Monitoring dams with distributed fiber optic sensing

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Introduction

Gravity dams, tailings dams, earthen dams and associated penstocks 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. 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 responsible engineer 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 like with recent tailing dams failure in Brazil, 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 dams or reservoirs, and present an interesting, reliable, cost effective way of monitoring these large 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 of sensing cable. This 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.

Distributed fiber optic sensors are integrated in the engineering design phase or retrofitted on existing structures to provide information on asset integrity like potential residual strength after seismic event. Thus, using a limited number of very long sensors it is possible to monitor structural and functional behaviour of structures with a high measurement and spatial resolution at a reasonable cost. 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. 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 their strain and temperature.

1. Background

The current trend in monitoring operation of dams has evolved. Until recently, dam instrumentation consisted of networks of vibrating wire type piezometers, strain gauges and thermometers, which are distributed in equally spaced sections along the length of the retaining structures.

1.1 Advantages of fiber optic technology for dam monitoring

State of the art dam instrumentation today includes a new generation of instruments that operate on a completely new and revolutionary technology: Fiber Optic Sensing Technology. Fiber Optic technology broadens the possibilities formerly known to instrumentation engineers in several ways, but particularly in terms of precision, durability, reliability, density of information and economical aspects [1].
1.2 Fiber optic point sensors at Dickson dam, Canada

In the early 2000s the Dickson River dam was monitored with fiber optic pressure sensors; performances of fiber optic versus vibrating wire sensors have been compared. Dickson dam is located on the Red Deer River, Alberta, Canada and began operation in 1981. This is a multi-zones earth fill dam of 40 m high and 650 m long, with storage of reservoir capacity 203 million cubic meters.

![Diagram of Dickson dam with locations of Fiber Optic Pressure sensors (FOP) and Vibrating Wire piezometers.]

**Fig. 1.** Dickson dam; location of Fiber Optic Pressure sensors (FOP) and Vibrating Wire piezometers

The dam is retrofitted with Fiber Optic Piezometer and Temperature sensors installed alongside with Vibrating Wire Piezometers; for redundancy and long term comparison purposes. Significant results showed in Fig. 2 show lightning strikes impact on readings of electrical sensors; by exceeding alarm threshold values electrical sensors trigger false
alarms [2]. Fiber optic point sensors offer measurement performance equivalent to vibrating wire sensors but are not sensitive to lightning strikes and other electromagnetic disturbances. Additionally they can operate with longer cables with no degradation of signal, and lower cable cost, size and weight.

1.3 Enhanced monitoring with distributed fiber optic sensing

Unlike electrical and fiber optic point sensors, distributed sensors offer the unique characteristic of being able to measure physical parameters along their whole length and allow the measurements of thousands of points using a single transducer [3].

The most developed technologies of distributed fiber optic sensors are based on Raman and Brillouin scattering [4]. 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 injected into a fiber, a very small amount of it is scattered back at every point along the fiber. The scattered light contains components of the wavelengths that are different from the original signal and are called the Brillouin and the Raman scattering components. These shifted components contain information on the local properties of the fiber, in particular their strain and temperature (i.e. leak detection). While Raman scattering is only sensitive to temperature variations, Brillouin scattering can detect both strain and temperature (Fig. 3) [5].

A distributed fiber optic monitoring system consists of one or more unique fiber optic sensing cables and a unique readout device. The area of coverage can be up to 50 km continuous length with one system. The sensor cables can easily be deployed either during or after construction, and it is possible to retrofit on existing structures for extending their life [6].

Typically a temperature resolution in the order of 0.1°C, a strain resolution of 2 µƐ and a spatial resolution of 1 m over a measurement range up to 50 km are obtained with commercially available interrogators. SMARTec commercializes a system based on Brillouin sensing and named DiTeSt, and a system based on Raman sensing and named DiTemp [7].

Distributed sensing instruments can return a huge amount of data. As an example, it is possible to measure every minute the temperature at 20,000 points along a single cable. Data management and analysis therefore becomes a very important task, since it is often impossible to manage and analyze the data manually, especially if the measurement is automated and continuous. Dedicated data management, analysis and visualization software has therefore been developed to help in those tasks. This software can allow the representation of data superimposed with location maps and using colors to represent strain/temperature or levels of alerts as a function of position. An example of such representation is shown in Fig. 4.
This software has been specifically developed to manage distributed data coming from the DiTeSt and DiTemp units, provides system status report informing the final user about the status of each single component, reading unit, sensor and software itself. It has been developed to work continuously 24 / 7 without the necessity of an external operator. When configured the DiView software can trigger alerts to a dedicated user recipient. Warning thresholds are set during commissioning phase. It provides an easy remote access to the implemented monitoring system offering possibility of remote troubleshooting and off-line data processing. Last it offers a friendly Graphical User Interface with data displayed on maps.

![DiView Data management and analysis software interface, showing temperature distribution](image)

**Fig. 4.** DiView Data management and analysis software interface, showing temperature distribution

### 1.4 Fiber optic distributed strain sensing cable for penstock and waterlines

The SMARTProfile sensor design (Fig. 5) 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 resistance (e.g. rodents’ bites) and increase the contact area in the soil.

![SMARTProfile strain sensing cable (left: details of SMARTProfile, right: geotextile integrated with SMARTProfile)](image)

**Fig. 5.** SMARTProfile strain sensing cable (left: details of SMARTProfile, right: geotextile integrated with SMARTProfile)

A Swiss penstock is monitored with SMARTProfile sensing cable since 2013, after discovery of rock movements: 120 meters of penstock are monitored with 4 lines of DiTeSt SMARTProfile distributed sensing cable glued to the inner wall (Fig. 6). Areas of structural weakness, even when relatively obvious, are difficult to identify by visual inspection alone. The DiTeSt system can not only detect structural failures, but also detect very slight differential settlements that can be considered as early warning of future issues.
The waterline crossing Calaveras fault zone in California is also equipped with SMARTProfile sensing cable since 2010: 300 meters of pipeline are monitored with 3 lines of SMARTProfile distributed sensing cable glued onto the pipe (Fig. 6). The project was awarded to monitor deformations of that pipe crossing a critical area as the Calaveras fault in Alameda County.

![Fig. 6. SMARTProfile strain sensing cable installations (left: Penstock, Switzerland, right: Waterline, USA)](image)

1.5 Long-term monitoring of dams and levees

A distributed temperature sensing system installed in a dam or levee is able to detect the following failure [8]: structural movement, overtopping, under levee seepage, through levee seepage, piping (internal erosion), external erosion, differential settlement and landslides.

Unlike “discrete monitoring systems” there are no coverage “gaps” between sensors, providing seamless coverage. The system collects data day and night, 24 hours a day. Using current internet technologies, effective warning systems can be integrated into current management methods. Sensor cables can be retrofitted on existing levees and dams by means of trenching the cable into the face of the structure, on either the upstream or downstream side. Often trenching is only necessary to a depth of protection for the cable itself. The location of the cable will depend on many different factors that must be carefully considered by the engineer.

Location of the sensor cable is critical for detecting both strain (settlement) and seepage (temperature change). With regard to strain, the sensing cable must be placed where changes in the shape of the structure will physically occur, directly transferring strain to the cable. The same is true for seepage. The sensing cable must be placed in a location where water is moving close to the cable, creating trends in temperature directly to the cable.

A levee or dam is in many ways like a chain, only as strong as its weakest link (or lowest point). An individual levee can be many miles long and can meander through urban, rural, remote, inaccessible and sometimes dangerous areas. Vegetation, sheer size and scale, can limit levee access and mask indicators from even the most well trained inspectors. Areas of structural weakness, even when relatively obvious, are difficult to identify. The DiTeSt system can not only detect structural failures, but also detect very slight differential settlements that can be considered as early warning of future issues.

1.6 Heat Pulse Method working principle

A fiber optic distributed system 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 liquid spilling. This method is typically used when a gradient of approximately 5°C between the 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 the sensing cable, and in particular the self-heating cable, is heat up and forced to change its natural temperature. Heating is provided by
flowing electrical current on the sensing cable, current injection is controlled by a dedicated module that is part of the system when this detection method is selected.

When forced to change temperature the cable will need a certain time to arrive at a certain temperature, defined as T-heating in the plot, 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 DiView software figure out automatically if some events are occurring. DiView system is controlling the heating as well as the analysis; the detection algorithm is applied to all the points of the sensing cable.

![DiTemp Heat Pulse Method working principle](image)

Fig. 7. DiTemp Heat Pulse Method working principle

1.7 Heat Pulse Method Sensing Cable

The DiTemp self-heating temperature sensing cable (Fig. 8) 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 geotechnical 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 reliable leak detection. 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 becomes possible to determine if the soil around each 1m section of cable is dry, wet or exhibits water flow.

![DiTemp self-heating temperature sensing cable](image)

Fig. 8. DiTemp self-heating temperature sensing cable

2. 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.

2.1 Purpose of monitoring

The main aims 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.

### 2.2 On-site implementation

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. 8). The rack contains a display the DiTemp unit with its accessories, the server PC where the DiView 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 breakdown.

![Fig. 9 Sensing cable installation at the plinth of the upstream face of the upper dam and one monitoring cabinet](image)

### 2.3 Distributed sensing system performances

Accuracy and repeatability tests were carried out during implementation phases (Fig. 10 and Fig. 11).

![Fig. 10 Absolute temperature measurements during heating](image)

It is possible to evince how temperature resolution is in the order of \( \pm 0.2 \) °C. The initial section showing higher deviation refers in fact to cable section not yet concreted and exposed to the environment. Thanks to the DiView customized visualization 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.
3. 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. This technique has been implemented in new or existing earth dam, RCC (Roller-Compacted Concrete) dam, CFRD (Concrete Face Rockfill dam), Arch dam, Tailing dam, Dikes/Levees and water reservoirs. Distributed sensing technologies have been applied on key hydraulic components such as penstock and waterlines. The main aims in developing and implementing a fiber optic distributed system to monitor a dam or a hydro-structure are the detection of seepage, internal erosion, hot spots and leaking cracks.

Fiber optic distributed sensing is a recognized technology in dams engineering and meets today’s goals of asset management. It overcomes 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.

References

7. www.smartec.ch
The Authors

Daniele Inaudi received a degree in physics at the Swiss Federal Institute of Technology in Zurich (ETHZ). In 1997 he obtained his Ph.D. in civil engineering at the Laboratory of Stress Analysis (IMAC) of the Swiss Federal Institute of Technology in Lausanne for his work on the development of a fiber optic deformation sensing system for civil engineering structural monitoring. Daniele Inaudi is co-founder and CTO of SMARTEC SA (Switzerland), a company active since 1996 in the domain of structural health monitoring and fiber optic sensing. He is also CTO of Roctest: a Nova Metrix company which acquired SMARTEC in 2006. Daniele Inaudi is author of more than 200 papers, three book chapters, and editor of a book on Optical Non-destructive Testing and co-author of the book “Fibre Optic Methods for Structural Health Monitoring”.

Régis Blin received a degree in Engineering with a specialization in Optoelectronics from Polytech Paris-Sud, University of Paris XI, France in 2004. Régis Blin has joined SMARTEC in May 2015 with more than 10 years’ experience, having served as an R&D Engineer in Germany, and more recently as an instrumentation engineer for a French service provider in Paris area, France. Régis Blin was involved in Fiber Optic solutions for Civil Engineering, Oil & Gas, Nuclear, Environmental and Geotechnical applications.