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Health monitoring of geotechnical structures by distributed fiber optic sensors

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Abstract:
Health monitoring of ground movement via highly sensitive fiber optic sensors allows operators to detect early potential or ongoing failures in critical geotechnical structures. Particularly, the fiber optic sensors can be embedded in geosynthetics which are nowadays widely used in many geotechnical applications including earth dikes, railway embankments, landfill liners, quarries and mines. Thereby, such smart geosynthetics can be used for reinforcement, layer separation, filtration or drainage while the embedded fiber optic sensors provide information about the condition of the geotechnical structures in real time. The paper highlights the results achieved in this innovative field in the framework of several German and European projects. The presented measurement methods for long-term monitoring are based on Brillouin scattering in silica glass optical fibers (GOFs) and optical time domain reflectometry (OTDR) in polymer optical fibers (POFs).

Key words: fiber optic sensor, distributed sensor, smart geosynthetics, Brillouin sensor, OTDR.

Introduction

In modern geotechnical structures it is common procedure to embed geosynthetics like nonwoven mats and geogrids into the ground. These geosynthetic materials mainly act as filters, reinforcement and drainage elements. By additionally incorporating fiber optic sensors, two-dimensional smart geosynthetics can be realized. Such smart sensor structures interact with their environment. They can sense and react to environmental conditions and external stimuli from mechanical, thermal, chemical or other sources.

Considering the development of fiber-sensor-based smart geosynthetics for stabilization and structural health monitoring of critical geotechnical structures, a number of research activities have been performed in Europe. This paper presents selected examples of development and using smart geotextiles and geogrids with embedded fiber optic sensors based on both GOFs and POFs for the monitoring of earth dikes and open-pit mines. The paper demonstrates the potential of distributed Brillouin sensing based on GOFs as well as practical advantages of OTDR based on POFs.

Smart Geosynthetics

Geosynthetics are commonly used within several industrial sectors ranging from medical, healthcare, earthworks, construction, civil engineering, transport, to name a few. The retrofitting of existing soil structures by geosynthetics [1] gains more and more importance especially in connection with protection of roads and railway embankments against landslides. The geosynthetic products are expected to provide one or more of the basic functions, i.e. reinforcement, filtration, separation, drainage or surface erosion control. Depending on the application, various types of geosynthetics can be used in geotechnical engineering, including two main product categories namely geotextiles and geogrids.

A collateral incorporation of optical fibers in the geosynthetics mentioned above leads to additional functionalities of the geomats, e.g. monitoring of mechanical deformation, strain, temperature, humidity, pore pressure, detection of chemicals, measurement of the structural integrity and the health of the geotechnical structure (structural health monitoring). Especially solutions for distributed measurement of mechanical deformations over extended areas of some hundred meters up to some kilometers are urgently needed. The geosynthetics-integrated distributed fiber optic sensors can provide information about critical soil displacement or slope slides via distributed strain measurement along the fiber with a high spatial resolution of less than 1 m for any position of extended geotechnical structures. So an early detection of failures and damages in geotechnical structures of high risk potential can be ensured.

In order to fulfill general target goals for distributed monitoring of extended geotechnical structures, several German projects like RIMAX (Risk Management of Extreme Flood Events) and the European project POLYTECT focused on the development of smart geotextiles and geogrids with integrated both POFs and GOFs as distributed fiber optic sensors.

An important task when considering integration of optical fibers in geosynthetics is to ensure an accurate transfer of the mechanical quantities to be measured, i.e. transfer of strain, from the soil to the geomat and so to the fiber core. For this, a stable and damage-free integration of the optical fibers in the geomats is of essential importance. The Saxon Textile Research Institute (STFI) e.V., Chemnitz, Germany has developed a technology to integrate optical fibers into nonwoven geotextiles (Fig. 1) so that the sensing fiber is well affixed onto the textile and the integration procedure does not affect the optical and sensing properties of the fibers.

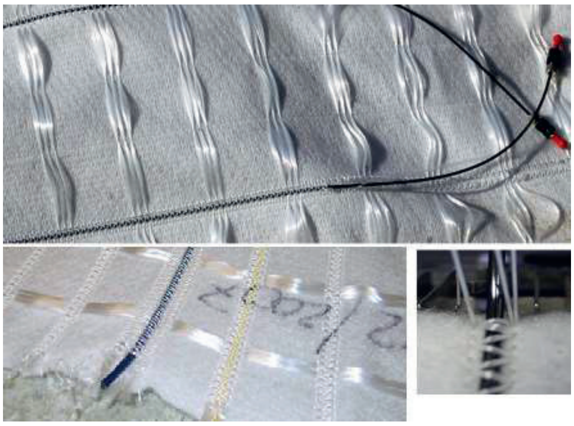

Fig. 1. Sensor-based nonwoven geotextiles.

Also the use of special coating and cable materials are of crucial importance to protect the fragile single-mode GOFs against fiber-breakage during the integration into the textiles and the installation on construction sites (Fig. 2). For that, a novel glass fiber cable was developed and manufactured by Fiberware, Mittweida, Germany to fulfill the above-mentioned requirements on robustness and to assure accurate strain transfer to the sensing fibers.

Fig. 2 shows an installation of a nonwoven geotextile containing single-mode GOFs as distributed sensors using heavy machinery, performed in the framework of RIMAX in Swinna Poremba, Poland. All GOF sensors have survived the installation on construction site without any damage.

Fig. 2. Installation of a nonwoven geotextile containing single-mode GOFs as Brillouin sensors in a gravity dam in Swinna Poremba, Poland.

Fig. 3 shows a damage-free integration of GOF into a geogrid, developed and demonstrated by Alpe Adria Textil, Italy in close cooperation with Glötzl Gesellschaft für Baumesstechnik mbH, Germany.

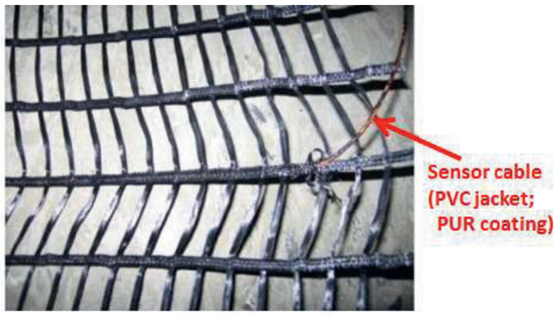

Fig. 3. Uniaxial geogrid for distributed strain measurements

At an early stage of development, the integration of GOFs into geosynthetics during the manufacturing process experienced problems of sensor brittleness, low strain range not exceeding 2% and bending-related attenuation increase. The optimization procedures of sensor integration processes led finally to the crucial improvement of optical properties of GOF sensor cables integrated into geosynthetics. Due to the achieved low optical

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attenuation of 1.5 dB/km, the measurement range of the GOF-based geosynthetics could be increased up to a few kilometers.

Unlike GOFs, the integration of POFs into various geosynthetics was easily achieved free of bending losses enabling distributed high strain measurements up to 40% using PMMA POFs. The first industrial product GEDISE based on a geogrid with integrated PMMA POFs is on the market. GEDISE was developed by Glötzl Gesellschaft für Baumesstechnik mbH (Germany), Alpe Adria Textile (Italy) and BAM.

Distributed Brillouin Sensors

The use of all Brillouin distributed measurement systems is based on the determination of the spatial distribution of the Brillouin gain spectrum (BGS) along the sensor fiber. Such a measurement of the BGS distribution along a GOF is shown in Fig. 4. The frequency shift of the Lorentz-shaped BGSs towards higher frequencies observed in some sections along the sensor fiber as showed in Figure 4 corresponds to local changes in longitudinal strain and temperature. Furthermore, such Brillouin frequency shift (BFS) varies linearly with temperature and applied strain.

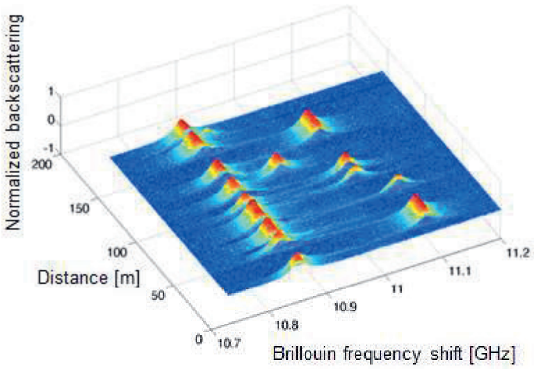

Fig. 4. Distributed Brillouin measurement using Brillouin optical-fiber frequency-domain analysis (BOFDA).

The BGS is measured by coupling a pump lightwave into the sensor fiber and by observing the amplification of a weak counterpropagating probe signal, coupled into the other end of the fiber, due to stimulated Brillouin scattering (SBS). The SBS is the most dominant nonlinear effect in GOFs and can be described as a three-wave-interaction of two contra-propagating light waves and an acoustic wave in the fiber. Because of the strain and temperature dependence of the Brillouin frequency shift (BFS) of the backscattered light, sensor systems based on this effect can be used for distributed strain and temperature measurements. The first distributed Brillouin sensing systems named Brillouin optical-fiber time-domain analysis (BOTDA) operated in a time-domain, which means that a short pulse is sent along the fiber and the backscattered light is recorded over time and contains information about the strain or temperature along the fiber [2–5].

In 1996 an alternative approach named Brillouin optical-fiber frequency-domain analysis (BOFDA) was introduced [6]. The BOFDA operates with sinusoidally amplitude-modulated light and is based on the measurement of a baseband transfer function in frequency domain by a vector network analyzer (NWA). A signal processor calculates the inverse fast Fourier transform (IFFT) of the baseband transfer function. In a linear system this IFFT is a good approximation of the pulse response of the sensor and resembles the strain and temperature distribution along the fiber. The frequency-domain method offers some advantages compared to the BOTDA concept. One important aspect is the possibility of a narrow-bandwidth operation in the case of BOFDA. In a BOTDA system broadband measurements are necessary to record very short pulses, but in a BOFDA system the baseband transfer function is determined point-wise for each modulation frequency, so only one frequency component has to be measured by the NWA with a narrow resolution bandwidth. The use of a narrow bandwidth operation (detectors) improves the signal-to-noise ratio and the dynamic range compared to those of a BOTDA sensor without increasing the measurement time. Another important advantage of a BOFDA sensor is that no fast sampling and data acquisition techniques are used. This reduces costs. Particularly, the low-cost potential of BOFDA sensors is very attractive for industrial applications.

With the objective of a cost-effective optimization of the BOFDA system a novel measurement concept based on a digital signal processing has been realized [7,8]. This concept employs a novel digital data acquisition technique, which takes advantage of the reduced bandwidth required in BOFDA sensor systems. The backscattered optical signals can be digitally sampled using state-of-the-art analog-to-digital converters and processed off-line by means of modern digital signal processing methods, avoiding complex and expensive analog components such as filters, oscillators and circuitry for signal analysis. The digital optical signal processing features several advantages compared to the measurement process using NWA: less hardware is required, an increase of the dynamic range due to the

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offline signal processing and improvement of the data acquisition time is expected.

As previously mentioned, in the framework of the German research program RIMAX, nonwoven geotextiles with embedded Brillouin sensing fibers were installed in gravity dams in Solina and Swinna Poremba, Poland in August 2006 to prove the feasibility of the whole monitoring concept using sensor-based geotextiles. The goal of the field test in Solina was to detect possible geophysical activities in the dam by the fiber-sensor-equipped geotextile of a length of 17.5 m manufactured by STFI, Germany and embedded in the soil. In 2009 the first distributed measurements by using a commercially available BOTDA system from Omnisens were conducted there. Such BOTDA measurements were finally repeated twice a year until 2013 giving information about the combined strain and temperature state of the sensing mat. Fig. 5 shows the distributed BFS measured on summer days between 2009 and 2013 on the fiber section between 205 m and 240 m where the geomat was embedded in the soil. In this period, no aging effects and no critical changes in the soil could be detected by the sensor fibers in form of local longitudinal strain.

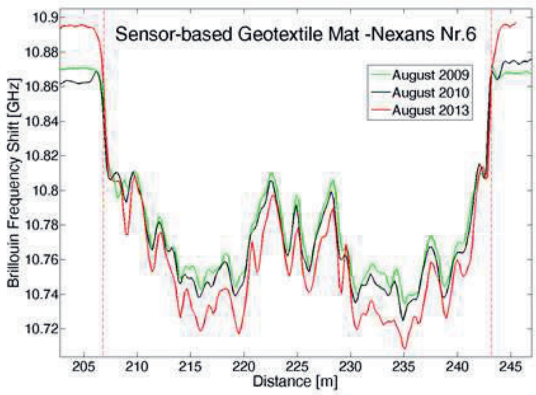

Fig. 5. Distributed Brillouin frequency shift measured on the fiber section embedded in the soil up to 7 years after installation of the geotextile.

Distributed POF OTDR Sensors

The measurement technique based on Brillouin scattering in GOFs reaches its limits when strong mechanical deformations, i.e. strain of more than 1% – 2% occurs. In such a case sensors based on GOFs cannot be reliably used. For that reason, the integration of POFs as distributed sensors into geosynthetics has become very attractive because of their high elasticity, high breakdown strain and their capability of measuring strain of more than 40%. Especially, the monitoring of relative small areas with an expected high mechanical deformation such as creeping or sliding slopes takes advantage of the outstanding mechanical properties of POFs. The monitoring of slopes is a very important task in the geotechnical engineering for prevention of landslide disasters.

To overcome the limit of GOF-based geosynthetics, distributed fiber optic sensors based on low-priced standard POF and using the OTDR technique have been developed for the monitoring purposes mentioned above [9, 10]. The OTDR is the most common distributed sensing technique and uses the Rayleigh scattering in optical fibers to measure the attenuation and backscatter profiles of the fibers. The physical effect that is being used to measure strain in POFs by the OTDR technique is the increase of the level of the backscattered light (Rayleigh scattering) in POFs at locations where strain is applied to the fiber. Fig. 6 shows the OTDR response of an unstretched POF (solid line) and of a stretched POF (broken line).

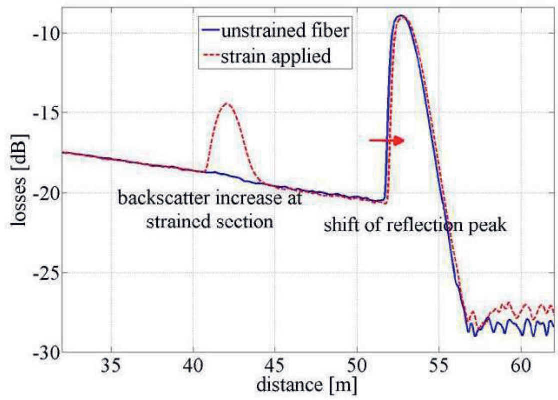

Fig. 6. OTDR trace of POF in unstretched condition (solid line) and of POF with a stretched fiber section (broken line).

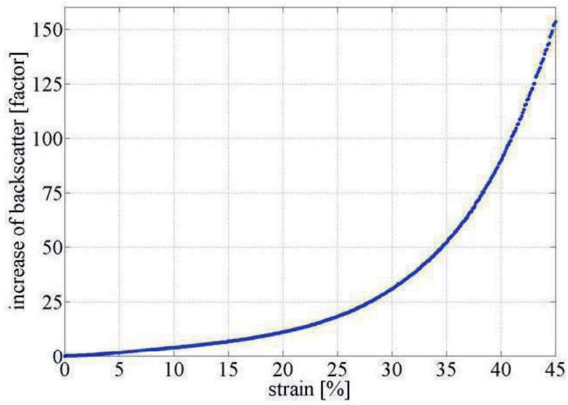

Fig. 7. Change of the backscattering as a function of strain measured on standard PMMA POF.

Fig. 7 shows the increase of the scattered light in the stretched POF relative to a reference measurement as a function of applied strain.

Strain of up to more than 45% was measured using standard PMMA POF.

Today, several POF OTDR devices are commercially available on the market and allow strain measurements along standard 100-m-long POFs with a spatial resolution of less than 1 m.

The first real field using POF-sensors-equipped geotextiles has been performed in an open-pit mine near Belchatow, Poland [11- 13]. The test was initiated, organized and supervised by Gloetzl Baumesstechnik, Germany in close cooperation with Budokop, Poland and the mine owner. Here, a 10-m-long geogrid based on PMMA POF and manufactured by Alpe Adria Textil, Italy was installed directly on top of a creeping slope and covered with 10-cm-thick sand layer. Fig. 8 shows the OTDR traces of the sensor fiber section in the middle of the geogrid where the fiber bridges the cleft.

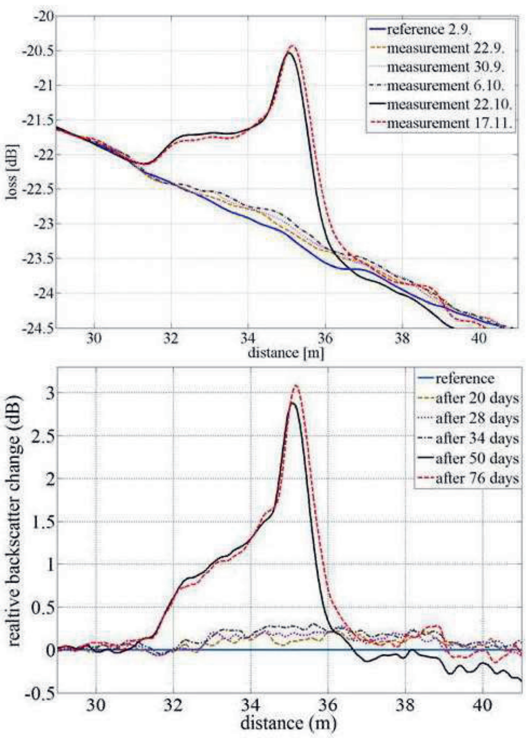

Fig. 8. OTDR traces of the PMMA POF sensor fiber at the position of the cleft.

The figure clearly shows backscatter increase due to strain in the fiber at the position where the cleft was expected. The magnitude of backscatter increase corresponds to a maximum strain in the fiber of more than 10%. Such high strain can only be measured by POF sensors.

Conclusions

A number of research activities considering the development of a new generation fiber-sensor-based geosynthetics in form of both nonwoven mats and geogrids for stabilization and structural health monitoring of critical geotechnical structures have been running in Europe. Several German projects and the European project POLYTECT dealt with the development of distributed Brillouin and POF OTDR sensors providing an alarm signal and distributed strain information in case of structural damage. Multifunctional, smart geosynthetics incorporating fiber optic sensors are a cost-effective solution to increase the structural safety. The intended breakthroughs include the use of such geotextiles and geogrids for reinforcement and for monitoring of earthworks at the same time, giving online information on the state and the performance of the structures and so preventing a total collapse. Such reliable on-line, long-term monitoring systems will improve the chance of an early detection and the location of “weak points” and damages, and will make it possible to react rapidly and to control damages. For that, distributed BOFDA Brillouin and POF OTDR sensors have been developed and successfully demonstrated. Sensors based on POFs take advantage of the low Young’s modulus and the high break-down strain of POFs allowing distributed sensing of strong mechanical deformations (strain of more than 40%) of soil. The POFs are robust, easy to handle and to install on construction sites. A number of field tests have successfully been conducted showing the suitability of using the geosynthetics-integrated Brillouin and POF sensors for the monitoring of geotechnical structures. Such smart geosynthetics with embedded optical fibers are a potential new market niche for fiber optic sensors.
Brillouin sensors based on GOFs take advantage of the low-loss characteristics of the sensor fibers making possible measurement ranges of several tens of kilometers with a high measurement accuracy and a spatial resolution in the meter range. The use of the narrow-band BOFDA approach offers new perspectives for improvement in terms of dynamic range, cost efficiency and signal-to-noise ratio.

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