Application of distributed Brillouin optical fiber sensor systems in geo-technical monitoring

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Abstract:
The potential of advanced commercial fiber optical Brillouin Distributed Strain and Temperature Sensor (DSTS) systems for safety monitoring of geo-technical structures such as railroad embankments, tunnel construction, and landslides has been demonstrated.

Distributed fiber optic sensor technology has progressed at a rapid pace over the last decade. Strain measurement with a distributed Brillouin scattering based sensor system provides excellent opportunity for geotechnical monitoring. Using this technology it will be possible to create the wide metrological basis for an evidence-based risk assessment in geotechnology. This makes it possible, among other things, to optimize the construction process in such a way that a balance is created between improving safety and reducing costs.

1. Distributed Brillouin scattering based sensing technology

One class of Brillouin-based sensors is based on the Brillouin loss technique, whereby two counter-propagating laser beams, a pulse and a CW, exchange energy through an induced acoustic field. When the beat frequency of the laser beams equals the acoustic (Brillouin) frequency, ν_B, the pulsed beam experiences maximum amplification from the CW beam. By measuring the depleted CW beam and scanning the beat frequency of the two lasers, a Brillouin loss spectrum centered about the Brillouin frequency is obtained.

The sensing capability of Brillouin scattering arises from the dependence of the Brillouin frequency, ν_B, on the local acoustic velocity and refractive index in glass, which has a linear strain dependence through

$$\nu_B (T_0 , \varepsilon) = C_\varepsilon (\varepsilon - \varepsilon_0) + \nu_{B0} (T_0 ,\varepsilon_0) \tag{1}$$

where C_ε are the strain coefficient, and ε_0 and T_0 are the strain and temperature corresponding to a reference Brillouin frequency ν_{B0}. By varying the spatial resolution, it can provide the scale of material strain measurement and structural strain monitoring.

Spatial information along the length of the fiber can be obtained through optical time domain analysis (OTDA) by measuring propagation times for light pulses traveling in the fiber. This allows continuous distributions of the strain to be monitored. The spatial resolution (gauge length) can be varied according to the application required, even after the fibers have been installed in the structure, by simply altering the length of the light pulse used. These systems offer unmatched flexibility of measurement locations and the ability to monitor a virtually unlimited number of locations simultaneously.

2. Application examples

2.1 Monitoring system for settlement observation of endangered railroad embankments

In karst areas may occur local sinkholes and large soil subsidences. Such phenomena represent a potential risk for the railway embankments, which have to pass such areas. Sheetpile retaining walls constructed in form of a cofferdam ensure the stability of the railway embankments in this zone. However, this construction is a black box. That means it is impossible to detect local sinkholes and soil subsidences within the cofferdam caused by deeper underground displacements visually.

Therefore, a two-stage fiber optic measurement and warning system is designed for installation within the cofferdam construction under the endangered dam section. This measurement system operates on the basis of the integral optical fiber length measurement (fiber optic extensometer FOX) and on the basis of the distributed strain sensing technology (Brillouin scattering).

Fig.1 Cable layout

Fig.2 Outdoor housing of the measuring units

In order to measure the deformations within the cofferdam construction, expansion sensitive fiber optic cables have been laid as sensors underneath the backing layer in a grid-like arrangement in six parallel cable trenches. In case of a sinkhole or a subsidence the strain sensitive cables are stretched or compressed in these areas. This length variations are monitored automatically in the first step by means of the integral optical fiber length FOX measurement.

The limits of the permissible length variations, which do not constitute hazards, were determined by geotechnical experts. If a length change is measured which exceeds this limit, the localization of the strain event takes place in the second step using the distributed fiber optic strain measurement based on the Brillouin scattering. After surveying of the track bed by the German Railways and analysis of all measurement results, the determination of further procedures takes place by German Railways in consultation with geotechnical experts.

In this paper the results of a real application project will be presented.

2.2 Monitoring system for previous convergence measurements in tunnel construction

Over the past few years the number of tunneling projects in Europe has increased considerably. The construction of tunnels is still one of the most dangerous construction projects. Although the safety measures have improved significantly in recent years, but during tunneling there are still numerous incalculable risks. Cause of accidents are mostly loose sand, gravel, and mud masses within solid rock layers that penetrate during excavation in the tunnel and very often lead to fatal accidents. The geology of the mountain range represents often a major problem for the tunnel builders, because certain geotechnical factors are often impossible to estimate by the geologist or civil engineers.

The objective of an ongoing R & D project is to develop a method for previous convergence measurements in tunnel new construction or renovations tunnel. The system is intended to allow the measurement of convergences (movements of the rock) qualitatively and quantitatively already during mined excavation, to assess and determine appropriate measures to secure the mountain and for correcting the forward speed. Thus, an amount to increase working safety will be made. To achieve this goal it is planned to install a measuring system during mined excavation along the tunnel axis using the DSTS System.

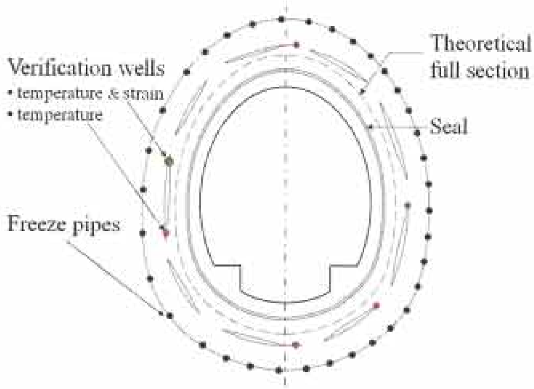

Fig.3 Freeze tunnel cross section

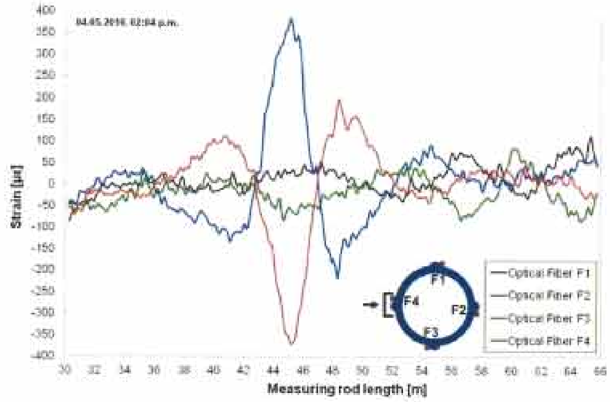

Fig.4 Measured strain distribution in the verification well

The Brillouin technology makes it possible to determine differences in temperature and expansions in fiber optic cables. The innovation of this R & D project is to fix a fiber optic cable rigidly to a support medium (tube) und the instrumentation in a borehole for connection to the surrounding rock. Possibly occurring temperature fluctuations must be compensated for in the measurements.

A large series of experiments were performed statistically supported. The results will be presented.

2.3 Sensor for prewarning debris flow

With climate change and deforestation, debris flows and debris avalanches have become the most significant landslide hazards in many countries. In recent years there have been numerous debris flow avalanches in China, Southern Europe, South America and the Indian Subcontinent, resulting in major catastrophes and large loss of life.

One of the major difficulties of monitoring debris flows and debris avalanches stems from the fact that the areas where debris flows and debris avalanches may happen can be kilometers and unknown a priori. Conventional sensors have difficulties surviving their surrounding harsh environments and have electrical noise problems. Since the areas where debris flows and debris avalanches may happen are not known a priori, conventional point sensors are not effective in debris flows and debris avalanches monitoring. Hence there is an urgent need for a real-time monitoring system that can intelligently monitor the areas where debris flows and debris avalanches may happen and pre-warn debris flows and debris avalanches.

Debris flows generally form when unconsolidated material becomes saturated and unstable, either on a hillslope or in a stream channel, which give us a hint that we can pre-warn debris flows if we can monitor the change of unconsolidated material by using appropriated technology.

Therefore it can pre-warn debris flows and debris avalanches by measuring the strain along the optic fiber cable. Since a distributed Brillouin scattering-based sensor system allows measurements to be taken along the entire length of the fiber, rather than at discrete points, by using fiber itself as the sensing medium, it gives the strain value versus the location of the optic fiber cable, i.e. the areas where debris flows and debris avalanches may happen will be indicated.

In this paper the fiber optic distributed strain and temperature sensor (DSTS) with sensing optic fiber cable up to 100km for pre-warning debris flows and debris avalanches will be presented.

3. Conclusions

Advanced commercial Brillouin DSTS systems like that of OZ Optics Ltd. were successfully tested for geotechnical monitoring. The successful tests open a lot of new possibilities in geotechnical monitoring with the goal to create a good balance between improving safety and reducing costs.