Distributed fiber optic structural health monitoring for dams

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Abstract

All types of dams, tailings dams, dikes and associated structures like penstocks, tunnels and reservoirs 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. Traditional instrumentation (both long base and point sensors) as well as no-contact sensors (laser scanning, SAR interferometry etc) are not sufficient to guarantee the detection and localization of early signs of degradation. A conscious combination of different technologies offers the best guarantee of a proper SHM. Distributed fiber optic technologies, along with years of experimentation, create sensors that finally match dams or reservoirs, and present an interesting, reliable, cost-effective way to monitor these large structures everywhere. These sensors can provide information about the strain and temperature distribution in a dam, every meter and over distances of several kilometers of sensing cable.

This allows the early detection, localization and sizing of defects and degradations such as erosion, leakages, settlements, shearing, cracks, abnormal joint movements and intentional tampering. In this scenario, distributed fiber optic sensing cable is playing the role of protagonist.

Keywords: Distributed fiber optic, leak detection, settlement

1. Introduction

The most developed technologies of distributed fiber optic sensors are based on Raman, Brillouin and Rayleigh scattering. The 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 its strain, temperature and vibration. After an appropriate analysis of those signals, the system can therefore provide a calibrated strain or temperature reading at every meter along the sensing cable, as depicted on Fig. 1.

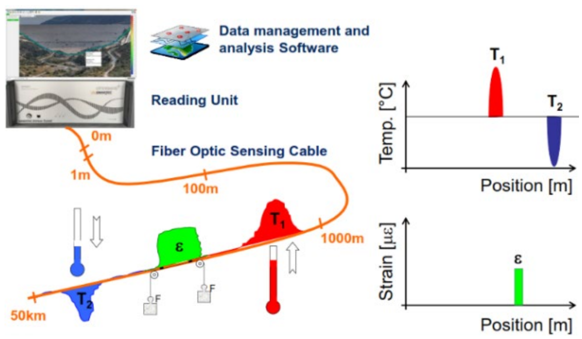

Figure 1: Fiber optic distributed sensing system

Distributed fiber optic sensors are suitable for all types of concrete and earth dams, including tailings dams and mines. Sensing cables are designed and manufactured for the specific purpose of the specific project, not all cables are suitable for all installations. The software is also realized according to the customer's needs and to the type of material and infrastructure.

2. Fibre optic sensing technologies

The first concept fibre optic is that there are several possible technologies and consequently a large variety of sensors, developed by academic and industrial institutions [1]. These technologies allow you to measure many parameters and can be implemented in different applications. Nowadays the main fibre optic technologies used for SHM are:

Technology	Measurable parameters	Sensor type
SOFO interferometric	Deformation	Long-gauge
FABRY-PEROT interferometric	Def, Strain, Temp, Load, Pressure	Point
Fibre Bragg Grating	Def, Strain, Temp, Tilt, Acc	Point and multiplexed
OPTICAL STRAND	Deformation, Strain	Long-gauge
RAMAN	Temperature	Distributed
BRILLOUIN	Temperature and Strain	Distributed
RAYLEIGH	Vibration/Acoustic	Distributed

Table 1: Classification of fibre-optic sensing technologies

SOFO sensor, for example, is normally used as multi-base extensometer in the foundation of gravity dams or if combined it becomes 3D extensometer and is useful for measuring the deformations of the body of earth-dams. Due to its size (1.5 cm in diameter) it can be adapted for special needs such as installation in a drainage pipe from the crest to the bottom gallery of a concrete dam, to monitor rotation and compression phenomena.

Another technology that is becoming more and more interesting is the one based on FABRY-PEROT interferometer. Some sensors, for example, have been deployed to check uplift at the concrete bed-rock foundation, seepage, cracks opening and temperature of the reservoir.

Sensors based on FBG (Fiber Bragg Grating) technology are the most popular with a great variety of probes produced by many manufacturers.

The Optical Strand typically are not very common and are used for long base deformation sensors.

All of these fiber optic solutions are fundamental for the safety of a dam and allow to understand and follow important issues accurately. They can work both statically and dynamically so they can be of real support for the engineers; but they are useful for localized points where typically the problem is already occurred or the area of investigation is small. [3] Distributed solutions are the answer for large area of analysis where a priori we do not know what can happen, where and when.

3. Brief description of distributed technologies

3.1 Raman -> DTS

Raman scattering is the result of a nonlinear 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 backscattered spectrum. The relative intensity of these two components depends on the local temperature of the fiber. Our systems based on Raman scattering typically exhibit a temperature resolution of the order of 0.1°C and a spatial resolution of 1m over a measurement range up to 30 km.

3.2 Brillouin -> DTSS

For strain measurements Brillouin has practically no rivals. Brillouin scattering is the result of the interaction between optical and sound waves in optical fibres. Thermally excited acoustic waves (phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light propagating in the fibre is diffracted backward by this moving grating, giving rise to a frequency-shifted component by a phenomenon similar to the Doppler shift. The most interesting aspect of Brillouin scattering for sensing applications resides in the temperature and strain dependence of the Brillouin shift. This is the result of the variation of the acoustic velocity according to the variation of the density of the silica.

Distinguishing the contribution of strain from temperature is what we do in our projects.

3.3 Rayleigh -> DAS

The Distributed Acoustic Sensor interrogation units transmit a pulse of laser light into the fibre optic. As this pulse of light travels down the fibre optic, interactions within the fibre, which result in light reflections known as backscatter, are determined by tiny strain (or vibration) events within the fibre optic which in turn are caused by localised acoustic energy.

Distributed acoustic sensing systems produce a huge amount of data so its management is fundamental, otherwise terabyte drive can be filled in few days. Here, more than in other cases, the supplier sells a solution and not a list of items.

4. A Distributed Temperature Sensing solution (DTS): a case study

The use of distributed temperature sensing cables is important for concrete gravity dams and arch dams. Creating a profile of temperatures for such structures is of great interest of responsible engineers and recently these cables are flanking, sometimes even replacing the use of common electrical temperature point sensors.

Structural issues together with meteorological events, earthquakes and poor management are the main causes of failure for a mine, a tailings dam or an embankment. Seepage and erosion phenomena can be monitored by a system able to detection leakage and measure soil liquid content.

The basic principle of leakage detection through the use of distributed fiber optic sensing relies on a simple concept: when a leakage occurs at a specific location inside the dam, the temperature distribution changes. This change in temperature is localized both in space (a few meters around the leakage location) and in time (the onset of the leak). There are two methods: passive method and active method (or Heat Pulse Method). The so-called passive method relies on direct detection of temperature anomalies induced by seepage. This method is typically used when a gradient of about 4-5°C between the leaking liquid and the sensing cable can be assured.

The Heat Pulse Method is used, on the other hand, when the gradient between the liquid and the sensing cable is negligible and smaller than 2°C. In order to ensure a reliable detection of the leak, the self-heating cable is heat up and forced to change its natural temperature. Heating is provided by flowing electrical current in copper wires of the sensing cable. When forced to change temperature, the cable needs a certain time (30 to 60min) to reach an asymptotic value, and also a certain time to return to its initial condition. Studying the cooling transient and the value of the new asymptotic (T_{MAX}) reached during the heating phase, the analysis software figure out automatically if some events are occurring.

This method has been recently used for moisture content measurements in a tailing dam in South America. The infiltrated liquid changes the thermal properties, in particular the heat capacity. The dry soil exchanges heat differently from saturated soil. To obtain the best results from the measurements, we calibrated the system with the contaminated soil of the dam. We embedded the self-heated cable inside a layer of material removed from the dam, composed of silt and sand for about 60% and clay for the remaining 40% and the results of such study can be appreciated in figure 2. The different thermal conductivities [W / (m K)] of water, air and waste material, all other conditions being equal, led to clear and distinct functions.

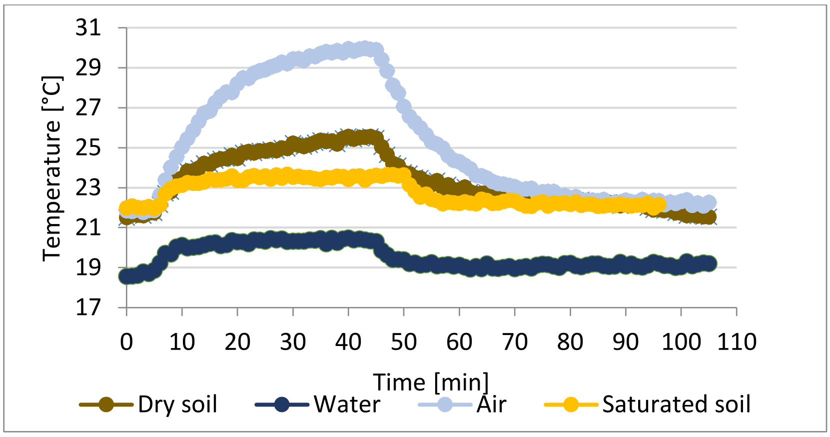

Figure 2: heat pulse method applied to dry and saturated soil of the dam. Comparison with water and air.

After a week of lab testing, we were able to create the calibration function by summing the temperature values of the heating process for each water content [2].

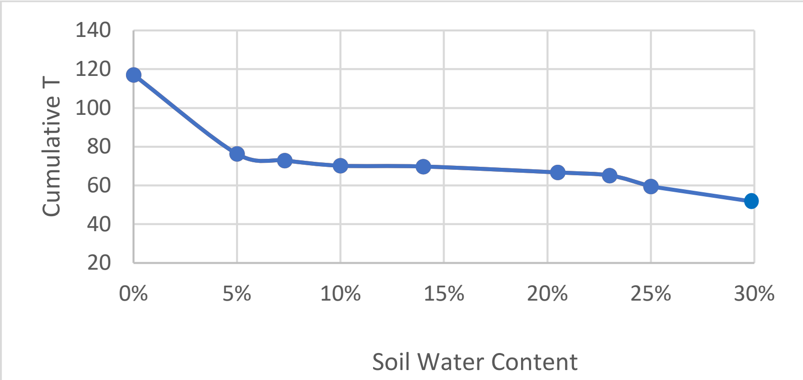

Figure 3: Cumulative temperature increase integrated over 45min as function of soil water content, about 3 W/m heat pulses.

Actually a similar function was obtained considering in ordinate ΔT ($T_{MAX} - T_{MIN}$, where T_{MAX} was the asymptotic value and T_{MIN} the ambient temperature) instead of $T_{cumulative}$, both mathematic approaches led to a similar (linear) regression line. Another interesting result of this study was the low power (3W/m) required to heat that special cable.

The installation done on-site consists of 12 lines of self-heated cable, 4 each horizontal layer of the dam. The cable lengths varies from 230m to 360m and they cover a large monitoring area, see Figure 4. The distributed temperature cable, for redundancay, is composed of 4 MM (multimode) fibers and 8 copper wires.

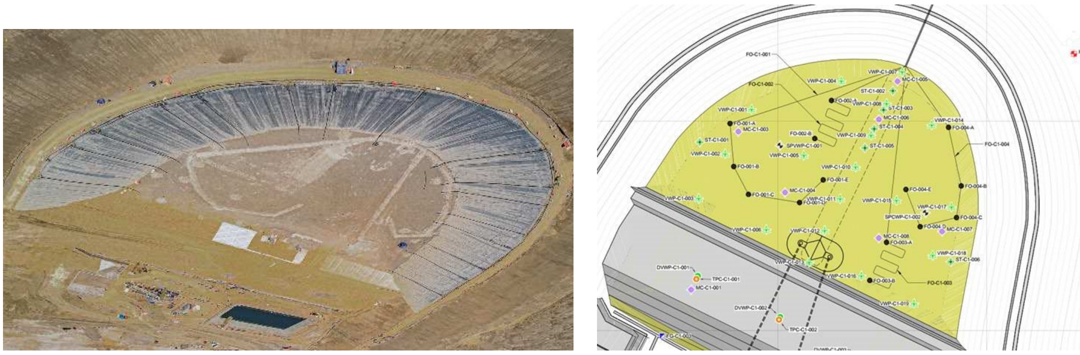

Figure 4: Top view of the first layer: 4 independent fibre optic cables

We deployed three heating modules, one per layer and four cables served simultaneously. Only one fibre optic reading unit is responsible for the measurements of all twelve cables.

Figure 5: Air-conditioned control room: black cabinet with reading unit and accessories + three heating modules

5. A Distributed Temperature and Strain Sensing solution (DTSS), an example

A tailings dam in Chile was considered very critical, the existing instrumentation was old and limited to a small area and the data were saved on papers locally [4]. The owner therefore decided to modernize the equipment installing modern piezometers, water level system, accelerometers and primarily the distributed strain sensing cable. All measurements are now automated and can be used to send alarms to the engineers responsible.

The distributed sensing cable has been installed in a trench that follows the path reported in figure 6.

Figure 6: Deployment of about 2km of distributed strain sensing cable

The selected cable, Hydro&Geo, is responsible to detect any abnormal movements of the structure. The measurement range of the cable is around 20'000 με while the breaking point is more than 50'000 με.

Figure 7: Maintenance of the dam and laying of Hydro&Geo strain sensing cable

To assess system capabilities in terms of ground deformation and alert triggering, settlement simulation tests were carried out. These tests are aimed to evaluate and confirm the performances of the final system intended as sensor, reading unit, and data management software working together. The tests consisted of displacing the sensing cables vertically in short sections without backfill, to induce strain and simulate the symptoms of ground deformation. It is possible to observe in Figure 8 that the location of the disturbance is visible easily. Increasing the displacement increases the area under the curve of the measured displacement.

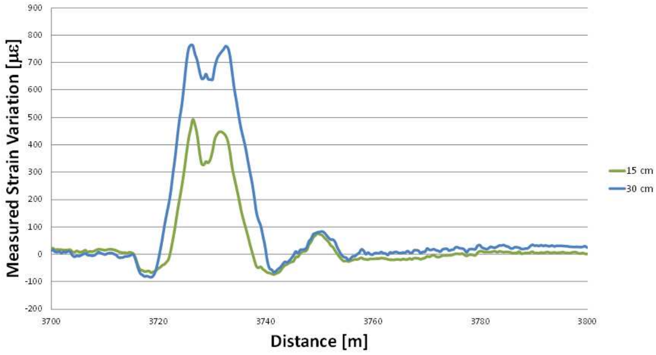

Figure 8: Strain measurements during the test

The correlation function between measured strain values and actual settlement values was implemented in our DiView software.

3. DiView software

The processing unit is programmed with a range of smart algorithms for interpreting the raw data. The fiber optic sensing cable may be divided into a number of zones in which specifically chosen algorithms will be selected and alarms allocated within each zone. There are a number of ways to visualise these events. One is to use visualisation software which is specific to the DTS which, for example, may show the path of the fiber optic against a site map or diagram and in the event there is an event it will highlight the location of the event and show an alarm. An alternative is that the DAS software is interfaced with an existing 3rd party SCADA, control or security software package in which case the event will be highlighted in the 3rd party software.

4. Conclusions

A suitable monitoring system for dams may involve different technologies (not only fibre optic) and different types of sensors. A smart mix of them is probably the best solution. Distributed sensing solutions play a key role in this game as they can cover large areas and return important information about temperature, leakage, moisture content, subsidence and instability. A distributed fibre-optic system provides a huge flow of measurement data along the entire length of the survey cable. The raw data must be analysed, selected and interpreted; customised software including algorithms, calibration functions and mathematical models are essential for the interpretation of all phenomena affecting dams.

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