loop is interrupted at any location. Therefore, installations in harsh environment require robust sensing cables and a well-trained installation crew. Both ends of the fiber loop are usually connected to a single interrogation unit which houses both laser sources and analyzes the light signals. The Brillouin frequency of the scattered light depends linearly on strain and temperature (Horiguchi et al., 1989 and Kurashima et al., 1990).

The interrogation unit records the Brillouin frequencies as well as their location along the fiber which can be calculated for instance from the travel time of the laser pulse. Figure 2 shows the result of one measurement. Displayed is the Brillouin frequency spectrum along 60m of fiber. Clearly visible is the center frequency of about 10.5GHz of the unstrained fiber. Strain was applied to different sections (25m, 36m and 42m) of the fiber which results in significant shifts of the Brillouin frequency. These frequency shifts can be converted into strain values when the strain coefficient of the fiber is known. Since this coefficient is usually not available with sufficient accuracy, a calibration in the laboratory is often necessary.

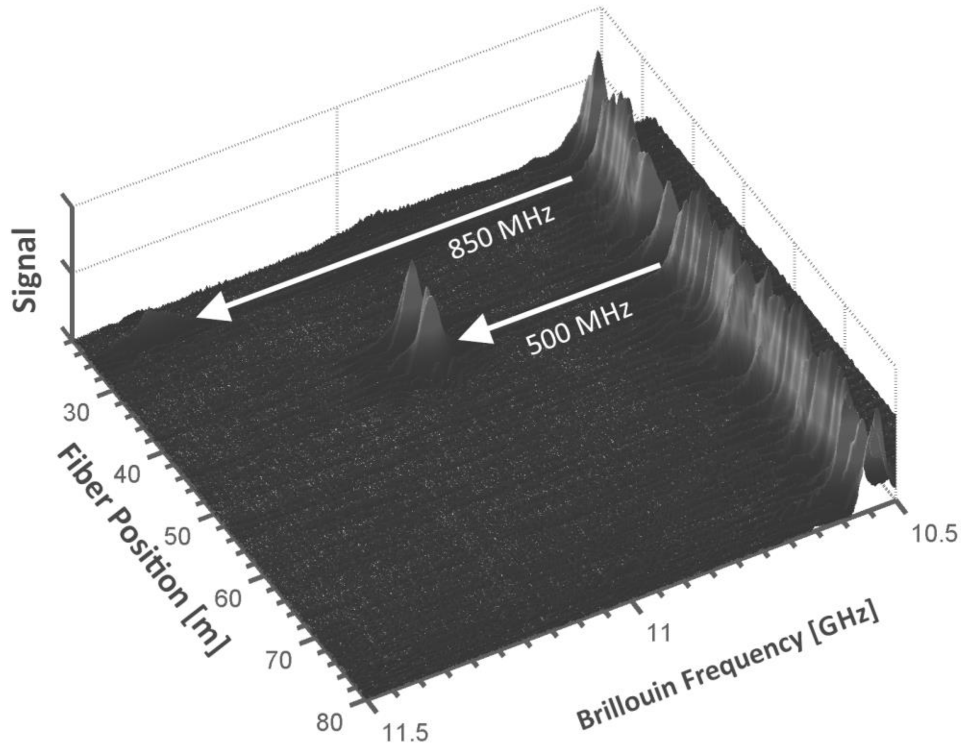

Figure 2. Brillouin frequency spectrum along a sensing fiber

3.2 *Development and Installation of the BOFDA Monitoring System*

The monitoring program at the disposal site focuses on four cross sections. Two cross sections (CS 3A and CS 3B) are located in the steep section of the new river bed, see Figure 3. The other two cross sections are in the reinforced earth ramp of the maintenance road.

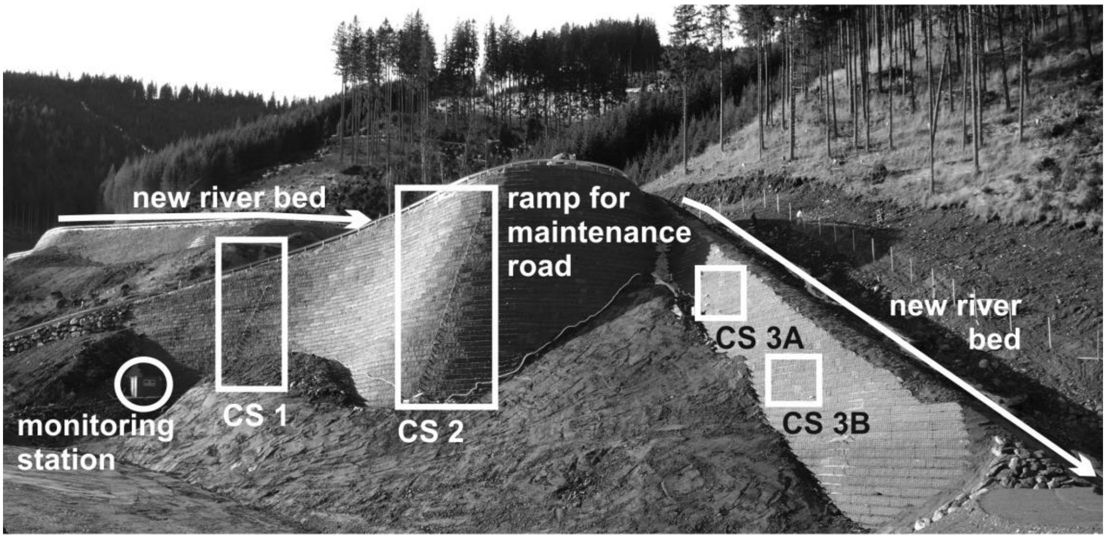

Figure 3. Overview of the cross sections of the reinforced earth structures

Although, geotextiles with already integrated fiber optic sensing cables exist (e.g. Krebber and Habel, 2011) they could not be used in this project. The goal was to measure the operation grade of the geogrids which are used within the entire structure. Therefore, the sensing cable had to be connected to the given geogrid.

Based on this requirement a fiber optic monitoring system was developed by the Institute of Engineering Geodesy and Measurement Systems (EGMS) of Graz University of Technology. The developed monitoring system consists of three components. First a BOFDA interrogation unit, second a fiber optic sensing cable and third adapters which connect the sensing cable to the geogrid. The BRUStrain V4 from Brugg Cables was selected as sensing element due to its high robustness. In total over 2km of this sensing cable was installed in the reinforced earth structure. Figure 4 shows the cross section CS2. In this cross section five geogrid levels were equipped with the sensing cable. Each level is subdivided into segments by the adapters. The minimal distance between two adapters is defined by the spatial resolution of the interrogation unit. For the used fTB121 of fibris Terre this is 1m (fibris Terre GmbH, 2012). With the developed concept 26 individual strain segments can be monitored in CS2.

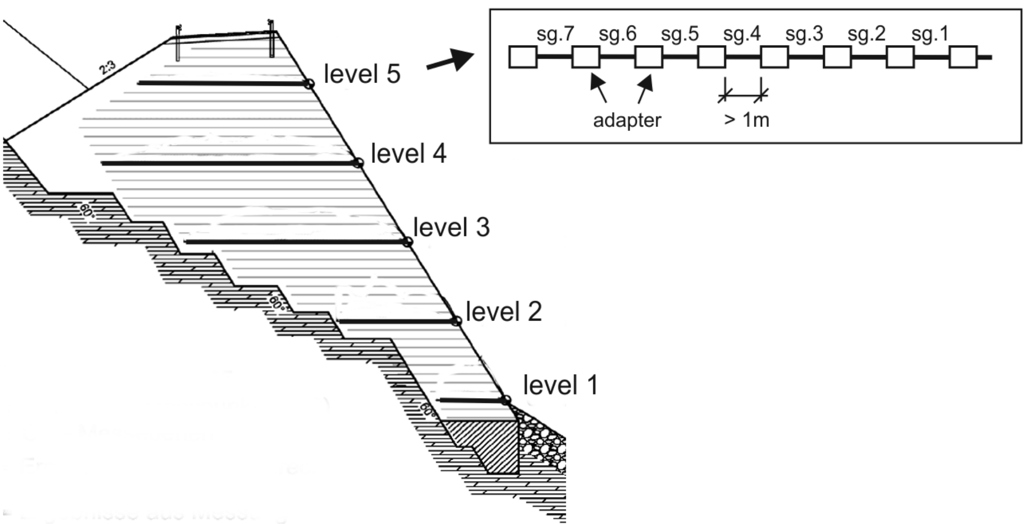

Figure 4. Cross section CS2 with monitoring levels and segments (sg.)

The anchors were specially designed for this project to reliably transfer deformations of the geogrids to the sensing cables. Extensive laboratory investigations (Figure 5-left) confirmed the force transfer from the geogrid to the fiber core. The linear strain coefficient was also obtained in these laboratory investigations.

Since the measurement principle (BOFDA) needs a closed loop each measurement level consists of a forward and return path. The forward path was pre-strained during installation and is therefore sensitive to strain and temperature (Figure 5-right). The return path was installed stress free and is therefore only sensitive to temperature. Thus, temperature compensation can be realized by combining the data from the forward and backward path of the same segment.

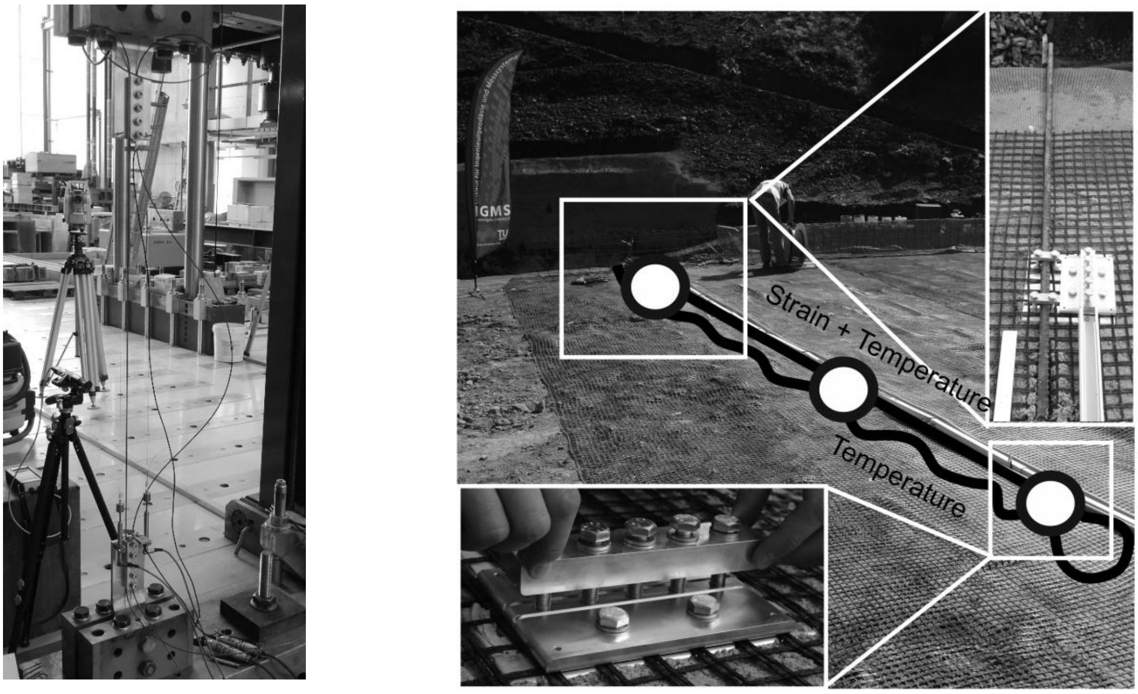

Figure 5. Strain coefficient determination in the laboratory (left); sensor installation on the construction site (right)

3.3 *Data Analysis*

All segments of the cross sections can be measured at the same time from a central monitoring station. Figure 6 shows a typical result of such a measurement. Displayed is the Brillouin frequency spectrum for the entire 2km sensing cable.

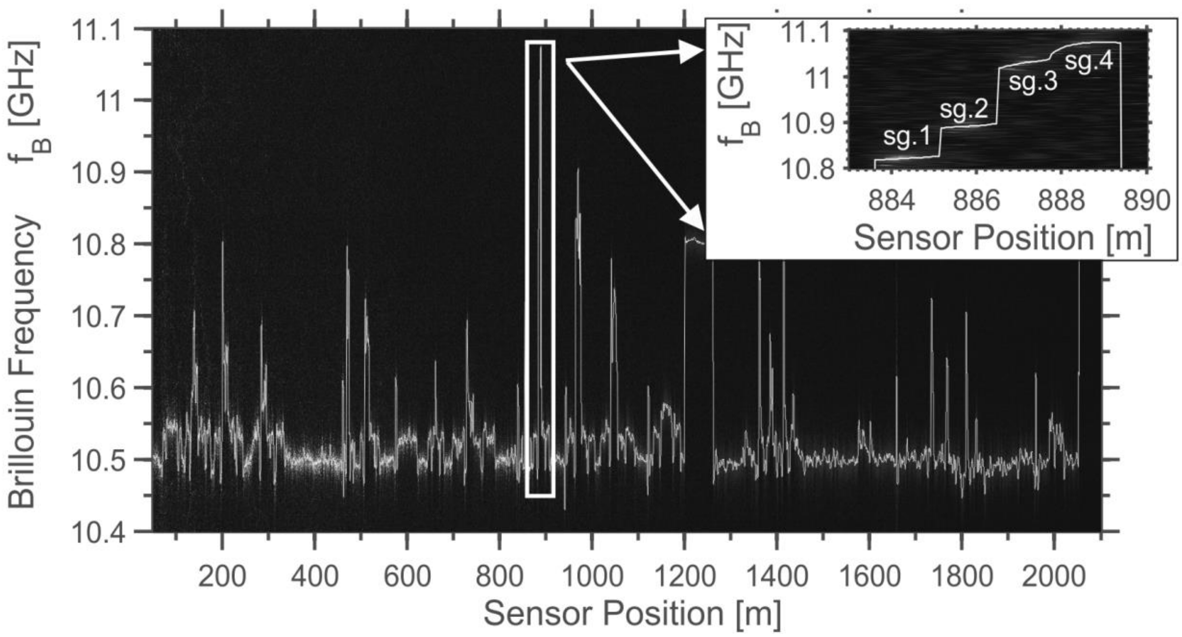

Figure 6. Measurement result of the 2km sensing cable

The detected Brillouin frequencies have to be allocated to the segments of the cross sections. The zoom view in Figure 6 shows the segments of the second level of cross section CS2. Identifiable are four different segments with a length of 1.2m each. EGMS developed software for an automatic classification of the segments and calculation of the frequency for the forward path (strain and temperature) and backward path (only temperature) segments. Next, temperature compensation is numerically performed using the signals from the forward and backward path of the same segment. Finally, the frequency shift between the current temperature compensated frequency and the value measured at the first measurement epoch is calculated and converted into strain values using the strain coefficient determined in the laboratory.

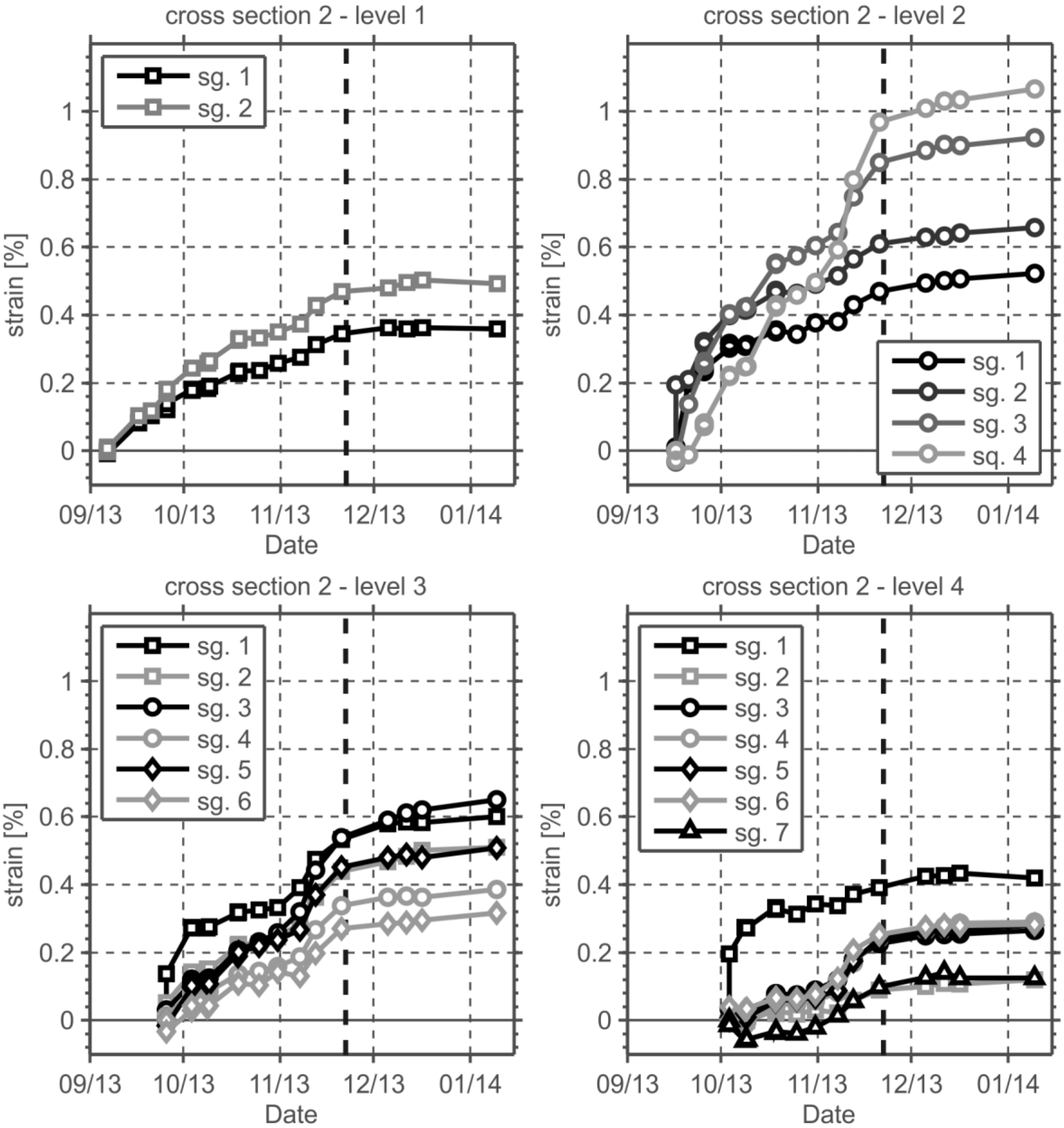

Figure 7. Strain development of the segments (sg.) in the levels 1 to 4 in cross section CS2; the bold dashed line marks the end of the construction works

Figure 7 shows the strain development of the first four levels of cross section CS2. The strain increases significantly in all segments during the construction phase. The strain continuous to grow in some sections after the end of the construction works, however at much lower rate. The largest strain values were observed in monitoring level 2 and reached values of about 1.1%.

4 INTERPRETATION OF STRAIN MEASUREMENT RESULTS

In the design process of the reinforced earth structures finite element (FE) analyses were used to obtain insight into the development of stresses, displacements and stress-redistributions. For example, the tensile forces in the geogrid were predicted. The geogrid forces derived from fiber optic strain measurements can be compared to the results of the finite element analyses carried out during design.

Figure 8 shows results for the critical cross section CS2 of the access ramp, where the reinforced earth structure reaches its maximum height of 25 m. In the lower diagram of Figure 8-right the tensile forces derived from strain measurements are displayed for the second level of the fiber optic system. Each line represents the distribution of tensile forces for a certain construction stage. Obviously, construction works in the upper areas of the ramp still result in an increase of geogrid forces near the foot of the reinforced earth body. The FE analyses result in an analog behavior, however, the resulting tensile forces are significantly higher. In Figure 8-left the predicted tensile forces using FE analyses are compared to the forces derived from strain measurements for the final construction stage. The difference could be resolved by parametric studies where a significant influence of the fill material's shearing resistance on the tensile forces in the geogrids was shown (Schuller et al., 2014b). Additional results and interpretations of the fiber optic strain measurements are presented by Schuller et al. (2014a).

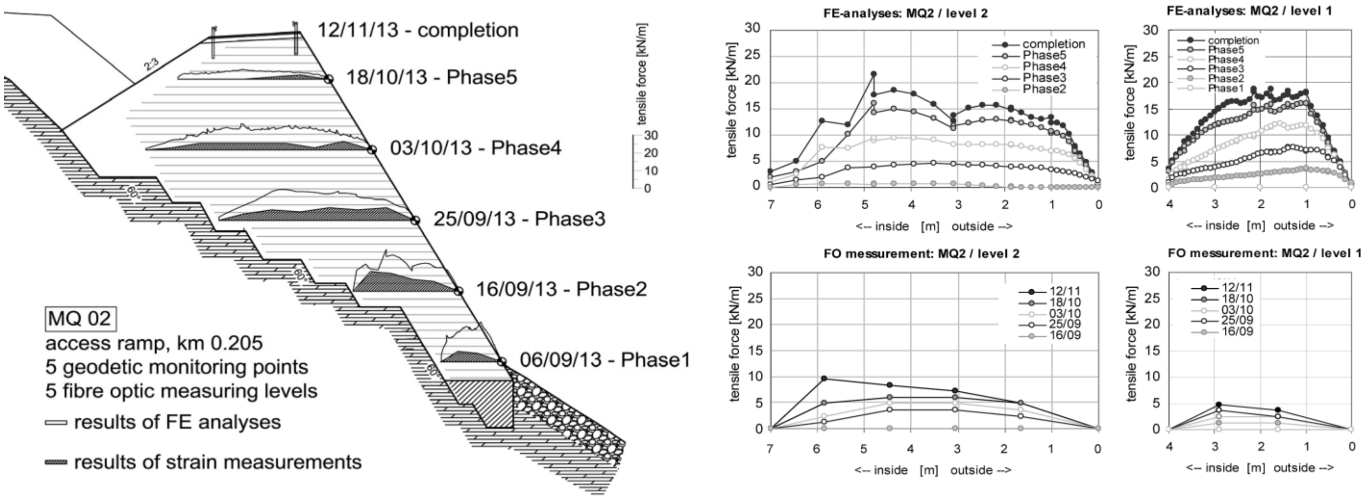

Figure 8. Cross section CS2 at the reinforced earth structure of the access ramp; geogrid tensile forces predicted using finite element (FE) analyses (top right) and derived from fiber optic strain measurements (bottom right)

5 CONCLUSION

Reinforced earth structures are often used for the construction of large earth bodies with steep slope angles. However, the measurement of surface deformations gives only limited information about the operation grade of the geogrids due to inhomogeneous strain distribution within the object. We demonstrated in this monitoring project that distributed fiber optic sensing can give valuable insight into the behavior of reinforced earth structures. The whole sensing fiber survived the installation due to the robustness of the cable, the well planned installation process and the great support of the construction company G. Hinteregger & Söhne Baugesellschaft m.b.H. More than half a year after the first installation the monitoring system is still fully operational and used for the long term monitoring of the earth structures as well as for investigations of the long term reliability of distributed fiber optic sensing.

ACKNOWLEDGEMENTS

We want to thank the Austrian Federal Railways (ÖBB)for the funding of this innovative monitoring project, especially the participating departments of ÖBB-Infrastruktur AG: Tunneling, Surveying and Data Management, Research and Development.

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