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LOCALIZATION OF INSTABILITY ZONES IN LEVEES, LANDSLIDES, SINKHOLES AND TUNNELS WITH DISTRIBUTED OPTICAL FIBER SENSORS

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Structural health monitoring (SHM) is a process that provides accurate and real-time information concerning structural condition and performance. Requirements for structural health monitoring in the last few decades have rapidly increased, and these requirements have stimulated many new developments of various sensing technologies. Distributed optical fiber sensing technology has opened new possibilities in structural monitoring. Distributed deformation sensors (sensing cables) are sensitive at each point of their length to strain and temperature changes. Such a sensor is therefore able to record one-dimensional strain fields and can be installed over the entire length of the structure (levee, landslide, sinkhole area, tunnel, etc.), and therefore provides assurance for integrity monitoring and for direct detection, characterization (including recognition, localization, and quantification or rating), and report of local strain changes and movements. These sensors are therefore not only able to measure strain (answering the "how much" question) but also how to localize damage areas (answering the "where" question). This makes them ideal for monitoring structures where the location of possible instability or failure is a-priori unknown. For example the sensor can detect and localize a seepage zone in a levee, the onset of a sinkhole in a subdivision or the formation of a crack in a tunnel liner.

Distributed sensing techniques and components based on Brillouin and Raman scattering are briefly introduced and their potential for use in monitoring is discussed. Finally, several large-scale case studies are presented, including levee monitoring, sinkhole detection and tunnel crack detection.

Keywords: distributed sensors, fiber optic sensors, structural health monitoring, damage localization, instability monitoring, sinkhole monitoring, levee monitoring, tunnel monitoring.

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ABSTRACT

Structural health monitoring (SHM) is a process that provides accurate and real-time information concerning structural condition and performance. Requirements for structural health monitoring in the last few decades have rapidly increased, and these requirements have stimulated many new developments of various sensing technologies. Distributed optical fiber sensing technology has opened new possibilities in structural monitoring. Distributed deformation sensors (sensing cables) are sensitive at each point of their length to strain and temperature changes. Such a sensor is therefore able to record one-dimensional strain fields and can be installed over the entire length of the structure (levee, landslide, sinkhole area, tunnel, etc.), and therefore provides assurance for integrity monitoring and for direct detection, characterization (including recognition, localization, and quantification or rating), and report of local strain changes and movements. These sensors are therefore not only able to measure strain (answering the "how much" question) but also how to localize damage areas (answering the "where" question). This makes them ideal for monitoring structures where the location of possible instability or failure is a-priori unknown. For example the sensor can detect and localize a seepage zone in a levee, the onset of a sinkhole in a subdivision or the formation of a crack in a tunnel liner.

Distributed sensing techniques and components based on Brillouin and Raman scattering are briefly introduced and their potential for use in monitoring is discussed. Finally, several large-scale case studies are presented, including levee monitoring, sinkhole detection and tunnel crack detection.

1 1 INTRODUCTION

The growing demand of safety awareness has stimulated, in the last few years, the development of several monitoring techniques capable of detecting early stage events, thus preventing structures from major failures and leading to a better knowledge of the structure itself [1], [2] . In the field of geotechnical applications such as levees, landslide, sinkhole and tunnels, where both structure dimensions and “a-priori” damage location forecast represent a challenge, distributed techniques offer the capability of monitoring over several kilometers using a single Fiber Optic Sensor, FOS. Thus, using a limited number of very long sensors it is possible to monitor structural and functional behavior of geo-structures with a high measurement and spatial resolution at a reasonable cost [3].

1.1 Read-out units

Developed for telecommunication applications, OTDRs (Optical Time Domain Reflectometers) have been the starting point of distributed sensing techniques. They use the Rayleigh scattered light to measure the attenuation profiles of long-haul fiber optics links. The time information is converted to distance information if the speed of light is known, similar to radar detection techniques. Raman and Brillouin scattering phenomena have been used for distributed sensing applications over the past few decades. Raman was first proposed for sensing applications in the ‘80s, whereas Brillouin was introduced later as a way to enhanced the range of OTDR and then for strain and/or temperature monitoring applications. Both Raman and Brillouin scattering effects are associated with different dynamic non-homogeneities in silica and therefore have completely different spectral characteristics.

The Raman scattered light is caused by thermally influenced molecular vibrations. Consequently, the backscattered light carries the information on the local temperature where the scattering occurred. Since the magnitude of the spontaneous Raman backscattered light is quite low, high numerical aperture multimode fibers are used in order to maximize the guided intensity of the backscattered light. However, the relatively high attenuation characteristics of multimode fibers limit the distance range of Raman-based systems to approximately 10 km, but with recent developments can go up to 30 km. The SMARTEC’s DiTemp system, Distributed Temperature, is based on Raman Scattering and shown in Figure 1 left.

Brillouin scattering occurs because of an interaction between the propagating optical signal and thermally excited acoustic waves in the GHz range present in the silica fiber, giving rise to frequency shifted components. It can be seen as the diffraction of light on a dynamic grating generated by an acoustic wave (an acoustic wave is actually a pressure wave which introduces a modulation of the index of refraction through the elasto-optic effect). The diffracted light experiences a Doppler shift since the grating propagates at the acoustic velocity in the fiber. The acoustic velocity is directly related to the density of the medium that is temperature and strain dependent. As a result, the so-called Brillouin frequency shift carries the information about the local temperature and strain of the fiber. The SMARTEC's DiTeSt system**,** Distributed Temperature and Strain, is based on Brillouin Scattering and depicted in Figure 1.

Figure 1. DiTemp (Raman), left, and DiTeSt (Brillouin), right, distributed read-out units

1.1 1.2 Distributed Strain and Temperature FOS

The development of such distributed technologies has led to the development of suitable fiber optic sensing cables capable of detecting strain and temperature with high accuracy and reliability [5]. The efforts done in such a field allowed production of different distributed FOS: SMARTape I / II, SMARTprofile, SMARTube and SMARTGeoTex Fabric and Rope.

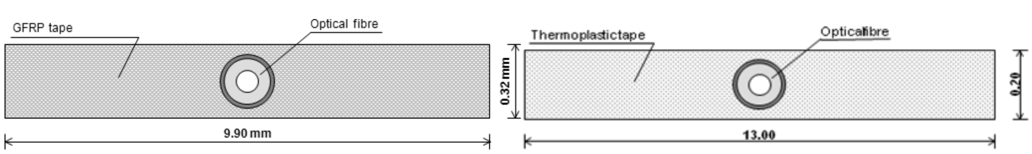

Figure 2. SMARTape I FOS, right, and SMARTape II FOS, left

The SMARTape I and SMARTape II FOS, Figure 2, are mainly suitable for high precision monitoring where sensitivity is important. These 2 sensors are typically used in applications where surface installation on flat surfaces is allowed and not in installations where direct embedding in ground/soil and concrete is requested. Made of a single FO they are used in strain-deformation and crack detection, this sensor provides a high level of reliability and sensitivity. The very limited dimensions and weight of the sensors make the installation, preferentially by gluing, easy and relatively fast.

The SMARTprofile FOS, Figure 3 right, is suitable both for structural and geotechnical monitoring over long distances, where precise localization of the event is a topic. This sensor can be used both in surface installation, by gluing or clamping with specifically customized anchor points, or in direct embedding, both in ground/soil or concrete. Made of 4 FO, 2 dedicated for strain monitoring and 2 for temperature monitoring or as loop back fiber, this sensor provides high level of mechanical protection and good sensitivity thanks to low longitudinal stiffness. The limited optical losses allow covering distances up to 10 km. Its dimensions and limited weight make the handling and installation easy and fast.

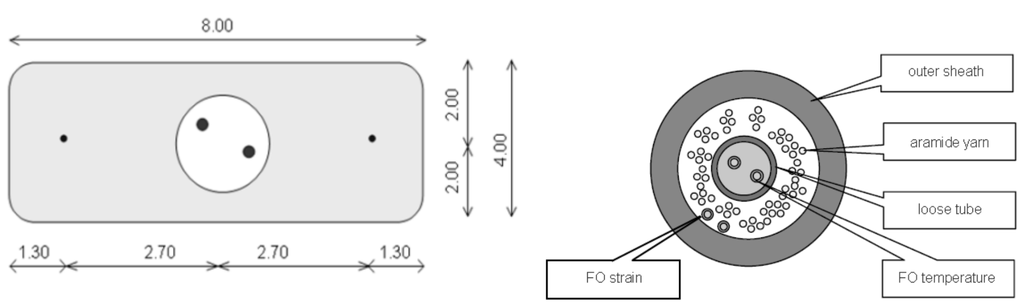

Figure 3. SMARTprofile FOS, right, and SMARTube FOS, left

The SMARTube FOS, Figure 3 left, has been specifically developed for geotechnical applications where direct embedding, both in ground/soil and concrete, is requested. Made of 4 FO, 2 dedicated for qualitative strain monitoring and 2 for temperature monitoring or as loop back fiber, this sensor provides good mechanical reliability and good sensitivity at low cost. The limited optical losses allow covering distances up to 10 km. Its circular shape, its dimensions and limited weight make the handling and installation easy and fast.

The increasing demand of monitoring of geotechnical structures such as levees, landslide, sinkholes, etc has encouraged the development of specialized FOS capable of fulfilling monitoring requirements, sensitivity and reliability, and at the same time provide mechanical robustness and strengthening features. This research has led to the production of SMARTGeoTex Fabric and SMARTGeoTex Rope, Figure 6. Made on the base of SMARTprofile and SMARTube FOS and integrated into geo-textile fabric and rope structures, these sensors are particularly suitable for direct embedding installation in ground/soil. The integration with geo-textile structure, besides offering a better mechanical protection, enhance sensor's performances in terms of sensitivity and detection of small events.

2 APPLICATIONS AND CASE STUDIES

In this paragraph some large-scale project, implemented exploiting the above presented technologies and components, are presented. The aim is to illustrate the suitability and flexibility of such technologies in different applications.

1.2 2.1 Levees monitoring

A levee or dyke is a barrier built in order to retain large water accumulations of large rivers, lakes or sea seaboards. There are different types of dyke, depending on their construction manner. In general, the main components are a watertight clay core, a filling material (such as earth or rocks) and, close to the surface, it may have a filtering layer and a reinforced concrete jacket [1].

Dykes are frequently founded on a soil with relatively bad mechanical properties. They have a trapezoidal cross-section, being very wide at the base and relatively narrow at the top. The angles of the slopes depend on the construction material and are imposed by stability conditions. Being a barrier for large water accumulations, in order to increase safety and insure structural reliability, dykes shall be monitored. The main aims of monitoring levees are early detection of slope instability, uncontrolled seepage and piping or internal erosion due to seepage. Uncontrolled seepage can be a consequence of cracking in the concrete jacket or clay core generated by water pressure combined with long-term settlement of dyke materials. That is why the deformation in the jacket, core and soil should be monitored.

The stability of slopes depends mainly on the construction material, the water table level in the dyke itself and the pore pressure in the soil. Pore pressure, therefore, is an important parameter to be monitored as well.

Due to their wide extensions and impossibility of clearly figure out "a-priori" critical sections, a distributed sensing system results to be particularly suitable for integrity monitoring and damage localization. This system is mainly intended to provide for crack detection and average strain monitoring, and can replace discrete deformation and temperature sensors. Schematic positions of the distributed sensors in the cross-section are presented in Figure 4.

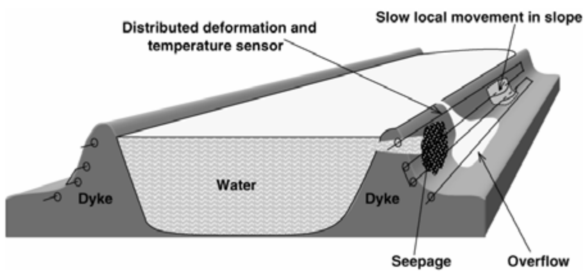

Figure 4. Schematic representation of distributed deformation and temperature FOS locations in a levee for seepage and overflow detection (distributed temperature FOS) and localization of slow slope movements (distributed strain FOS)

The distributed systems offer the unique capability of monitoring both strain and temperature simultaneously: distributed deformation FOS can provide for detection and localization of slow movements in the slopes; at the same time distributed temperature FOS can provide for seepage or overflow detection. Seepage or overflow changes the thermal properties of the soil, which are detected by the temperature sensor; the slow local movement of a slope puts the deformation sensor in tension. In both cases, localization and evaluation of the size of the area involved can be performed. The principles are shown schematically in Figure 4.

For such applications SMARTprofile and SMARTube FOS result to be very suitable, moreover selecting a SMARTGeoTex solution, detecting capabilities can be enhanced both in terms of early stage movement detection and seepage monitoring. In this case the choice of a SMARTGeoTex solution beside the monitoring capabilities can provide reinforcement capabilities thus leading to a double benefit and a better safety.

SMARTEC has recently joined the iLevees project" Intelligent Flood Protection Monitoring Warning and Response Systems", state of Louisiana – US, with the aim of providing an alerting / monitoring system capable of preventing early stage failure, both in terms of ground instability and seepage. The idea beyond the monitoring system is to improve safety awareness, provide sensible information about levees status / conditions, before, during and after floods, and avoid tragic events like the ones occurred after the Hurricane Katrina. The use of the DiTemp / DiTeSt systems will help in overcoming the issue of sensor location allowing full structure coverage over several kilometers. The continuous / long-term monitoring during levee lifetime will allow collecting data to improve our general knowledge on these structures, with unquestionable benefits in levees design, operation and maintenance.

1.3 2.2 Sinkholes and ground stability monitoring

A sinkhole, also known as a sink, shake hole, swallow hole, is a natural depression or hole in the Earth's surface caused by karsts processes, the chemical dissolution of carbonate rocks or suffusion processes for example in sandstone. Sinkholes may vary in size from 1 to 600 meters both in diameter and depth, and vary in form from soil-lined bowls to bedrock-edged chasms, Figure 5. Sinkholes may be formed gradually or suddenly, and are found worldwide. It is clear that such phenomena represent a risk for ground stability and a non-negligible safety risk for surface infrastructure in the surrounding areas.

In such applications where critical area localizations and the use of the discrete sensors is practically impossible because of the installation complexity and costs, the DiTeSt distributed system and the SMARTGeoTex FOS result to be particularly suitable [5].

Figure 5. Sinkhole formation

SMARTEC has developed a monitoring solution where the DiTeSt monitoring system was selected in large part because its capability of providing thousands of monitored points using a single FO sensing cable, all measured at the same time, in a single scan. This is well suited to defining a monitored perimeter, where the exact location of where a sinkhole might form, in the vicinity of the old salt wells, is not known precisely. The DiTeSt monitoring system was also selected because of the ease of installation, by burial in a shallow trench.

The selection of the sensing cable represents a key aspect, and at the same time, a big challenge, in the development of this project: the cable needs to be capable of withstanding hostile environmental conditions, such as wide temperature variations and burial in the earth, as well as being resistant to burrowing rodents. The cable also needs to be sensitive enough to provide early and reliable displacement detection, and capable of optimizing the transfer of forces from the ground to the fiber. Such a trade-off between robustness and sensitivity is obtained through in-house cable development and extensive testing to assess both the mechanical reliability and its sensitivity to displacements and external forces.


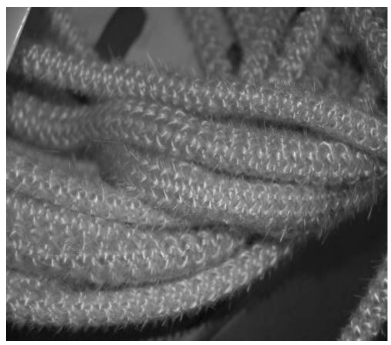

Figure 6. SMARTGeoTex Rope, left, site-installation, right

The SMARTGeoTex Rope FOS is directly buried, Figure 6, at a depth of approximately 1.4 meters over a potential sinkhole area above and around salt caverns over a path with a total length of over 4 km.

After digging the trench, the soil is mechanically compacted, and the sensing cable deployed on the compacted soft ground before the trench is finally backfilled. The sensing cable is installed in several segments in order to provide easier handling during installation, and to adapt to the site by running the cable through several short, horizontally bored segments beneath a large drainage ditch, multiple road crossings, and other obstacles at the surface. All cable segments are later linked together to form a single sensing loop by FO fusion splicing; the splices between segments as well as some extra lengths of non-buried cable are stored in dedicated, above-ground junction boxes, that can be accessed for maintenance as well as for re-routing segments of cable in case a break were to be caused by the formation of a sinkhole.

2.3 Tunnel monitoring

Being underground structures, tunnels shall be monitored during their whole lifespan [1]. The selection of suitable monitoring instrumentation as well the sensors location shall be decided according to tunnel typology, soil mechanical quality and purpose of the tunnel. The main goal of tunnel monitoring is to achieve a better knowledge of the structure behavior in order to plan effective maintenance and prevent major damages. Beside traditional monitoring techniques and point-wise FOS to monitor convergence, local strain and temperature, the innovation is the use of distributed FOS for average strain, temperature and integrity monitoring. A distributed monitoring system is, by its own nature very suitable and efficient for the monitoring of tunnels where total lengths can reach several kilometers.

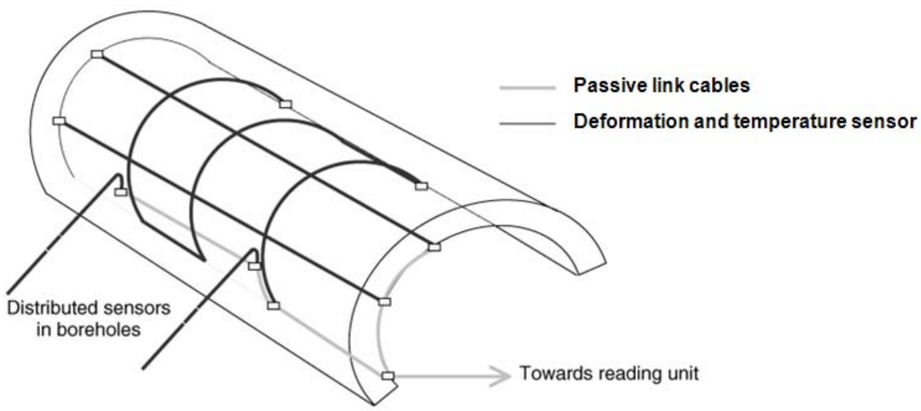

Figure 7. Schematic example of tunnel integrity monitoring

Distributed fiber optic sensing cables are installed on the walls and vaults, depending on the tunnel typology and shape, in longitudinal and tangential directions, Figure 7. These sensors provide for crack detection and localization and for detection of local average strain changes due to damage or ground settlement.

Moreover the distributed sensors provide for average strain distribution and temperature monitoring. With proper installation, FOS can be even used for fire detection.

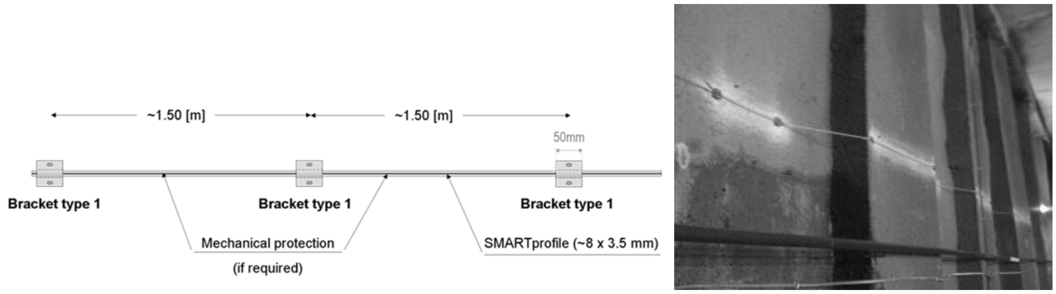

Figure 8. SMARTprofile FOS surface installation

Taking into account the number of monitoring parameters and tunnel dimensions, distributed sensing techniques represent convenient, cost effective and multi-purpose solution.

SMARTEC has developed a monitoring solution where the FO DiTeSt and SMARTprofile solution were selected. In order to insure structural safety during construction works in a critical area affected by soil settlement, 15 km of SMARTprofile sensors are installed at 5 different locations around the tunnel section, 2 locations on each vertical wall and 1 in the horizontal deck between the 2 railway lines. Installation is carried out by surface clamping the SMARTprofile FOS to the concrete walls, Figure 8.

3 CONCLUSIONS

This publication is aimed to present integrated solution for instability monitoring in geotechnical applications.

The flexibility of the presented FO distributed systems, the easiness of installation and the variety of distributed sensor, make these systems suitable for different application from pure ground stability monitoring, such as sinkhole area, to structural / integrity monitoring of geotechnical structure such as levees and tunnels. Multiple detection capabilities make these systems suitable for monitoring of several parameters and events like, such as strain, deformation, temperature, crack opening and development, seepage / tunneling, sinkhole formation and ground instability.

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