Optical Fiber Sensors for Dam and Levee Monitoring and Damage Detection

Daniele Inaudi

Abstract Optical fiber sensors can be used advantageously for monitoring dams and levees and to detect and localize damage in them. This technology is relatively new, but in the last 20 years numerous applications have been successfully carried out in dams, dykes and levees worldwide. There are two main usage scenarios for optical fiber sensing technology. Some sensors replace conventional, e.g. vibrating wire, sensors with equivalent optical versions. In this case the main benefits come from their immunity to electromagnetic interference—such as lightning strikes or power lines—and the possibility to use cables of up to several km long to connect the sensors and the readout units. The second main application of optical fiber sensing relies on the use of distributed sensors. Those sensors can measure strain and temperature every meter along a cable that can reach several km in length. This enables detecting and localizing undesired events such as leaks or cracks that produce a local change of strain or temperature. In this chapter we will introduce the different optical fiber sensing technologies and corresponding sensors. Several applications example will illustrate the abovementioned use scenarios.

Introduction

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 large size, age and uncertainty of material properties in these sometimes mammoth structures, all combine to present a difficult array of parameters for the dam and levee professionals to navigate when analyzing a new or existing levee or dam.

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. In the wake of

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flood disasters associated with Hurricane Katrina and others, a complex regulatory environment has emerged; requiring engineers to certify structural and geotechnical fortitude, and levee and dam asset owners and engineers are therefore facing new challenges.

Levees have many different failure modes (Sills et al. 2008). Many of the most common failure modes have indicators (erosion, seepage and/or settlement) that are often difficult to detect with the human eye during a superficial inspection. Relying on visual inspection alone, weaknesses in these structures can remain undetected, until a failure occurs during a storm or surge event. Visual inspection and surveying are vital parts of any levee management program, and neither can or should be replaced; however, current inspection practices have some limitations:

- Levees and dams are too large in scale (many miles long, very wide, very tall) to thoroughly inspect visually and survey consistently.
- Inspections and surveys can be spaced by several months or even years
- Differential settlement, structural weakness, and warning signs can be nearly impossible to detect with visual inspection
- Water, vegetation and other obstruction can limit the surface that can be visually inspected.
- Many structural failures originate underground with no initial surface expression
- Many "warning signs" are not intuitively obvious and difficult to detect even by the most well trained inspectors.

Recent advances in instrumentation technologies and applications are providing new ways for the civil engineer to examine these structures, and offer a set of monitoring tools previously thought impossible. Distributed fiber optic technologies (Inaudi and Glisic 2006) are among those emerging technologies and enable sensing over the whole length or volume of a dam or levee. Those distributed sensors are able to detect and localize defects and damage occurring anywhere along the levee or dam, providing a new and cost effective way of monitoring these structures.

Optical fiber sensors, when used as point sensors to measure quantities such as pore water pressure, strain, displacement, or temperature, present significant advantages over conventional electrical sensors in terms of long-term reliability and insensitivity to external perturbations, such as lightning strikes or proximity to power lines (Udd 2011).

In this chapter, we will review commonly available fiber optic sensing technologies and explore their applications to the monitoring of dams, levees, and other geotechnical applications.
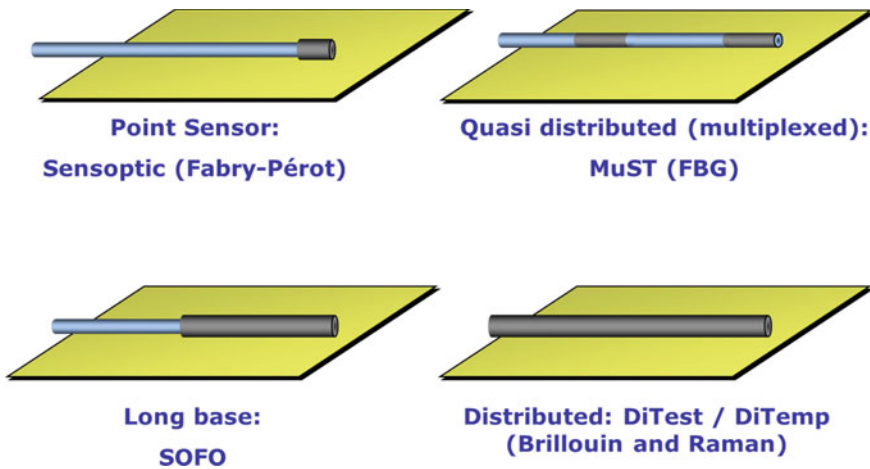
Fiber Optic Point Sensors

From many points of view, fiber optic sensors are the ideal transducers for structural monitoring (Glisic and Inaudi 2008). Being durable, stable and insensitive to external perturbations, they are especially useful for long-term health assessment

of civil structures and geostructures. Many different fiber optic sensor technologies exist and offer a wide range of performance and applicability, as will be detailed in the following paragraphs. Fiber optic sensors often offer measurement performance similar to those of the corresponding conventional sensors, such as vibrating wire or electrical sensors. This technology can however offer other advantages in terms of reliability and accuracy when operation in harsh environments or in the presence of electromagnetic disturbance.

Finally, distributed fiber sensors offer new exciting capabilities that have no parallel in conventional sensors.

There exists a great variety of fiber optic sensors (FOS) for structural and geotechnical monitoring. In this overview we will concentrate on those that have reached a level of maturity, allowing a routine use for a large number of structural monitoring applications. Figure 1 illustrates the four main types of fiber optic sensors (Table 1).

The greatest advantages of the FOS are derived from the characteristics of the optical fiber itself that is either used as a link between the sensor and the signal conditioner, or becomes the sensor itself in the case of long-gauge and distributed sensors. In almost all FOS applications, the optical fiber is a thin glass fiber that is protected mechanically by a polymer coating (or a metal coating in extreme cases) and further protected by a multi-layer cable structure designed to shield the fiber from the environment where it will be installed. Since glass is an inert material very resistant to almost all chemicals, even at extreme temperatures, it is ideal for use in harsh environments such as those encountered in geotechnical applications. Chemical

Point Sensor:
Sensoptic (Fabry-Pérot)

Quasi distributed (multiplexed):
MuST (FBG)

Long base:
SOFO

Distributed: DiTest / DiTemp
(Brillouin and Raman)

Fig. 1 Main types of optical fiber sensors: point sensors have a single measurement point at the end of the fiber optic connection cable, similarly to most electrical sensors. They measure a quantity in a small area of typically less than 1 cm length. Multiplexed sensors allow the measurement at multiple points, spaced by a few cm or several meters, along a single fiber line. Long-base sensors integrate the measurement over a long measurement base (typically 1 m or more). They are also known as long-gage sensors. Distributed sensors are able to sense at any point along a single fiber line, typically every meter over many kilometers of length

Table 1 Illustrates the main types of sensors and their characteristics

	Fabry-Perot interferometric	Fiber Bragg gratings	SOFO interferometric	Raman scattering	Brillouin scattering
Type of sensor	Point	Point	Long-gauge (integral strain)	Distributed	Distributed
Measurable parameters	Strain Temperature Pressure Displacement	Strain Temperature Acceleration	Deformation Strain	Temperature	Strain Temperature
Multiplexing (several sensors on same fiber)	No	Yes	No	Fully distributed	Fully distributed
Number of measurement points in one fiber	1	10–30	1	30,000	50,000
Typical accuracy					
Strain	1 με	1 με	1 με	0.1 °C	10 με
Deformation	10 μm	1 μm	1 μm		0.2 °C
Temperature	0.1 °C	0.1 °C			
Pressure	0.25% full scale				
Range			20 m gauge length	30 km	50 km
Type of optical fiber	Multimode	Singlemode	Singlemode	Multimode	Singlemode

resistance and durability are great advantages for long term reliable health monitoring of civil engineering structures (Inaudi and Glisic 2006; Inaudi 2004). Since the light confined to the core of the optical fibers used for sensing purposes does not interact with any surrounding electromagnetic field, FOS are immune to interference. With such unique advantage over sensors using electrical cables, FOS are obviously the ideal sensing solution when the presence of EM, Radio Frequency or Microwaves cannot be avoided. For instance, FOS will not be affected by any electromagnetic field or electrical currents generated by lightning hitting a monitored dam, nor from the interference produced by a subway train running near a monitored zone. FOS are intrinsically safe and naturally explosion-proof, making them particularly suitable for monitoring applications of risky structures such as gas pipelines, coal mines or chemical plants. But the greatest and most exclusive advantage of such sensors is their ability to offer long range distributed sensing capabilities.

The main disadvantages of fiber optic sensors include the higher cost and complexity of the readout systems and the need to specialized equipment to splice or repair optical fibers.

Let's now review some of the most common optical fiber sensors used for structural and geotechnical monitoring.

Piezometers and Other Point Sensors

Fabry-Pérot Interferometric sensors (Pinet 2009) are typical examples of point sensors and have a single measurement point at the end of the fiber optic connection cable. An extrinsic Fabry-Pérot Interferometer consists of two partially mirrored optical fibers facing each other, but leaving an air cavity of a few microns between them, as shown in Fig. 2. When light is coupled into one of the fibers, a back-reflected interference signal is obtained. This is due to the reflection of the incoming light on the two mirrors. This interference can be demodulated using coherent or low-coherence techniques to reconstruct the changes in the fiber spacing allowing a precise measurement of the gap width, with nanometer accuracy. Since the two fibers are attached to the capillary tube near its two extremities (with a typical spacing of 10 mm), the gap change will correspond to the average strain variation between the two attachment points shown in Fig. 2.

Many sensors based on this principle are currently available for geotechnical monitoring, including weldable and embedded strain gauges, temperature sensors, and displacement sensors. Examples are shown in Fig. 3.

A particularly interesting sensor type for the monitoring of Dams and levees is the Fabry-Perot optical piezometer. In this type of sensor, the second fiber is replaced by a membrane that deforms due to the applied external pressure. This enables piezometers that are externally identical to their conventional vibrating-wire equivalents, as shown in Fig. 4 left, but also miniature sensors adapted for installation in small ducts or in geotextiles (Rodrigues et al. 2010) as shown in Fig. 4 right. Those sensors can be used advantageously in applications where frequent lightning strikes of very long cables limit the use of electrical and vibrating wire sensors.
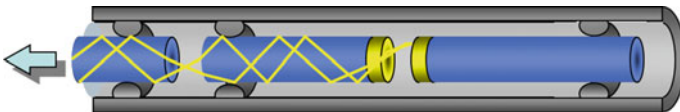
**Fig. 2** Functional principle of a Fabry-Perot sensor
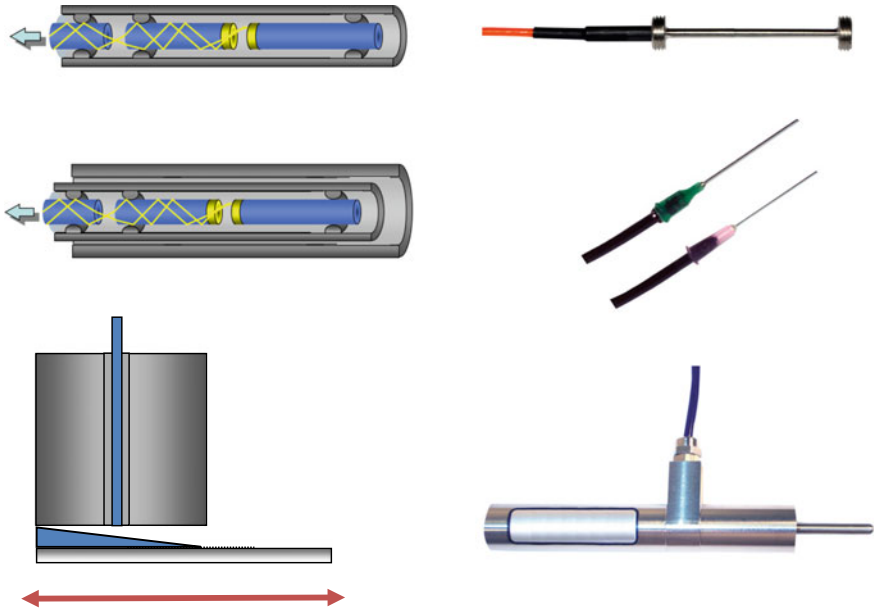
Fig. 3 Examples of strain, temperature and displacement sensors based on Fabry-Perot sensing

Fig. 4 Fabry-Perot piezometer with conventional (left) and miniature (right) packaging

Long-Base Deformation Sensors

The SOFO (French acronym for Structural Monitoring with Optical Fibers) Interferometric sensors are long-base sensors, integrating the measurement over a long measurement base that can reach 10 m or more (Inaudi et al. 1994). Long-base fiber optic displacement sensors offer a resolution in the micrometer range and excellent long-term stability, allowing measurements over more than ten years with micrometer accuracy (Glišić et al. 2005). The measurement setup uses low-coherence interferometry to measure the length difference between two optical fibers installed on the structure to be monitored (Fig. 5), by embedding in concrete or surface mounting.
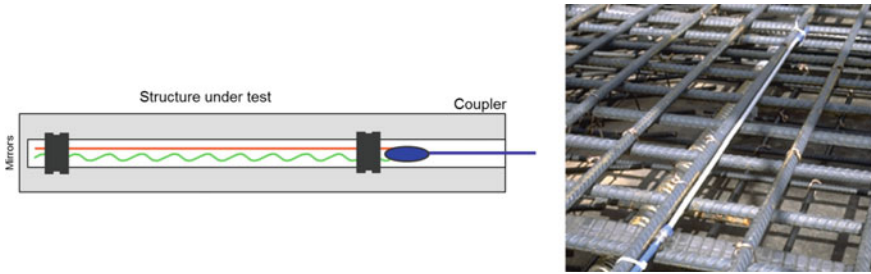
Fig. 5 Functional principle of SOFO sensors and sensor installation in concrete

The measurement fiber is pre-tensioned and mechanically coupled to the structure at two anchor points in order to follow its deformations, while the reference fiber is free and acts as temperature reference. Both fibers are installed inside the same plastic pipe and the gage length can be chosen between 200 mm and 10 m. The readout unit, shown in Fig. 6, measures the length difference between the measurement fiber and the reference fiber with micrometer accuracy.

Those sensors are particularly adapted when an accurate and long-term stable deformation measurement is required. They are particularly useful when installed inside or on the surface of inhomogeneous materials such as concrete, rock, soil, masonry or timber. Thanks to their long gauge length, those sensors average the strain recording and make their reading less sensitive to local material inhomogeneity or defects. Examples of application include the measurement of internal deformations of dams, tailing dams and levees, as well as deformation monitoring of walls, piles and other retaining structures (Glisic et al. 2002). These sensors have been installed inside ground anchors for long-term deformation monitoring (Inaudi and Casanova 2000).

**Fig. 6** Example of SOFO readout unit

Fiber Optic Distributed Strain and Temperature Sensors

Even before the optical fiber sensors described above even existed, many different types of discrete instrumentation for dams have been available to civil engineers. These sensors incorporate different types of sensing technologies an, including piezometers, inclinometers, and settlement plates. Levees traditionally have not included sensors, but occasionally have relied on traditional point sensors for limited data gathering at a specific location or to investigate a specific defect (Dunnicliff 1993). For such extended structures, deciding where to install point sensors becomes a challenge in itself. Placing traditional, discrete sensors made defect detection and localization highly improbable, and was seldom considered a cost effective method in comparison to regular visual inspection.

Through advances in Structural Health Monitoring (SHM) and civil engineering instrumentation, new monitoring technologies and applications have emerged that are complementing the traditional methods engineers use to evaluate and inspect levees and earthen dams. The fiber optic distributed strain/temperature monitoring systems can provide actionable operation and maintenance information, provide powerful inspection and assurance tools, and provide warning to engineers and asset managers about failures before they occur, increasing safety for all dam and levee stakeholders. Now engineers have tools to seamlessly monitor levee segments of lengths up to 30 km, with no breaks or gaps, allowing 100% coverage (see Fig. 7). These distributed sensors allow engineers to both localize and quantify movements and leaks (Inaudi and Glisic 2005). In addition, earthen tailings dams can be hundreds of feet high, and can similarly achieve full same coverage.

A distributed fiber optic monitoring system consists of one or more unique sensor cables (fiber optic) and one readout device. The area of coverage can be up to 30 continuous kilometers in length with one system. The sensor cables can be deployed either during construction or after construction and is possible to retrofit existing structures by cable plowing or trenching. The readout system can monitor strain and temperature along the entire length of cable, and is able to detect the following failure modes (Inaudi and Church 2011):
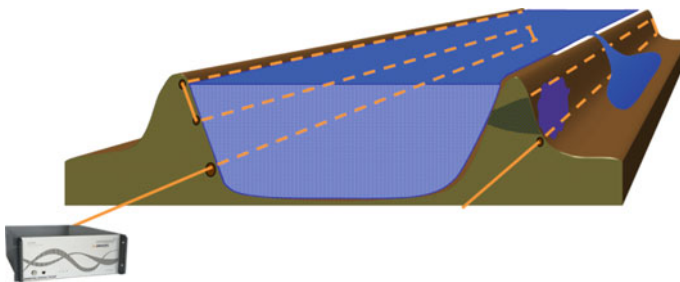

Fig. 7 Use of a single distributed sensor to monitor the strain and temperature along the full length of a levee at multiple levels

- Structural movement or failure,
- Overtopping,
- Under-seepage,
- Through-seepage,
- Piping (internal erosion),
- External erosion,
- Differential settlement,
- Landslides.

Unlike electrical sensors and localized fiber optic sensors, distributed sensors offer the unique characteristic of being able to measure physical parameters, in particular strain and temperature, along their entire length, allowing the measurement of thousands of points from a single readout unit.

The most developed technologies of distributed fiber optic sensors are based on Raman and Brillouin scattering. Both systems make use of a nonlinear interaction between the light and the glass material of which the fiber is made. If an intense light at a known wavelength is injected into a fiber, a very small amount of it is scattered back from every location along the fiber itself. Besides the original wavelength (called the Rayleigh component), the scattered light contains components at wavelengths that are higher and lower than the original signal (called the Raman and Brillouin components). These shifted components contain information on the local properties of the fiber, in particular its strain and temperature at the location where the scattering occurred. Figure 8 shows the main scattered wavelengths components for a standard optical fiber and how they can be sued for sensing purposes.
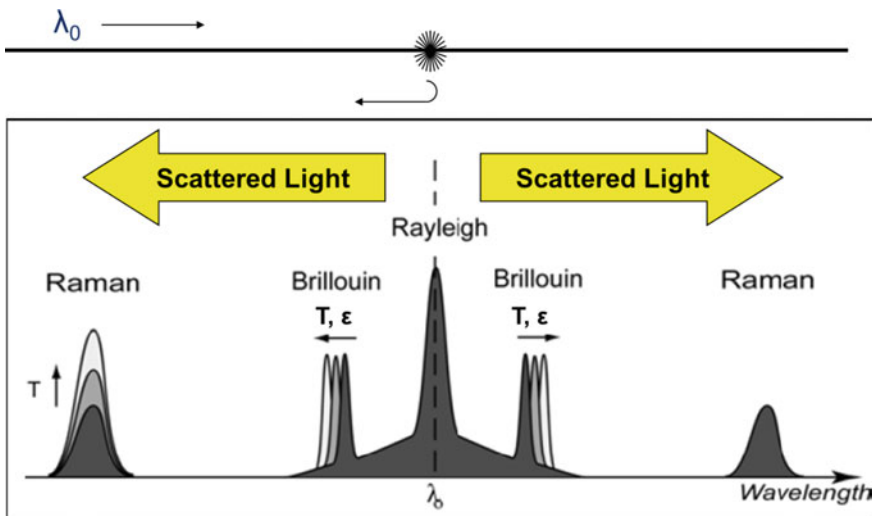

Fig. 8 Wavelength components of scattered light in silica fibers, Raman and Brillouin peak location and intensity are temperature and strain dependent and can be sued for sensing those parameters

If λ_0 is the wavelength of the original signal generated by the readout unit, the scattered components appear at both higher and lower wavelengths. The two Raman peaks are symmetric to the original wavelength. Their position is fixed, but the intensity of the peak at lower wavelength is temperature dependent, while the intensity of the one at higher wavelength is unaffected by temperature changes. Measuring the intensity ratio between the two Raman peaks therefore yields the local temperature in the fiber section where the scattering occurred.

The two Brillouin peaks are also located symmetrically at the same distance from the original wavelength. Their position relative to λ_0 is however proportional to the local temperature and strain changes in the fiber section. Brillouin scattering is the result of the interaction between optical and ultrasound waves in optical fibers. The Brillouin wavelength shift is proportional to the acoustic velocity in the fiber which is related to its density. Since the density depends on the strain and the temperature of the optical fiber, we can use the Brillouin shift to measure those parameters.

When light pulses are used to interrogate the fiber it becomes possible, using a technique similar to RADAR, to discriminate different points along the sensing fiber through the different time-of-flight of the scattered light. Combining the radar technique and the spectral analysis of the returned light one can obtain the complete profile of strain or temperature along the fiber. Typically it is possible to use a fiber with a length of up to 30 km and obtain strain and temperature readings every meter, as depicted in Fig. 9. In the professional jargon, this is referred to as a distributed sensing system with a range of 30 km and a spatial resolution of 1 m.

Systems based on Raman scattering typically exhibit temperature accuracy of the order of ± 0.1 °C and a spatial resolution of 1 m over a measurement range up to 30 km. The best Brillouin scattering systems offer a temperature accuracy of
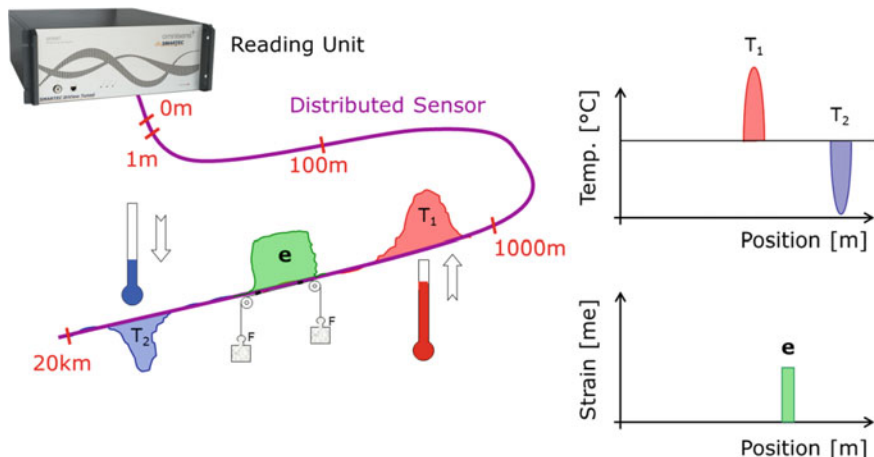
Fig. 9 Example of distributed strain and temperature sensing setup. If the cable is subject to temperature changes (red and blue zones) or strain (green zone) the instrument is able to identify and localize those events as illustrated in the corresponding graphs

± 0.1 °C, a strain accuracy of ±20 microstrain and a measurement range of 50 km, with a spatial resolution of 1 m. The readout units are portable and can be used for field applications.

The optical fibers are only 1/8 of a millimeter in diameter and are therefore difficult to handle and relatively fragile. For practical uses, it is therefore necessary to package them in a larger cable, much like copper conductors are incorporated in an electrical cable. Since the Brillouin frequency shift depends on both the local strain and temperature of the fiber, the sensor set-up will determine the actual response of the sensor. For measuring temperatures it is necessary to use a cable designed to shield the optical fibers from an elongation of the cable (Inaudi and Glisic 2005). The fiber will therefore remain in its unstrained state and the frequency shifts can be unambiguously assigned to temperature variations. Measuring distributed strains also 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. Since the system is sensitive to both strain and temperature variations, it is also necessary to install a reference temperature sensing fiber along the strain sensor, so that the effect of temperature can be removed from the strain reading. Special cables (Fig. 10), containing both free and coupled fibers allow a simultaneous reading of strain and temperature.

Applications to Dam and Dykes Leak/Seepage Detection and Temperature Monitoring

The use of distributed temperature sensing is of particular interest for the monitoring of dams, dykes and levees. Leaks and seepage can be detected and localized by observing temperatures anomalies along the sensing cable. It is therefore important to place the sensing cable at those locations in the levee or dyke cross-section where such undesired events might occur.

The following examples illustrate a few typical applications of distributed temperature sensing for leak and seepage detection.
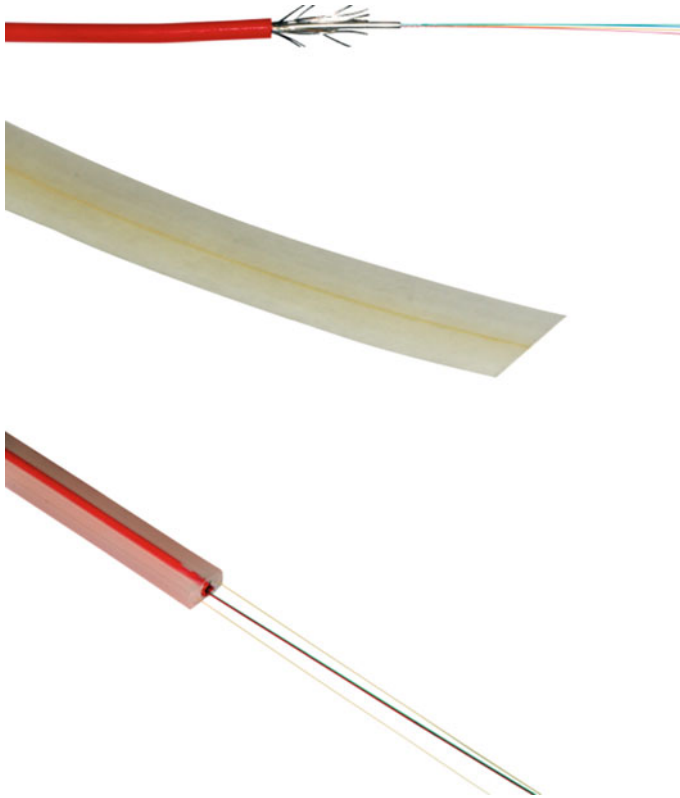
Water reservoirs in Spain

Type of Structure: Water reservoir with plastic membrane
Monitoring aim: Detect leaks through membrane and perimeter levee
Fiber Optic sensing technology employed: Distributed Raman temperature sensing with heated cable

A water reservoir in Spain consists in a square levee structure and an inner synthetic membrane. This large structure is used to store freshwater and potentially presents a risk of internal erosion if the watertight membrane were to leak. A distributed temperature monitoring cable was installed in the sand below the membrane at two levels around the levee perimeter as shown in Fig. 11 and interrogated with the system depicted in Fig. 12. To enhance the detection capability of the system,

Fig. 10 Example of distributed sensing cables to monitor temperature, strain and combined strain/temperature

Fig. 11 Water reservoir (Spain) after laying waterproof membrane. The sensing cables are installed at the bottom and at mid-height around the circumference of the levee

Fig. 12 Distributed
temperature sensing system
and ancillary equipment
installed at pumping station

a hybrid cable containing both optical fibers and copper wires was used. By circulating an electric current in the copper wires, it is possible to slightly increase the temperature of the cable itself and the surrounding ground. Since dry sand has lower thermal capacity than wet sand, for the same heating power it will increase its temperature more rapidly. By observing the locations along the cable where the temperature increases more slowly, it is possible to identify potential leak locations.

Nam Gum Dam in Laos

Type of Structure: Concrete Face Rockfill Dam
Monitoring aim: Detect leaks through concrete face along the plinth
Fiber Optic sensing technology employed: Distributed Raman temperature sensing

Nam Ngum Reservoir is the largest water impoundment in Laos; it was built in 1971 as a result of the construction of the first dam across the Nam Ngum River. The reservoir was designed 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 90 km from 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 m high and it can produce 2300 kW of electric power per hour.

The main aim of the installed instrumentation is to monitor the seepage at the foundation plinth level with an active detection system, using the heated cable method. A total of 2 independent armored sensing cables (approx. 900 m each) have been integrated in the filter zone by surface installation as shown in Fig. 13. The DTS reading unit with 4 channels is located in the dam control station with the aim of measuring the temperature profiles of the 2 sensing cables. Thanks to the customized visualization software it's possible to follow in real time any variation in the temperature profiles (Fig. 14) of the two sensing cable, launching a warning in case of seepage or leakage.

Luzzone Dam in Switzerland

Type of Structure: Concrete Arch Dam
Monitoring aim: Monitor temperature evolution during concrete setting
**Fiber Optic sensing technology employed**: Distributed Brillouin temperature sensing

In 1997 the Luzzone Dam in Switzerland was raised by 18 m to increase the capacity of the reservoir. Adding fresh concrete on top of existing concrete presented challenges related to differential shrinkage and temperature evolution during


Fig. 13 Distributed temperature sensing cable installation along the plinth dam of the Nam Ngum Dam, Laos
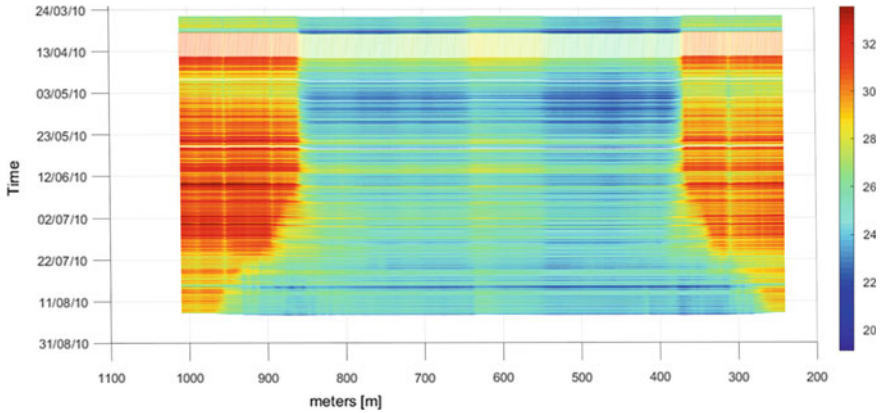
Fig. 14 Temperature evolution along the dam plinth during impounding. The horizontal axis represents position along the plinth, while the vertical axis represents time, with older dates on top. The color represents the recorded temperature in °C. The blue area, representing lower temperatures, expands outwards as the water level increases, indicating that the recorded temperature is mostly influenced by the water temperature and no longer sensitive to air temperature evolution

setting. The new concrete was instrumented with long-gage fiber optic sensors to monitor its shrinkage deformation and to evaluate the interaction between the newly added concrete and the old one (see Fig. 15) (Inaudi et al. 1998). Additionally, a distributed temperature sensor was installed in one of the largest concrete blocks to monitor the temperature evolution during concrete setting. In Fig. 16 it is possible to observe the temperature distribution within the concrete (Thévenaz 1999). The concrete block warms up rather uniformly, but during the cool-down phase, that can last several months, significant temperature gradients of up to 35 °C were observed. Those gradients can lead to concrete cracking.
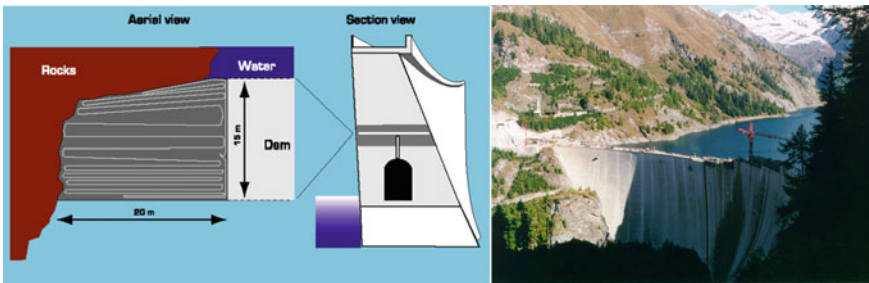
Fig. 15 Luzzone (Switzerland) dam raising, cable location and picture during work
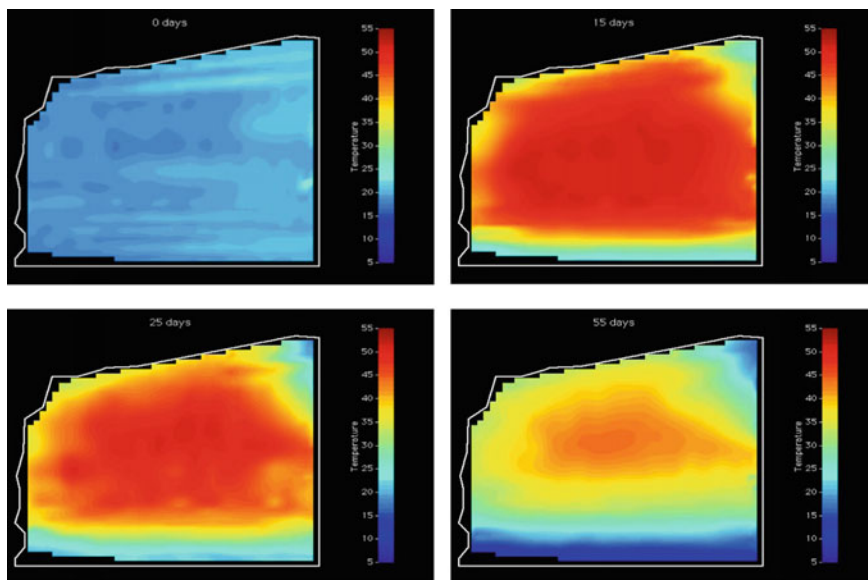
Fig. 16 Evolution of internal temperature in °C in Luzzone dam during concrete setting and after 15, 25 and 55 days

Application to Dams and Levee Deformation Monitoring

Local and distributed optical fiber strain sensors have found several useful applications in dam, dyke and levee monitoring. They are deployed to monitor the deformations of the dam body and its foundations. Long-gauge deformations sensors can be used to monitor large-scale deformations, averaging strain over several meters and therefore providing a more representative value of the measured deformation. On the other hand, distributed strain sensors are generally used to identify and localize damage such as cracks, settlements, abnormal joint movements or internal erosion. The following paragraphs provide a few application examples of those sensing technologies.

I Wall Levee in USA

Type of Structure: I levee wall
Monitoring aim: Monitor movements between wall panels to detect anomalies and impending panel failure
Fiber Optic sensing technology employed: Distributed Brillouin strain sensing

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 (Wang et al. 2014). The motivation for the monitoring system is to improve safety awareness, to provide relevant 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 helps in overcoming the issue of optimal sensor location allowing full structure coverage. Continuous long-term monitoring during the complete levee lifetime allows 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 different sensing technologies, a number of test sections have been instrumented; including I-wall and T-wall sections instrumented with distributes strain and temperature sensors. Figure 17 shows the installation of a distributed strain and temperature sensing cables in the levee foundations and on top of the I-wall and T-wall sections. 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.

An example of calculated deformation on the sensor placed on the top of the I-wall section is presented in Fig. 18. Deformation is plotted as a function of position along the wall and as a function of 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 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.

Earthen Levee in Netherlands

Type of Structure: Earthen levee
Monitoring aim: Detect early signs of levee failure on full-scale levee test section
Fiber Optic sensing technology employed: Distributed Brillouin strain sensing

Fig. 17 Installation of distributed strain and temperature sensing cables in the levee foundations and on top of the I-wall and T-wall sections in New Orleans, Louisiana, USA
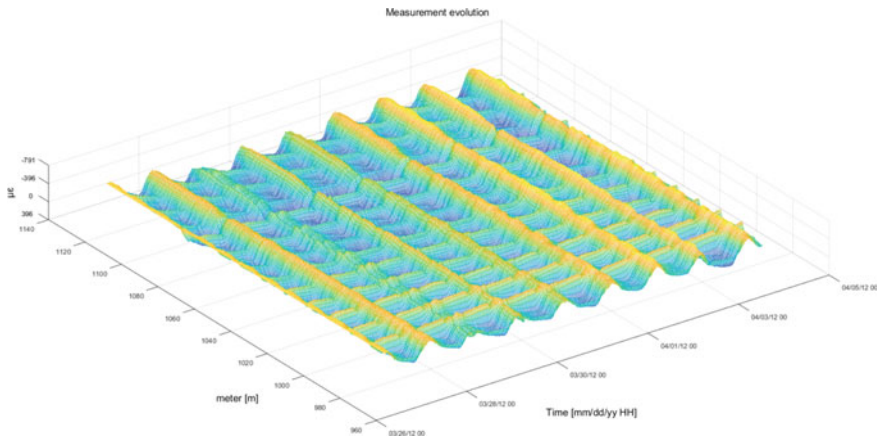
Fig. 18 Strain evolution as a function of time and position along a levee wall section

The IJkdijk was a collaborative project in the Netherlands to test dikes and to develop several existing sensor network technologies for dikes early warning systems. In 2008 a full-scale section of dike was constructed and destroyed in the Macrostability Experiment. The dike section (see Fig. 19) was roughly 100 m long, 30 m wide and 6 m high and consisted of a core of white sand and a shell of clay. A drainage system was placed at the bottom of the sand core, allowing the increase of the internal water pore pressure. Containers were placed on top of the dike, eventually to be filled with water to increase the normal load on top to reach the failure. Among many other sensing technologies, geotextile sensing strips embedding several distributed fiber optic strain cables were installed at four levels along the levee section. Those geotextile sensing strips were able to detect and localize the upcoming failure

Fig. 19 Levee section under test, Netherland. Courtesy of Deltares

zone up to 42 h before the final failure of the levee. Figure 20 shows the evolution of strain along the sensing strips at the 4 different heights (Artières et al. 2010).

River dam in Latvia

Type of Structure: River dam and hydropower plant
Monitoring aim: Detect and localize leaks across bitumen joint
Fiber Optic sensing technology employed: Distributed Brillouin strain sensing

Plavinu hes is a dam belongs to the complex of three most important hydropower stations on the Daugava River in Latvia (see Fig. 21). 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 in 1960, 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 power plant building is merged with a water spillway. The entire building complex is extremely
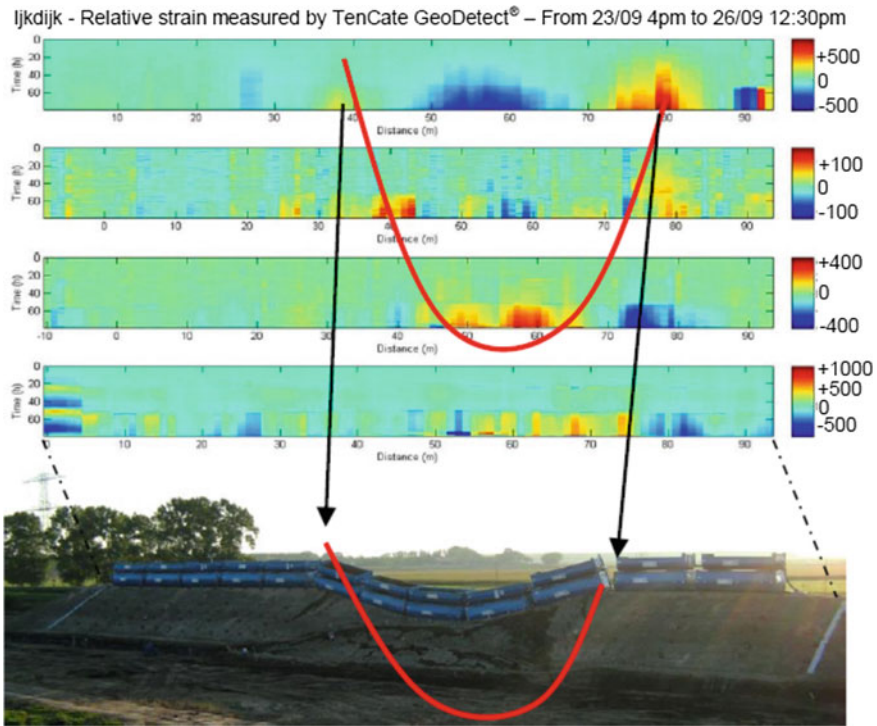
Fig. 20 Distributed strain evolution along four lines of sensing cables and. The four graphs represent the measured strain as a function of position (horizontal axis) and time (vertical axis). Red color indicates higher tensional strain, blue color indicates compression strain. It is possible to observe how the locations of the strain peaks correspond to the boundary zones of the collapsing area in the picture taken after failure. Courtesy of TenCate Geosynthetics

Fig. 21 Aerial photograph of Plavinu hes dam, Latvia

compact. There are ten hydro aggregates installed at the hydropower plant and its current capacity is 870,000 kW.

One of the dam inspection galleries coincides with a system of three bitumen joints that connect 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 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 next to the joints. A distributed strain monitoring system and a temperature sensing cable is used for this purpose (see Fig. 22). Threshold detection software with a relay alarm module was installed in order to send pre-warnings and warnings from the instrument to the Control Office in case of abnormal movements. In case of abnormal joint movements or appearance of cracks, the system is able to detect and localize those events and automatically generate an alert. The use of distributed sensing enables sensing along the whole length of the gallery, so that no matter where the undesired events takes place, there will always be a section of sensing cable to pick up the response.

Sinkhole detection in USA

Type of Structure: Sinkhole area affecting rail and road structures.
Monitoring aim: Detect and localize impending sinkhole formations
Fiber Optic sensing technology employed: Distributed Brillouin strain sensing

Fig. 22 Distributed strain sensing cable installed by clamping in the dam inspection gallery. The sensor runs along the length of the gallery and is therefore able to pick-up deformations generated by transverse cracks crossing its path. The blue temperature sensing cable installed along the strain cable is used for temperature compensation, but can also detect water ingress in the gallery by observing rapid temperature changes

Although it is not directly a dam or levee application example, this project is included because it shows the use of distributed sensing for the detection of localized settlements that are also very relevant for levee monitoring.

A sinkhole, also known as a sink, shake hole, swallow hole, is a natural or man-made depression or hole in the Earth's surface caused by karst processes or mining activities. Sinkholes may vary in size from 1 to 600 m both in diameter and depth, and vary in form from soil-lined bowls to bedrock-edged chasms as exemplified by Fig. 23. 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

Fig. 23 Example of sinkhole formation in the area under monitoring near Hutchinson, Kansas, USA
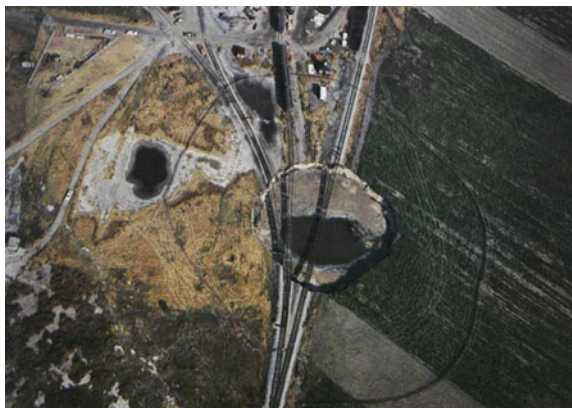
safety risk for surface infrastructure in the surrounding areas, such as roads or rail lines. In such applications where critical area localization and the use of the discrete sensors are practically impossible because of the installation complexity and costs, a distributed sensing system is particularly suitable.

The city of Hutchinson is located in Reno County, Kansas. Hutchinson is on the route of the trans-continental, high-speed main line of one of the nation's largest railroads. The railway passes near a former salt mine well field, where mining was carried out in the early part of the twentieth century. The salt mining was performed at depths of over 400 feet by drilling wells through the shale bedrock into the thick under-ground salt beds, and then pumping fresh water into the salt, dissolving the salt to be brought back to the surface as brine, for processing and sale. This solution mining process resulted in the presence of multiple, large underground voids and caverns, which have been reported to be up to 300 feet tall and over 100 feet in diameter. In places, the shale roof rock over some of these old mine voids has collapsed, forming crater-like sinkholes that can be over 100 feet in diameter and 50 feet deep at the surface. The collapse and sinkhole formation can occur very rapidly, over a period of hours to days. Figure 23 is a photograph of a sinkhole that opened up virtually overnight at this site in 2005, by collapse of a salt cavern that was last mined in 1929. The potential rapid formation of sinkholes by collapse of old mine caverns clearly represents an issue for ground stability and a non-negligible safety risk for surface infrastructure, including the railway.

An area on the site containing old, potentially unstable salt caverns adjacent to sensitive surface infrastructure was identified with the aim of establishing an effective monitoring system in order to provide early stage detection, continuous monitoring, and automatic telemetry. Arrangements were made for alerting via cell phone and email, in case of ground deformation (strain) that may be the early signs of sinkhole formation. The distributed fiber-optic (FO) monitoring system was selected in large part because it provides thousands of monitored points using a single fiber-optic sensing cable, all measured at the same time, in a single scan (Shefchik et al. 2011). This is well-suited to defining a monitored perimeter where the exact location of where a sinkhole might form is not known precisely. In addition, this monitoring system was selected because of the ease of installation by burial in a shallow trench.

The selection of the sensing cables represents a key aspect and at the same time a 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.

The fiber optic sensing cable is directly buried, Fig. 24, at a depth of approximately 1.4 m over a potential sinkhole area above and around salt caverns over a path with a total length of over 4 km, as shown in Fig. 25. After digging the trench, the soil is mechanically compacted, and the sensing cable deployed on the compacted soft ground before the trench is 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

Fig. 24 Distributed strain sensor installation in a trench

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 occur due to formation of a sinkhole. An example of strain recording obtained during a sinkhole simulation is depicted in Fig. 26.

Dam core monitoring in Spain

Type of Structure: Embankment dam with clay core.
Monitoring aim: Deformation monitoring of the clay core
Fiber Optic sensing technology employed: Long-gauge interferometric sensors

The Canales Dam is built on the Genil River, in Granada, Spain. It was constructed from 1975 to 1989 and activated in 1989. The dam is 156 m tall and the crown is 340 m long. The dam is used to produce electrical power, but it is also an important tourist attraction, notably for people who like to fish. The Canales Dam controls the river flow during the year while ensuring that there is always sufficient water to keep the river ''alive'' even during the driest months of July and August. A view of the Canales Dam is given in Fig. 27.

The aims of the monitoring were crack detection and monitoring of the deformation of the stiff-clay core of the dam. The zone where the cracks can occur was estimated to be between 60 and 110 m deep in the clay core. This whole length was
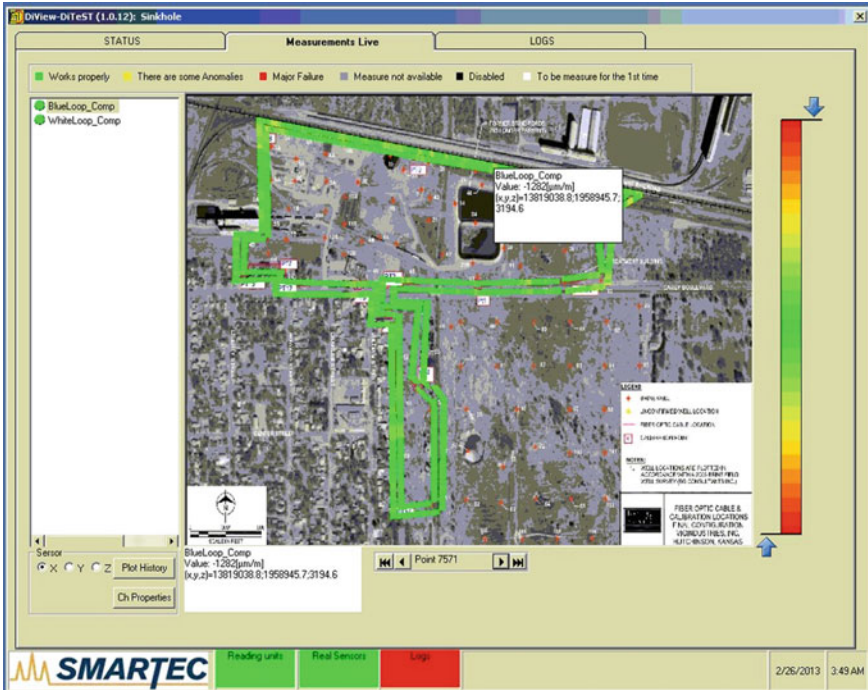
Fig. 25 Example of user interface showing the path of the sensing cable on a map. Green color indicates no strain; red color indicates 100% of the warning threshold

equipped with a 50 m long multipoint extensometer with 10 measurement zones (10 chained 5 m long deformation sensors). Preparation of the extensometer for the installation is shown in Fig. 28. The sensors were installed in a 110 m deep and 30° inclined borehole using a customized installation procedure. A mass with wheels was attached to the low-stiffness cord and slipped into the borehole. While the mass was pulling the cord into the borehole, the extensometer was attached to the cord, so the cord was used as a guide for the extensometer. The installation procedure is shown schematically in Fig. 3. After the placement of the extensometer in the desired position, the borehole was alternatively filled with grout on the anchor segments and sand was packed over the active zone. This was done to avoid perturbing the strain field in the clay core and to guarantee good deformation transfer from the clay core to each deformation sensor. Until the time of writing, no abnormal leak event has been recorded, reassuring the owner about the good performance of the watertight membrane.

Silica Alkali reaction monitoring in a concrete Dam

Type of Structure: Concrete dam
Monitoring aim: Monitor deformations induced by alkali silica reaction in concrete
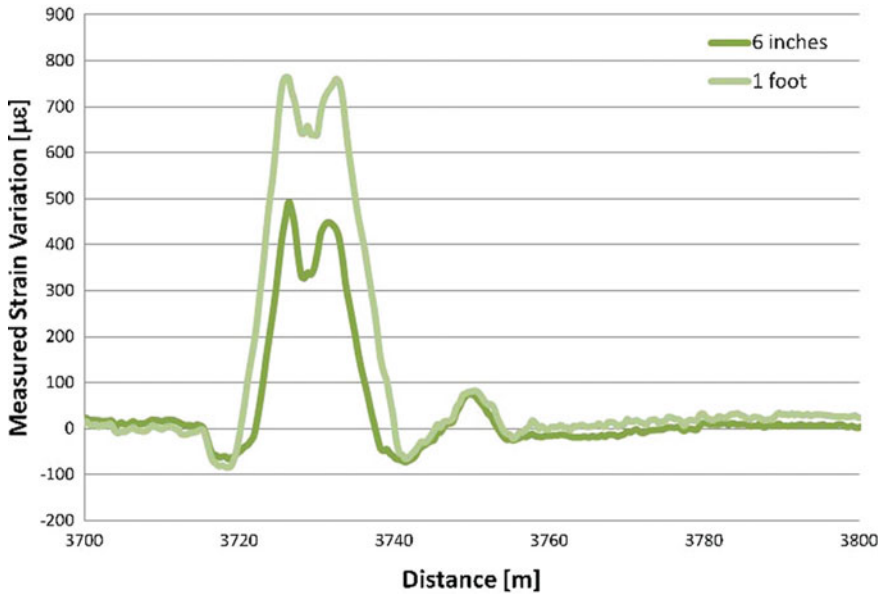
Fig. 26 Example of strain reading during sinkhole simulation test. The sensing cable is vertically moved by 6 in. and 1 foot, respectively and the resulting strain is recorded. It is possible to observe how the peak of recorded strain corresponds to the location of the test with an accuracy of a few meters. When the lateral movement is increased, more of the sensing cable records strain, indicating that a longer length of cable is being elongated by the event

Fiber Optic sensing technology employed: Long-gauge interferometric sensors

Val De La Mare reservoir (see Fig. 29) is constrained by a mass concrete dam situated on the west side of Jersey Island and was built between 1957 and 1962. The crest length is about 190 m; the dam height is 30 m above general foundation level. The dam was built in 27 monoliths (blocks) and it is owned and operated by Jersey Water. Val de la Mare dam is widely known to suffer from both Alkali Aggregate Reaction (AAR) and water seepage through existing construction joints. The dam exhibited differential displacement of some of the blocks and patches of humidity were visible on the downstream face of affected blocks. Long-gauge fiber optic deformation sensors have been installed to monitor the behavior of three blocks. The sensors have been completely integrated in the existing dam monitoring system. The fiber optic sensing system consists of 10 m long base SOFO sensors complete with a corresponding reading unit. The sensors have been installed in three of the existing vertical drain holes in blocks 11, 15 and 18. The location of the drain holes is shown in red on the right of Fig. 30. The sensors are 10 m in length and two sensors were joined mechanically together, effectively creating one 20 m sensor, placed in an 80 mm diameter drain hole. The output from reading unit has been linked to the Jersey Water SCADA system to provide a visual output showing historic trends. Multi-year data acquisition and multi-parameter regression analysis is used to evaluate the effects
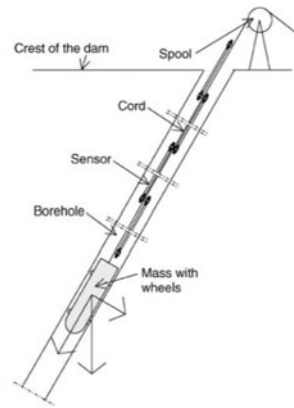
Fig. 27 Canales Dam, Spain

Fig. 28 Installation of long-gauge strain sensors in a borehole

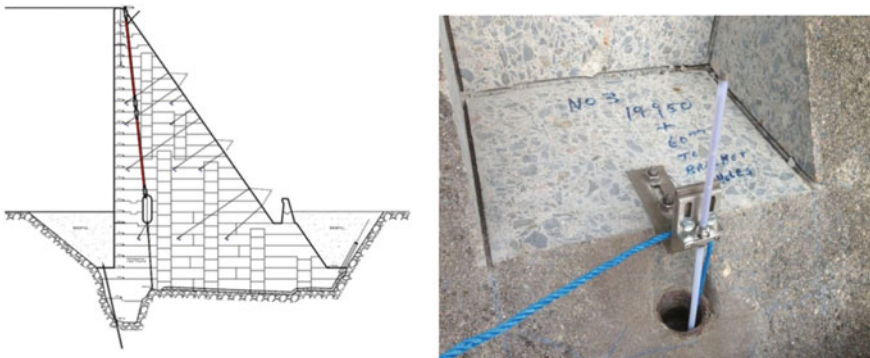**Fig. 29** Val De La Mare dam, Jersey Island

Fig. 30 Location of long-base extensometers in the inclined boreholes between the dam crest and the inspection gallery (red lines). Picture shows a detail of the upper anchor point installation

of alkali-silica reaction, aiming to separate its effects from the one of cyclic actions such as seasonal temperature and water-level variations.

Application to Tailing Dams

El Mauro Tailing dam in Chile

> **Type of Structure**: Mining tailings dam
> **Monitoring aim**: Monitor long term deformations and pore water pressure

Fiber Optic sensing technology employed: Long-gauge interferometric sensors and Fabry-Perot piezometers

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 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 of the open drainage matrix.

This called for a tight control of the presence of water in the base of the dam by means of 10 fiber optic piezometers and 2300 m of DiTemp distributed armored temperature cable, located some 2 m above drainage layers (Fahrenkrog and Fahrenkrog 2012). 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 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. Three long-gauge SOFO sensors are joined to form a tridimensional gauge for settlement and lateral deformation as shown in Fig. 31.

Fig. 31 Installation of long-gauge extensometers in the body of the tailing dam. Courtesy of Geomediciones

Additionally, fiber optic piezometers have been installed at several locations in the dam body. Those sensors were selected because of their insensitivity to damage produced by lightning strikes that are common in the area. Additionally, optical fiber sensors allow the use of cables longer than 1 km, without loss of performance. This enables installation in very large structures such as those tailing dams. Optical connection cables can also be lighter and less expensive than the equivalent copper wires used to connect conventional sensors over long distances.

Conclusions

The monitoring of new and existing structures is one of the essential tools for modern and efficient management of the infrastructure network. Sensors are the first building block in the monitoring chain and are responsible for the accuracy and reliability of the data. Progress in sensing technologies comes from more accurate and reliable measurements, but also from systems that are easier to install, use and maintain. In recent years, fiber optic sensors have taken the first steps in structural monitoring, particularly in civil and geotechnical engineering. Different sensing technologies have emerged and evolved into commercial products that have been successfully used to monitor hundreds of structures. No longer a scientific curiosity, fiber optic sensors are now employed in many applications where conventional sensors cannot be used reliably or where they present application difficulties.

The use of distributed fiber optic sensors for the monitoring of civil and geotechnical structures opens new possibilities that have no equivalent in conventional sensors systems. 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 strain and temperature distribution in the structure. This technology is therefore particularly suitable for applications at large or elongated structures, such as dams, dikes, levees, large bridges and pipelines.

Three characteristics of fiber optic sensors can be highlighted as the reasons of their present and future success: (1) the precision of the measurements; (2) the long-term stability and durability of the fibers; and (3) the possibility of performing distributed and remote measurements over distances of tens of kilometers.

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