Displacement Monitoring in Geotechnical Applications Using Optical Fiber Sensors in Geosynthetics

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ABSTRACT

This paper reports on a novel approach to displacement detection in geotechnical structures. To provide an accurate monitoring of soil displacement – giving indications for failure mechanisms such as slope breaks, settlements and alike – optical fiber sensors for distributed strain measurement have been integrated into geosynthetic grid structures, resulting in a two-dimensional sensing element with the ability to detect arbitrarily oriented displacement events with a spatial accuracy down to 1 m.

INTRODUCTION

When the long-term stability of geotechnical structures is to be relied on, visual inspection will generally not suffice to obtain a feasible estimation of the structure's health; the application of constant monitoring systems becomes unavoidable for structures of ever increasing size, complexity and vulnerability. Brillouin sensing in silica optical fibers has proven to be a very promising approach for monitoring of large structures when a truly continuous profile of possibly occurring deformations is required. However, to provide reliable monitoring on the basis of sound measurement data, a readout unit alone will not suffice: For the fiber sensors that are to be applied in the field, considerations on cabling, integration techniques and a reliable mechanical coupling between structure and sensor are required. This leads to a complete system solution, to be designed and customized for each new monitoring task.

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DISTRIBUTED FIBER-OPTIC SENSING

Distributed Brillouin Sensing

Fiber-optic sensing techniques have become increasingly important in structural health monitoring during recent years. As a focus of these investigations, the technology of distributed strain and temperature sensing (DTSS) or distributed Brillouin sensing shall be introduced here.

In silica glass optical fibers (as they are used in millions of meters for data transmission over the world), the nonlinear effect of stimulated Brillouin scattering can be employed to create a truly distributed sensor to measure strain and temperature with a resolution down to 1 m, gapless at every location along a fiber over tens of kilometers [1]. With other fiber-optic sensing methods (such as point-wise or long-gauge strain measurement, quasi-distributed FBG sensing etc.), this technology shares the robustness to chemically harsh environments, strong electromagnetic fields and long term drifting effects [2]. Moreover, it provides an uninterrupted profile of information on strain and temperature along a large structure, allowing for precise estimations on fatigue and beginning failure.

The read-out system that has been employed within these investigations uses the principle of the Brillouin optical frequency domain analysis [3]: The sensing fiber is embedded into the structure under test in a loop configuration, both ends being connected to the read-out system. Optical signals of modulated laser light are injected into either end. Anywhere the two signals meet along the fiber, interaction (the so-called stimulated Brillouin scattering) occurs, after which the optical signals carry the information on temperature and strain at the meeting point. By analyzing both the quantity of interaction and the time of flight from the meeting point back to the read-out system, a spatially resolved profile for the temperature and strain distribution of the entire fiber can be created.

In contrast to the more classical approach of Brillouin optical time domain analysis – where the time of flight of short optical pulses leads to the spatial information – the frequency domain approach splits up the pulses into its spectral components, measuring them one after another. For the measurement unit, this approach implies considerable improvements in signal contrast and system robustness to fibers that have been suffering mechanical stress during integration. Moreover, it allows for a cost and power efficient digital implementation of the signal processing hardware.

Integration of Fiber-Optic Sensors in Geotechnical Structures

In geotechnical engineering, the technology is a powerful tool to detect critical soil displacement, such as slope breaks, settlements, erosion, piping etc. in railway/road embankments, river and coastal dikes etc. (Figure 1). With the aim to reliably detect deformation and displacement of arbitrary orientation and dimension within a three-dimensional structure by means of a one-dimensional fiber sensor, an accurate force transfer from the soil into the sensor needs to be provided.

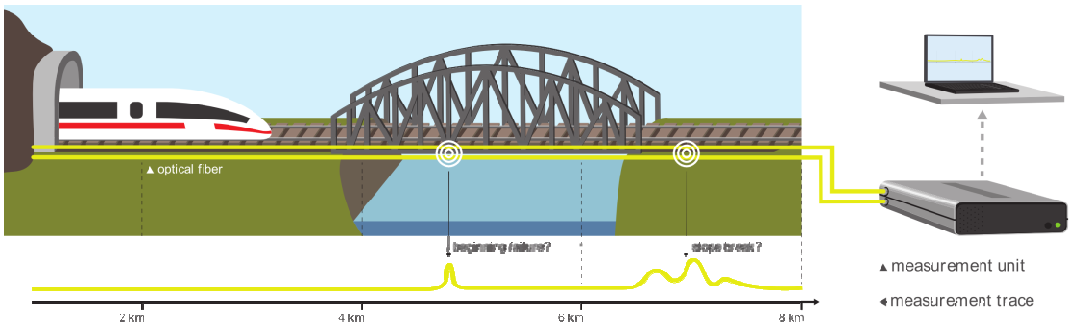

Figure 1. Distributed optical fiber sensors for deformation detection in large geotechnical structures.

For the coating and cabling of the fiber, a trade-off is needed between protection of the fiber from mechanical stress during transport on the one hand, and a good coupling to outside mechanical events to preserve the fiber's sensitivity on the other hand. Such a cable can be can be applied to rigid structures (concrete or steel); yet, for detection of critical soil displacement, a sole cable buried into the earth would not suffice, lacking mechanical grip to the structure and areal geometry for reliable coverage of narrow events.

INTEGRATING DISTRIBUTED FIBER SENSORS INTO GEOSYNTHETICS

Motivation

The use of various types of geosynthetics has become an essential instrument for the solution of a large number of geotechnical problems [4]. In addition to their native capabilities – draining, erosion prevention, layer separation etc. – the idea of a sensor-equipped geosynthetic fabric opens up a large field of applications where monitoring of geotechnical structures is required.

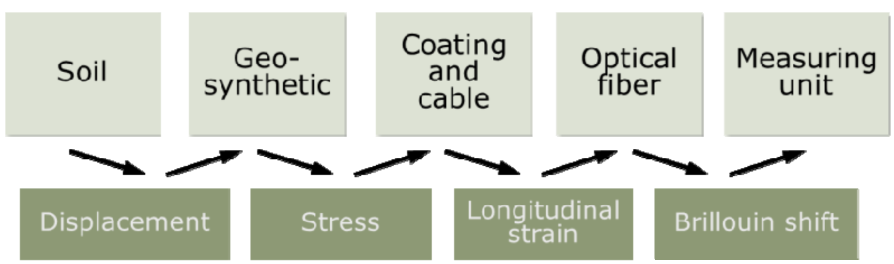

Figure 2. Transfer chain of the physical quantities from a displacement event in the soil to the measured sensor signal.

From the sensor point of view, the integration of the sensing cable into geosynthetics offers a way to take care of the entire, complex transfer chain from the actual geotechnical event to the measured quantity (Figure 2).

Two critical tasks are fulfilled by such a configuration: First, the coupling between soil and geosynthetic prevents slipping of the sensor within the soil; second, it will transfer the three-dimensional deformation into stress in the two dimensions of its own geometry, including the dimension of the sensing fiber. Thus, a sensing fiber, being coated with a specialty cable and integrated into a geotextile or geogrid, will experience stress from soil movement, even if the event occurs at a certain distance from the position of the fiber.

Integration Technique

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.

The read-out system reaches a spatial distribution of one meter and a strain accuracy of 2 με (corresponding to 2 μm elongation of 1 m fiber or 0.0002 % of strain) on a bare fiber. The uncertainty that is produced by cabling and textile integration will lower the sensitivity of the entire system due to unavoidable imperfections in the transfer chain (fiber slipping, elastic cable deformation etc.); earlier investigations have shown that more than 60 % of the elongation experienced by the geosynthetic in the orientation of the sensor are transferred into measurable fiber strain [3].

SETTLEMENT SIMULATION ON THE LABORATORY TEST BENCH

Measurement Setup

At the University of Applied Sciences (HTW) Dres-den 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. Figure 3 shows the cross-section of the test setup.

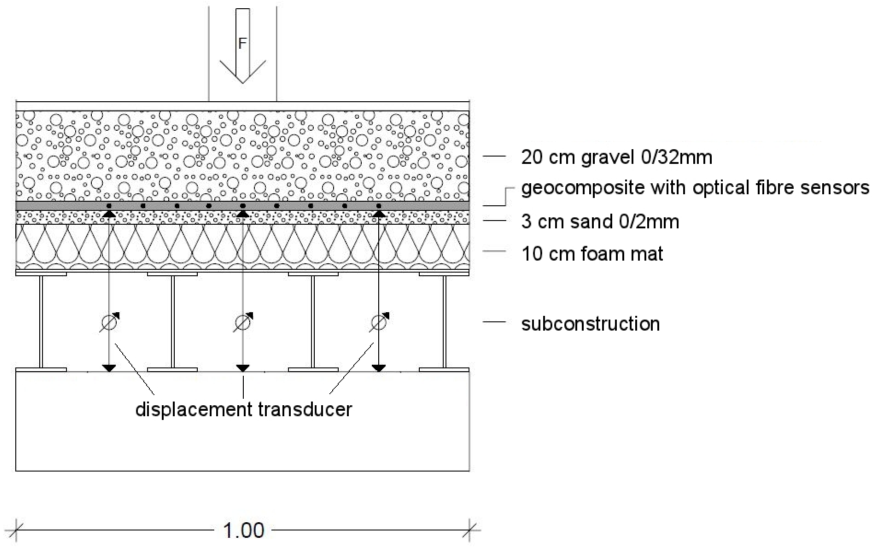

Figure 3. Cross-section of the test setup.

Digital displacement transducers for the continuous recording as well as analog displacement transducers being fixed to additional support points served to reference the settlements.

As shown in Figure 3, the geotextile is embedded between a 3 cm thick sand layer 0/2 mm at the bottom and a 20 cm thick gravel-sand-composite 0/32 mm at the top, to simulate a soil-soil-contact and thus to be able to make a test close to reality.

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 4). 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.

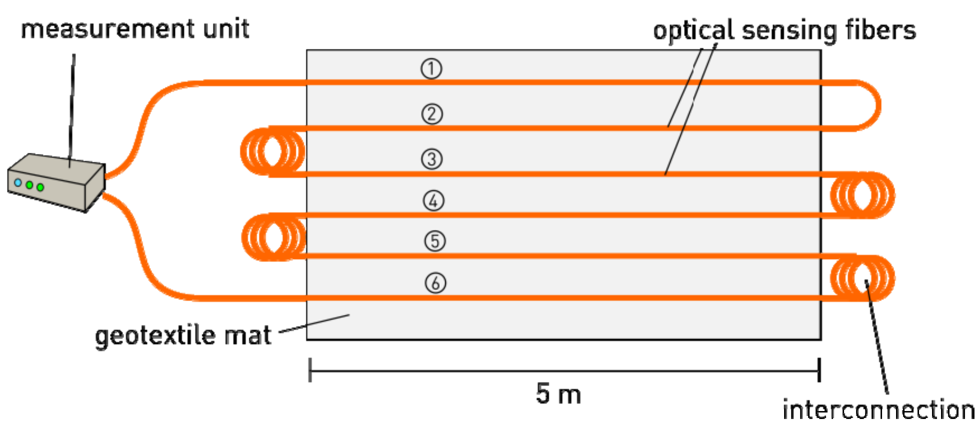

Figure 4. Layout of the optical fiber sensors embedded into the geosynthetic fabric at the settlement test bench.

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 5. 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.

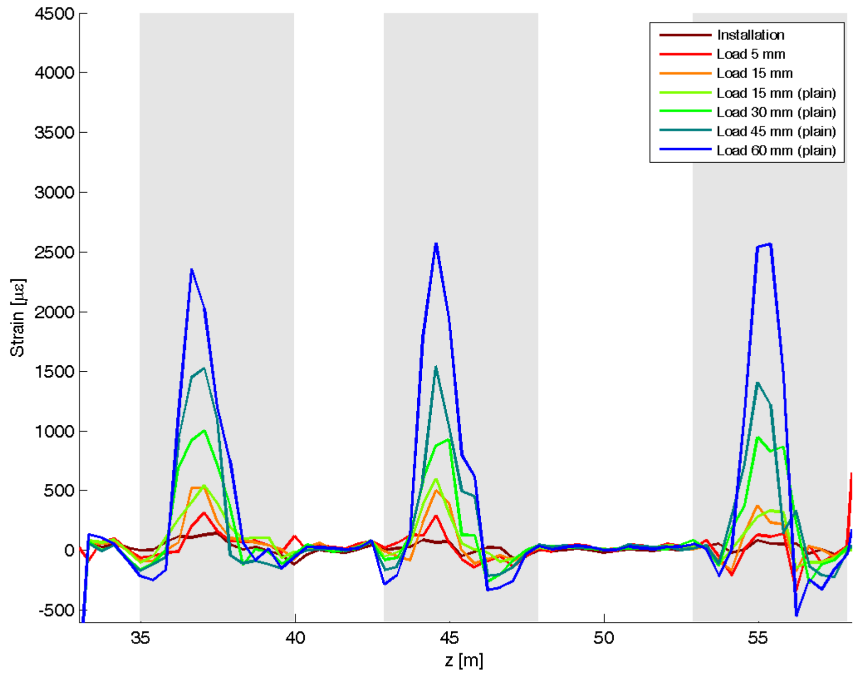

Figure 5. Results of distributed strain measurements, fiber samples 3, 4, 5 at the different deformation values induced by the hydraulic indenter load. The shaded areas correspond to the fiber sections that are integrated into the geosynthetic.

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. Further sensor calibration and modeling of the geometry of the cavity will be needed in order to produce quantifiable results.

On the test bench, a number of further measurement series was performed, including parallel displacement of one entire section of the bench – leading to shearing strain within the geosynthetic – as well as settlement measurements using polymer optical fibers instead of silica fibers. Details and results on these tests are reported [5].

CONCLUSIONS AND OUTLOOK

The integration of optical fiber sensors for distributed strain measurement into geosynthetics provides a promising, reliable and sensitive tool for monitoring of large geotechnical structures.

Further field testing will be needed to gather experience in terms of on-site handling, interconnection of sensor segments, quantifiable calibration and interpretation of the results. Within the next steps, adjacent distributed sensing technologies such as strain measurements using perfluorinated polymer optical fibers [6] will be investigated, in order to combine the technology of distributed Brillouin sensing with redundancy for higher strain ranges.

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