The 6th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Hong Kong | 9-11 December 2013

MONITORING DAMS AND LEVEES WITH DISTRIBUTED FIBER OPTIC SENSING

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ABSTRACT

Dams and Earthen embankments including levees, tailings dams, and earthen dams present many challenging problems for Civil Engineers, particularly in the verification of their structural integrity and capacity, operation and maintenance (O&M), inspection, and safety. The sheer size and scale, age and uncertainty of materials in these sometimes mammoth structures all combine to present a difficult array of parameters for the levee professional to navigate when analyzing a new or existing levee or dam. Traditional instrumentation based on localized point sensor is not sufficient to guarantee the detection and localization of early signs of degradation.

To make things more difficult, there are an ever growing number of assets and lives these structures protect downstream or in the “flood plain,” and more and more emphasis is being placed on the vulnerability of these structures. Also, in the wake of flood disasters associated with Hurricane Katrina and others, a complex regulatory environment has emerged; requiring engineers to certify structural and geotechnical fortitude. Levee and dam asset owners and engineers are exposed to more responsibility and liability than ever.

Recent advances in instrumentation technologies and applications are providing new ways the Civil Engineer examines these structures, and present engineers with a set of monitoring tools never thought possible. Distributed fiber optic technologies create sensors that are of scale and size to finally match the dam or levee, and present an interesting, reliable, cost effective way of monitoring these structures everywhere. These sensors can provide information about the strain and temperature distribution in a dam, every meter and over distances of up to several tens of kilometers. This allows the early detection, localization and sizing of defects and degradations such as seepages, leakages, settlements, shearing, abnormal joint movements, intentional tampering and over-flooding.

This contribution will present numerous application examples of this new technology to real dams and dykes in Europe, the Americas and Asia.

KEYWORDS

Monitoring systems, dam monitoring, levee monitoring, leakage detection, fiber optic sensor, DTS and DTSS, Raman, Brillouin.

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. In the field of structural and 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). Thus, using a limited number of very long sensors it is possible to monitor structural and functional behavior of structures with a high measurement and spatial resolution at a reasonable cost (Glisic and Inaudi 2007).

DISTRIBUTED FIBER OPTIC TECHNOLOGY

Unlike electrical and localized fiber optic sensors, distributed sensor offer the unique characteristic of being able to measure physical parameters along their whole length, allowing the measurements of thousands of points using a single transducer (Inaudi and Glisic 2007).

The most developed technologies of distributed fiber optic sensors are based on Raman and Brillouin scattering (Inaudi D. et al. 2012). Both systems make use of a non-linear interaction between the light and the silica material of which a standard optical fiber is made. If light at a known wavelength is launched into a fiber, a very small amount of it is scattered back at every point along the fiber. The scattered light contains components at wavelengths that are different from the original signal. These shifted components contain information on the local properties of the fiber, in particular their strain and temperature.

Raman Distributed Temperature Technology

Raman scattering is the result of a non-linear interaction between the light traveling in a fiber and silica. When an intense light signal is shined into the fiber, two frequency-shifted components called respectively Raman Stokes and Raman anti-Stokes will appear in the back-scattered spectrum. The relative intensity of these two components depends on the local temperature of the fiber. If the light signal is pulsed and the back-scattered intensity is recorded as a function of the round-trip time, it becomes possible to obtain a temperature profile along the fiber (Dakin et al. 1986). Systems based on Raman scattering are commercialized by SMARTEC in Switzerland and Sensornet in UK (Figure 1).

Typically a temperature resolution of the order of 0.1°C and a spatial resolution of 1m over a measurement range up to 30 km are obtained for multimode fibers.

Figure 1: DiTemp Harsh (5-12km) and DiTemp Light (4km)

Brillouin Distributed Strain Technology

Brillouin scattering sensors show an interesting potential for distributed strain and temperature monitoring (Karashima et al. 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 (Niklès et al. 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 (see Figure 2). It features a measurement range of 50 km per channel with a spatial resolution of 1 m. The strain resolution is 2 $\mu\varepsilon$ and the temperature resolution 1°C. The number of channels can be extended by a 4-20 channel Switch. The system is portable 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 cable designs to measure strain and temperature in different applications.

Figure 2: DiTeST unit and Multiple Channel Switch

DISTRIBUTED FIBER OPTIC SENSING CABLE

Traditional fiber optic cable design aims to the best possible protection of the fiber itself from any external influence. In particular it is necessary to shield the optical fiber form external humidity, side pressures, crushing and longitudinal strain applied to the cable. These designs have proven very effective in guaranteeing the longevity of optical fibers used for communication and can be used as sensing elements for monitoring temperatures in the –40°C to +80°C range, in conjunction with Brillouin or Raman monitoring systems. For Brillouin scattering systems, it is important to guarantee that the optical fiber does not experience any strain that could be misinterpreted as a temperature change due to the cross-sensitivity between strain and temperature. On the other hand, the strain sensitivity of Brillouin scattering prompts to the use of such systems for distributed strain sensing, in particular to monitor local deformations of large structures such as pipelines, landslides or dams. In these cases, the cable must faithfully transfer the structural strain to the optical fiber, a goal contradicting all experience from telecommunication cable design where the exact opposite is required. In a distributed sensor, the whole optical fiber is the sensor itself.

Finally when sensing distributed strain it is necessary to simultaneously measure temperature to separate the two components. This is usually obtained by installing a strain and a temperature sensing cables in parallel. It would be therefore desirable to combine the two functions into a single packaging. The next paragraph explores cable designs that address hose different needs.

Distributed armoured temperature sensing cable

The DiTemp/DiTeSt armored temperature sensing cable (Figure 3) is a small fiber optic cable, composed of stainless steel loose tube gel filled stainless steel strength members and plastic outer sheath. The central loose tube is hermetically sealed and contains 4 fibers for redundancy and layout flexibility.

This sensor is particularly suitable for outdoors and harsh environment applications with different methodology of installation: direct burial in the ground or concrete, clamped to a pipe, anchored or glued.

Thanks to the special package design this cable offers high tensile strength, crush resistance, lateral water tightness, chemical and abrasion resistance and excellent rodent protection. At the same time, the small cross-section and the metallic construction insure a quick transfer of temperature changes from the outside environment to the fibers.

Figure 3: DiTemp armored sensing cable

Distributed self-heating temperature sensing cable (copper + fiber optic)

The DiTemp self-heating temperature sensing cable (Figure 4) is a unique sensor for the evaluation of distributed temperature over distances up to 1.5 km. This cable is mainly used in a range of hydro and geo-technical applications that require distributed temperature sensing, where the temperature contrast between the ground and the leaking fluid to be monitored is not sufficient to provide a reliable detection. Therefore it is particularly used in the monitoring of dams, dikes and levees where heat pulse method is required. . The outer HDPE sheath ensures the cable to be watertight. This sensor is particularly suitable for outdoors and harsh environment applications with different methodology of installation: direct burial in the ground or concrete or anchored to an already existing structure.

Thanks to the special package design the cable offers high tensile strength, crush resistance, lateral water tightness, chemical and abrasion resistance and standard rodent protection.

The isolated copper wires permit to heat the cable up by circulating an electrical current in it. The temperature increase and the velocity of cooling depend on humidity content and the water flow in the soil surrounding the cable. By measuring the temperature response with the DiTemp system, it become possible to determine if the soil around each 1m section of cable is dry, wet or exhibits water flow.

Figure 4: DiTemp self-heating temperature sensing cable

Distributed strain sensing tape: SmarTape II

The DiTeSt SmarTape II sensor (Figure 5) consists of a single mode optical fiber embedded in a Glass Fiber Reinforced Polymer / Epoxy tape. The tape itself provides high mechanical, chemical and temperature resistance. The size of the tape makes the sensor easy to transport and install. The SmarTape II sensor is designed for use in harsh environments often found in civil and geotechnical engineering applications. It is usually glued to the structures, but can also be clamped or embedded into composite. The sensor can be read by a DiTeSt reading unit. A distributed temperature sensing cable installed in parallel is recommended if thermal effects on the measurements have to be compensated.

Figure 5: SmarTape II

Combined distributed strain and temperature sensing: SmartProfile

The SmartProfile sensor design (Figure 6) 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. The SmartProfile 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 6: SmartProfile cable and integration in geo-textile

Hybrid distributed sensing cable: Hydro&Geo

The Hydro & Geo Sensing cable is a unique sensor for the evaluation of distributed strain and temperature over several kilometers. The Hydro & Geo 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 (see Figure 7). The Hydro & Geo Sensing cable contains 4 Single Mode and 2 Multi Mode optical fibers, allowing the sensor to be used both with DiTeSt and DiTemp reading unit for distributed strain and temperature monitoring. This sensor is particularly suitable for outdoors geotechnical applications with different methodology of installation: direct burial in the ground or concrete, integration into geo-textile fabric. The Hydro & Geo cable is fully compatible with the DiTeST and DiTemp systems and all its accessories.

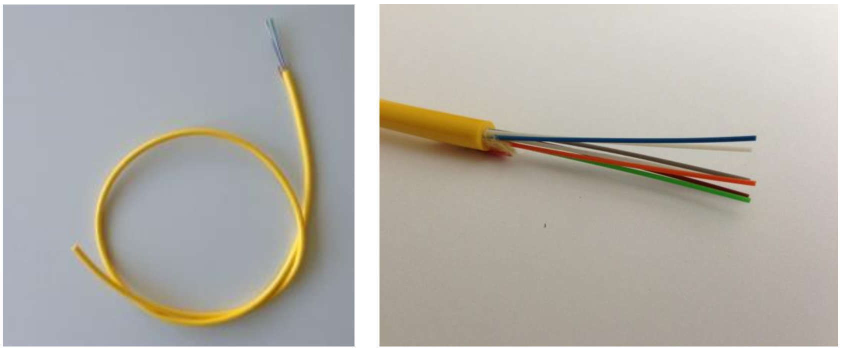

Figure 7: Hydro & Geo cable

DiView Software

The main functions of DiView software are aimed to measure distributed sensors automatically. The operator can view in real time the sensor's measurement history in graphical form (see Figure 8). Software is also able to trigger alerts (SMS, mail and phone call) and show warnings on the display. Warnings can be generated for different types of events, including: strain, temperature, leakage and crack. The software is able to combine measurements from different sensing cable, to obtain complex results, such as temperature compensated strains. An optional module is dedicated to the detection of leakages form pipelines, dikes, reservoirs and other similar structures, by identification of local temperature anomalies. Another optional module is dedicated to the detection of crack from distributed strain data. The DiView software and the additional module offer numerous configurable parameters and options.

The software stores all information related to a sensor in a single data-base structure. All data can be easily exported to third-party software included MS Excel and MS Access. Multiple users can access the software simultaneously from different PC (locally or remotely over a modem or LAN).

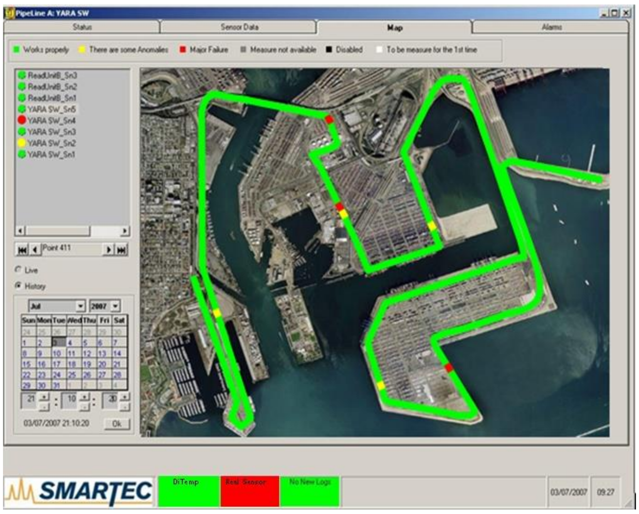

Figure 8: DiView: Distributed Data Management Software ScreenShot

INSTRUMENTATION OF DAMS AND LEVEES WITH DISTRIBUTED SENSORS

In the following sections, we will illustrate several applications of distributed strain and temperature sensing for the monitoring of dams and levees.

Application Example: Nam Ngum 2 Dam (Laos)

Nam Ngum Reservoir is the largest water impoundment in Laos; it was created in 1971 by the construction of a first dam across the Nam Ngum River. The reservoir was conceived primarily for the production of hydro-electric power and flood control. The Nam Ngum 2 Hydroelectric Power Project is located approximately 35 km upstream of the existing Nam Ngum 1 dam, about 90km out of Vientiane, on the Nam Ngum River, which is one of the major tributaries to the Mekong River.
The project, with an installed capacity of 615 MW is being built to produce energy for the Thai electricity grid and for local consumption. The dam is 181 meters high and it can produce 2300 KW of electric power per hour.

The main aim of the instrumentation installed is to monitor the seepages at the foundation plinth level by an active detection system, using the heat pulse method. A total of 2 independent armored sensing cables (approx 900m each) have been integrated in the filter zone by surface installation. The DTS DiTemp reading unit with 4Ch is located in the dam control station with the aim of measuring the temperature profiles of the 2 sensing cables. Thanks to the *DiView* customized visualization software it's possible to follow in real time any variation in the temperature profiles of the two sensing cable, launching a warning in case of any seepage or leakage.

Figure 9: Upstream side of the Nam Ngum 2 dam in Laos PDR

Figure 10: Distributed temperature sensing cable installation at plinth level

Application Example: Tailing dam (Chile)

The operation of tailing dams, typical of mining operations, in their construction phases includes the hydraulic deposit of the sand, which will form the retaining structure of the reservoir. This deposit phase is programmed, forming thin layers of coarse, clean sand which is further compacted. This volume dries out the excess water to accept the next layer. This system has shown to be cost and quality effective, and has been used for the last century, changing from an upstream to a downstream deposition method, which has proven to be safer for the retaining structure under seismic conditions. The area of deposit of the sand is moved along the dam in order to assess the dissipation of the transport water, which has to evaporate and/or drain into the underlying compacted sand strata. At the initial state of the dams, the sand deposition is not simple for the operators, as the cyclone plant, which selects the coarse sand fraction from the fine silty slime, has an excess elevation pressure due to their physical locations, the deposit area is very small, the runs for dissipating the excess water are very short and the surplus water tends to accumulate over the horizontal drains, with possible clogging the open drainage matrix.

A tight control of the presence of water in the base of the dam by means of 10 fiber optic piezometers and 2300m of DiTemp distributed armored temperature cable, located some 2 meters above drainage layers (*Fahrenkrog C. and Fahrenkrog A. 2012*). The fine slimes are deposited into the basin, usually at a close location to the retaining dam, which allows to naturally select the remaining coarse fraction to be in close contact with the dam profile and later moves to the far upstream side, where the water separates from the fines and is pumped again into the process, forming a lagoon against the natural hillsides of the reservoir. As indicated in the figure 11 - the hydraulic conditions of a tailing dam are changing during the different construction stages and have to be addressed with a monitoring layout, which will allow the most of the variables to be recorded and controlled during the active and passive phase of the basin.

In order to control the stability and prevent landslides, 9 SOFO sensors (long base fiber optic sensors) have been installed in the body of the dam. The sensor has been inserted in a special structure that adheres completely to the soil (see figure 12). Three SOFO sensors put together forms a tridimensional gauge for settlement and lateral deformation.

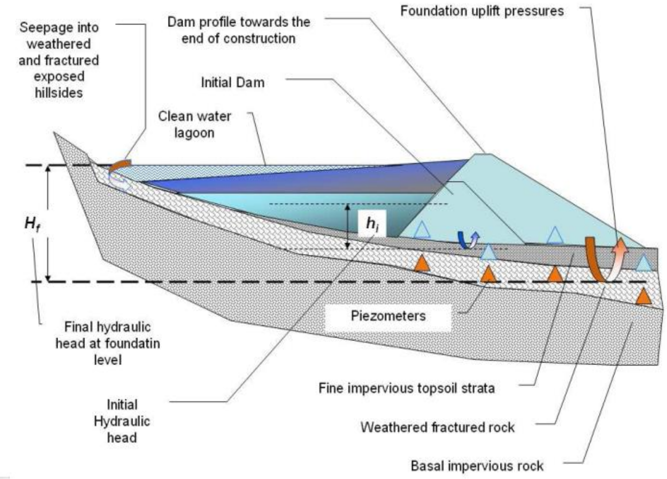

Figure 11: the hydraulic conditions of a tailing dam

Figure 12: Special packaging for SOFO sensor and cable installation

Application Example: River Dam (Latvia)

Plavinu hes is a dam belongs to the complex of three most important hydropower stations on the Daugava River in Latvia (see figure 13). In terms of capacity this is the largest hydropower plant in Latvia and is considered to be the third level of the Daugavas hydroelectric cascade. It was constructed 107 km distant from the firth of Daugava and is unique in terms of its construction - for the first time in the history of hydro-construction practice; a hydropower plant was built on clay-sand and sand-clay foundations with a maximum pressure limit of 40 m. The HPP building is merged with a water spillway. The entire building complex is extremely compact. There are ten hydro aggregates installed at the hydropower plant and its current capacity is 870,000 kW.

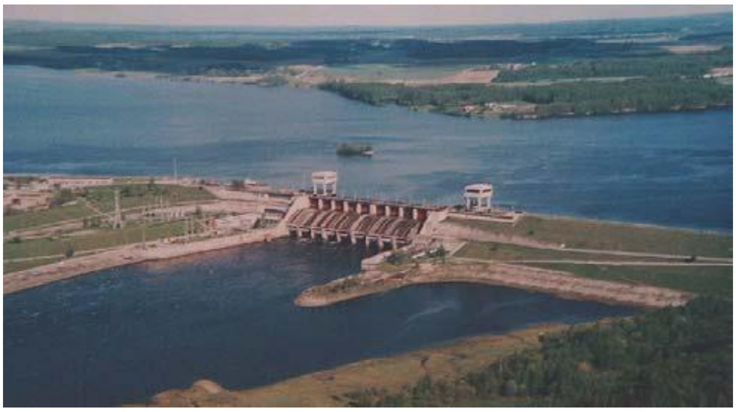

Figure 13: Daugava River and dam

One of the dam inspection galleries coincides with a system of three bitumen joints that connects two separate blocks of the dam. Due to abrasion of water, the joints lose bitumen and the redistribution of loads in concrete arms appears. Since the structure is nearly 40 years old, the structural condition of the concrete can be compromised due to ageing. Thus, the redistribution of loads can provoke damage of concrete arm and as a consequence the inundation of the gallery. In order to increase the safety and enhance the management activities it was decided to monitor the average strain in the concrete arm next to the joints. The DiTeSt system with SMARTape deformation sensor and Temperature Sensing Cable is used for this purpose (see figure below). The sensors were installed by company VND2 with SMARTEC support and configured remotely from the SMARTEC office. Threshold detection software with a relay alarm module was installed in order to send pre-warnings and warnings from the DiTeSt instrument to the Control Office.

Figure 14: Installation of SmarTape and Temperature Sensing Cable

Application Example: iLevee project (USA)

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 distributes strain and temperature sensors.

Figure 15 and 16 show the installation of SMARTProfile distributed strain and temperature sensing cables in the levee foundations and on top of the I-wall and T-wall section. These sensors allow the detection and localization of events such as levee failure onset, seepage, tunneling, and formation of cracks in wall sections or abnormal joint movements.

Figure 15: Installation of SMARTprofile sensor in a trench on the protected side of the levee

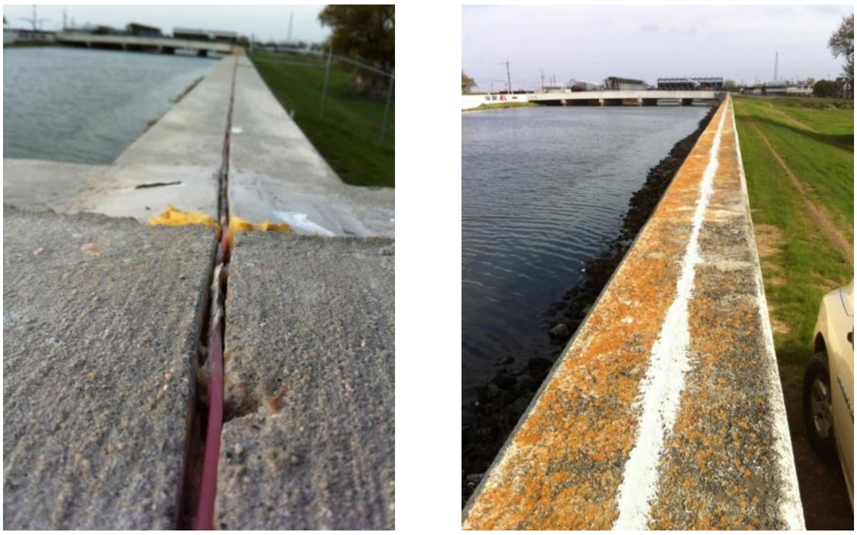

Figure 16: Installation of SMARTprofile sensor in a groove on top of the levee wall section

CONCLUSIONS

The use of distributed fiber optic sensors for the monitoring of civil structures and infrastructures opens new possibilities that have no equivalent in the conventional sensors system. Thanks to the use of a single optical fiber with a length of tens of kilometers, it becomes possible to obtain dense information on the structure's strain and temperature distribution. This technology is therefore particularly suitable for applications to large or elongated structures; such as dams, mines and levees but also bridges and pipelines. The presented applications examples show that using an appropriate sensor design, it is possible to successfully install distributed sensors on large structures and obtain useful data for the evaluation and management of the monitored structures.

ACKNOWLEDGMENTS

The authors would like to thank all partners that have contributed to the realization of the cited application examples, including owners, engineering companies and installation companies. In particular we would like to acknowledge the contribution of STS - Soil Testing Siam in Thailand, Geomediciones in Chile, VND2 Ltd In Latvia, Geocomp Inc in the USA, Shannon and Wilson Inc in the USA as well and the Louisiana Office of Coastal Protection and Restoration in the USA.

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