Distributed Sensors for Underground Deformation Monitoring

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ABSTRACT: Distributed fiber optic sensing offers the ability to measure temperatures and strains at thousands of points along a single fiber. This is particularly interesting for the monitoring of large structures such as dams, dikes, levees, tunnels, pipelines and landslides, where it allows the detection and localization of movements and seepage zones with sensitivity and localization accuracy unattainable using conventional measurement techniques. Sensing systems based on Brillouin and Raman scattering are used to detect and localize seepage in dams and dikes, allowing the monitoring of hundreds of kilometers along a structure with a single instrument and the localization of the water path with an accuracy of 1 meter. Distributed strain sensors are also used to detect landslide movements and to detect the onset of cracks in concrete dams. The contribution will concentrate on long-term field applications of this technology for the monitoring of an I-wall levee in New Orleans (USA), a sinkhole area in Kansas (USA) and an underground penstock in Switzerland. The paper will review the sensor design and installation technique used in each application and provides feedback on the use of such systems over several years of operation.

1 INTRODUCTION

The growing demand of safety awareness, cost effective operations and effective maintenance has rapidly stimulated, in the last decade, the development of smart monitoring techniques capable of detecting early-stage events, thus preventing structures from major failures and leading to a better knowledge of the structure itself. In the field of geotechnical applications such as dams, levees, bridges, buildings, landslide, sinkhole and tunnels, where both the large structure dimensions and damage location forecast represent a challenge, distributed techniques offer the capability of monitoring over several kilometers using a single Fiber Optic Sensor, (FOS). The advantage of using a, few, single sensors encourage the use of this new technology that offers high measurement resolution, high spatial resolution, continuous monitoring at an affordable cost, Glisic Inaudi (2007).

1.1 F.O. Strain Distributed Technology

Distributed Strain F.O. Technology is based on the exploitation of the Brillouin scattering, Karashima (1990). Systems able to measure strain or temperature variations of fibers with length up to 50 km with spatial resolution down in the meter range are now demonstrating their usefulness in field applications. Brillouin scattering is the result of the interaction between optical and sound waves in optical fibers. Thermally excited acoustic waves (phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light propagating in the fiber is diffracted backward by this moving grating, giving rise to a

frequency-shifted component by a phenomenon similar to the Doppler shift. This process is called spontaneous Brillouin scattering. Acoustic waves can also be generated by injecting in the fiber two counter-propagating waves with a frequency difference equal to the Brillouin shift. Through electrostriction, these two waves will give rise to a traveling acoustic wave that reinforces the phonon population. This process is called stimulated Brillouin amplification. If the probe signal consists in a short light pulse and its reflected intensity is plotted against its time of flight and frequency shift, it will be possible to obtain a profile of the Brillouin shift along the fiber length.
The most interesting aspect of Brillouin scattering for sensing applications resides in the temperature and strain dependence of the Brillouin shift, Nikles (1997). This is the result of the change of the acoustic velocity according to variation in the silica density. SMARTEC commercializes a system based on this setup and named DiTeSt (Figure 1). It features a measurement range up to 50 km, depending on sensing cable intrinsic attenuation, per channel with a spatial resolution that can go down to 1 m.
The strain resolution is observed in the range of 2 με and the temperature resolution 1°C. The number of channels can be extended by a 4-20 channel Switch. The system is transportable and can be used for field applications.
Since the Brillouin frequency shift depends on both the local strain and temperature of the fiber, the sensor setup will determine the actual sensitivity of the system. For measuring temperatures it is sufficient to use a cable designed to shield the optical fibers from an elongation of the cable. The fiber will therefore remain in its unstrained state and the frequency shifts can be unambiguously assigned to temperature variations. Measuring distributed strains requires a specially designed sensor. A mechanical coupling between the sensor and the host structure along the whole length of the fiber has to be guaranteed. The next section will introduce different types of cable typically used in real, large scale projects.

Figure 1. DiTeSt – Distributed Temperature and Strain analyzer.

1.2 F.O. Strain Distributed Sensors

This paper wants to focus on distributed strain monitoring for geotechnical application. We will therefore shortly present the most common distributed sensing cable used for these particular applications.

1.2.1 SMARTprofile – Combined Strain and Temperature sensor

The SmartProfile sensor design (Figure 2) combines strain and temperature sensors in a single package. This sensor consists of two bonded and two free single mode optical fibers embedded in a polyethylene thermoplastic profile. The bonded fibers are used for strain monitoring, while the free fibers are used for temperature measurements and to compensate temperature effects on the bonded fibers. For redundancy, two fibers are included for both strain and temperature monitoring. The profile itself provides good mechanical, chemical and temperature resistance. The size of the profile makes the sensor easy to transport and install by fusing, gluing or clamping. This sensor is designed for use in environments often found in civil, geotechnical and oil & gas applications. The sensor can be placed inside a fiber glass socks or a geo-textile in order to improve its mechanical resistant (e.g. rodents' bites) and increase the contact area in the soil.

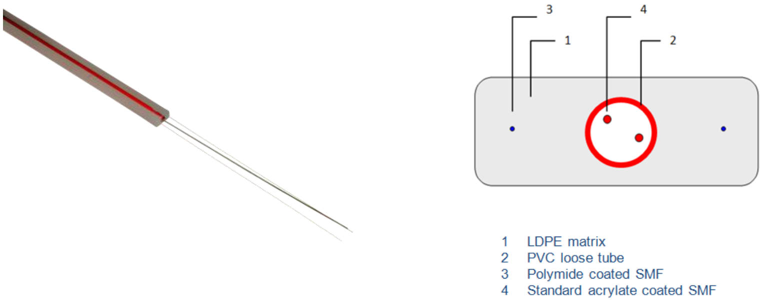

Figure 2. SMARTprofile - combined Strain and Temperature sensor.

1.2.2 Hydro & Geo – Hybrid distributed Strain and Temperature sensor

The Hydro & Geo Sensing cable is a unique sensor for the evaluation of distributed strain and temperature over several kilometers. This sensing cable is a small fiber optic cable, with a symmetric circular section protected by a dense member of aramid and an outer Low Smoke Zero Halogen – Non Corrosive jacket (Figure 3). The cable contains 4 SM, Single Mode, and 2 MM, Multi-Mode, optical fibers, allowing the sensor to be used both with Brillouin and Raman reading units for distributed strain and temperature monitoring. This sensor can be used with different methodology of installation: direct burial in the ground and concrete or integration into geo-textile fabric.

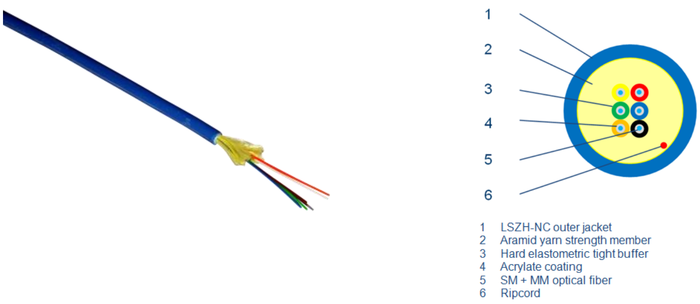

Figure 3. Hydro & Geo - Hybrid distributed Strain and Temperature sensor.

1.2.3 Reinforced Hydro & Geo – Hybrid distributed Strain and Temperature sensor

This particular sensor (Figure 4) is a natural evolution of the Standard / regular Hydro & Geo sensors. Thanks to an additional layer of CST, Corrugated Steel Tape, this sensor can be used in very harsh environments where big displacement, large rodent presence or uncontrolled, potentially dangerous, mechanical events are expected. The sensor offers the same technical features of the standard Hydro & Geo sensors with higher mechanical robustness.

Figure 4. Reinforced Hydro & Geo - Hybrid distributed Strain and Temperature sensor.

2 GEOTECHNICAL MONITORING – LARGE SCALE PROJECTS

In the following sections the aim is to concentrate on long-term, large-scale field applications based on the presented distributed technology and sensors.

2.1 I-Wall levee – New Orleans (US)

The iLevees project "Intelligent Flood Protection Monitoring Warning and Response Systems", in the state of Louisiana, has the goal of providing an alerting and monitoring system capable of preventing early stage failure, both in terms of ground instability and seepage. The motivation for the monitoring system is to improve safety awareness, provide sensible information about levees' status and conditions, before, during and after floods, and to avoid the tragic events like the ones that occurred following Hurricane Katrina in 2005. The use of distributed fiber optic sensing will help in overcoming the issue of optimal sensor location allowing full structure coverage over several kilometers. The continuous long-term monitoring during the complete levee lifetime will allow for the collection of data that can improve our general knowledge of these structures, with unquestionable benefits in future levee designs, operation and maintenance. To demonstrate difference sensing technologies, a number of test sections have been instrumented, including an I-wall and T-wall section instrumented with different distributed strain; SMARTprofile and Hydro & Geo, and temperature sensors.
The project had the goal to monitor the levee wall, deformation and shear, and the surrounding soil, movements and water infiltration / seepage.
The particularity of the project was the installation technique adopted for the levee wall integration. In order to provide a good transfer of the acting forces from the wall to the sensor itself a good bonding strength shall be given: to do this it was decided to "cut" a groove all along the installed section, where the SMARTprofile sensor was deployed and sealed by means of specific episodic resins. The SMARTprofile sensor was not the only strain sensor installed.

The site challenges and the big shears measured during the first months persuaded to equip a section with Hydro & Geo sensor, less sensitive to small movements but more flexible and suitable to measure shears in the range of 5 cm and more.
For the surrounding soil a more common ground embedding technique was chosen on the base of our previous returns of experience. Sensors are embedded between 0.5 and 1 m below the ground level, after compacting the trench, the sensors are deployed and covered with soft filling material. After this operation the trench is back-filled and compacted. Installation details are presented in Figure 5 and Figure 6.

Figure 5. Installation of SMARTprofile sensor in a trench on the surrounding of the levee wall.

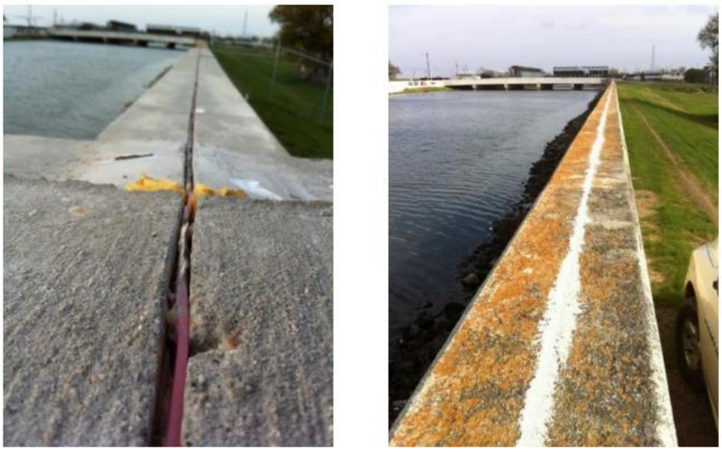

Figure 6. Installation of SMARTprofile sensor in a groove on top of the levee wall section.

An example of calculated deformation on the sensor placed on the top of the wall section I presented in Figure 7. Deformation is plotted as a function of position along the wall and as a function of time.

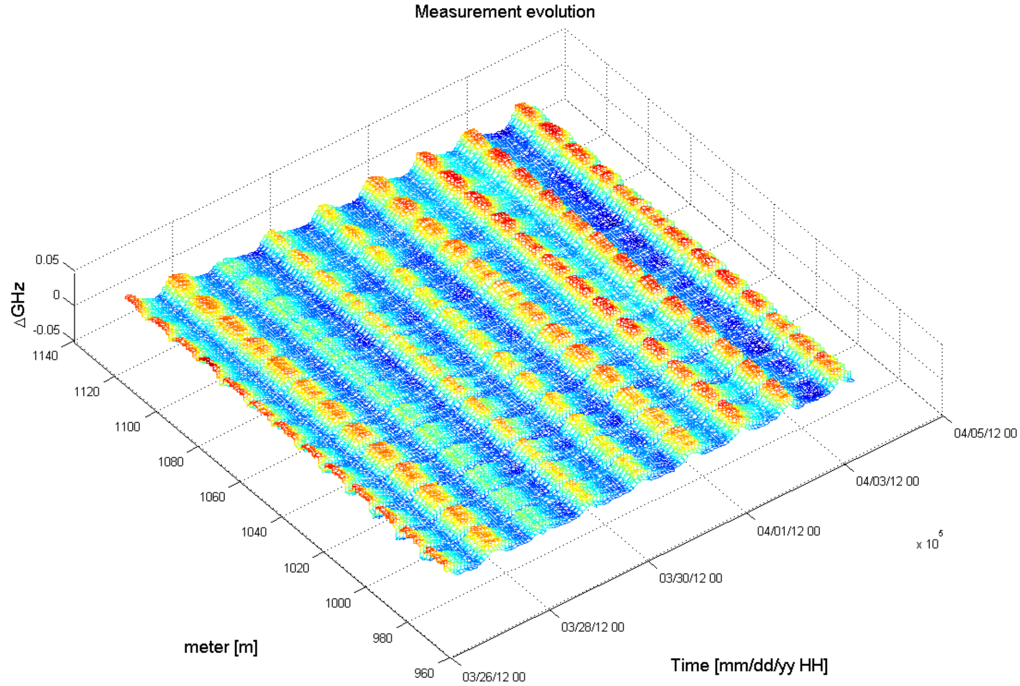

Figure 7. Recorded deformations on a levee wall as a function of position and time.

In the plot it is possible to observe the daily expansion-contraction cycles of the wall due to temperature fluctuations. It is also possible to localize the expansion joints along the levee wall that shows a different behavior. In case of an event along the levee section, a localized deformation peak will appear in the visualization software and would automatically trip an alarm.

2.2 Sinkhole early development monitoring project – Hutchinson (US)

The city of Hutchinson is located in Reno County, Kansas. Hutchinson is on the route of the trans-continental, high-speed mainline of one of the nation's largest railroads. The railway passes near a former salt mine well field, where mining was carried out in the early part of the twentieth century. The salt mining was performed at depths of over 400 feet by drilling wells through the shale bedrock into the thick underground salt beds, and then pumping fresh water into the salt, dissolving the salt to be brought back to the surface as brine, for processing and sale. This solution mining process resulted in the presence of multiple, large underground voids and caverns, which have been reported to be up to 300 feet tall and over 100 feet in diameter.
In certain places, the shale roof rock over some of these old mine voids has collapsed, forming crater-like sinkholes that can be over 100 feet in diameter and 50 feet deep at the surface. The collapse and sinkhole formation can occur very rapidly, over a period of hours to days.

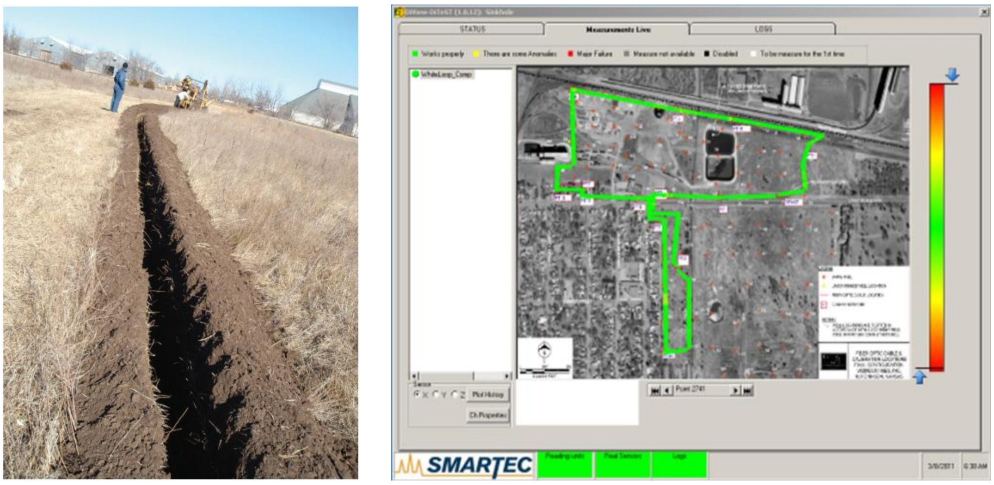

Figure 8 Installation of Reinforced Hydro & Geo sensor in a trench and cable path on map.

A Distributed Strain Monitoring system was selected because its advantage of providing thousands of monitored points using a single F.O. cable, measured in a single scan, Shefchik Tomes Belli (2011). The system can detect and determine the exact location of where a sinkhole might appear, giving an automated alarm to the Hutchinson Fire Brigade. In addition to this, the system was selected because of the ease of installation by burial in a shallow trench, Figure 8. The sensing cable, Reinforced Hydro & Geo, selected because of the presence of big size rodents, is directly buried at a depth of approximately 1.4 m, (4 ft), over a potential sinkhole area above and around salt caverns over a path with a total length of over 4 km, (13,000 ft) – see Figure 8 right. After digging the trench, the salty soil was mechanically compacted, and the sensing cable installed on the compacted soft ground before the trench was backfilled.

In order to assess system capabilities in terms of ground deformation detection and alert triggering, sinkhole simulation tests were carried out. These tests are aimed to evaluate and confirm the performances of the whole final system intended as sensor, reading unit and data management software working together. The tests consisted in vertically displacing the sensing cables in short sections without backfill, in order to induce strain and simulate the symptoms of ground deformation, Figure 9. It is possible to observe that the location of the disturbance is clearly visible and increasing the displacement increases the area under the curve of the measured displacement.

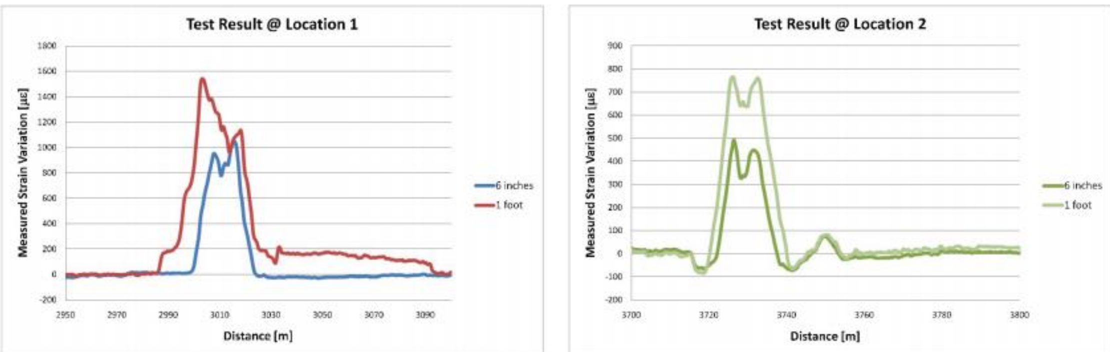

Figure 9 Distributed strain measurements during tests.

2.3 Penstock movement monitoring project – Nendaz (CH)

The penstock of an important mountain dam in the Swiss Alps, is subject to rock mass movements that can influence its mechanical performance, Jordan Papilloud 2015. In order to provide a safe installation, the penstock is made of several pipe sections welded together in order to form a more flexible pipe, thus allowing a higher degree of movement. Nevertheless a deformation monitoring system is necessary to detect any abnormal penstock deformation and penstock curvature. In addition to this, the penstock access tunnel is also affected by concrete cracking due to the water pore pressure and rock movements. A distributed strain monitoring system was selected because of its capability to monitor long lengths trough a single cable, thus simplifying installation. A different installation technique is chosen for the 2 different sections: in the penstock, where precise and accurate monitoring under water is required, the SMARTprofile is directly glued on the internal surface. The steel penstock is sand-blasted to offer a smooth and clean installation surface where 510 m, linear length, of SMARTprofile is glued along 4 different lines, Figure 10.

Figure 10 SMARTprofile sensor installation inside the penstock.

On the other hand, for the access tunnel a mixed installation technique was selected: SMARTprofile was directly glued on concrete for most of its length, but fixed with stainless steel bracket where wide cracks were already visible and developing; this decision was taken in order to preserve sensor from breaking in case the crack keep developing, Figure 11. This installation technique allows a precise and accurate monitoring over the whole length of this tunnel of approximately 70 m.

Figure 11 SMARTprofile sensor installation on penstock access tunnel.

After 3 years of monitoring the collected results are in line and good agreement with the mathematical predictions and other geo-matic measurements provided by additional monitoring systems installed at site. A typical example of Strain distribution measured in the penstock access tunnel clearly shows the location of open developing cracks, peaks can be seen and easily localized along the SMARTprofile length, Figure 12.

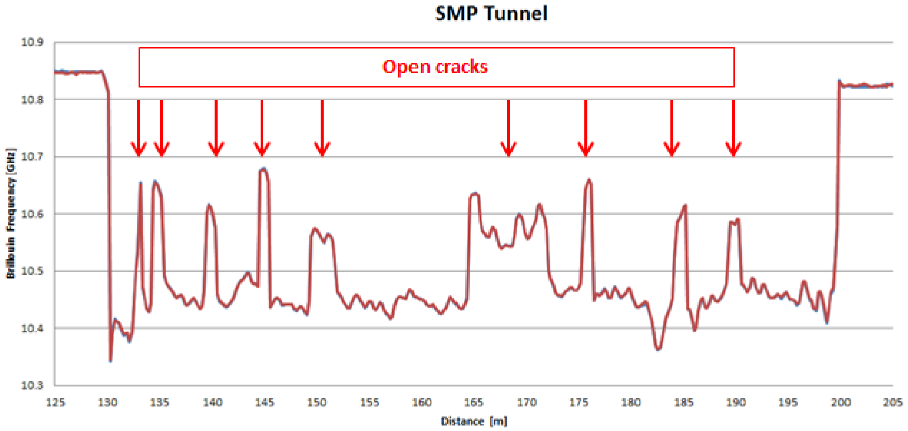

Figure 12 SMARTprofile strain distributed measured along the penstock access tunnel.

3 CONCLUSIONS

The use of distributed fiber optic analyzes and sensing cables in the development of geotechnical projects offers features and capabilities that are not common and does not have any equivalent in the conventional sensors market. Thanks to main advantage of using a single, or few, F.O. sensing cables of long lengths, up to kilometers, it becomes possible to obtain dense information on the structure's strain distribution / profile. This technology is therefore particularly suitable for applications to large or elongated structures; such as levees, dams, pipelines and other geotechnical structures. The presented applications examples show that selecting the appropriate system design and suitable distributed sensor, it is possible to successfully install distributed sensors on large structures and obtain useful data for the evaluation and management of the monitored structures.

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