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Experience report on the use of distributed fibre optic sensing on ground anchors

Rapport d'expérience sur l'utilisation de la détection à fibre optique distribuée sur les tirants d'ancrage

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ABSTRACT: The paper presents an overview of 5 years of experience with ground anchor monitoring with fibre optic sensing. The major part of this experience was obtained in the research project Linafos, in which predicted ground anchor behaviour by numerical modelling was compared to real anchor behaviour measured by distributed fibre optic sensing. Focus of the analyses was put on understanding the load transfer mechanism between tendon, grout and surrounding ground in different soil conditions. Detailed ground anchor behaviour was captured by distributed fibre optic sensing enabling continuous measurements of axial strains over the entire anchor length with a spatial resolution of 10 mm. The fibre optic cables were installed along selected steel strands as well as embedded in the grout. Development of tension cracks of grout was identified by measured peaks along the longitudinal strain profile. Load-displacement curves and the strain distribution obtained from numerical simulations compared well with the in-situ results. The constitutive model selected for the grout was capable of reproducing the crack development in the grout and the numerical simulations suggested that in some cases local debonding between tendon and grout occurred.

RÉSUMÉ : L'article présente un aperçu de 5 ans d'expérience dans la surveillance des tirants d'ancrage avec détection à fibre optique. La majeure partie de cette expérience a été acquise dans le cadre du projet de recherche Linafos, dans lequel le comportement des tirants d'ancrage prédit par modélisation numérique a été comparé au comportement des tirants mesuré par détection distribuée à fibre optique. L'accent des analyses a été mis sur la compréhension du mécanisme de transfert de charge entre le tendon, le coulis et le sol environnant dans différentes conditions. Le comportement détaillé du tirant d'ancrage a été capturé par une détection à fibre optique distribuée permettant des mesures continues des contraintes axiales sur toute la longueur de l'ancrage avec une résolution spatiale de 10 mm. Les mesures de déformation ont été effectuées par des câbles à fibres optiques installés le long du toron d'acier ainsi que encastrés dans le coulis. Le développement de fissures de tension du coulis a été identifié par des pics mesurés le long du profil de déformation longitudinale. Les courbes charge-déplacement et la distribution des déformations obtenues à partir des simulations numériques se comparent bien aux résultats in-situ. Le modèle constitutif choisi pour le coulis était capable de reproduire le développement des fissures dans le coulis, et les simulations numériques ont suggéré que dans certains cas, il se produisait un décollement local entre le câble et le coulis.

KEYWORDS: ground anchors, distributed fibre optic sensing

1 INTRODUCTION

Although ground anchors are widely employed for soil and rock stabilization, monitoring of such structures during load tests are traditionally performed with local sensors installed at the anchor head. Therefore, the anchor behaviour along depth is rarely assessed and anchor design relies on simplified assumptions such as a constant shear stress distribution (skin friction) in the grout-ground interface. Proposals of typical ultimate shear stresses for different soil types are given for example in Ostermayer & Scheele 1978 and can be used when estimating the load carrying capacity of ground anchors.

Distributed Optical Fibre Sensors (DOFS) provide sensing points along the entire fibre length, thus enabling measurements in a truly distributed way. They are based on different backscattering phenomena in the optical fibre. Systems based on Brillouin backscattering have been used for monitoring of geotechnical structures over more than 15 years (e.g., Iten et al. 2008, Mohamad et al. 2011). They allow long distance distributed sensing with a spatial resolution of about 1 m. However, due to the small scattering effects, integration and thus measuring times of at least several minutes are needed. These drawbacks were overcome about 10 years ago, by sensing systems based on Rayleigh scattering, which is much stronger compared to Brillouin scattering. Thus systems based on optical backscatter reflectometry (OBR) can reach millimetre scale with scan rates of a few seconds, together with a better measuring precision, but then sensing length is often limited to less than 100 m (Barrias et al. 2016).

If the fibre optic sensors are applied for monitoring of anchor pullout tests, the detailed strain profile along the anchor length is a valuable information for understanding the load transfer behaviour of the system. The fibre optic sensors can be used for strain measurements along the steel tendon and along the grouted section.

For the case where strains are monitored along the tendon, the strain profile can be easily employed to calculate the load acting at the free and at the fixed length or integrated to obtain the displacements along depth. On the other hand, if measurements are performed along the grout, cracking during the pullout test can be evaluated and, if the grout is not cracked, displacements can be calculated in a straightforward manner.

This paper presents an overview of all performed ground anchor pullout test we have performed within the last years, with fibre optic cables installed along the steel strands and embedded into the grout. Very high spatial resolution measurements were obtained by recording strains at approximately every 10 mm using the OBR technique. Additionally, traditional monitoring at the anchor head was performed.

2 INSTRUMENTATION OF ANCHORS

In civil engineering, applications in harsh environments are prevalent. Therefore, robust sensing cables are needed to protect the fragile optical fibre during installation, but also to allow the proper embedment into the structure of interest. Furthermore, the sensing cables should have acceptable properties for the strain transfer from the structure to the optical fibre. Based on positive experiences in geotechnical applications, e.g. Iten 2011 and Lienhart et al. 2014, and on own investigations, sensing cables from Solifos, Switzerland (formerly Brugg Cables), were used.

The strands are equipped with a 0.9 mm thick fibre optic sensing cable type FiMT (Fig. 1a), which is used because of the limited space between the individual wires of a tendon. In order to protect the sensing cable, it was glued along two separate wires using special epoxy, following the torsion of the wires (Fig. 2). The increased length due to the torsion must be considered during data analysis. Strand instrumentation is typically performed during anchor assembly in the anchor assembly plant.

For the embedment into the grout, the more robust cables BRUsens Strain V9 (Fig. 1b) and BRUsens Strain V3 (Fig. 1c) are used. The V9 and the V3 cables have an outer diameter of 3.2 mm and 7.2 mm, respectively. Both have a structured surface at the outside, which provides good bonding with the grout. The cables are attached outside of the corrugated plastic sheath using an adhesive tape and are conducted in loops during the anchor installation into a borehole. Due to this redundancy, the robustness of the measuring system was increased and thus measurements may be even continued in the case of one single fibre breakage.

Because of the short duration of the tests, which is approximately less than a day, and due to the essentially constant ground temperature few meters below the ground surface, a separate cable for temperature compensation has not been used. Fig. 2 shows the installation of cables for the tendon and the grout measurements. In addition to the fibre optic system, the displacements at the anchor head are automatically monitored with a linear transducer in all tests. This allows for a cross checking of results as anchor head displacements may be obtained from strain measurements by integration along the entire anchor length.

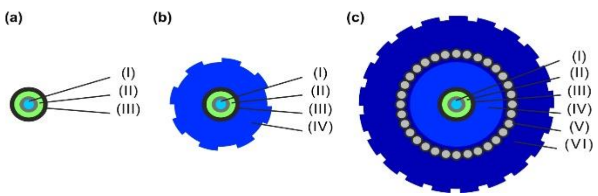
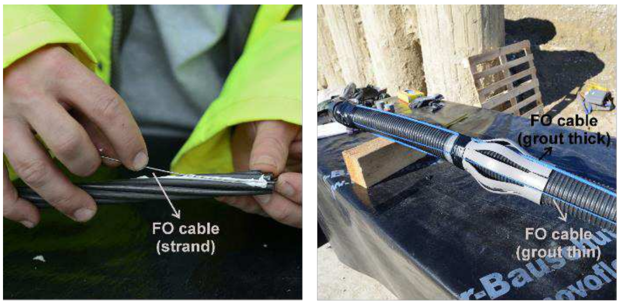


Figure 1. Structure of different strain sensing cables from Solifos GmbH - a) type FiMT; b) type V9 and c) type V3. (I) strain sensing single mode fibre (Ø250 µm), (II) multi-layer buffer with strain transfer layer, (III) metal tube, (IV) polyimide protection layer, (V) special steel armouring and (VI) polyimide outer sheath



a) b)

Figure 2. Installation of the fibre optic cables – a) type FiMT for the tendon measurements and b) types V9 and V3 for the grout measurements

Fig. 3. shows the general scheme of a ground anchor with terminology being used in the paper. Fig. 4 shows, exemplarily for a 6 strand anchor, cross-sections at the free and the fixed length, including the position of the fibre optic sensing cables, denoted "FO cable V3" and "FO cable V9" for the cables situated in the grouted body and "FO cable FiMT" for the cables along the tendon. In Fig. 4, in the free length cross-section, the debonding sleeves covering the strands are depicted.

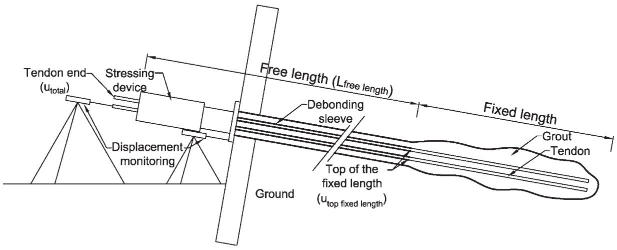


Figure 3. Schematic presentation of a ground anchor with free and fixed length (Fabris 2020)

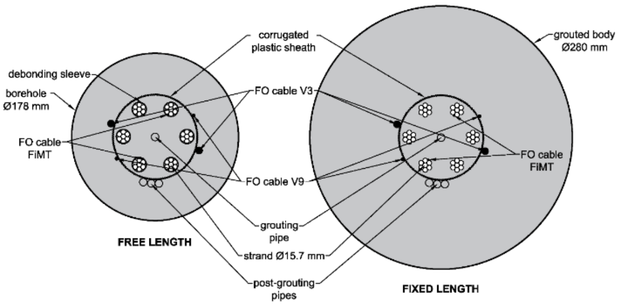


Figure 4. Anchor cross-sections at the free and fixed lengths

An Optical Backscattered Reflectometer (OBR) was used which is capable to record sensing information with a very high precision of about ± 1 µm/m for strain measurements (Luna 2014). The reading unit of the distributed fibre optic system emits laser light into a passive optical sensing fibre and analyses the backscattered light which is generated along the sensing fibre due to Rayleigh backscattering. Measurements are carried out continuously along the fibre and show a typical spatial resolution of 10 mm, depending on the quality of the signal. One single optical fibre is used for both, sensing and signal transmission. Results on the calibration of the measuring system are shown in Woschitz et al. 2016.

3 CASE STUDIES

Since year 2015 Distributed Fibre Optic Sensing on ground anchors was performed on multiple projects and in different soil conditions:

Table 1. Overview of projects and ground anchor parameter where DFOS was used:

Year	Location	Anchor length free+fixed length	Max. test load	Soil type
2015	Söding, Austria	12+8 m	2500 kN	sandy silt (OC)*
2016	Aliağa, Turkey	13+12 m	3700 kN	claystone
2017	St. Kanzian, Austria	12+8 m	1200 kN	silt (NC)*
2018	A10 Highway, Austria	15+10 m	1495 kN	claystone
2019	Ljubljana, Slovenia	6+6 m	1700 kN	silty gravel, dense
2021	Bratislava, Slovakia	30+20 m	4200 kN	highly weathered granite

* OC – overconsolidated, NC – normally consolidated

The measurements were successfully performed for 6 different projects on 10 ground anchors. It was proved that the monitoring system is very robust as it was possible to measure on all instrumented anchors during the whole anchor testing procedure.

Measurement time lag is less than 2 minutes, so the axial strains in the ground anchor along the entire anchor length can be observed during anchor testing on site. With this insight it is possible to predict how the ground anchor will perform in the next loading steps allowing an estimation of the ultimate capacity of an anchor before actually reaching it.

In the following part several case studies are presented in more detail.

3.1 *Söding, Austria*

This very first anchor load test monitored with DFOS was performed on vertical ground anchor with fixed length located in overconsolidated sandy silts and silty sands. The most important anchor parameters are:

- free length 12 m, fixed length 8 m
- cased drilling – bore hole outer diameter: 178 mm,
- grout: W/C ratio = 0.5; Cement type CEM II/A-S 42.5
- average USC of Grout after 28 days: 32.12 MPa
- Strands: 11 Pcs.; ϕ15.7 mm Y1870 S7; Steel cross section of a tendon $A_{st} = 150$ mm²

For more details please refer to Racansky et al. 2016. The instrumentation scheme of sensing cables is given in Fig. 5. The same scheme was kept on all reported projects.

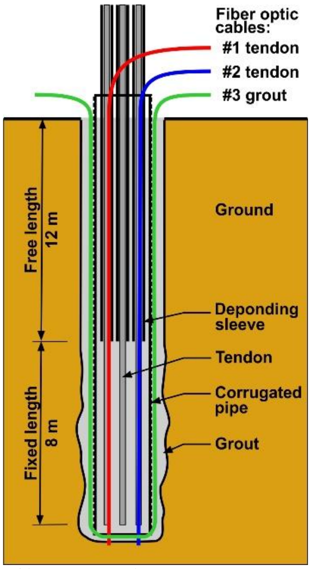


Figure 5: Scheme of instrumentation.

Measured strains (Fig. 6) along the tendon confirm expectations. Strains are more or less constant in the free length and are reducing in the fixed length as the anchor force is transferred into the subsoil. Larger strain oscillations in the free length are caused by insufficient fixation of the fibre in the anchor free length. After this first proof-of-concept anchor the fixation technology was improved.

Highly nonlinear strain reduction can be observed in the fixed length. The slope of the tendon strain curve is indicating the rate of load transfer at the steel/grout interface. A steeper slope indicates higher load transfer from the steel tendon to the grout body. The kink at position -5.6 m in tendon strain indicates an abrupt change of load transfer. From a core drilling which was executed at the test anchor location afterwards, a layer with higher sand content was identified at this depth which caused much higher load transfer from that position (-5.6 m) towards the anchor end. Failure at the grout/ground interface was reached.

Looking at the grout strain curve, tension strains (positive values) can be observed in the fixed length, whereas in the free length, compressive strains are measured. This means that the grout in the fixed length is pushing onto the grout in the free length. Compression stresses are reducing with increasing distance from the transition between free and fix length, but are noticeable as far as 6 m away from the transition point. It can be clearly seen that grout in the free length of an anchor contributes to the anchor bearing capacity. The length of the grout compression zone depends on soil stiffness and is much more pronounced in soft soils compared to stiff soils.

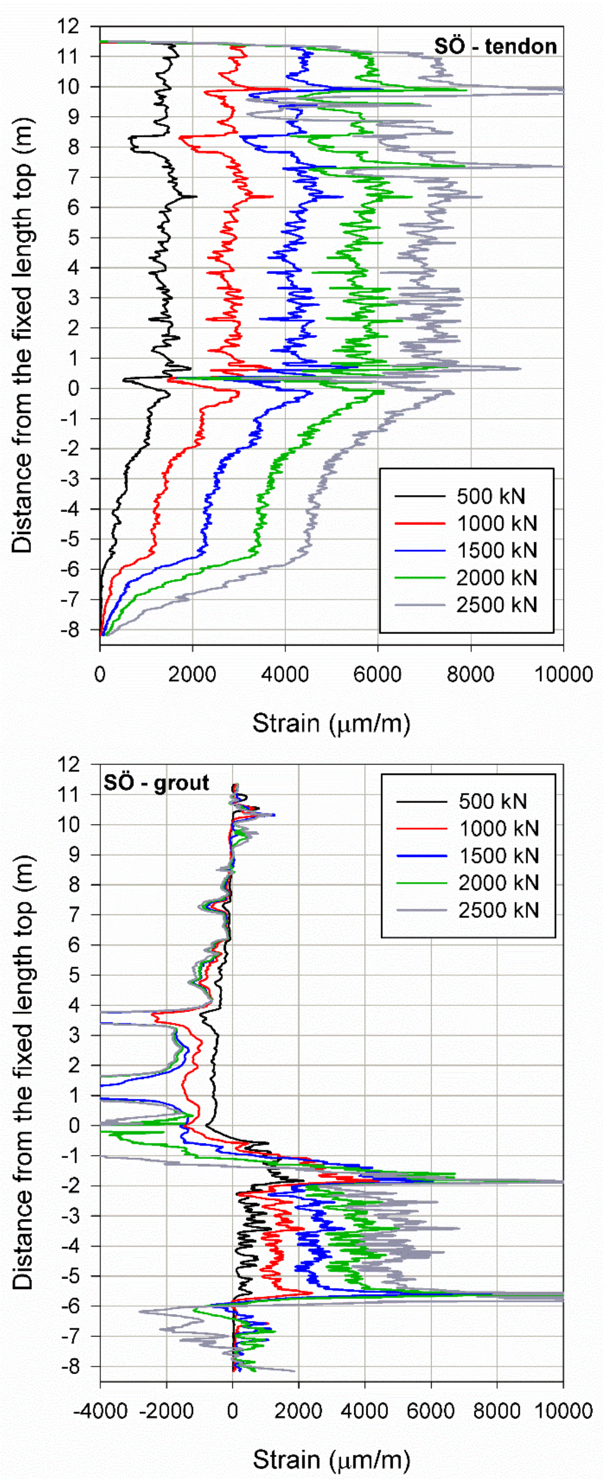


Figure 6. Söding – Measured strains along the tendon and the grout (positive values = tension, negative values = compression)

3.2 *St.Kanzian, Austria*

Within this project, 3 test anchors were equipped with DFOS but only one will be presented here in more detail as all anchors showed similar results. A vertically aligned test anchor was located in normal consolidated clayey, sandy silt locally known as “Seeton”. The grain size distribution is approx. 15-30% clay, 60-70% silt and 10-15% sand. Most important anchor parameters were:

- free length 12 m, fixed length 8 m
- cased drilling – bore hole outer diameter: 178 mm,
- grout body diameter in fixed length: 250 mm due to postgrouting
- grout: W/C ratio = 0.5
- Strands: 6 Pcs.; ϕ15.7mm Y1870 S7; Steel cross section of a tendon A_{st} = 150 mm²

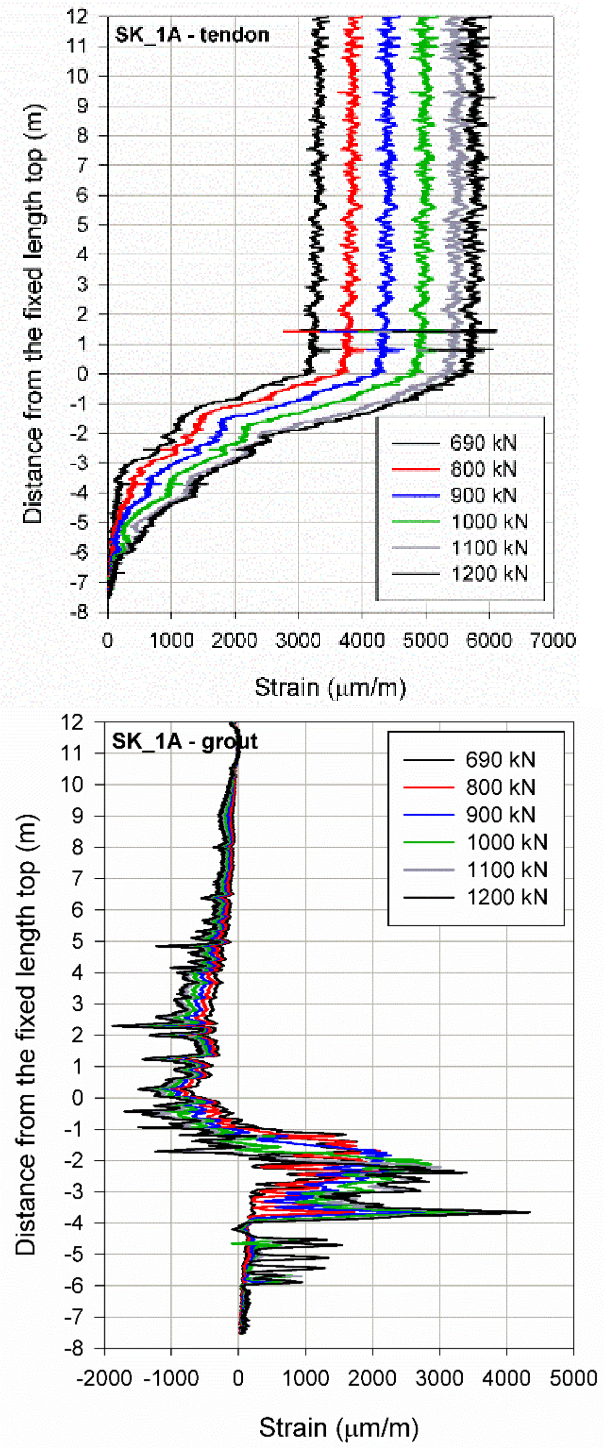


Figure 7. St. Kanzian – Measured strains along the tendon and the grout (positive values = tension, negative values = compression)

Measurements at this anchor confirmed the behaviour which was observed in the first test in Söding. The technology for fixation of fibre cable to the tendon was improved in the anchor free length and therefore the tendon strain oscillations are much smaller compared to the Söding test. Reduction of the tendon strains in the fixed length are much more homogeneous which means that soil conditions are more homogeneous in this location. Tendon strains are activated on the entire fixed length and the failure of the anchor was reached at the grout/ground interface (Fig. 7).

Compression stresses in the grout in the anchor free length are even more pronounced compared to the previous case and are detectable nearly along the entire anchor free length. This is due to the fact that soil stiffness of normal consolidated soils is much smaller than the soil stiffness of overconsolidated soils as presented in the previous example. This behaviour is confirmed by means of numerical simulations, see Fabris et. al 2021 for further details.

Numerical back calculations of the tested anchor revealed that the grout in the free length may increase the anchor capacity up to 25 % if the free length is grouted (Fabris 2020).

Looking at the grout strain profile in the fixed length more closely, tension cracking of the grout may be identified during the measurement. Fig. 8 shows tension cracks in the anchor fixed length at a load level of 485 kN. Further research is necessary to answer the question whether DFOS is capable of measuring proper crack width in the grout body. Such measurement could be of interest to the geotechnical community, as the grout has not only load transfer function but a corrosion protection function as well.

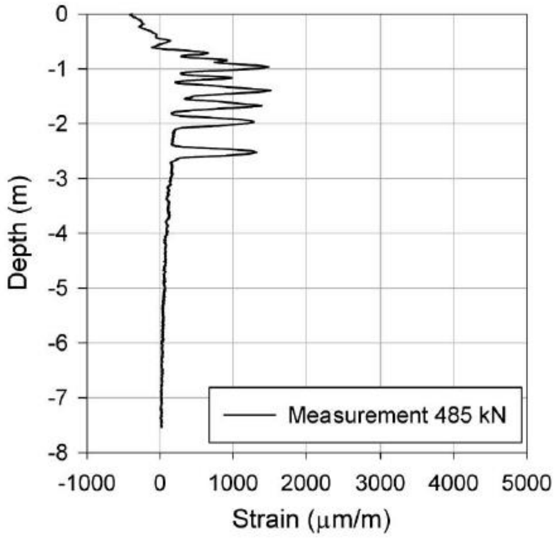


Figure 8. Measured strains along the grout in the anchor fixed length. Spikes identify existence of tension cracks in the grout.

3.3 *A10 Highway, Austria*

The tested anchor in this project was a system anchor and part of the permanent retaining structure. Therefore a "suitability test" according to EN ISO 22477-5:2019 was performed without reaching the ultimate bearing capacity of the anchor. The fixed length of a sub-horizontally aligned anchor with 10° inclination was located in fragmented claystone (RQD 50-75%). Most important anchor parameters were:

- free length 15 m, fixed length 10 m
- cased drilling - outer diameter (free length): 178 mm
- non-cased drilling (fixed length): 150 mm
- grout: W/C ratio = 0.5
- Strands: 8 Pcs.; ϕ15.7mm Y1870 S7; Steel cross section of a tendon A_{st} = 150 mm²

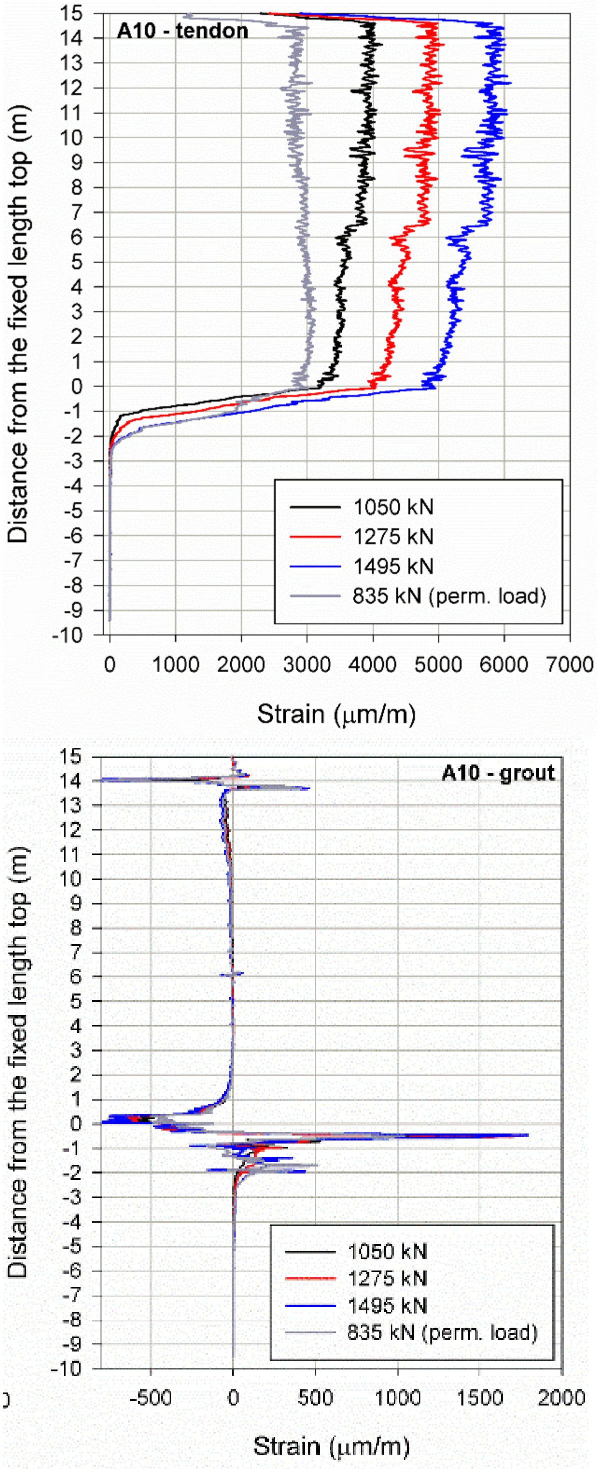


Figure 9. A10 Highway – Measured strains along the tendon and the grout (positive values = tension, negative values = compression)

The stiffness of the ground (rock) in this case study is substantially higher than stiffness in previous two case studies. This has several consequences on the anchor behaviour. One can observe pronounced friction loss in the anchor free length when looking on tendon strain curve. This friction loss amounts up to 15% and is very high compared to the previous cases. A similar high friction loss was observed on another project where the monitored anchor was also located in rock. This suggest that high stiffens of the ground is increasing friction loss in the anchor free length, but this hypothesis is not proved yet.

In the anchor fixed length a very high load transfer can be observed as can be seen from the inclination of the strain curve.

At the proof load of 1495 kN only 2.5 m of the fixed length are activated. Therefore this anchor has a high safety margin with respect to ultimate bearing capacity. Optimisation of required anchor fixed length is easily possible when such measurements are available.

The grout strain curve is qualitatively showing the same behaviour as in the previous cases, i.e. compression strains ahead of the fixed length and tension strains in the fixed length. However, due to much higher ground stiffness the part of the grouted section influenced by the load transfer is very short, only around 4.5 m (Fig. 9).

After successful finishing the anchor suitability test, the anchor corrosion protection (anchor head) was done in a way that fibre cables can be accessed at any moment. This allows for an execution of long term monitoring as repeated measurements are possible. Additionally, a Brillouin based system is used for repeated measurements, for the case that the relative measuring OBR instrument needs to be replaced. Although the spatial resolution (about 0.5 m) and measuring precision (about 20 µm/m) is less than the one of the OBR system, it is still much better, compared to more traditional methods such as strain gauges, or similar. Long-time monitoring with DFOS is very attractive as grout strain measurements can be used in similar way as sliding deformeter measurements. Therefore, even minor occurrences of slope instabilities can be detected in grout strain profile in case that monitored anchor is crossing a potential sliding surface.

4 CONCLUSIONS

Distributed Fibre Optic Sensing was successfully performed on various anchoring projects within the last 5 years. It proofed to be a very robust system which allows to perform strain measurements along the anchor with 10 mm resolution.

A typical ground anchor consists of a tendon and the grout. These elements behave differently and therefore both elements must be monitored in order to understand the mechanical behaviour of the anchor.

The tendon strain curve clearly shows some friction loss in the free length and the load transfer in the fixed length. The safety margin of the anchor can be assessed when comparing the activated fixed length with the total fixed length. This can be used for anchor length optimisation.

The grout strain curve can be used to identify tension cracks in the fixed length. In addition it helps to assess which part of the anchor load is being transferred into anchor free length in case that the anchor is grouted along the entire length. Grout strain curve can be used for an identification of possible slip surfaces (slope instabilities) if used in long time measurements. Installed instrumentation with fibre optic cables can be conveniently used for long time monitoring of anchors.

5 ACKNOWLEDGEMENTS

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