INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Advanced monitoring techniques for a wide range of geotechnical applications

Techniques de monitoring avancées pour un large domaine d'applications géotechniques

Noël Huybrechts
Geotechnical Division, Belgian Building Research Institute (BBRI) & University of Leuven, Belgium, nh@bbri.be

Gust Van Lysebetten, Monika De Vos
Geotechnical division, Belgian Building Research Institute (BBRI), Belgium

ABSTRACT: Design of geotechnical structures by preliminary testing and/or based on the observational method are cost-effective methods to optimize design, accepted by Eurocode 7. However, reliable measurement techniques are indispensable when applying these design methods. Classical sensing techniques, e.g. electrical or vibrating wire strain gauges, thermocouples and PT100 sensors, are widely used for local measurements and have proven their high accuracy and reliability. Nowadays, new measurement techniques based on optical fibre technology offer a huge potential for accurate strain and temperature sensing with compact sensors and cables and thus limited impact on the structure. This paper briefly presents the available different optical fibre sensing techniques and illustrates the implementation of Fibre Bragg Grating (FBG) optical strain sensors to measure deformations in a wide range of geotechnical applications. An overview of the obtained experiences and points of particular attention are given. Besides that, the potential of the Raman principle based technique, allowing continuous high resolution temperature measurements, is assessed and illustrated.

RÉSUMÉ : Le dimensionnement des structures géotechniques sur base d'essais préliminaires et/ou de la méthode observationnelle sont des méthodes rentables et conformes à l'Eurocode 7 permettant une optimisation du dimensionnement. Cependant, l'utilisation de techniques de mesure fiables est indispensable lorsque l'on a recours à ces méthodes. Les techniques de mesure classiques, telles que les jauges de déformation électriques ou à corde vibrante, les thermocouples, les capteurs PT100, sont largement utilisés et ont prouvé leur grande précision et efficacité. Actuellement, de nouvelles techniques de mesure basées sur la technologie de la fibre optique offrent un énorme potentiel en termes de mesure de déformation et de température et ce, au moyen de capteurs et de câbles compacts ayant un impact limité sur la structure. Cet article présente les différentes techniques de mesure par fibre optique disponibles et illustre l'implémentation des capteurs FBG (Fibre Bragg Grating) pour la mesure des déformations pour une large gamme d'applications géotechniques. Un aperçu d'expériences et de points d'attention est donné au lecteur. Finalement, le potentiel de la technique basée sur le principe de Raman, permettant des mesures de température en continu et en haute résolution, est illustré.

KEYWORDS: Fibre Bragg Grating, FBG, strain and temperature sensing, observational method, monitoring, geotechnics

1 INTRODUCTION

During the past few years design of geotechnical structures by preliminary testing and/or based on the observational method has been increasingly applied. Such approach is accepted by Eurocode 7 and allows a more cost-effective and optimized design.

By preliminary testing soil resistance parameters can be defined more accurately and the applied safety factors might be reduced. In this way e.g. foundation pile design can be optimized by performing preceding static pile load tests. An important condition is that the construction works allow to perform and analyse these tests in order to apply the results in the final design.

A reduction of the safety factors for the soil resistance parameters can also be considered when the designer imposes the observational method, which requires a (continuous) monitoring campaign of the relevant acting deformations, forces and/or displacements during the execution of the works and the implementation of a contingency plan in the case that the measured parameters exceed the limits that have been set out (Patel et al. 2007). Of course, this innovative method of designing requires a very good communication between the interacting parties, such as contractor, designer and monitoring team.

In the framework of the evolution towards the (extensive) monitoring of geotechnical structures innovative measurement techniques have become very important. Classical measurement techniques for strain sensing (e.g. electrical or vibrating wire strain gauges) and temperature sensing (e.g. thermocouples and PT100 sensors) are widely used and have proven their accuracy and reliability. However, when these classical sensors are applied in extensive monitoring campaigns, cable handling becomes more complicated, increasing the risk of sensor damage, and readout units quickly reach their limits, as they have no unlimited number of channels. On the contrary, fibre optic measurement techniques offer the advantage of extensive strain and temperature sensing with only limited cabling. During the last decade, these new techniques have been increasingly used. On the one hand, their performance in terms of e.g. accuracy and spatial resolution is still increasing, approaching the accuracies of classical measurement techniques. On the other hand, advances in cable types has made the optical fibre sensors more robust and applicable in almost all cases.

This article presents the latest experiences of the Belgian Building Research Institute (BBRI) with optical fibre sensing. A brief overview of the existing sensing techniques is given and some practical examples of FBG and Raman based sensing are presented. Finally, some future perspectives are presented.

2 OPTICAL FIBRE SENSING: BRIEF OVERVIEW

2.1 Multi-point sensing techniques

One way to classify all different optical fibre sensing techniques is by the position on the fibre where the parameters are sensed. The first type measures strain and temperature at well-defined positions on the fibre (so-called Fibre Bragg Gratings or FBG).

A Bragg grating reflects incident light at a specific wavelength, depending linearly on strain and temperature at that position. A multi-point sensing fibre is obtained by putting multiple FBG sensors at the desired positions on one and the same fibre, all reflecting light at their own specific Bragg wavelength (Huybrechts et al. 2016). The spacing of the Bragg wavelengths of different sensors should be sufficiently large to avoid interference between difference sensors, which limits the number of FBG sensors that can be put on one single fibre. Typically, up to 20 FBG sensors can be integrated on one fibre. However, new readout units tend to have a broader measurement range, allowing a higher number of sensors. Only one fibre extremity is necessary to perform the measurements. Accuracies of 1 µstrain and 0.1 °C can be obtained and sampling rates of 4 kHz and more are possible.

2.2 *Distributed sensing techniques*

The second group of optical fibre sensing technologies are distributed sensing techniques. This means that the whole fibre length acts as a strain and/or temperature sensor. The measurement principle is based on light scattering phenomena in the optical fibre. The scattering is composed of Brillouin, Rayleigh and Raman scattering processes, which linearly depend on strain and temperature (except Raman scattering which only depends on temperature). For a more detailed description of the working principle of the different processes reference is made to specialized literature (Zou et al. 2015, Huybrechts et al. 2016).

Brillouin scattering allows strain and temperature sensing for distances up to 50 km. Dual-ended (or a fibre loop) configuration tend to result in higher accuracy (recently up to 2 µstrain and 0.1 °C for BOTDA with measurement times of 5 to 10 minutes). Single-ended measurements are possible as well (BOTDR) with decreased accuracy (e.g. 20 µstrain and 1°C). More recently, BOFDA technology provides higher accuracies at lower measurement time (e.g. up to 2 µstrain and 0.1 °C for 2 to 3 minutes). Typically, spatial accuracy (i.e. sampling spacing) and spatial resolution (i.e. the distance on the fibre along which the measurement is done) start from 0.5 to 1.0 m.

Rayleigh scattering also allows the determination of strain and temperature along the fibre, but the total length is limited to 80 m and recently up to 1 to 2 km. Single-ended measurements with high accuracy (e.g. 2 µstrain and 0.1 °C) and high spatial accuracy and resolution (e.g. 10 mm) at relatively high sampling rate (more than 1 Hz) are possible with this technique.

Finally, Raman scattering is not influenced by strain variations and thus only depends on temperature. Measurement ranges up to 10 – 15 km are common. Best accuracy is obtained with a dual-ended configuration (up to 0.1 °C for 1.0 m spatial accuracy and resolution). However, single-ended measurements are also possible.

Note that the measurement accuracy of the different techniques highly depends on the applied spatial accuracy, spatial resolution and measurement time and the fibre length. That is why one should be careful when comparing different distributed sensing techniques. Another remark is that all discussed fibre sensing techniques use single mode fibres (SMF), except from the Raman scattering technology which uses multimode fibres (MMF).

2.3 *Optical fibre integration in the geotechnical structure*

In fact, an optical fibre is a very small diameter wire, consisting of a core and cladding made of glass with a diameter of respectively 9 and 125 µm for SMF and 50 to 62.5 and 125 µm for MMF. The glass strand is strengthened and protected by coating and buffer layers.

2.3.1 *Temperature or strain sensing*

For strain sensing, it is important that the coating and buffer layers allow the deformation transfer of the monitored structure to the sensing part of the fibre. Conversely, for temperature sensing applications, the sensing part of the fibre should behave free from its support to be subject to temperature variations only. In practice, it is a big challenge to find a good equilibrium between accurate sensing and robust fibres, applicable in often harsh environments.

2.3.2 *Instrumentation after or prior to installation of the geotechnical element*

In order to limit the risk of damaging the sensors, it is often preferred to integrate the sensing fibres into steel reservation tubes after installation of the geotechnical structure (see Figure 1a). These tubes need to be connected to the geotechnical structure, e.g. by welding them prior to installation to the reinforcement cage, the sheet pile, etc. After insertion of the sensor array, the reservation tube is filled with a grouting type of material, which is engineered to assure a good transfer of the deformations to the sensors through the grout.

Alternatively, the sensors can be attached to the geotechnical element prior to its installation, mostly by gluing them with an appropriate adhesive to the geotechnical structure (on a steel beam, reinforcement bar, tendon, etc.). Different measures can be taken to protect the sensors during installation of the instrumented element, dependent on the installation technique and forces that have to be resisted. For some applications, the optical fibre can be embedded in a narrow incision in the steel element (e.g. 1.5 to 2 mm², see Figure 1b) and protected over the entire length with a (shock adsorbing) adhesive. Additionally or alternatively, a steel protection profile might be welded or glued on the steel element over the entire length of the fibre (e.g. Figure 6b).

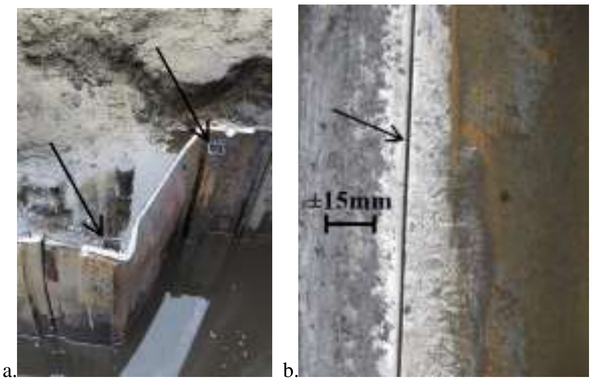

Figure 1. (a) Steel reservation tubes welded on a sheet pile prior to its installation. (b) Narrow incision in a sheet pile in which the FBG sensor array is embedded.

2.3.3 *Local or extensometer measurement configuration*

FBG sensors can be used as local sensors by gluing the optical fibre at the position of the Bragg gratings. However, in many geotechnical applications an extensometer configuration of the sensors is more appropriate, e.g. to average local stress concentrations. This configuration is obtained by gluing the optical fibre at both sides of the FBG sensor, leaving the sensing part free to move over the desired measurement base.

3 EXPERIENCES WITH FBG SENSING

3.1 *Deformations and bending moments of a sheet pile wall*

Within the framework of large road infrastructure works around Antwerp (Belgium), a fully monitored trial pit was excavated (De Nijs et al. 2015). The 20 x 20 m² excavation had a final depth of 25 m (Figure 2). Soil and groundwater were retained by means of 30 m long sheet piles and 5 strut levels. BBRI was in charge of the continuous monitoring of the strut forces, the deformations of the sheet pile wall and the swelling of the

Boom clay with a 25 m long vertical extensometer with FBG sensors each 2.5 m. The monitoring lasted for more than 15 months and was very successful.

Figure 3a shows the deformations measured by 2 FBG arrays with each 27 sensors (O1 and O2), which were installed and grouted in 2 steel reservation tubes after sheet pile driving (Figure 1a). The measurements are shown at the moment the test pit reached its final depth. As both sensor arrays are symmetrical with respect to the neutral axis of the sheet pile, resulting bending moments can be derived (Figure 3b). The fact that the effect of the 2 deepest struts is not clearly visible in the bending moment might be explained by the soft filling between the sheet pile wall and the struts, allowing an important horizontal displacement before activating these struts.

Figure 2. Picture of the trial pit in Antwerp (Belgium).

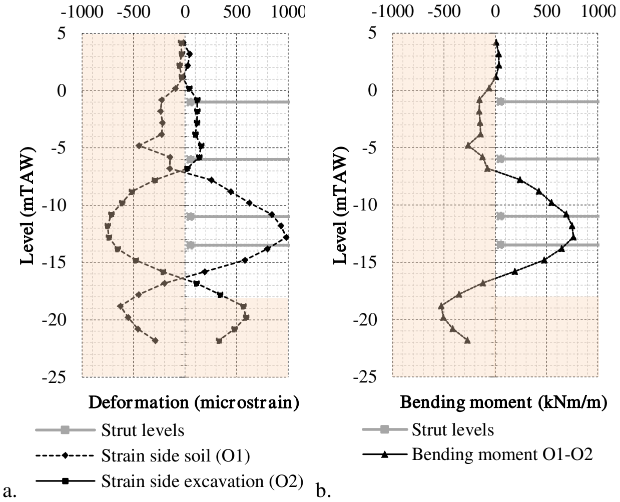

Figure 3. (a) Deformations from 2 FBG arrays O1 and O2 grouted in a reservation tube after installation of a sheet pile. (b) Bending moments calculated from the deformations O1 and O2.

3.2 Deformations of a ground anchor

Deformation measurements of grouted anchors, of which the reinforcement exists out of pre-stressed steel strands is very difficult with classical measurement devices. BBRI has conducted tests with robust 1 mm diameter glass fibre reinforced polymer (GFRP) optical fibres glued directly to the strands prior to their installation (see Figure 4). The results of the deformation measurements at 19 FBG positions along the strand of a 39 m long grouted anchor during the different steps of a load test are illustrated in Figure 5.

From this test it can be concluded that the correspondence between the measured and the expected (calculated) strains is very good. The transition zone between the tendon free length and the bonded length, where deformations decrease quickly due to the mobilisation of the soil resistance, can also clearly be identified on the illustrated measurements in Figure 5.

Figure 4. Pre-stressed steel strand instrumented with a GFRP optical fibre with 19 FBG sensors.

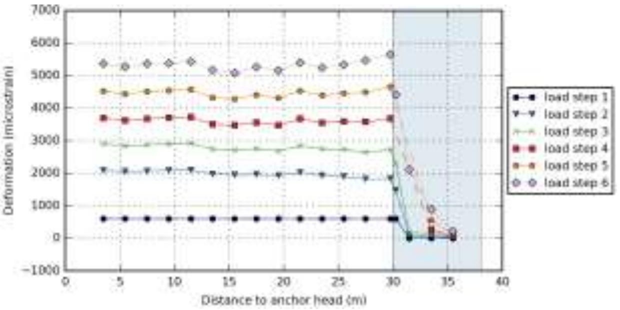

Figure 5. Deformation along the ground anchor at different steps of the load test. The bonded length is indicated by the shaded zone.

3.3 Deformations of a MV pile

A second example where FBG sensors embedded in GFRP optical fibres were used is illustrated in Figure 6. It concerns MV piles with lengths up to 53 m, which were instrumented over their entire length with FBG sensors prior to installation. The MV piles consisted of steel HEB600 beams and were driven into the soil with an inclination of approximately 45° (Figures 6a and b). Despite the heavy pile-driving in very dense sand layers, satisfying results were obtained during static tensile load tests up to 10 000 kN.

The measured deformations during one of these tests are illustrated in Figure 7. This example shows that optical fibres that have been installed with appropriate adhesives and protection can survive hard driving work. It also shows the advantages and added value of multi-point sensing for the interpretation of this kind of load tests.

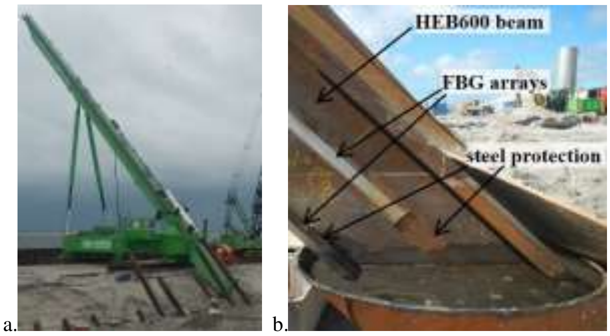

Figure 6. (a) MV pile driving. (b) Installed MV pile with indication of the FBG arrays and their steel protection.

4 EXPERIENCES WITH RAMAN BASED SENSING

In Figure 8a an undisturbed soil temperature profile measured with the Raman scattering technique in a 120 m deep geothermal borehole in Limelette (Belgium) is shown. The first 10 m is clearly influenced by seasonal temperature variations. Starting from 40 m depth soil temperature increases with depth due to the geothermal flux. Above 40 m depth the soil temperature profile is probably disturbed by thermal losses through the foundation slab of nearby buildings during decades.

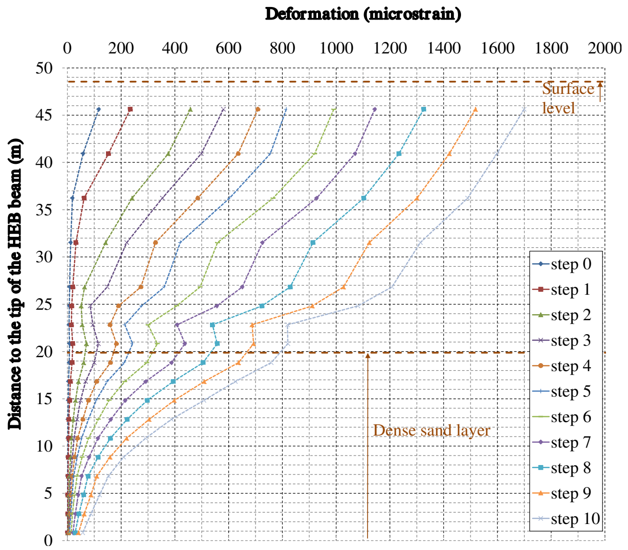

Figure 7. Deformations of a MV pile measured by FBG sensors for different tensile loading steps.

The optical fibre that measured the temperature profile of Figure 8a is actually part of a "hybrid cable". Apart from one or more optical fibres, this hybrid cable also contains a number of copper heating wires (Figure 9) and is used to perform Enhanced Thermal Response Tests (ETRT). An ETRT allows the determination of the soil thermal conductivity along the borehole length. During the test a user-defined amount of energy is dissipated into the soil by electrically heating the copper cable. The temperature evolution along the optical fibre is continuously monitored during the heating and relaxation phase. According to the infinite line source theory, the slope of the temperature evolution in function of the logarithmic time is inversely proportional to the thermal conductivity (Carslaw and Jaeger 1959). An example of the results of the ETRT performed on the 120 m deep borehole is given in Figure 8b. For example, the ground water level in the upper sand layer can be easily distinguished by the increasing conductivity of the saturated sand. The ETRT was performed in the framework of Smart Geotherm, a project subsidized by Flanders Innovation & Entrepreneurship (VLAIO, former IWT).

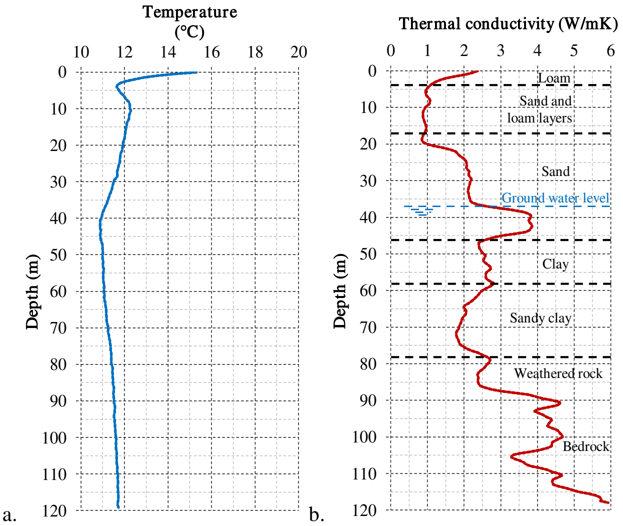

Figure 8. (a) Undisturbed soil temperature profile measured in a 120 m deep borehole with Raman based sensing. (b) Thermal conductivity profile resulting from an Enhanced Thermal Response Test.

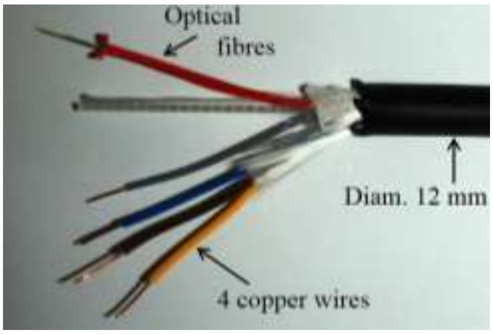

Figure 9. Picture of a hybrid cable consisting of optical fibres, copper wires, some rigidizing elements and an external protective coating.

5 CONCLUSION

During the past 10 years BBRI gathered a lot of experience with respect to FBG sensing in a broad range of geotechnical applications. The main advantages of the technique are the accurate strain and temperature sensing performance, the multi-point sensing possibilities with up to 20 sensors or more on one optical fibre line, the high sampling rates and the relatively low cost of the readout units, even with multiple channels.

However, distributed sensing technology keeps improving its performance in terms of measurement accuracy and spatial accuracy and resolution with always lower measurement times. The relatively low cost of the sensing fibre and the fact that fibres do not have to be manufactured on demand but can be cut from a coil on the desired length make those techniques in particular interesting for geotechnical monitoring and offer a cost-effective alternative for FBG sensing in the case that high sampling rates are not required.

The main challenge for both FBG and distributed techniques remains the temperature compensation of the strain measurements in a more 'customer-friendly' way. Recently, hybrid optical sensing cables combining both a strain and temperature sensing fibre in one single cable appeared on the market. This would allow for direct temperature compensation and seems in the author's opinion very promising for the future.

Finally, an example where the distributed Raman scattering technique in the context of geothermal ETRT-testing was shown. This technique has the advantage that it is only susceptible to temperature variations. Moreover the use of hybrid cables, which make it possible to inject heat into the instrumented element and at the same time to measure locally the temperature dissipation, seem very promising for other geotechnical applications (e.g. leak detection and thermal integrity testing).

6 REFERENCES

Carslaw H.S. and Jaeger J.C. 1959. *Conduction of heat in solids.* Oxford University Press, Oxford, 510p.

De Nijs R., Kaalberg F., Osselaar G., Couck J. and Van Royen K. 2015. Geotechnical monitoring of a trial pit excavation toward the Boom clay in Antwerp (Belgium). *Proceedings of the 5th ISGSR*, Rotterdam, Netherlands, 13-16 October 2015, 577-582.

Huybrechts N., De Vos M. and Van Lysebetten G. 2016. Advances and innovations in measurement techniques and quality controls tools. *Proceedings of the ISSMGE – ETC 3 International Symposium on Design of Piles in Europe*, Leuven, Belgium, 28-29 April 2016, Vol. 1, 209-233.

Patel D., Nicholson D., Huybrechts N. and Maertens J. 2007. The Observational method in geotechnics. *Proceedings of the 14th ECSMGE*, Madrid, 24-27 September 2007, Vol. 2, 365-370.

Zou W., Long X. and Chen J. 2015. Brillouin scattering in optical fibres and its application to distributed sensors. In: *Advances in Optical Fiber Technology: Fundamental Optical Phenomena and Applications*, Intech.