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Distributed Fiber Optic Smart Geosynthetics for Geotechnical Applications in Transportation

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Abstract

We present the latest works in the design, development, validation and industrial application of geosynthetic materials equipped with integrated fiber-optic sensing cables for distributed strain and temperature measurements. The integration of fiber-optic sensors into geotextiles and geogrids – as they are commonly used in geotechnical construction for soil stability improvement, erosion protection, draining, filtering and other tasks – provides a feasible integration method for the sensors into the structure under monitoring. The one-dimensional characteristic of a longitudinal fiber-optic strain sensor is thereby transformed into a two-dimensional shape sensing plane, providing distributed, uninterrupted information on deformation, sinkholes, slope movements, settlements and many more geotechnical indications on structural failure.

Keywords: Distributed fiber-optic sensing, smart geosynthetics, geotechnical monitoring, fiber-optic strain measurement

1. The concept of geotechnical monitoring with smart geosynthetics

1.1. Smart geosynthetics

The use of various types of geosynthetics has become an essential instrument for the solution of a large number of geotechnical problems. The most relevant forms of geosynthetics are woven and non-woven textiles, geogrids,

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geomembranes and geocomposites. They perform several geotechnical functions: filtration (allowing water to pass through while retaining particles of the filtered soil), drainage, separation of soil layers with different particle sizes, and reinforcement (prevention from slope erosion and increase of the overall stability of the earth structure).

The integration of fiber optic sensors into geotextiles offers the opportunity to extend their functionality and effectiveness in assessing and mitigating potential risks and challenges in construction projects and in monitoring the natural environment (Voet et al. (2005); Wu et al. (2020)).

1.2. Distributed fiber-optic sensing technologies

Distributed fiber-optic sensing (DFOS) refers to a family of technologies that exploits different scattering phenomena in optical fibers to provide spatially resolved and continuous profiles of various physical quantities along their length. The most commonly used DFOS technologies are the following:

- Distributed Temperature Sensing (DTS), using Raman scattering: This technology is widely used in fire detection, power cable monitoring and leakage detection in pipelines and geotechnical structures. It is sensitive to temperature only and provides distributed measurement data over several tens of kilometers with a spatial resolution below 1 m.

- Distributed Acoustic Sensing (DAS), using Rayleigh scattering, is mainly used in geophysics and seismic investigations, as well as in security applications. With DAS, vibrations and acoustic events can be recorded and spatially resolved over tens of kilometers. In geotechnical monitoring, DAS is used for leakage detection, slope monitoring and structural health assessment.

- Distributed Temperature and Strain Sensing (DTSS): Both Rayleigh scattering and Brillouin scattering can be used for simultaneous strain and temperature measurements. While Rayleigh scattering traces a geometrical signature of the fiber, thereby measuring displacements with mm resolution over distance range in the order of 100 m, Brillouin scattering allows for measurement of the absolute material density state of an optical fiber, thus providing strain and temperature profiles over more than 50 km, with a spatial resolution below 50 cm.

- Distributed Strain Sensing in Polymer Optical Fibers (POF): The above technologies use largely standard telecom (single-mode or multi-mode) silica optical fibers. However, it has been shown that polymer optical fibers offer a range of scattering effects that can also be used for distributed displacement and strain measurements. The relatively high optical attenuation accessible by today commercially available POF imposes limitations in terms of achievable distance range and accuracy. Nevertheless, Polymer Optical Fibers offer the advantage of being easy to handle on site, and to provide a large strain range (> 10% as compared to maximum 1-2% for silica fibers), as reported by Königsbauer et al. (2022).

Especially Brillouin DTSS has gained great significance in geotechnical monitoring (Iten et al. (2009); Bado and Casas (2021), Minardo A. et Al. (2021)). In Brillouin DTSS, the light backscattered from Brillouin interaction experiences a downshift of its optical frequency. This Brillouin frequency shift depends on the local density of the medium (the silica optical fiber), and is linearly proportional to strain and temperature changes. Since the density is an inherent material characteristic, Brillouin DTSS measurements are extremely long-term stable. A measurement compared to a baseline taken even years earlier will still provide reliable and precise information about changes in strain and temperature at each position along the sensing element.

In the following, we will focus on Brillouin DTSS for integration of fiber-optic sensing cables in geosynthetics. Additionally, the subject of POF integration will be discussed.

1.3. The transfer chain in soil monitoring

The different DFOS technologies that have been introduced above primarily analyze the spatially resolved backscattering, to derive the information about the desired physical quantities. In the case of Brillouin DTSS, this is the Brillouin frequency shift, linearly related to strain and temperature at each position along the fiber. In geotechnical monitoring, the looked-for information, however, is the structural behavior and possible failure modes, namely the deformation and temperature changes that hint towards settlements, subsidence, slope failure, erosion, leakages, etc, in the medium surrounding the sensing element.

Between the desired information and the measured physical quantities, there is a series of transformations to consider, each requiring knowledge about the structural behavior, the materials involved, the nature of the structure-sensor interface, and the sensing technology (see Fig. 1).

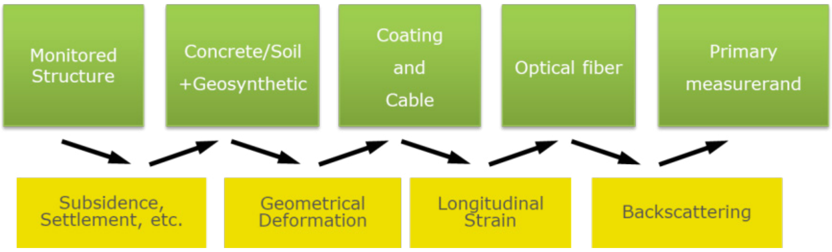


Fig. 1. The transfer chain in geotechnical monitoring using DFOS

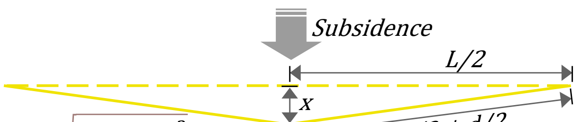
For distributed strain measurements using the DTSS Brillouin technology, the transfer chain - considering backward from the optical system to the monitored structure - consists of the following elements:

- The Brillouin Frequency Shift of the backscattered light is converted to strain and temperature at each position along the optical fiber by a set of linear coefficients, characteristic for the specific fiber type, and remain long-term stable during operation. The temperature may need to be compensated, as it induces a superimposed influence on the strain profile (this can be achieved e.g. by combining dedicated strain and temperature sensing cables, see below).

- The longitudinal strain along the optical fiber is the result of a transfer of the deformation from outside the cable sheath, through multiple buffer and protection layers (metallic or non-metallic) and finally into the sensing fiber itself. The efficiency of the strain transfer depends on different factors such as the elasticity of the coating layers and the adhesion between adjacent layers (both effects defining how large a spatial blur of the strain response into the fiber may be) and plastic deformation of sensor elements (reducing reversibility and repeatability of the strain response).

In order to separate strain and temperature, the use of a dedicated loose-tube fiber-optic temperature sensing cable, in which the fiber is mechanically decoupled, in parallel to a tight-buffered strain sensing cable, which is designed for most efficient strain transfer from the hosting medium into the sensing fiber, is advisable.

- The longitudinal strain experienced by the fiber-optic sensing cable in total is a geometrical projection of the actual three-dimensional deformation event of the soil structure into the one-dimensional cable. In order to evaluate the actual deformation (e.g. heave or subsidence) from the longitudinal strain measured along the optical fiber sensor, knowledge about the orientation of the cable with respect to the 3D-deformation field is required. For example, a lateral deflection of the fiber-optic sensing cable that is bent due to a settlement occurring perpendicularly to the sensing cable direction will induce a longitudinal strain (d/L), which not only depends on the settlement amplitude (x), but also on the width (L) of the settlement event (see Fig. 2) and the position/direction of the cable within the region of the settlement.



$$x = \sqrt{\frac{Ld}{2} + \left(\frac{d}{2}\right)^2}$$

Fig. 2. Strain (d/L) induced in a fiber optic sensing cable due to a lateral deflection (x) of the sensing cable along a subsidence zone.

All these steps of the transfer chain must be taken into account when installing, operating DFOS sensors and analyzing measurement data in geotechnical monitoring.

2. Smart geosynthetics as sensor carriers

In the transfer chain from a geotechnical event into the measured strain along the optical sensing fiber, the deployment of geosynthetics can largely help to make installation easier, increase the sensing efficiency, and make the measurement analysis more deterministic.

While a fiber-optic sensing cable is a one-dimensional element, as discussed above, a geosynthetic mat is a two-dimensional structure. By fixing a fiber-optic sensing cable onto a geotextile or geogrid, deformation in an arbitrary direction (with respect to the orientation of the fiber-optic sensing cable) will be transferred reliably into longitudinal strain of the fiber. Also, the region of sensitivity extends to a larger area around the sensing cable, making the DFOS technique an even more effective tool for geotechnical monitoring.

2.1. On-site fixation of fiber-optic sensing cables onto geogrids

One means of achieving this transformation from a 1-D-sensor into a 2-D-sensor is to deploy and fix the fiber-optic strain sensing cable after the geosynthetic, originally deployed for soil stabilization, has been rolled out on the construction site. This was realized by Moser et al. (2016) for the monitoring of the Longsgraben disposal yard during tunnel excavation for the Semmering Base Tunnel in Austria.

Periodic measurements were performed in a total of 2.5 km loop of fiber-optic strain sensing cable in order to monitor slope stability within the reinforced earth structure. In four different levels, geogrid mats were installed horizontally, with fiber-optic strain sensing cables attached to them with specially developed clamps. Fig. 3 shows the following details: (a) schematic view of the layers of geogrids with attached fiber-optic strain sensing cables in 4 layers; (b) attaching fiber-optic sensing cables to geogrid mats; (c) view of the installation setup within the reinforced earth structure; (d) evolution of strain along a measurement period of 6 years, using Brillouin DTSS.

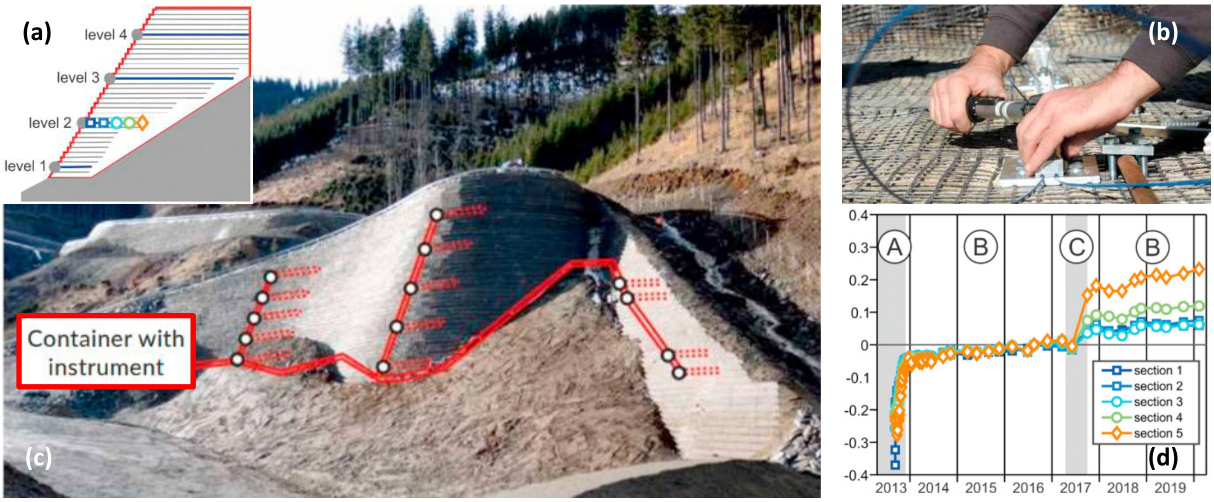


Fig. 3. Monitoring of a reinforced earth structure at Longsgraben disposal site, Austria.
(Pictures: ÖBB / Engineering Geodesy and Measurement Systems, Graz University of Technology)

2.2. Factory integration of fiber-optic sensing cables into geosynthetics

Already during earlier research activities, fiber-optic strain sensing cables have been integrated into non-woven geotextiles for dike monitoring, see Nöther et al. (2009). Tests were performed to systematically quantify the strain transfer from an induced deformation (stretching of the geotextile buried in soil with a controlled settlement events) into the fiber-optic sensing cable, and, eventually, the optical fiber.

The tests aimed at verifying the reliable transfer from a plane (2-dimensional) strain event into the longitudinal strain measured by the Brillouin DFOS system. Particularly challenging was the task to ensure mechanical and optical integrity of the optical fiber during production, transport and installation.

Recently, a commercial geogrid structure with integrated fiber-optic strain sensing cables has been proposed by Huesker Synthetic GmbH. Different types of dedicated fiber-optic strain sensing cables have been integrated directly into the soil reinforcement grid during production (see Fig. 4).

The developed production process is compatible with the integration of various types of sensing cables, among them metallic designs (offering enhanced mechanical protection of the sensing fiber) and non-metallic sensing cable designs (providing lower stiffness and thus a more efficient transfer of arbitrary deformation into longitudinal fiber strain).

Fig. 4. Geogrid with factory-integrated fiber-optic sensing cables (comprising an additional non-woven mat for filtering purposes)

Compared with earlier works on non-woven geosynthetics that have been mentioned above, this novel design features the following technical improvements:

- The integration process has been optimized for straight integration of the sensing cables during production of the grid structure, avoiding lateral deflection and shearing forces onto the sensing cables. This minimized residual strains in the profile of the sensing fiber, making the sensing response more reliable and efficient.
- The proven compatibility with a wide range of state-of-the-art fiber-optic sensing cables (for both strain and temperature) allows for a flexible design approach, relying on a selection of industry-proven products made fit for specific application requirements.
- Unlike non-woven geotextiles, the elastic modulus of the grid is much closer to that of the fiber-optic sensing cables. This means that the sensing cable far less impacts the mechanical properties of the geogrid, and thereby interferes less with the geotechnical design.

3. Field validation of smart geogrids

The recent design steps towards a market-ready geogrid with factory-integrated fiber-optic sensing cables as introduced above have been validated with respect to their functionality and operational readiness in various field installations in geotechnical monitoring projects.

3.1. Smart geogrids for ground movement detection in railway construction

A significant campaign of field implementation of smart geogrids has been recently presented by Xu et al. (2022). In this work, the specimen of geogrids equipped with non-metallic fiber-optic strain sensing cables were subject to three validation test stages:

First, tensile strain tests were performed in the laboratory to characterize the strain transfer function of the geogrid / fiber-optic sensing cable compound. A hysteresis-free, linear and repeatable transfer from the deformation applied to the geogrid into the strain measured by the integrated DFOS system was confirmed with a high degree of fidelity.

Second, a field mock-up trial was realized in which a 3x3 matrix of lifting cushions was used to simulate a sinkhole-type ground deformation. The sensor-equipped geogrid was placed on top of the cushions; the deformation was referenced by a total station. The tests, using Brillouin DFOS (BOTDA-based) resulted in measurable displacement (settlement depths) of below 5 mm (see Fig. 5).

Third, an in-situ durability assessment was conducted in a real construction field at Tilehouse Lane Cutting (UK), part of the HS2 project.

Fig. 5. Field-trial of sensor-equipped geogrids. Left: Installation above water-inflated lifting cushions; center: loaded installation; right: DFOS strain results *(all pictures and data: CSIC, Huesker, Epsimon, Jacobs, Align, HS2).*

3.2. Smart geogrids for ground movement detection in road construction

Geogrids with factory-integrated fiber-optic sensing cables were deployed for on-site validation during construction works at the federal road B91 near Leipzig, Germany. The renovation work on this section involved the upgrade of the route to a more massive motor road, construction of a new embankment, and laying new asphalt layers.

For long-term stability monitoring of the road embankment, the bottom layer of geosynthetic ground reinforcement involved sensor-equipped geogrids. A fiber-optic strain sensing cable including a tight-buffered FIMT (fiber in metal tube) surrounded by a structured polymer sheathing and a non-metallic fiber-optic telecom-grade cable were respectively integrated in the smart geogrid. The geogrid was placed in an orientation such that two loops of fiber-optic sensing cable were perpendicularly oriented with respect to the road direction (see Fig. 6). A first layer of sand was deployed to cover the geogrid and provide primary protection of the smart geogrids. All buried sensor cables inside the geogrid remained undamaged throughout construction works. This is a confirmation of the good robustness provided by well-chosen sensing elements and of their compatibility with the severe requirements imposed in the construction environment. Nevertheless, some external optical interconnections were damaged during the construction works. This, on the other hand, underlines the need of defining suitable installation and handling procedures that must not impair the flow of construction operations.

Fig. 6. Field-integration of sensor-equipped geogrids in road construction. *(pictures: GGB, BAM, Huesker, fibrisTerre)*

Three series of measurements were performed on November 11, 2022 (after installation); on March 09, 2023 (after placing the full soil load); and on August 15, 2023 (after completion of the pavement construction). In Fig. 7 are shown the measured differential strain distributions relative to the baseline acquired immediately after installation, for two distinct sensing cables and installation sections.

The measurement results confirm the expectation that the longitudinal strain experienced by the geogrid increases with each construction stage, as the load from additional layers of soil and pavement builds up. In the region where the earthwork exerts a greater load (under the embankment and the road itself), as expected, the amplitude of the evolution of the strain distribution gets more important. The deformation distributions along the geogrid on two distinct sensing cables and at two distinct cross-sections beneath the embankment are shown in Figure 7. Further analysis is needed to understand the origin of the significant difference in the measured deformations. More periodic measurements will have to be performed in order to pursue the further geotechnical development of this site.

The strain distributions of the two monitored sections shown in Fig. 7 might also be partly influenced by temperature changes, especially in the shallow region (between position 0 and 6 meter). Indeed, the Brillouin DTSS measurements were performed at different ambient temperatures between winter (installation) and summer (third measurement). The effect of temperature gets negligible in regions where the smart grid is buried at larger depth. However, this cannot be precisely quantified without actual temperature measurements, conventional or by fiber-optic (a fiber optic DTS cable could not be installed because of logistical issues). Indeed, a limitation in the project layout is the lack of a temperature compensation. This additional feature could easily be implemented in future realizations, as the manufacturing process of smart geogrids allows straightforwardly the integration of fiber optic cables for distributed temperature sensing in combination with deformation sensing elements.

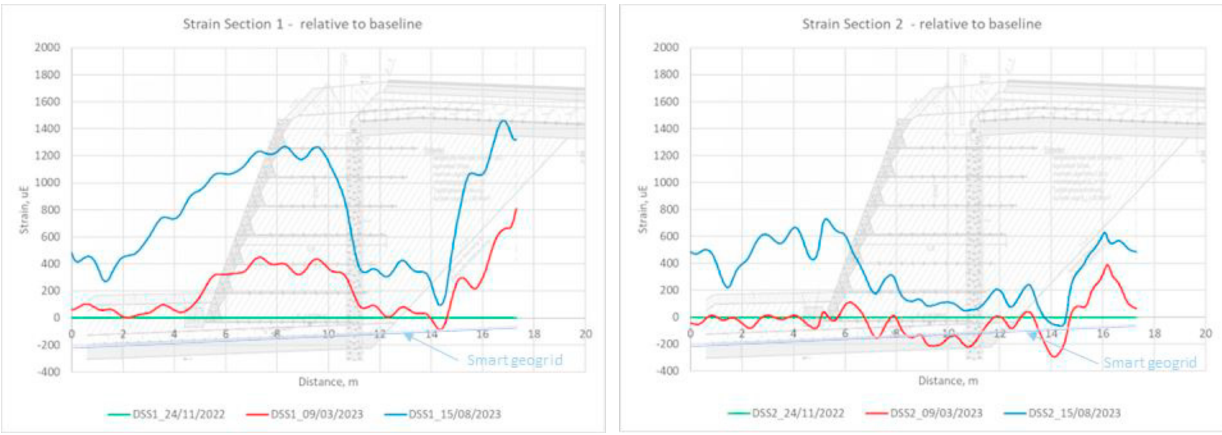


Fig. 7. DFOS measurement data from field-trial of sensor-equipped geogrids in road construction. Relative strain distributions at two distinct cross-sections and on two different sensing cables, at different construction phases, referenced to the baselines obtained directly after installation.

4. Outlook: Polymer fiber-optic sensors in geogrids

Within the scope of the field validation of sensor-equipped geogrids in road construction as presented above, also the use of polymer fiber-optic (POF) sensors integrated into geogrids was evaluated. Polymer Optical Fibers are an interesting choice for integration in geogrids because of the extended strain range of more than 10% that can be achieved. Specifically, perfluorinated PMMA POF are also characterized by an optical attenuation of about 30 dB/km at 1300 nm wavelength, which is relatively low among POF products, but still 2 to 3 orders of magnitude larger than that of telecom grade fused-silica optical fibers. Considering the fairly significant optical linear attenuation and optical losses at connectors, perfluorinated PMMA POF enable a measurement range over one hundred meters. Such POF were manually integrated into geogrids after production, under controlled lab conditions. For distributed strain measurements in POF, commercially available OTDR (Optical Time Domain Reflectometer) devices as well as a novel incoherent OFDR (Optical Frequency Domain Reflectometer) set-up from BAM (Federal Institute for Materials Research and Testing in Germany) were used. Both techniques record linear backscattering events along the sensing fiber, enabling a geometrical assessment of the displacement, as well as the quantification of the intensity of the backscatter events (backscattering in POF increases linearly with strain, Liehr et al. (2009)).

The field validation proved the general feasibility of POF for geotechnical monitoring.

As reported by Wosniok et al. (2024), challenges remain in terms of the integration method into a geogrid on an industrial production scale, the limited durability on site of polished connector surfaces, and the availability of perfluorinated POF with tight-buffered coatings needed for efficient strain sensing capability, and the short achievable distance range limited by the intrinsically high optical attenuation.

5. Conclusions

The integration of fiber optic sensors into geotextiles offers the opportunity to extend their functionality and effectiveness in assessing and mitigating potential risks and challenges in construction projects and in monitoring the natural environment, enabling a more informed approach to geotechnical design of transportation projects.

The practicality and benefits of this multi-functional technology have been illustrated by case studies from several construction projects. The long-term reliability of the materials used in the production of these smart geogrids and the stability of the fiber optic sensing measurement technology enable consistent geotechnical measurements during the construction phase and throughout the life cycle of the structure.

The results and insights gained from the development of the industrial production process and the successful deployment of smart geogrids emphasize the benefits of early detection of geotechnical events, enhanced safety, and cost savings in long-term maintenance, all of which are crucial for building a resilient and sustainable infrastructure.

Acknowledgements

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