GIN
&John

Celebrating 50 Issues of *Geotechnical Instrumentation News*

Gord McKenna

"Put your hand in your pocket and drill separate boreholes!" and so began the words of wisdom in John Dunnicliff's *Geotechnical Instrumentation News (GIN)* – an edited section of the last fifty issues of BiTech's *Geotechnical News* magazine.

John often writes that it is "*our* GIN" but truly it's *his* GIN, *his* heart and soul – his readers and contributors help keep it going by writing, arguing, commenting, and sharing. John is an inspiration to the entire geotechnical instrumentation community – a community that he has helped to create, to bring together, and to nurture. A self-styled "stickler" and "curmudgeon", John's insights and thoroughness from his famous Red Book, his instrumentation short courses, and his writings in GIN echo in our ears as we struggle to measure up to his clear standard of care and thoroughness. Getting people to present and argue passionately about the intricacies of geotechnical instrumentation in GIN is one more way that John helps us keep high standards even when we're knee deep in the mud, tricking sensors a hundred feet into the solid earth.

Leafing through fifty issues of GIN, I'm struck by the breadth of our geotechnical instrumentation community – it's not just soil and rock – it's concrete and steel, it's tunnels and dams, pavements and shafts, piles and tires, it's the permafrost, the seafloor, and residual soils in the tropics, it's shallow, deep, and everything in between. It's about understanding the past, signing off on the present, predicting the future.

We often allow ourselves to forget what a small community we are, and how so many of us are geographically isolated. Geotechnical instrumentation is a small industry – there are only a few manufacturers, a few key workshops and conferences, a few major projects on the go at any given time. It takes nearly a generation to work the kinks out of new technologies – many don't survive the harsh field conditions, and many old favourites are no longer manufactured (yet must still be lovingly read and maintained). GIN offers a running dialog of new technologies, improvements on old ones, ideas and understanding for continuous improvement. Issues are sprinkled with adages from Ralph Peck and Karl Terzaghi to remind us where we have been, where we are going, and the need for both understanding and the utmost care. GIN provides a place for us to meet – it brings us together.

John uses GIN to bring together manufacturers, designers, field practitioners, spec writers, and procurement specialists to get the most out of geotechnical instrumentation. We take to heart the need to understand exactly how each sensor works – how each one reacts differently with the ground, and how every borehole is different. No cookbook or standard can cover all conditions, but there are some important recurring themes in GIN that include:

- The Golden Rule: Every instrument on a project should be selected and placed to assist with answering a specific geotechnical question; if there is no question, there should be no instrumentation
- The person held responsible should be the one with the greatest vested interest in the data
- If an instrument is not working perfectly before installation, there's not much hope of it working well after installation (so make absolutely sure it is working perfectly before you install it)
- Don't allow dust to grow on data
- We almost never know the actual value of the quantity being measured, so we must resort to other methods to ensure accuracy
- Never shy from an opportunity to interrogate sensors under controlled condition – to ensure their accuracy, and to better understand their behaviour in the ground.
- Installation is *always* a professional endeavour, not something to be left to the inexperienced or to simply the lowest bidder.

GIN is a wonderful mix of articles about the success and failure of instruments and instrumentation programs, users' complaints and answers from manufacturers, short book reviews, checklists for doing things right, and plugs for upcoming instrumentation conferences and workshops. Weaving it all together is John's running commentary on everything from liquid level gages, to measuring unsaturated pore-water pressures, to comparing accuracy, resolution, and precision, to writing specification packages for those who insist on assigning their instrumentation programs to the lowest bidder. Mixed in for good measure are pointers on cricket, pleas for good grammar and punctuation, and an ongoing explanation to North Americans on what it means to be British ("two nations separated by a common language").

At the start, some were concerned that GIN would be too controversial for manufacturers (a.k.a. advertisers) – highlighting disagreements with clients, inviting comments on reliability, or dredging up problems solved long ago. John's solution is to invite comment from all interested parties, often published together, but also often running as major themes over three or four issues. The reader not only understands the solutions, but how people go about arriving at them, and an understanding that there are many things we all struggle with together. His success in this regard provides an example of how to approach such disagreements with integrity. But it requires skill and effort on John's part – GIN works because of John's commitment to excellence in writing, in instrumentation, and to getting the word out.

How long can we expect John to carry the torch? He'll tell you that GIN depends on all of us – keeping the articles coming, hopefully a little faster than in the past, and adhering to his 26 point manifesto on style. But then he'll confide that editing GIN is "Part of who I am." So I'm assuming the first fifty issues are the sign of more good issues, more good controversies, and more good insights to come.

Thank you, John, for your dedication in bringing our community together, and offering a thoughtful, well edited, and diverse mix of articles, reviews, notices, philosophy and discussion that teaches and inspires all of us.

Gord McKenna, PhD, PEng, PGeo, Senior Geotechnical Engineer, BGC Engineering Inc, Suite 500 - 1045 Howe Street, Vancouver, BC, Canada, V6Z 2A9, Telephone: (604) 684-5900, e-mail: gmckenna@bgcengineering.ca, www.bgcengineering.ca

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Geotechnical
Instrumentation
NEWS

Geotechnical Instrumentation News

John Dunnicliff

Introduction

This is the fifty-second episode of GIN. Two articles this time.

Fiber Optic Sensors

In the previous episode of GIN I mentioned fascinating updates on fiber optic sensing and time domain reflectometry at the March instrumentation course in Florida. I said that I hoped to have GIN articles on these two topics. Here are two on the first topic. The authors of the two articles are employed by SMARTEC in Switzerland, a member of the Roctest Group. Their company manufactures the fiber optic sensing systems that are described in the articles.

Time Domain Reflectometry (TDR)

There will be a paper on TDR by Kevin O'Connor (GeoTDR, Westerville, Ohio) in the proceedings of the FMGM-2007 symposium, to be held in Boston in September. We'll re-publish this in GIN, probably in the March 2008 episode.

Fully-grouted Piezometers

There will also be a paper in the proceedings of the FMGM symposium by Iván Contreras, Aaron Grosser and Rich VerStrate (Barr Engineering Co., Minneapolis) on the use of the fully-grouted method for piezometer installation. We'll also re-publish this in GIN next year.

What Else Can I Tell You About?

While trying to answer this I re-read the May 2007 editorial by Scot Litke, Editor of *Foundation Drilling*, the magazine of ADSC, The International Association of Foundation Drilling. Even though the editorial has nothing to do with instrumentation, no way can I do better. So, with Scot's helps and permission, 'ere 'tis, as they say in Devon:

Older Workers Can Fill an Important Role

> Much has been written about the changing population demographics in the United States and how it may affect the world of work. It has been a traditional assumption in our society that once one reached the age of 65 one was expected to retire. In fact several vocations mandate retirement at this age, if not sooner. This assumption is 'now under review'.
>
> There are several important factors that contribute to the re-evaluation of this societal expectation. Firstly, there is the fact of numbers. The folks on the front end of the baby boom generation, those born between 1946 and 1950, are getting real close to retirement age. At close to 76 million, the boomers are the largest population block in our nation. Secondly, people are living longer, more productive lives. The average life expectancy in the U.S. for a man is now up to 83. Women can expect, on average, to live till 88. Of course not all will, an unfortunate aspect of averaging, but many, many more will. Thirdly, retirement isn't what it used to be, in a number of ways. The economics of retirement have changed drastically. The days when one could lay back and get along on social security are long gone. As people live longer, more active lives, their expectations for how they will live in their retirement years has changed. Few are now satisfied with the notion of kicking back and heading to the porch rocker. It used to be assumed that once one reached 'a certain age' they wouldn't need the kind of revenue stream that they had earlier in their lives, as after all, they weren't going to be as active. Guess again. If anything retirement has become to mean for many, a more active life doing things one 'wanted' to do but for which one could never find the time. Translation, if you expect to continue to do more, and social security isn't going to cut it, you had better be saving and investing aggressively.
>
> Here's another gotchya - Americans aren't very good at saving. By and large wages have not kept up with inflation over the long haul. So, what have we got here? A formula for working past 65. At this time only about 15 percent of those over 65 are in the workforce. In 2006, 28 percent of those in the workforce were age 50 plus, up from less than 20 percent 20 years earlier. This will continue to change dramatically over the next 10 years as the boomers show up as quasi-retirees in large numbers.
>
> Now the interesting part - it is not only that folks **need** to work longer. It is that our economy needs them to do so. Remember that those 76 million baby boomers are not being replaced by Gen-Xers or Gen-Yers in near the numbers the previous gener-

ation represents, perhaps half. Next on the thought agenda is the fact that the boomers possess a great deal of institutional knowledge, knowledge that is critical to organizational continuity and success. We have already established that folks are living longer, more productive lives. Industry is realizing that these graying workers still have plenty to offer. Here's an interesting statistic - the average age of a construction worker in our part of the industry is 55. The same holds true for the civil engineering profession. Employers are now discovering that contrary to the assumption that older workers may cost you more because of health expenses, health related absenteeism, loss of focus, etc., in fact older healthy workers may cost you less. Those over 65.6 are not only collecting social security payments, but they are on Medicare as well. If an employer is able to offer flex time and fewer hours, older workers are able to supplement the employer's pay check with their own draws on social security and/or retirement plans. Employers are also discovering that these folks by and large have a work ethic that is not found in younger folks. For people of this ilk, 'work is life', not something you have to do as little of as possible and get paid as much as possible. These workers are not running home to take young children to soccer practice, ballet, piano lessons, or the orthodontist. They are not committed to attending parent teacher association meetings, or linking their vacations to school holiday breaks. The ones that want to work, or have to work, appreciate having the opportunity. They don't think they are owed anything. They relish the chance to continue to contribute to a company's objectives. While there may be initial problems with older workers having to report to youngsters they quickly get over it. These seasoned citizens want the work, they need the work. They will do the work.

None of the above precludes the need to aggressively recruit young folks into our industry on the design and the construction sides of the coin. I have already written about the need to begin the recruitment process early and often. We are competing for fewer young people with lots and lots of choices. We must make our profession attractive. But that's another topic.

Here's the point – don't discount the value of keeping your older employees. Don't be afraid to bring ambitious seniors back to help mentor the younger folks. The blend of experience and hopefully wisdom, with exuberant youthful energy and excitement is a terrific combination for any company.

It's shift the paradigm time.

Please don't misunderstand my motive in reprinting this – it has nothing to do with hopes for my own future. Just a good sermon for others!

Closure

Please send contributions to this column, or an article for GIN, to me as an e-mail attachment in MSWord, to *john@dunnicliff.eclipse.co.uk, or by fax or mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England. Tel. and fax +44-1626-832919.*

Happy Landings!

Overview of Fiber Optic Sensing Technologies for Geotechnical Instrumentation and Monitoring

Daniele Inaudi
Branko Glisic

Introduction

From many points of view, fiber optic sensors are the ideal transducers for structural health monitoring. 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 performances and suitability for different applications. In the last few years, fiber optic sensors have made a slow but significant entrance in the sensor panorama. After an initial euphoric phase when fiber optic sensors seemed on the verge of becoming prevalent in the whole world of sensing, it now appears that this technology is mainly attractive in the cases where it offers superior performance compared with the more proven conventional sensors. The additional value can include an improved quality of the measurements, a better reliability, the possibility of replacing manual readings and operator judgment with automatic measurements, an easier installation and maintenance or a lower lifetime cost. Finally, distributed fiber sensors offer new exciting possibilities that have no parallel in conventional sensors.

This article reviews the four main fiber optic sensor technologies:

- Fabry-Pérot Interferometric Sensors
- Fiber Bragg Grating Sensors

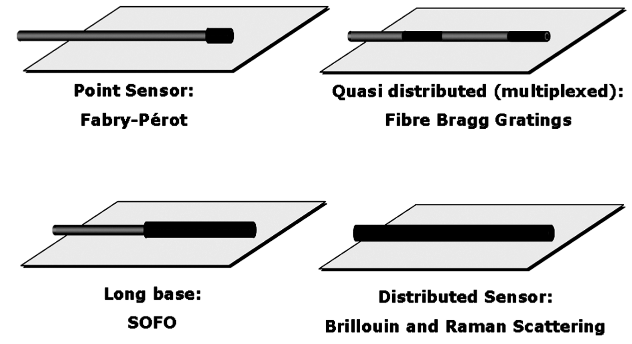

Figure 1. Fiber optic sensor types.

- SOFO Interferometric Sensors
- Distributed Brillouin Scattering and Distributed Raman Scattering Sensors

and their practical implementation in the form of packaged sensors and readout instruments.

Selected application examples illustrate the practical use of these sensing systems.

Fiber Optic 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 applications. Figure 1 illustrates the four main types of fiber optic sensors:

- *Point sensors* have a single measurement point at the end of the fiber optic connection cable, similarly to most electrical sensors.
- *Multiplexed sensors* allow the measurement at multiple points along a single fiber line.
- *Long-base sensors* integrate the measurement over a long measurement base. 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.

The greatest advantages of the FOS are intrinsically linked to 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 protect 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 an ideal material for use in harsh environments such as encountered in geotechnical applications. Chemical resistance is a great advantage for long term reliable health monitoring of civil engineering structures, making fiber optic sensors particularly durable. Since the light confined into the core of the optical fibers used for sensing purposes does not interact with any surrounding electromagnetic field, FOS are intrinsically immune to any electromagnetic (EM) interferences. 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 generated by lightning hitting a monitored bridge or 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 or chemical plants. But the greatest and most exclusive advantage of such sensors is their ability to offer long range distributed sensing capabilities.

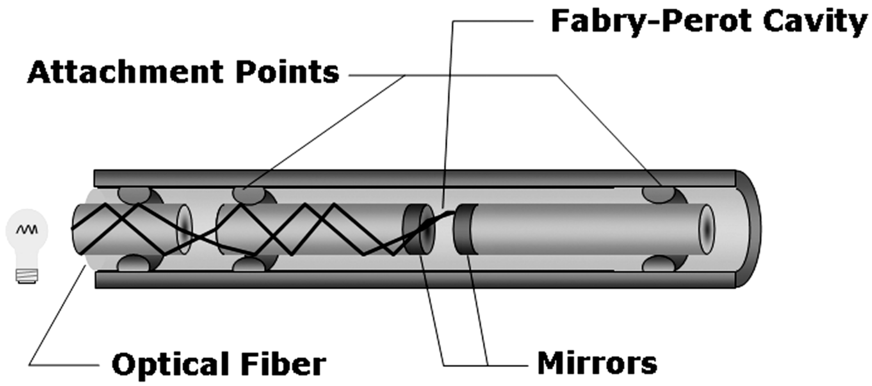

Figure 2. Operating principle or a Fabry-Pérot cavity sensor.

Fabry-Pérot Interferometric Sensors

Fabry-Pérot Interferometric sensors are typical example of point sensors and have a single measurement point at the end of the fiber optic connection cable.

An extrinsic Fabry-Pérot Interferometer (EFPI) consist of a capillary glass tube containing two partially mirrored optical fibers facing each other, but leaving an air cavity of a few microns between them, as shown in Figure 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-co-

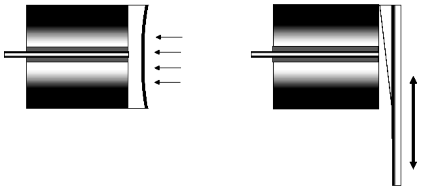

Figure 3. Examples of geotechnical sensors based on the Fabry-Pérot Cavity principle. Depicted are a piezometer and a displacement transducer.

herence techniques to reconstruct the changes in the fiber spacing. 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 Figure 2.

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

As an example, this technology has been installed for the monitoring of a mining dam. Located in the mountains north of Santiago, Chile, El Mauro tailings dam is being built as part of the Los Pelambres mine project. Approximately 1.4km wide, El Mauro will have a final height of 240m at an altitude of 938m asl. Work began on the infrastructure of the dam following environmental approval received in 2004. Expected to cost around US$450M, the dam is scheduled to be completed in 2007.

In September 2005, Los Pelambres selected Fabry-Pérot fiber optic sensors for the instrumentation at El Mauro – a first example of fiber optic instruments for this type of application. The instruments include piezometers, temperature sensors and seismographs.

Because they are immune to electromagnetic interferences, static electricity and frequent thunderstorms that are found at high altitudes, fiber optic instruments offer in this case an important advantage over the traditional vibrating wire technology. They are more rugged in such a harsh environment and allow very long cable lengths without the need of any lightning protection. This is important because Los Pelambres mine is located at an altitude of 3200m where dry air produces static electricity. The area is also affected by earthquakes, which are monitored by the installation of seismographs connected to the fiber optic instruments so that high-speed dynamic measurements can be taken during a seismic event. This system allows the dam to be monitored throughout its construction and all other phases of its life.

Fiber Bragg Grating Sensors

Fiber Bragg Grating Sensors are the most prominent example of multiplexed sensors, allowing measurements at multiple points along a single fiber line.

Bragg gratings are periodic alterations of the density of glass in the core of the optical fiber produced by exposing the fiber to intense ultraviolet light. The produced gratings typically have a length of about 10 mm. If light is coupled in the fiber containing the grating, the wavelength corresponding to the grating period will be reflected while all other wavelengths will pass through the grating undisturbed, as shown in Figure 4. Since the grating period is strain and temperature dependent, it becomes possible to measure these two parameters by analyzing the spectrum of the reflected light. This is typically done using a tunable filter (such as a Fabry-Pérot cavity) or a spectrometer. Precision of the order of 1 με and 0.1 °C can be achieved with the best demodulators. If strain and temperature variations are expected simultaneously, it is necessary to use a free reference grating that measures the temperature only and employ its reading to correct the strain values. Set-ups allowing the simultaneous measurement of strain and temperature have been proposed, but their reliability in field conditions has yet to be proved. The main interest in using Bragg gratings resides in their multiplexing potential. Many gratings can be produced in the same fiber at different locations and tuned to reflect at different wavelengths as shown in Figure 4. This allows the measurement of strain at different places along a fiber using a single cable. Typically, 4 to 16 gratings can be measured on a single fiber line. It should be pointed out that since the gratings have to share the spectrum of the source used to illuminate them, there is a trade-off between the number of grating and the dynamic range of the measurements on each of them.

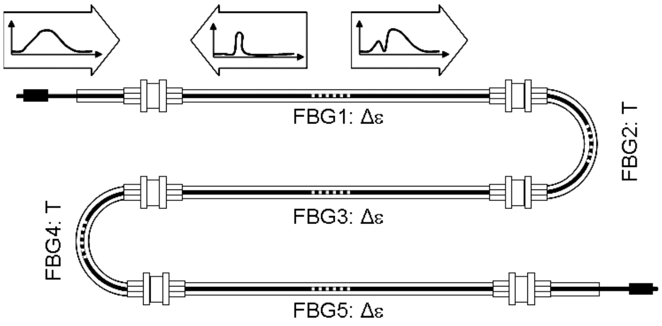

Figure 4. Chain for Fiber Bragg Grating sensors containing strain and temperature sensors. Each sensor reflects a specific wavelength.

Figure 5. SOFO sensor installed on a rebar. The plastic pipe contains the coupled measurement fiber and a free un-coupled reference fiber. The metallic anchors at both ends of the white plastic pipe define the gage length.

Because of their short length, Fiber Bragg Gratings can be used as replacements for conventional strain gages, and installed by gluing them on metals and other smooth surfaces. With adequate packaging they can also be used to measure strains in concrete over gage length of typically 100 mm.

SOFO Interferometric Sensors

The SOFO Interferometric sensors are

Figure 6. Portable SOFO system readout unit.

long-base sensors, integrating the measurement over a long measurement base that can reach 10m or more.

The SOFO system is a fiber optic displacement sensor with a resolution in the micrometer range and excellent long-term stability. It was developed at the Swiss Federal Institute of Technology in Lausanne (EPFL) and is now commercialized by the authors' company, SMARTEC in Switzerland.

The measurement set-up uses low-coherence interferometry to measure the length difference between two optical fibers installed on the structure to be monitored (Figure 5), by embedding in concrete or surface mounting. The measurement fiber is pre-tensioned and mechanically coupled to the structure at two anchorage 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 200mm and 10m. The SOFO readout unit, shown in Figure 6, measures the length difference between the measurement fiber and the reference fiber, by compensating it with a matching length difference in its internal interferometer. The precision of the system is of ±2 µm independently from the measurement basis and its accuracy of 0.2% of the measured deformation even over years of operation.

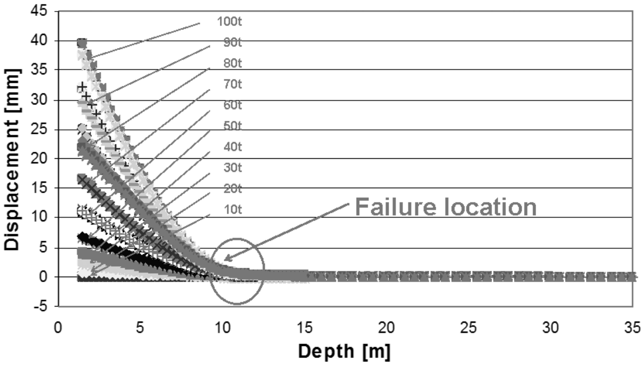

Figure 8. Deformed shapes of the pile and identification of failure location.

The SOFO system has been used to monitor more than 300 structures, including bridges, tunnels, piles, anchored walls, dams, historical monuments, nuclear power plants as well as laboratory models. An example of such an application was the monitoring of cast-in-place piles during a load test. A new semi-conductor production facility in the Tainan Scientific Park, Taiwan, is going to be founded on a soil consisting mainly of clay and sand with poor mechanical properties. To assess the foundation performance, it was decided to perform an axial compression, pullout and flexure test in full-scale on-site condition. Four meter long SOFO sensors were selected in order to cover the whole length of the pile with sensors, and obtain averaged strains over long pile sections. The pile was divided into eight sections. In the case of axial compression and pullout tests, a simple sensor arrangement was used: the eight sensors were installed in a single chain, placed along one of the main rebars, one sensor in each section (A1 to A8), as shown in Figure 7. To detect and compensate for a possible load eccentricity, the top cell was equipped with one more sensor (B1) installed on the opposite rebar with respect to the pile axis.

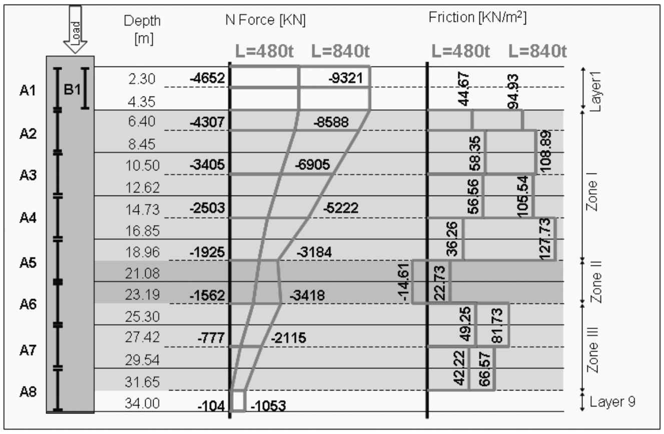

Figure 7. Sensor location and results obtained by monitoring during the axial compression test of a cast-in-place pile.

As a result of monitoring, valuable information concerning the structural behavior of the piles was collected. Important parameters were determined such as distributions of strain, normal forces, displacement in the pile, distribution of frictional forces between the pile and the soil, determination of Young's Modulus, ultimate load capacity and failure mode of the piles as well as qualitative determination of mechanical properties of the soil (three zones are indicated in Figure 7).

For the flexure test, a parallel arrangement was used: each section contained two parallel sensors (as in section 1 of Figure 7) installed on two opposite main rebars, constituting two chains of sensors. This sensor arrangement allowed determination of the average curvature in each cell, calculation of deformed shape and identification of the plastic hinge depth (failure location). A diagram of horizontal displacement for different steps of load as well as the failure location on the pile is shown in Figure 8. More details can be found in Glisic et al (2002).

This example shows an interesting application of long-gauge fiber optic sensors. The use of long-base SOFO sensors allows the gapless monitoring of the whole length of the pile, and provides average data that is not affected by local features or defects of the pile.

Distributed Brillouin Scattering and Distributed Raman Scattering Sensors

Distributed sensors are able to sense at any point along a single fiber line (as shown in Figure 1), typically every meter over many kilometers of length.

In fully distributed FOS, the optical fiber itself acts as sensing medium, allowing the discrimination of different positions of the measured parameter along the fiber. These sensors use an intrinsic property of standard telecommunication fibers that scatter a tiny amount of the light propagating through it at every point along their length. Part of the scattered light returns backwards to the measurement instrument and contains information about the strain and temperature that were present at the location where the scattering occurred. 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 by the different time-of-flight of the scattered light. Combining the radar technique and the spectral analysis of the returned light it becomes possible to 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. In this case we would talk of a distributed sensing system with a range of 30 km and a spatial resolution of 1 m.

Although the fiber used for the measurement is of standard telecommunication type, it must be protected inside a cable designed for transferring strain and temperature from the structure to the fiber while protecting the fiber itself form damage due to handling and to the environment where it operates. To take full advantage of these techniques it is therefore important to select the appropriate sensing cable, adapted to the specific installation conditions.

The article immediately following this one is dedicated to distributed fiber optic sensors. It presents the different scattering sensing techniques, known as Brillouin and Raman Scattering, and their applications in geotechnical monitoring.

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 and in particular 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.

If three characteristics of fiber optic sensors should be highlighted as the reasons of their present and future success, we would cite the precision of the measurements, the long-term stability and durability of the fibers and the possibility of performing distributed and remote measurements over distances of tens of kilometers.

Reference

Glisic, B., Inaudi, D., Nan, C. (2002) "Piles monitoring during the axial compression, pullout and flexure test using fiber optic sensors", 81st Annual Meeting of the Transportation Research Board (TRB), Washington, DC, January 13-17, 2002

Daniele Inaudi and Branko Glisic,
SMARTEC SA, Roctest Group, Via Pobiette 11, 6928 Manno, Switzerland,
Tel. +41 91 610 18 00,
email: inaudi@smartec.ch,
email: glisic@smartec.ch

Distributed Fiber Optic Sensors: Novel Tools for the Monitoring of Large Structures

Daniele Inaudi
Branko Glisic

Introduction

Distributed fiber optic sensing offers the ability to measure temperatures and strains at thousands of points along a single fiber. This is particularly interesting for the monitoring of large structures such as dams, dikes, levees, tunnels, pipelines and landslides, where it allows the detection and localization of movements and seepage zones with sensitivity and localization accuracy unattainable using conventional measurement techniques.

Sensing systems based on Brillouin and Raman scattering (the difference

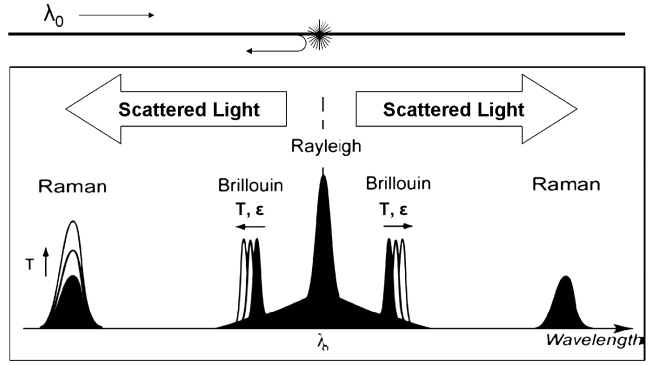

Figure 1. Light scattering in optical fibers and its use for strain and temperature sensing. At every section of fiber, the incoming wavelength λ_0 is scattered backwards. The backscattered light contains new wavelengths that carry information about the strain and temperature conditions at the location where the scattering occurred.

between the two will be explained later) are used to detect and localize seepage in dams and dikes, allowing the monitoring of hundreds of kilometers along a structure with a single instrument and the localization of the water path with an accuracy of 1 or 2 meters. Distributed strain sensors are also used to detect landslide movements and to detect the onset of cracks in concrete dams.

Early applications of this technology have demonstrated that the design and production of sensing cables, incorporating and protecting the optical fibers used for the measurement, as well as their optimal locating and installation in the structure under scrutiny, are critical elements for the success of any distributed sensing instrumentation project.

This article presents advances in distributed sensing systems and in sensing cables design for distributed temperature and strain measurements. The article also reports on a number of significant field application examples of this technology.

Distributed Fiber Optic Sensors

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 whole length, allowing the measurements 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 non-linear interaction between the light and the glass material of which the fiber is made. If an intense light at a known wavelength is shone 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. Figure 1 shows the main scattered wavelengths components for a standard optical fiber. If λ_0 is the wavelength of the original signal generated by the readout unit, the scattered components appear both at higher and lower wavelengths.

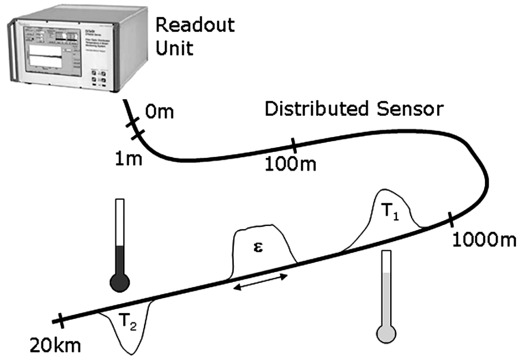

Figure 2. Schematic example of a distributed strain and temperature measurement.

The two Raman peaks are located symmetrically to the original wavelength. Their position is fixed, but the intensity of the peak at lower wavelength is temperature dependant, 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 form 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 that 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. For temperature measurements, Brillouin scattering is a strong competitor against systems based on Raman scattering, while for strain measurements it has practically no rivals.

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. In this case we would talk of a distributed sensing system with a range of 30 km and a spatial resolution (note that "spatial resolution" is a standard concept of distributed sensing, even though this is not 100% correct in metrological terms) of 1 m. Figure 2 schematically shows an example of distributed strain and temperature sensing. Systems based on Raman scattering typically exhibit temperature accuracy

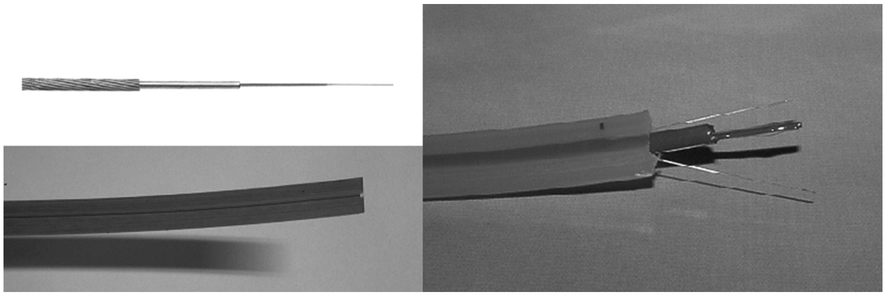

Figure 3. Distributed sensor cables examples. Left-top: temperature sensor; Left-bottom: strain sensor; right: combined strain and temperature sensor.

of the order of ± 0.1°C and a spatial resolution of 1m over a measurement range up to 8 km. The best Brillouin scattering systems offer a temperature accuracy of ± 0.1°C, a strain accuracy of ±20 microstrain and a measurement range of 30 km, with a spatial resolution of 1 m. The readout units are portable and can be used for field applications.

The optical fibers themselves 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. 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. To resolve the cross-sensitivity to temperature variations, it is also necessary to install a reference fiber along the strain sensor. Special cables, containing both free and coupled fibers allow a simultaneous reading of strain and temperature. Figure 3 shows examples of temperature, strain and combined cables.

Application Examples

This section presents brief application examples of distributed sensing for the monitoring of civil and industrial structures.

Temperature Monitoring in a Concrete Dam

In this application, a Brillouin scattering sensor system was used to monitor the temperature development in the concrete used to build a dam. The

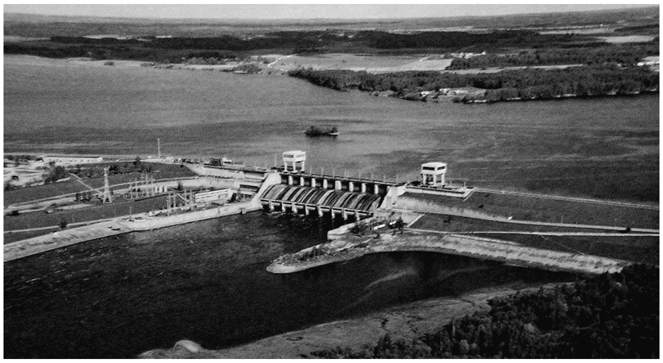

Figure 5. Plavinu Dam in Latvia.

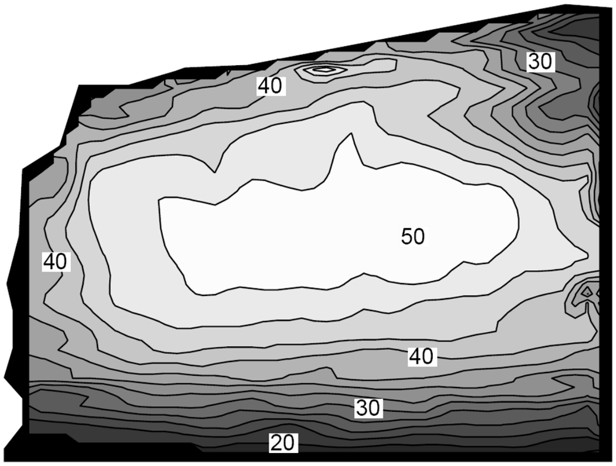

Figure 4. Contour plot (isothermal lines) of the temperature measurements in °C at the Luzzone Dam 30 days after concrete pouring (courtesy of L. Thévenaz).

Figure 6. Strain sensor installation in the Plavinu Dam inspection gallery.

Figure 7. Strain and temperature sensing cables installed on a gas pipeline. The picture shows a sensor line attached to the top of the pipeline and one on the side. The sensors are protected with an black neoprene pad. Another sensor line is attached symmetrically on the opposite side. The temperature sensing cable is also installed on top of the pipe. The vertical tube at the center of the picture, brings the optical cables form the pipeline to the junction box.

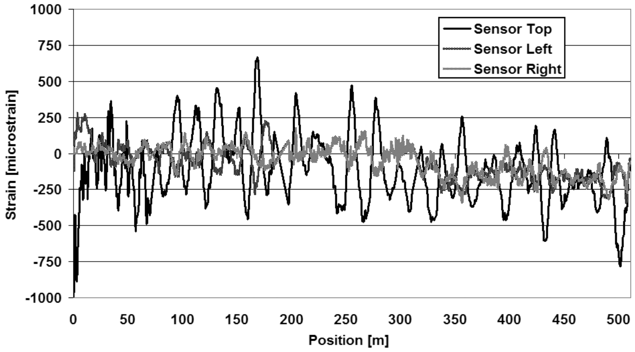

Figure 8. Strain distribution over the monitored part of the pipeline measured by the three distributed strain sensors. Each curve is composed of 500 individual strain points.

Luzzone concrete arch dam was raised by 17 meters to increase the capacity of the reservoir. The raising was achieved by successively concreting 3m thick blocks. The measurements concentrated on the largest block to be poured, the one that rests against the rock foundation at one end of the dam. An armored cable installed in a zigzag pattern during concrete pouring constituted the Brillouin sensor and was placed in the middle of the concrete block thickness. The cable therefore became embedded in the concrete.

The temperature measurements started immediately after pouring and continued over six months. The measurement system was proved reliable even in the demanding environment present at the dam (dust, snow, and temperature excursions). The temperature distributions after 30 days from concrete pouring are shown in Figure 4. Comparative measurements obtained locally with conventional thermocouples showed agreement within the error of both systems. This example shows how it is possible to obtain a large number of measurement points with relatively simple sensors. The distributed nature of distributed sensing make it particularly adapted to the monitoring of large structures where the use of more conventional sensors would require extensive cabling.

Monitoring Bitumen Joints in a Dam

Plavinu dam belongs to the complex of the three most important hydropower stations on the Daugava River in Latvia (see Figure 5). One of the dam inspection galleries coincides with a system of three bitumen joints that connects two separate blocks of the dam. Due to abrasion of water, the joints loose bitumen, and a redistribution of loads in the concrete arms appears. Since the structure is nearly 40 years old, the structural condition of the concrete can be compromised because of its ageing. Thus, the redistribution of loads can crack the 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 Brillouin scattering system, combined with a strain and temperature sensing cable is used for this purpose (see Figure 6). The strain sensors are coupled to the concrete with bolted metallic plates every two meters. The readout unit automatically performs measurements every 15 minutes and a threshold detection software sets off warnings and alarms to the Control Office. Fortunately, so far this has never been the case.

Since it is not possible to predict where a crack might appear along the length of the dam, instrumenting it with conventional discrete sensors, even long-gage ones, would have required the installation of hundreds of sensors, along with their cables and data acquisition systems. Thanks to distributed sensing the same goal can be achieved with just two cables and a single readout unit.

Monitoring a Gas Pipeline

About 500 meters of a buried 35-year old gas pipeline, located in Italy, lie in a landslide-prone area. Distributed strain monitoring was selected in order to improve an existing vibrating wire strain gage monitoring system. The landslide progresses with time and could damage

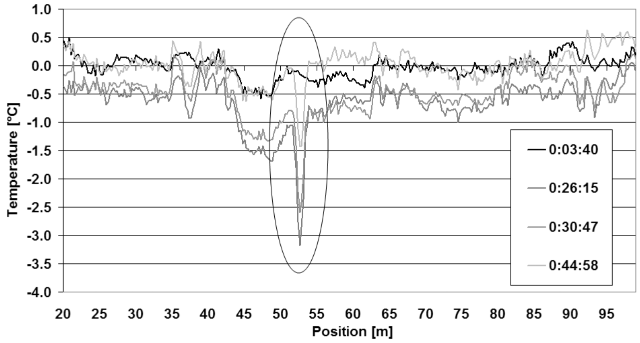

Figure 9. Results of leakage test; leakage is detected as temperature drop at the leakage location.

the pipeline until it would be put out of service. In the past, three symmetrically located vibrating wires strain gages were installed in several sections at a distance typically of 50 to 100m, chosen as the most stressed locations according a preliminary engineering evaluation. These sensors were very helpful, but could not fully cover the length of the pipeline as they provide only local measurements.

Distributed strain and temperature sensing cables were installed at the project. Three parallel lines consisting of five segments of strain sensing cable were installed over whole length of the pipeline for which there were concerns, at approximately 0°, 120° and –120° around the pipeline circumference (see Figure 7). The sensing cables were epoxy-glued to the surface of the pipeline along their whole length and protected with a neoprene mat. This instrumentation allows the monitoring of strain, curvatures and deformed shape of the pipeline every meter (corresponding to the spatial resolution of the Brillouin system in use). The temperature sensing cable was installed onto the upper line (0°) of the pipeline in order to compensate the strain measurements for temperature and for leakage detection purposes. All the sensors are connected to a central measurement point by means of optical extension cables and connection boxes. They are interrogated from this point using one single readout unit. Since the landslide process is slow, the measurement sessions were performed manually once a month.

In case of need, a dedicated readout unit can be installed onsite and the data transmitted wirelessly to the pipeline owners. All the measurements obtained with the system are correlated with the measurements obtained with vibrating wire strain gages placed at a few selected locations.

Figure 8 shows the strain changes recorded after burying the pipeline. This figure contains more than 1,500 strain measurement points, a coverage that could never be achieved with any conventional strain sensing technology.

During the installation of the sensors and the burying of the pipeline, a gas leakage simulation test was performed by installing an empty plastic tube over a distance of 50m at the beginning of the first monitored segment, connecting the surface of the pipe at that point with the open air. Carbon dioxide was injected into the tube, cooling down the pipe end to mimic conditions expected in the case of a gas leakage. A reference temperature measurement was performed before injecting the carbon dioxide. Afterwards temperature measurements were performed every two to ten minutes and compared with the reference measurement. The results of the test are presented in Figure 9. The test was successful, and the point of the simulated leakage was clearly observed and localized (encircled area in Figure 9).

Conclusions

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.

Daniele Inaudi and Branko Glisic, SMARTEC SA, Roctest Group, Via Pobiette 11, 6928 Manno, Switzerland,
Tel. +41 91 610 18 00,
email: inaudi@smartec.ch,
email: glisic@smartec.ch