Displacement and Settlement Monitoring in Large Geotechnical Structures with a Novel Approach to Distributed Brillouin Sensing

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Abstract. Distributed Brillouin sensing for temperature and strain measurements in optical fibers has become a well-known tool for health monitoring of large structures in industry, geotechnical engineering and public infrastructure. This paper reports on a novel approach to this technology, replacing the common pulse-based measurements by a frequency-domain analysis. It outlines the evolvement of the system from the architecture development via lab and field evaluation to an industrial product.

1. Introduction

For long-range measurements in geotechnical and industrial applications, distributed optical fiber sensors have become a tool of increasing importance throughout the past decade [1]. Classic deformation monitoring (performed by strain gauges etc.) and temperature monitoring (Pt100 and alike) deliver data from fixed, single spots of a structure; quasi-distributed measurements (fiber bragg gratings) provide a chain of discrete measurement points along a limited sensing length. In contrast, an optical fiber connected to a device for distributed strain and temperature sensing (DTSS) will provide a continuous profile of strain and temperature – spatially resolved down to less than 1 m – over a range of several tens of kilometers.

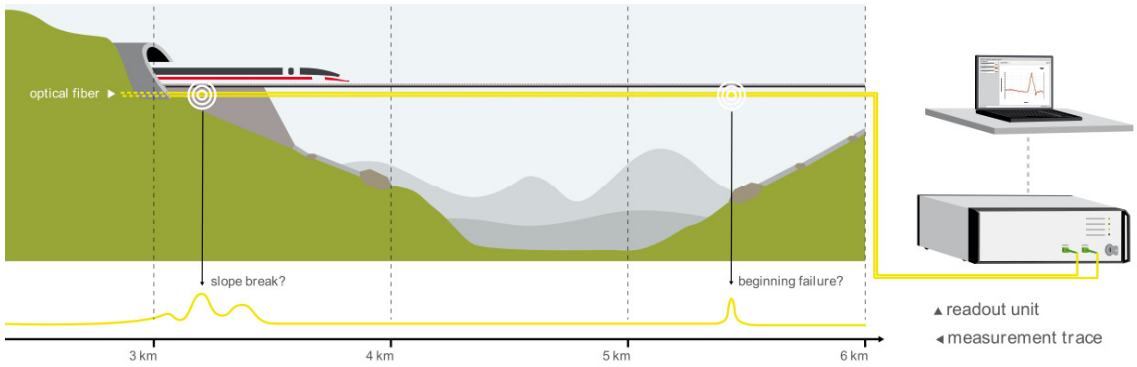

Figure 1: Distributed strain measurements for structural health monitoring using Brillouin sensing in optical fibers

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2. Distributed Brillouin sensing in optical fibers

In DTSS measurements, the nonlinear optical effect of stimulated Brillouin scattering (SBS) is employed: two light waves with a stable, tunable frequency offset are injected into opposite ends of the sensing fiber, where they will form a beat pattern, at which parts of the light will be scattered. By matching the frequency offset of the light waves to the propagation of acoustic fluctuation in the optical fiber, a power transfer from one light wave to the other can be measured; since the acoustic propagation directly shifts with strain and temperature of the fiber, these two quantities can be measured by tuning the light waves' frequency offset.

The most common technique to acquire the spatially resolved profile of Brillouin interaction along an optical fiber is the Brillouin optical time domain analysis (BOTDA): One of the light waves is injected in the form of very short pulses (< 10 ns); by recording the scattering signal over time, the location of a scattering event can be reallocated from the time of flight of the optical pulses [2]. Devices using this technique are commercially available.

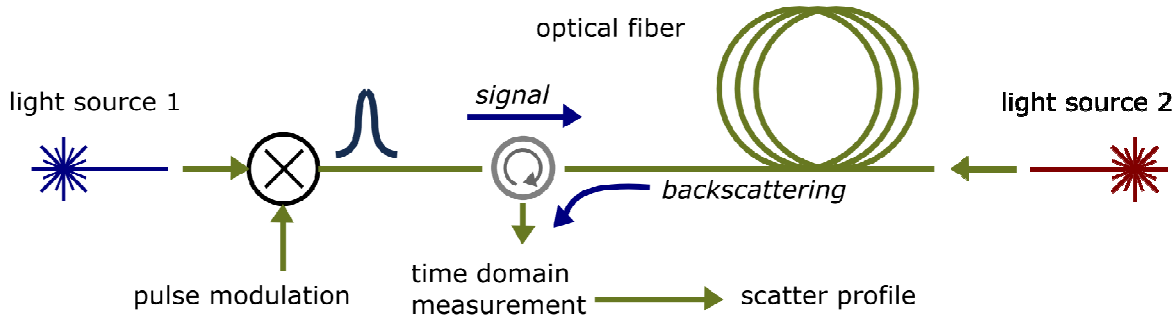

Figure 2: Schematic principle of the Brillouin optical time domain analysis

An alternative technique is the Brillouin optical frequency domain analysis (BOFDA). Here, the pulses are replaced by sinusoidal waves of a tunable frequency (ca. 5 kHz to 100 MHz). By measuring the system's response to these frequencies (being the spectral components of the optical pulses in a harmonic representation), the transfer function of Brillouin interaction along the fiber is recorded. As in a linear, time-invariant system, the pulse response can be entirely constructed from the system's transfer function, a Fourier transform of the measured data will yield the same strain and temperature profile along the fiber that would have been acquired by the use of pulses [3].

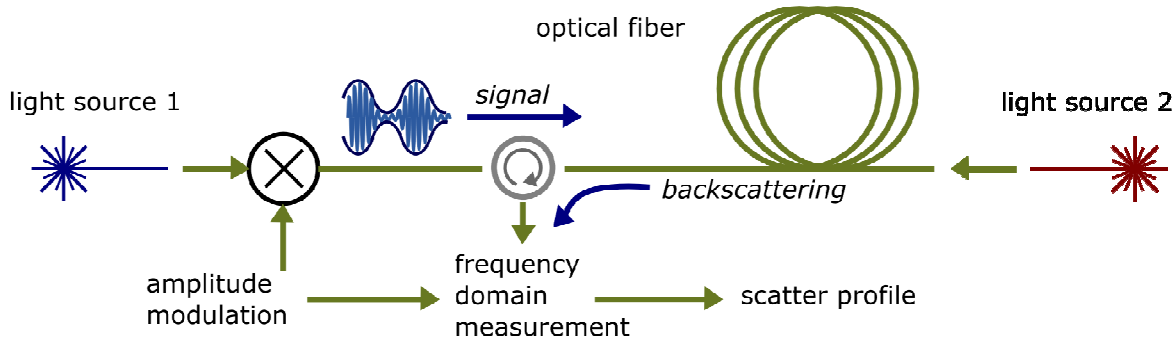

Figure 3: Schematic principle of the Brillouin optical frequency domain analysis

In both systems, the signal chain, going from the physical quantities to be measured to the final analysis giving insight into structural integrity, requires the following key elements:

- For deformation measurements in geotechnical or rigid structures, a reliable force transfer from the surrounding medium (soil, concrete, etc.) to the sensing fiber is needed. In most applications, this implies a rugged, but flexible coating material of the sensing cable, protecting the fiber from mechanical damage while still maintaining its sensitivity.
- Since Brillouin measurements are sensitive to both mechanical strain and temperature in the optical fiber, the temperature influence on deformation measurements must be accounted for.
- The measurement unit itself, where the optical signals are generated and received, bears the task of converting the real-time occurrences of Brillouin interaction into a signal trace showing mechanical strain versus fiber length. In BOTDA devices, this is done by analog recording of the backscattered light for each pulse that has been injected into the fiber. In contrast, the BOFDA approach allows to sample each spectral component in the frequency domain, and then to continue all following signal processing steps offline. The implications of this advantageous long-way round are briefly described in the following.

3. Implementation and Validation of the BOFDA System

While the first publications on the BOFDA system had to rely on bulky, analog vector network analyzers, the measurements presented here were performed with a novel all-digital implementation of the BOFDA system. The key advantages in implementation when compared to state-of-the-art BOTDA systems are:

- By measuring the spectral components of the signal pulses one after another, frequency-domain filtering not only decreases noise within the received signal, but also unwanted characteristics of optical and electrical components which would not be distinguishable from the signal in the time domain.
- The digital implementation allows for the use of state-of-the-art electronic devices such as fast signal converters and embedded signal processing. This makes the measurement unit small, robust and efficient both in cost and power consumption.

The system has been validated by means of representative distributed measurements along a testing fiber, consisting of fiber segments from two different manufacturers, resulting in a varying distribution of Brillouin frequency shift. Quantitatively, the shift between the two fiber types (caused by material parameters) corresponds to a roughly estimated strain value of 100 με and a temperature value of 5°C, respectively (the accurate strain and temperature coefficients are dependent on ambient parameters and must be derived from in-situ calibration). The measurement results are depicted in figure 4.

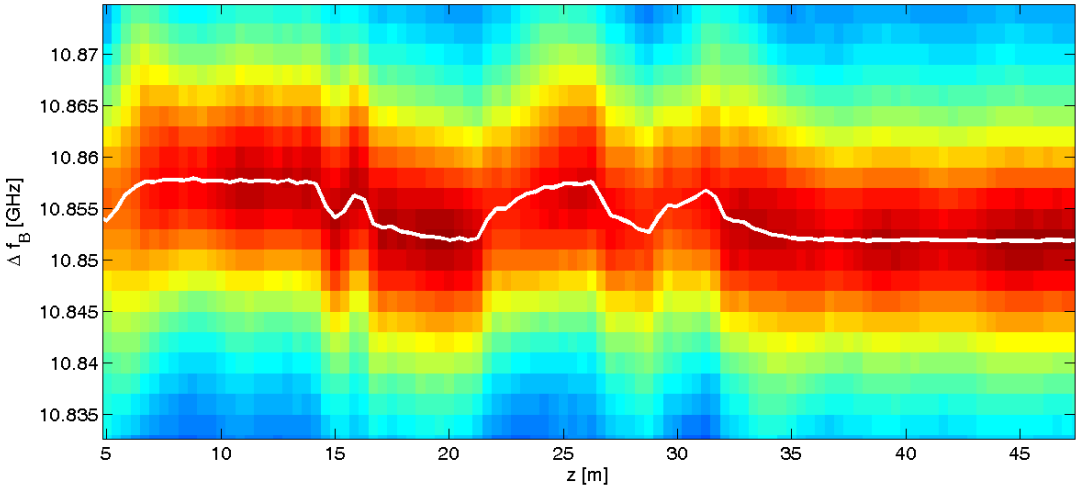

Figure 4: Distributed measurement of the Brillouin frequency shift of a specimen, consisting of interconnected fiber segments from two different manufacturers. The color pattern denotes the intensity of the Brillouin interaction along the fiber at different frequency offsets of the exciting light waves. The white line is drawn at the maximum interaction for each location, thereby representing the Brillouin shift profile which can be translated into a strain or temperature trace.

4. Applications in Geotechnical Engineering

For the application of distributed optical fiber sensors in geotechnical structures – such as soil displacement detection in embankments or settlement detection in foundations – a feasible method is needed that provides an accurate and reliable force transfer from the soil to the sensor. Displacement and movement of soil cannot be measured directly by the sensors. The detection is performed via the measurement of longitudinal strain of the optical fibers. This means that there is a long transfer chain of various physical quantities to be considered. This chain is sketched in figure 5. If critical displacement occurs within the soil, it will have impact on the stress of the geotextile in both dimensions (the geotextile is seen as a two-dimensional object inside the soil).

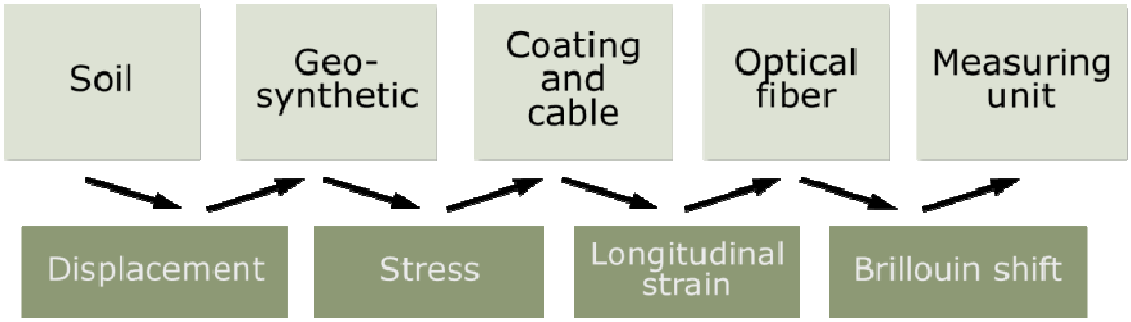

Figure 5: The components of a distributed system for dike monitoring and the transfer chain of physical quantities from the event to be detected (soil displacement) to the quantity that is measured by the system (Brillouin frequency shift).

This stress will apply longitudinal (one-dimensional) strain in the cabling and coating material of the optical fiber, which will transfer the strain to the silica optical fiber. In this last transfer the slipping of the fiber inside the cable has to be considered.

For providing an accurate force transfer from the soil into the optical fiber cable, the method of integrating optical fiber sensors into geotextiles is a significant advancement in all geotechnical applications:

- Any displacement of arbitrary orientation will stretch the geotextile and is thereby transformed into longitudinal strain in the optical fiber. The one-dimensional fiber sensor becomes a two-dimensional sensing mat.
- Even soil events that occur within a certain distance (to be quantified in empirical measurements) will be detected and reallocated to their spatial position within the structure. A remote event might still be detected, but with the consequence of losing accuracy in quantifying the strength or significance of the event.

5. Settlement simulation on the laboratory test bench

5.1 Measurement Setup

At the University of Applied Sciences (HTW) Dresden a test setup was developed which is able to show induced deformation of geosynthetics embedded in soil analogous to deformations at the bottom of constructions in situ.

The test setup was designed as a large-scale box with two sections, where one part could be moved horizontally and vertically separately. This segmental box could be quickly set up and removed after completion of the tests. For the test setup, dimensions of 5 m length, 1 m width and approx. 0.8 m height were chosen.

A geocomposite, comprising a geogrid structure as the carrier of the optical fiber sensor cables and a geotextile layer, has been chosen for the investigations on the settlement simulation laboratory test bench.

Nine samples of a fiber-optic cabling solution have been integrated into the fabric under test; six of them were interconnected to a chain of sensing fibers, running in parallel thorough the test bench (Figure 6). The fiber samples numbered 1, 2, 6 correspond to a 3.5

mm three-layer outdoor sensor cable solution; the fiber samples numbered 3, 4, 5 correspond to a 2 mm two-layer PVC/PUR cable.

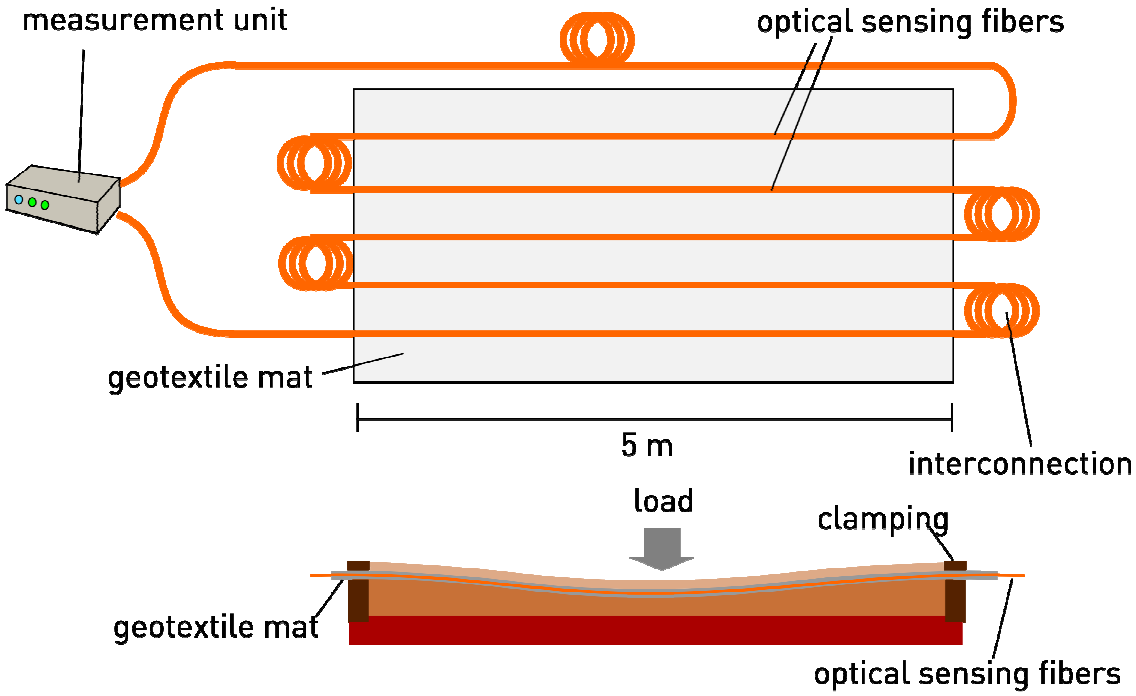

Figure 6: Layout of the optical fiber sensors embedded into the geosynthetic fabric at the settlement test bench

5.2 Measurement Results

Distributed strain measurements of the entire sensor chain were performed after integration as well as after each step of displacement induced by the hydraulic indenter load. After an induced displacement of 15 mm, the load was changed from a punctual indention to a plain load. Results from the fiber-optic measurements during the settlement tests on the test bench at HTW Dresden are shown in Figure 7. Depicted are the results from the two-layer cable solution; the scaling of the vertical axis corresponds to strain experienced by the sensing fibers, relative to the strain after the embedding.

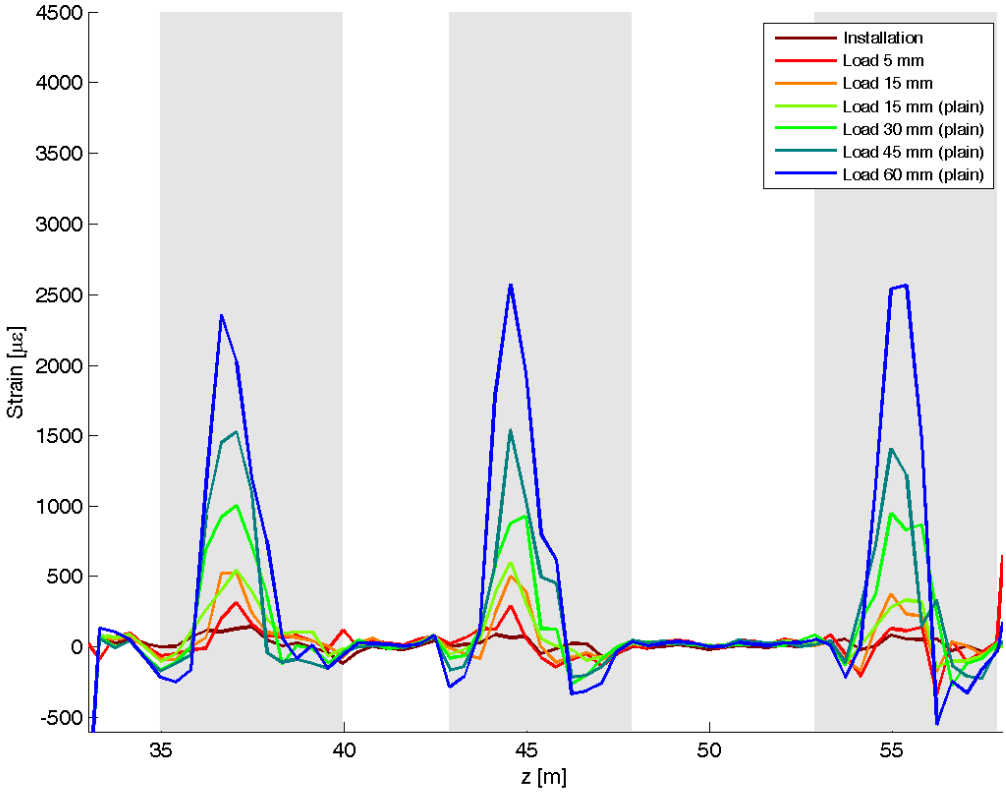

Figure 7: Results of distributed strain measurements, fiber samples 3, 4, 5 at the different deformation values induced by the hydraulic indenter load. The shaded areas correspond to the fiber sections that are integrated into the geosynthetic.

As a result, it can be seen that even a small settlement of 5 mm depth over a length of 5 m can be detected by the system. Details and results on these tests are reported [4].

6. Conclusions and Outlook

A novel architecture for a read-out unit for distributed Brillouin sensing has been introduced; the implementation is presented and validated by laboratory measurements. A technique for integration of distributed optical fiber sensors has been presented along with the proof of concept for its application as a settlement detection system.

Within the next months, field evaluation of the system will be performed with the focus on structural health monitoring both in geotechnical and rigid (steel/concrete) structures.

References

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