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**PERMANENT SAFETY ASSESSMENT OF DAMS, LEVEES,
RESERVOIRS, WATERWAYS WITH FIBER OPTIC DISTRIBUTED SENSING**

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1. EARLY DETECTION AS A KEY FOR SAFETY MANAGEMENT

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 this publication, the aim is to concentrate on long-term, large-scale field applications on dams, dikes and levees, based on the presented distributed technology and sensors.

2. FIBER OPTIC DISTRIBUTING SENSING

2.1. TECHNOLOGY

The most developed technologies of distributed fiber optic sensors are based on Raman and Brillouin scattering. 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 its strain and temperature. 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.

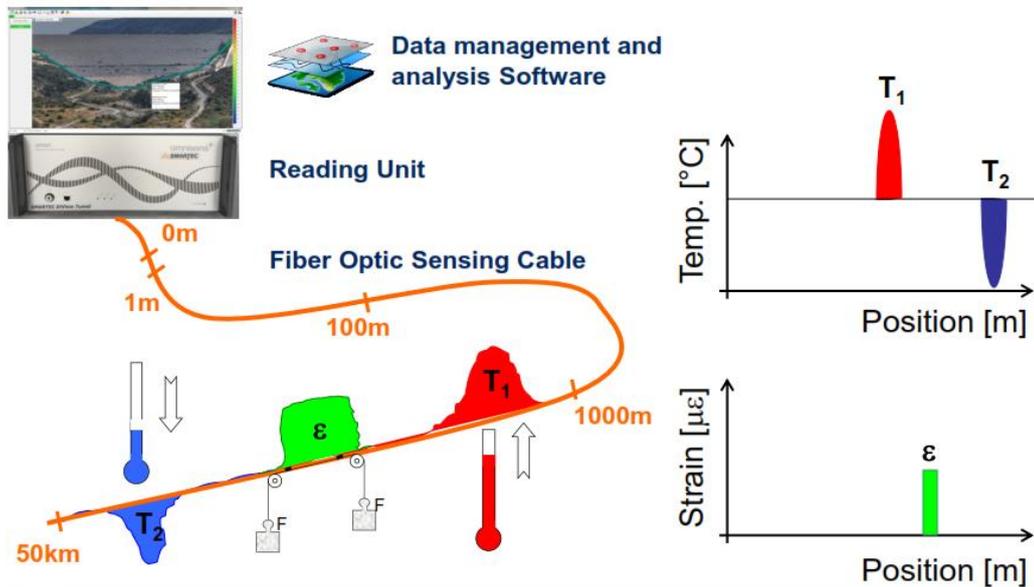


Fig. 1
Fiber Optic Distributed Sensing System

2.2. DATA MANAGEMENT

Direct data analysis based on distributed temperature or strain data has limitations and does not provide real-time data to the operator that often becomes overwhelmed by the amount of data he receives. It is therefore necessary to automate the data management and analysis process. The developed software displays measurement profiles, status maps of temperature or strain, evolution of the structure and events automatically recognized and logged by the monitoring system. All measurements are imported and stored into a single database and data is processed to apply calibrations and select zones of interest. Alarms are generated automatically, based on complex criteria (e.g. for leak detection). The user can then dig-down into raw data for deeper analysis, as shown in Fig. 2.

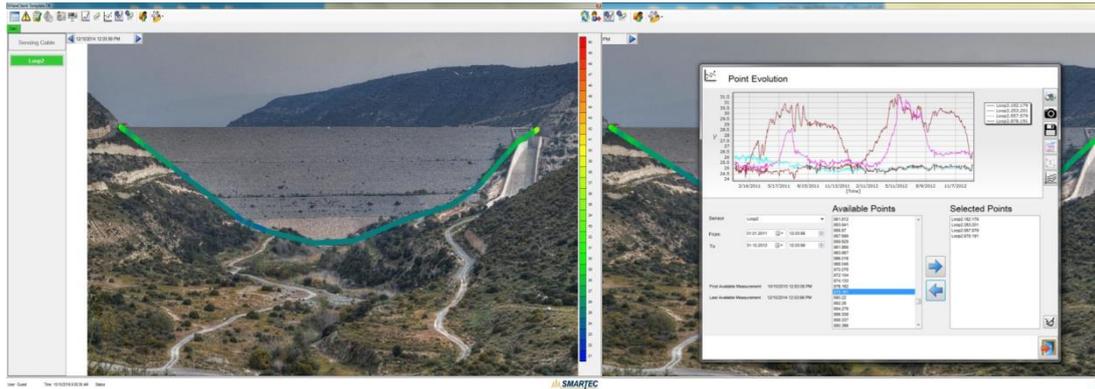


Fig. 2
 Distributed Data - Strain and Temperature - Management and Analysis Software
 Color coding representation (left) - Point evolution display (right)

2.3. BENEFITS

The scale, age and uncertainty of materials in the sometimes huge hydro engineering structures combine a difficult array of parameters for the responsible engineer to navigate when analyzing its structural integrity.

Traditional instrumentation based on localized point sensor is not sufficient to guarantee the detection of early signs of damage and localization of unknown events. Distributed fiber optic sensing allows the early detection, localization and sizing of defects and degradations such as seepages, leakages, settlements, shearing, cracks, abnormal joint movements, intentional tampering and over-flooding.

3. INFILTRATION DETECTION FOR DAMS, DIKES AND RESERVOIRS

A fiber optic distributed system for infiltration detection relies on Raman distributed thermal sensing and can work in two different configurations; the passive and active methods.

The so-called passive method relies on direct detection of temperature anomalies induced by seepage or leak. This method is typically used when a gradient of approximately 5°C between the leaking liquid and the sensing cable can be assured.

The so-called Heat Pulse Method or active method is on the other hand used when the gradient between the liquid and the sensing cable is negligible and smaller than 1°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 will need a certain time to arrive at a certain temperature, defined as T_{heating} , and as well a certain time to go back in its initial condition. Studying the cooling transient and the value of the maximum temperature reached during the heating phase the analysis software figure out automatically if some events are occurring.



Fig. 3
Sensing cable installation at Grand Ethiopian Renaissance Dam (GERD)

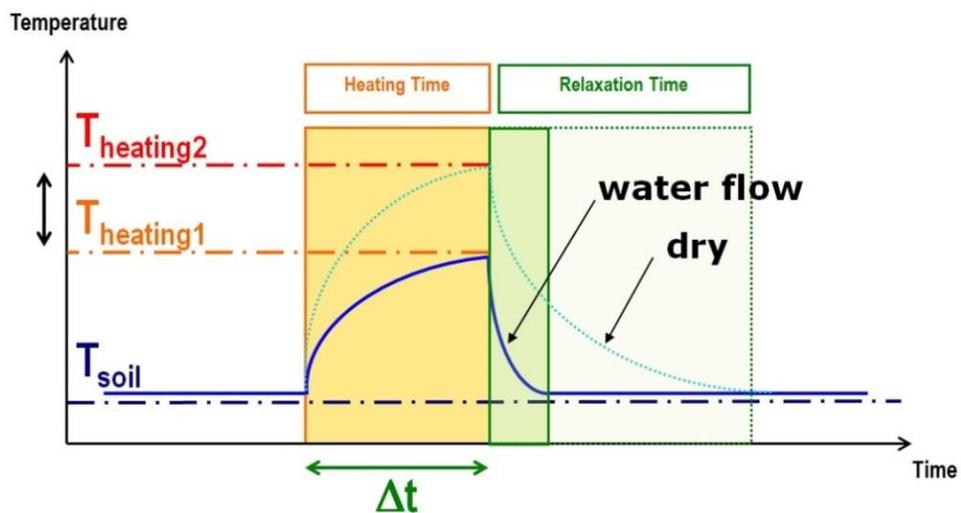


Fig. 4
DiTemp Heat Pulse Method working principle

As an example, a cable surrounded by still water will require more time to heat up, while a cable within flowing water will cool down more quickly.

3.4. APPLICATION: SIAH BISHEH UPPER DAM, IRAN

The Siah Bisheh Pumped-storage Hydroelectric Power Project is the first of this type in Iran. Located 125 km from Tehran it has an installed capacity of 1000 MW. The plant is intended to play a vital role in stabilizing the entire North Iran power grid, ensuring the safe operation of thermal power plants in the surrounding provinces.

The main aims of fiber optic instrumentation are seepage at plinth level and active detection system with Heat Pulse Method technique. Beside this direct detection, the monitoring system can offer an effective analysis of the evolution of the detected anomaly, and a way to define reasonable threshold and trigger alerts if they are overcome. Moreover fiber optic systems are easily integrated with already existing traditional / standard monitoring systems. Distributed sensing offers the unique capacity of locating precisely the event using only few distributed sensors.

Two independent systems are developed to monitor the existing dams. A dedicated control room where the instrumentation rack is located is specifically built on the crest of each dam (Fig. 5).



Fig. 5

Sensing cable installation at the plinth of the upstream face of the upper dam and one monitoring cabinet

The rack contains a display, the DiTemp unit with its accessories, the server PC where the analysis software is installed and the heating module necessary to heat up the cable at scheduled times. All the system is plugged into a network stabilizer and UPS in order to prevent general functionality in case of power failure.

Accuracy and repeatability tests were carried out during implementation phases (Fig. 6 and Fig. 7).

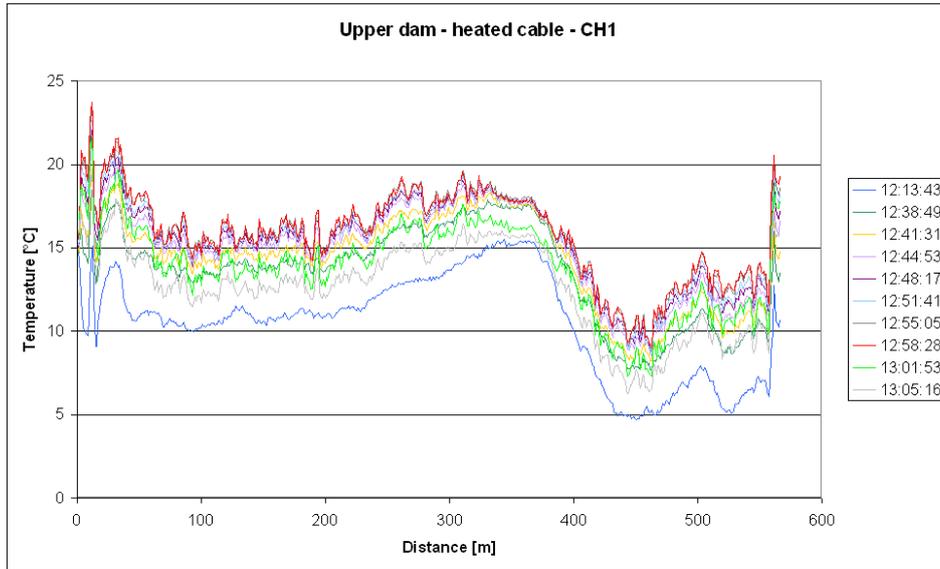


Fig. 6
Absolute temperature measurements during heating

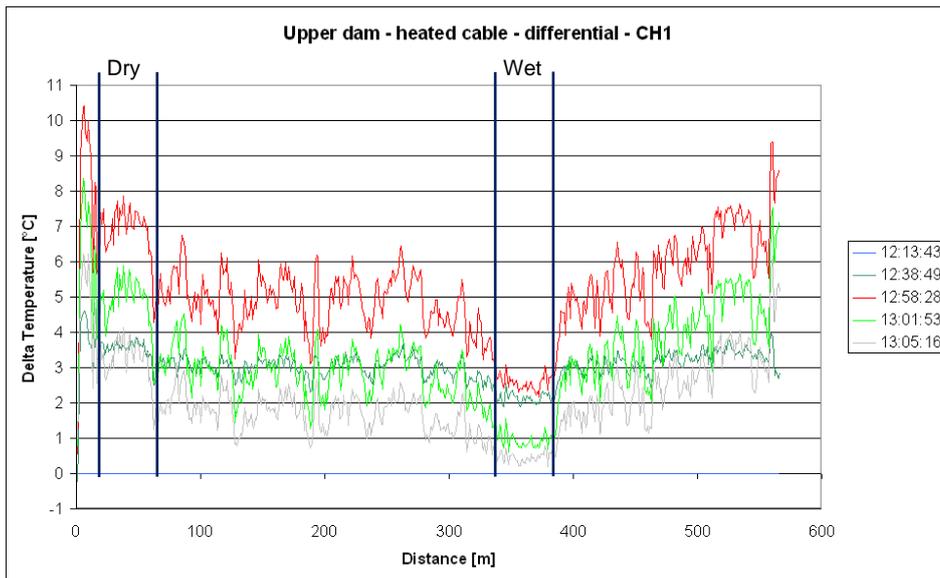


Fig. 7
Differential temperature measurements during heating

It is possible to evince how temperature resolution is about ± 0.2 °C. The initial section showing higher deviation refers in fact to cable section not yet concreted and exposed to the environment. Thanks to the customized visualization and analysis software it is 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.

4. DEFORMATION EARLY WARNING SYSTEMS

A fiber optic distributed system for deformation relies on Brillouin sensing and provides early detection of ground settlements and heaves, local cracks and internal erosion.

4.1. APPLICATION: 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 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 sensing cable was deployed and sealed by means of specific episodic resins (Fig. 8).



Fig. 8

Installation of sensor in a groove, on top of the levee wall section and in a trench

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.

An example of calculated deformation on the sensor placed on the top of the wall section I presented in Fig. 9. Deformation is plotted as a function of position along the wall and as a function of time.

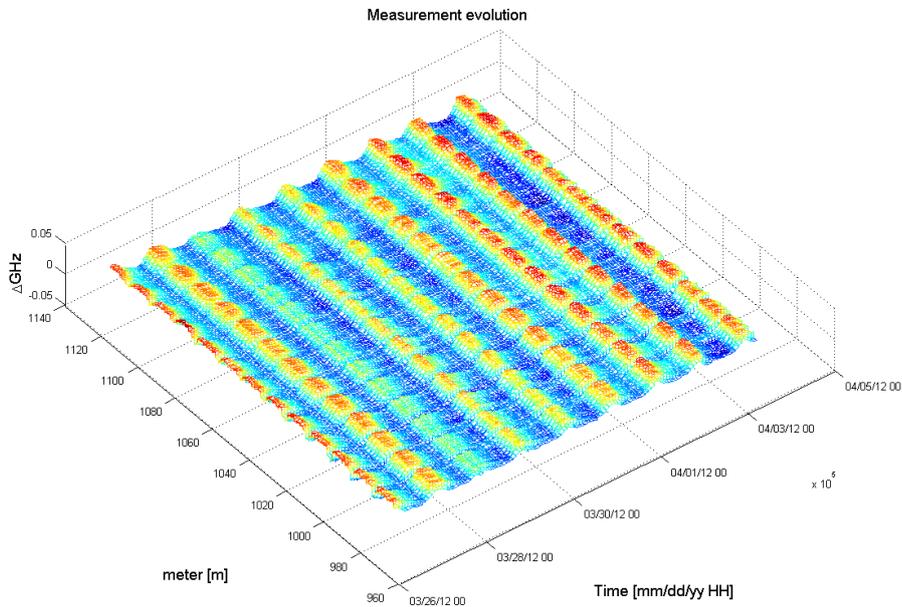


Fig. 9

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.

4.2. APPLICATION: 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 through a single cable, thus simplifying installation and increasing data density. A different installation technique is chosen for the 2 sections: in the penstock, where precise and accurate monitoring under water is required, the sensing cable (flat profile) 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 sensing cable is glued along 4 different lines, Fig. 10.



Fig. 10
Strain sensing cable installation inside the penstock

On the other hand, for the access tunnel a mixed installation technique was selected: sensing cable 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, Fig. 11. This installation technique allows a precise and accurate monitoring over the whole length of this tunnel of approximately 70 m.



Fig. 11
Strain sensing cable 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 sensing cable length, Fig. 12.

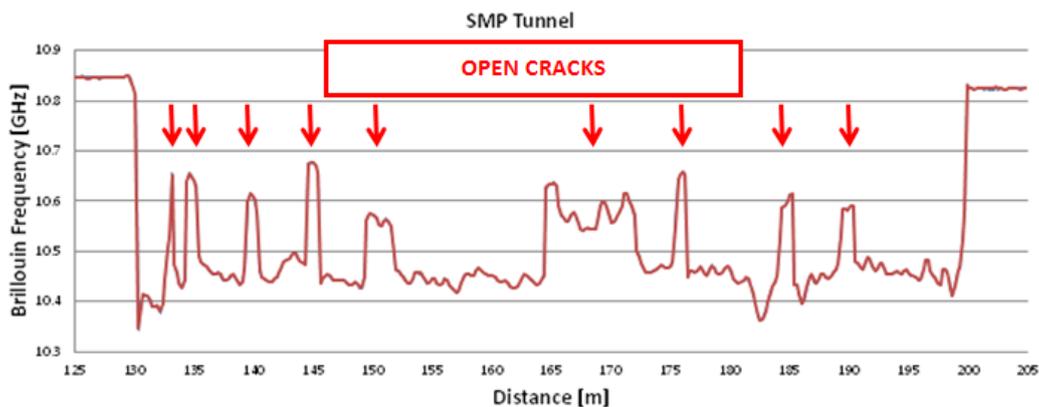


Fig. 12
Strain distribution measured along the penstock access tunnel

5. CONCLUSION

SMARTEC has instrumented more than 20 dams with fiber optic distributed sensing within the last 15 years. 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. Distributed sensing technologies have been applied on key hydraulic components such as penstock and waterlines.

Fiber optic distributed sensing is a recognized technology in dams engineering and meets today's goals of asset management. It overcomes the limited capability of conventional sensors with reduction of maintenance expenses. Distributed sensing is often combined with fiber optic point sensors (temperature, piezometers) and data communications are fully compatible with plant DCS or SCADA system.

6. REFERENCES

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