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Title	Distributed fibre optic strain sensing of CERN infrastructures in the molasse region;Distribué fibre optique des infrastructures du CERN dans la région des molasse
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Publication date	2019
Original Citation	Di Murro, V., Soga , K., Fern, E. J., Pelecanos, L., Li, Z. and Scibile, L. (2019) 'Distributed fibre optic strain sensing of CERN infrastructures in the molasse region', Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavík, Iceland, 1-6 September, pp. 1-7. doi: 10.32075/17ECSMGE-2019-0061
Type of publication	Conference item
Link to publisher's version	https://www.ecsmge-2019.com/ - 10.32075/17ECSMGE-2019-0061
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Download date	2026-10-15 02:46:24
Item downloaded from	https://hdl.handle.net/10468/11758

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University College Cork, Ireland
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Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3
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doi: 10.32075/17ECSMGE-2019-0061

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Distributed fibre optic strain sensing of CERN infrastructures in the molasse region

Distribué fibre optique des infrastructures du CERN dans la région des molasse

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ABSTRACT: The European Centre for Nuclear Research (CERN) is a large underground laboratory and it is home to two large particle accelerators, including the «Large Hadron Collider» (LHC). The particles travel at the speed of light through a series of tunnels which must comply with the high serviceability requirements. However, the underground facilities have expanded over a period of 40 years with new tunnels, shafts and caverns. Structural ageing and deterioration of the infrastructure can alter the drainage conditions around tunnels and this can cause, in turn, excess deformation of the tunnels and serviceability issue for the particle accelerators. A remote monitoring system based on distributed fibre-optic strain sensing technology has been implemented in some of the concrete-lined tunnels in order to gain insight in the long-term mechanical behaviour of the underground system. This paper presents the results of the monitoring programme and the results show a slow development of ovalisation of the tunnel over a period of three years.

RÉSUMÉ: Le Centre Européen pour la Recherche Nucléaire (CERN) est un grand laboratoire souterrain qui héberge deux accélérateurs de particules dont le « Large Hadron Collider » (LHC). Les particules se déplacent à la vitesse de la lumière à travers un réseau de tunnels qui doivent répondre à des exigences élevées de service. L'infrastructure souterraine du CERN s'est étendue sur une période de 40 ans avec la construction de nouveaux tunnels, puits et cavernes. Le vieillissement des matériaux et la détérioration structurelles des ouvrages peuvent altérer les conditions de drainage autour des tunnels ce qui peut engendrer, à son tour, des déformations

excessives et atteindre la limite de service des accélérateurs de particules. Un système de monitoring à distance avec des câbles en fibre optique a été mis en place dans certains tunnels afin d'étudier le comportement à long terme. Cet article présente les résultats de la compagne de monitoring et démontre une ovalisation des tunnels sur une période de trois ans.

Keywords: long-term tunnel deformation; long-term monitoring, distributed fiber-optic sensing; red molasse.

1 INTRODUCTION

The massive Large Hadron Collider (LHC) built at the European Organisation for Nuclear Research (CERN) has been designed to provide insight into the fundamental law of nature by using particle accelerators to fire particles through a network underground tunnels. The maintenance of these large infrastructure plays a crucial role as it aims to guarantee the structural safety required. Therefore, the use of distributed optical fibers (DFOS) to monitor CERN tunnels allows to assess the tunnel lining performance as a long-term plan, by offering monitoring data remotely for long distances. Compared to conventional monitoring systems that can only provide spatially-discrete measurements during short tunnel shutdowns, distributed fibre optic strain sensing enables to understand the tunnel lining behaviour in both cross-sectional and longitudinal direction through continuous strain profiles.

This paper briefly presents an overview of the DFOS technology adopted for the case study presented. A trial monitoring instrumentation that aims to identify the deformation mechanism of a section of CERN tunnel (TT10 tunnel) is also described. Some monitoring data results obtained for one of the fiber optic installation carried out are also analysed and discussed, providing an insight into the expected future tunnel behaviour.

2 DISTRIBUTED FIBRE OPTIC STRAIN SENSING (DFOS) MONITORING

Since the last decade, innovative distributed fiber optic sensors have been widely deployed in the civil engineering field as one of most promising tool for the structure health monitoring (Soga & Luo, 2018). It has been used for monitoring the behaviour of various infrastructures such us tunnel linings (de Battista et al., 2015; Di Murro et al., 2016; 2019; Gue et al. 2015; 2017; Mohamad et al., 2010; Soga et al., 2017) piles (Mohamad et al., 2007; Pelecanos et al., 2015; 2016; 2017; 2018) and other geotechnical structures.

The principle of the DFOS system lies in the propagation of a light signal in the optical fibers from a FO analyzer through a Brillouin scattering. Due to the fiber impurities, a small amount of the light returns to the source (i.e. the Fo analyzer) (Figure 1). The Brillouin frequency peak experienced by the fiber is shifted, which is generally linear proportional to the applied strain. Therefore, a distributed strain profile can be evaluated along the entire fiber optic cable.

The analyser employed in CERN project is a Brillouin Optical Time Domain Analysis interrogator (BOTDA), manufactured in Switzerland (Omnisens, 2013).

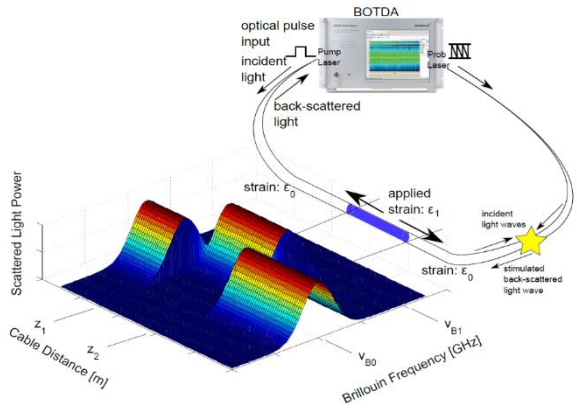

Figure 1. Distributed fibre optic sensing using BOTDA system.

3 INSTRUMENTATION OF CERN TT10 TUNNEL

3.1 Introduction

In the deep underground network at CERN, TT10 tunnel is an inclined tunnel transferring the beam particles from the Proton Synchrotron Booster (PS) to the circular accelerator ring, the Super Proton Synchrotron (SPS) at the French-Swiss border (Figure 2).

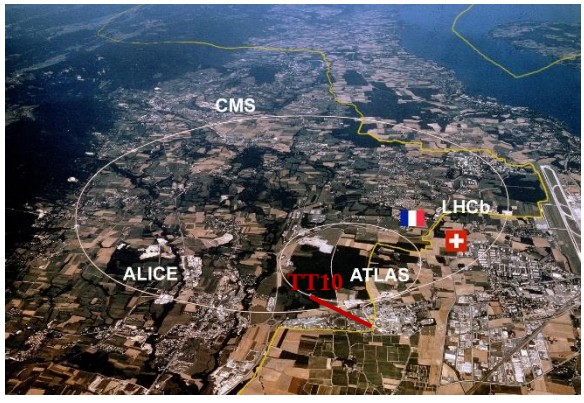

Figure 2. TT10 transfer tunnel location.

With an horseshoe shape and an internal diameter of 4.5 m, TT10 tunnel is entirely embedded in a sedimentary rock mass called the *red molasse*. It is composed of alternating layers of sandstones and marls (Fern et al., 2108; Di Murro et al., 2018).

In 2013, the development of localised cracks on TT10 tunnel lining triggered the attention of CERN surveyors and engineers, arising the concern about the structural health of the infrastructure and consequentely its safety. The cracking observed consists of heave on the tunnel floor and compression and tension cracks on the crown and shoulder respectively.

After careful consideration, distributed fibre optic strain sensors was adopted for long-term tunnel monitoring as to guarantee the stability of the infrastructure without interfereing with the regular operation of the LHC experiments. DFOS was identified as the ideal monitoring system because of its distributed nature that could reveal locations of cracks from localised strains.

3.2 Fiber optic monitoring instrumentation

The deployment of distributed fibre optic strain sensors in TT10 tunnel took place in May 2014, by installing six tunnel loops in the circumferential direction, in the most critical tunnel section affected by the majority of cracks. The optical fiber is attached to the tunnel lining by using a series of hooks and pulleys where the fiber is glued. Only the FO cross-sections of interest are pretentioned introducing a tension strain to the optical fiber using cable clamps whereas the others are loose as shown in Figure 3. Both ends of the FO cable are then brought out of the tunnel through a vertical shaft to a safe and convenient monitoring area where the BOTDA analyser is located.

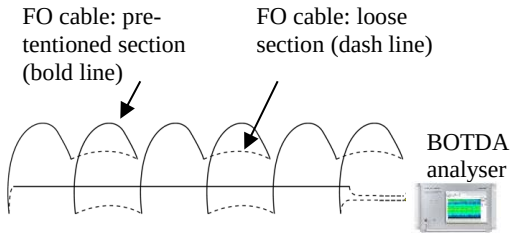

Figure 3. FO installation setup.

The optical fiber is sensitive to change in both thermal and mechanical strain, therefore conventionally two types of FO cables (temperature and strain) are required. In this study, however, only a strain fiber optic cable was installed, as isothermal conditions were considered in deep CERN tunnel underground environment. The FO cable deployed is a tight buffered single mode strain sensing cable manufactured by Suzhou Nanzee Sensing Co. Ltd in China.

3.3 FO monitoring results

As mentioned above, a shift in the Brillouin frequency peak is caused by the application of a strain. Under isothermal conditions, the change in the frequency is linearly proportional to the axial strain $\Delta\varepsilon$ applied to the optical fiber according to Eq. (1)

$$\Delta\nu = C_\varepsilon \Delta\varepsilon \quad (1)$$

Where $\Delta\nu$ (Hz) is the change in frequency, $\Delta\varepsilon$ (με) is the applied mechanical strain and C_ε is the strain coefficient, which depends on the fiber properties and a value around 493 (MHz/με) is assumed for the strain cable adopted (Kechavarzi et al. 2016).

Therefore, the frequency change at any location along the optical fiber indicates the strain development therein.

After cable installation, a baseline reading was collected in July 2014, which shows a good signal transfer and a clear trend for all the interested cross-sections (Soga et al., 2017). The accumulated strain increments were computed by taking several measurements every few months and by subtracting the dataset from the baseline reading. Table 1 shows the monitoring readings taken for the FO tunnel sections.

Table 1. Monitoring measurements: baseline and progress readings.

Monitoring Section		**Readings**
6 tunnel loops	July 2014	Baseline
	August 2014	Progress
	May 2015	
	June 2015	
	October 2015	
	March 2016	
	April 2016	
	July 2016	
	November 2016	
	February 2017	
	April 2017	
	October 2017	

Figure 4 shows the FO results in terms of the accumulated axial strain recorded for some FO loops: loop 1, loop 2, loop 3 and loop 4, with a total of 12 measurements taken within a monitoring period of three years (July 2014 – October 2017). The axial strain experienced by the instrumented sections was plotted along the optical fiber distance (Figure 4). The horizontal axis in Figure 4 represents the fiber cable distance, where the right and the left sides indicate the positive strain (e.g. tension) computed at the lateral sides of the tunnel lining, whereas the centre denotes the crown behaviour (e.g. compression).

Insignificant strain values were detected by the first reading taken after a month (July 2014 – August 2014). Tensile and compressive strains were recorded at the sides and at the crown of the

tunnel lining respectively, indicating that the tunnel tends to be deforming in a mechanism of vertical elongation shape (Di Murro et al., 2016; 2019). The tensile and compressive strain values seem not to exceed 100 με for loop 3 and loop 4, and 50 με for loop 1. Slightly larger strain values were recorded for loop 2, reaching 300 με and around 200 με at the crown and at the sides of the tunnel lining respectively.

Overall, the examined monitored loops seem to develop small values of axial strain continuously with time.

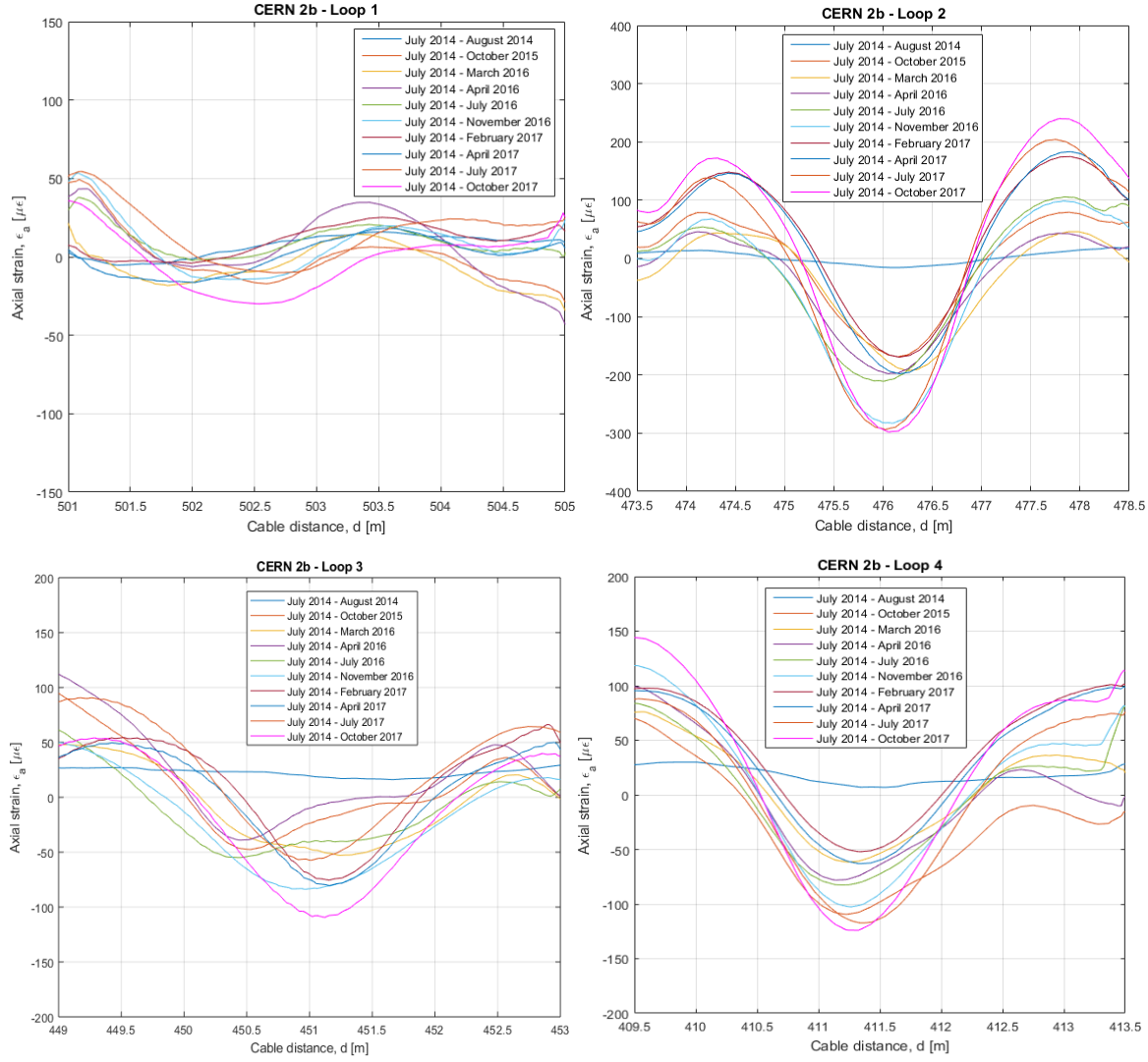

Figure 3. Fibre optic monitoring results: axial strain along cable distance for loop1, loop2, loop3, loop4.

4 CONCLUSIONS

This paper presents the instrumentation of a critical section of CERN TT10 tunnel by using distributed fibre-optic strain sensing technology for the long-term monitoring.

The use of a BOTDA system has enabled the measurement of continuous strain profiles in the circumferential direction. Six FO tunnel loops were deployed in May 2014, with a baseline reading taken in July 2014. Further measurements were recorded within a monitoring period of around three years. This is a novel monitoring, as it allows for a spatially-continuous circumferential strain profile to be obtained and thus reveal the actual tunnel mode of deformation.

The results in terms of axial strain show the development of minor axial strain with time for the presented tunnel cross-sections with peak values of 300 με. Positive tensile strains appear at the sides of tunnel lining whilst compressive strains occur at the tunnel crown. The strain distribution profile around the tunnel circumference indicates a vertical tunnel elongation mechanism with time. These preliminary monitoring results are compatible to the expected tunnel deformations usually observed in overconsolidated soils.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge the SMB-SE group at CERN for the financial support provided during the research project. The research was conducted in collaboration with University of California, Berkeley and the Centre for Smart Infrastructure and Construction (CSIC) of the University of Cambridge which is funded by EPSRC and Innovate U.K.

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