SOFO: Tunnel Monitoring with Fiber Optic Sensors

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ABSTRACT:
The management and the security of civil engineering works demands a periodical monitoring of the structures. The current methods (such as triangulation, water levels, vibrating strings or mechanical extensometers) are often of tedious application and require the intervention of specialized operators. The resulting complexity and costs limit the frequency of these measurements. The obtained spatial resolution is in general low and only the presence of anomalies in the global behavior urges a deeper and more precise evaluation. There is therefore a real need for a tool allowing an automatic and permanent monitoring from within the structure itself and with high precision and good spatial resolution.
In many civil structures like tunnels, bridges and dams, the deformations are the most relevant parameter to be monitored in both short and long-terms. We have found that fiber optic deformation sensors, with measurement bases of the order of one to a few meters, can give useful information both during the construction phases and in the long term.
SOFO is a structural monitoring system using fiber optic deformation sensors. It is able to measure deformations between two points in a structure, which can be from 20 cm up to 10 meters (or more) apart with a resolution of two microns (2/1000 mm) even over years of measurements. The system is composed of optical deformation sensors adapted to direct concrete embedding or surface mounting, the cable network, the reading unit and the data acquisition and analysis software. The system is particularly adapted to precise short and long-term monitoring of deformations. The SOFO system is successfully used in a number of bridges tunnels dams and geostructures.
This paper presents the measurement principle of the SOFO system as well as examples of application to the monitoring of three tunnels. The Luzzone dam tunnel was excavated using conventional blasting techniques; the SOFO sensors were installed in radial boreholes to evaluate the tunnel convergence and to help in the assessment of the required shotcrete

thickness. The N5 tunnel is a cut and cover tunnel; the SOFO sensors were used to evaluate the shrinkage properties of concrete in the short and long term. Finally, a multi-point SOFO sensor was installed in the Mt. Terri tunnel to evaluate the rock decompression during excavation with a tunnel-boring-machine. The sensors were installed in a borehole from an existing tunnel parallel to the new one.

1 Introduction

The management and the security of tunnels requires periodic monitoring, maintenance and restoration. Excessive and non-stabilized deformations are often observed and although they rarely affect the global structural security, they can lead to durability problems. Furthermore, an accurate knowledge of the behavior of a tunnel is becoming more important as new building techniques are introduced and the existing tunnels are required to remain in service beyond their theoretical service life. Monitoring, both during construction and in the long term, helps to increase the knowledge of the real behavior of the tunnel and in the planning of maintenance intervention.

In the long term, static monitoring requires an accurate and very stable system, able to relate deformation measurements often spaced over long periods of time.

On the other side, short term monitoring, requires of a system capable of measuring deformations occurring over relatively short periods of time.

Currently available monitoring transducers, such as inductive and mechanical extensometers, triangulation, fiber optic microbending sensors or accelerometers are only suitable for performing measurements in a limited range of frequencies. Other systems do not offer sufficient information about the desired parameter (for example, displacements calculations from accelerometer data are not very accurate).

Thus, there is a real need of a unique system capable of covering structural deformation requirements in wide range of frequencies.

2 Short and long term fiber optic monitoring system

In recent past years, fiber optic sensors have gained in importance in the field of structural monitoring. They are the ideal choice for many applications, being easy to handle, dielectric, immune to EM disturbances and able to accommodate deformations up to a few percents.

The laboratory IMAC (EPFL) has developed a non-incremental long term monitoring system based on low-coherence interferometry, which has already been successfully applied in several bridges, tunnels, dams and other civil engineering structures.

This system is named SOFO. SOFO is the French acronym of “Surveillance d’Ouvrages par Fibres Optiques“ (or structural monitoring by optical fibers).

2.1 The SOFO system

The functional principle of the SOFO system is schematized in Figure 2.1.

The sensor consists of a pair of single-mode fibers installed in the structure to be monitored. One of the fibers, called measurement fiber, is in mechanical contact with the host structure itself, while the other, the reference fiber, is placed loose in a neighboring pipe. All deformations of the structure will then result in a change of the length difference between these two fibers.

To make an absolute measurement of this path unbalance, a low-coherence double Michelson interferometer in tandem configuration is used. The first interferometer is made of the measurement and reference fibers, while the second is contained in the portable reading unit. This second interferometer can introduce, by means of a scanning mirror, a well-known path unbalance between its two arms.

Because of the reduced coherence of the source used (the 1.3 micron radiation of a LED), interference fringes are detectable only when the reading interferometer compensates the length difference between the fibers in the structure.

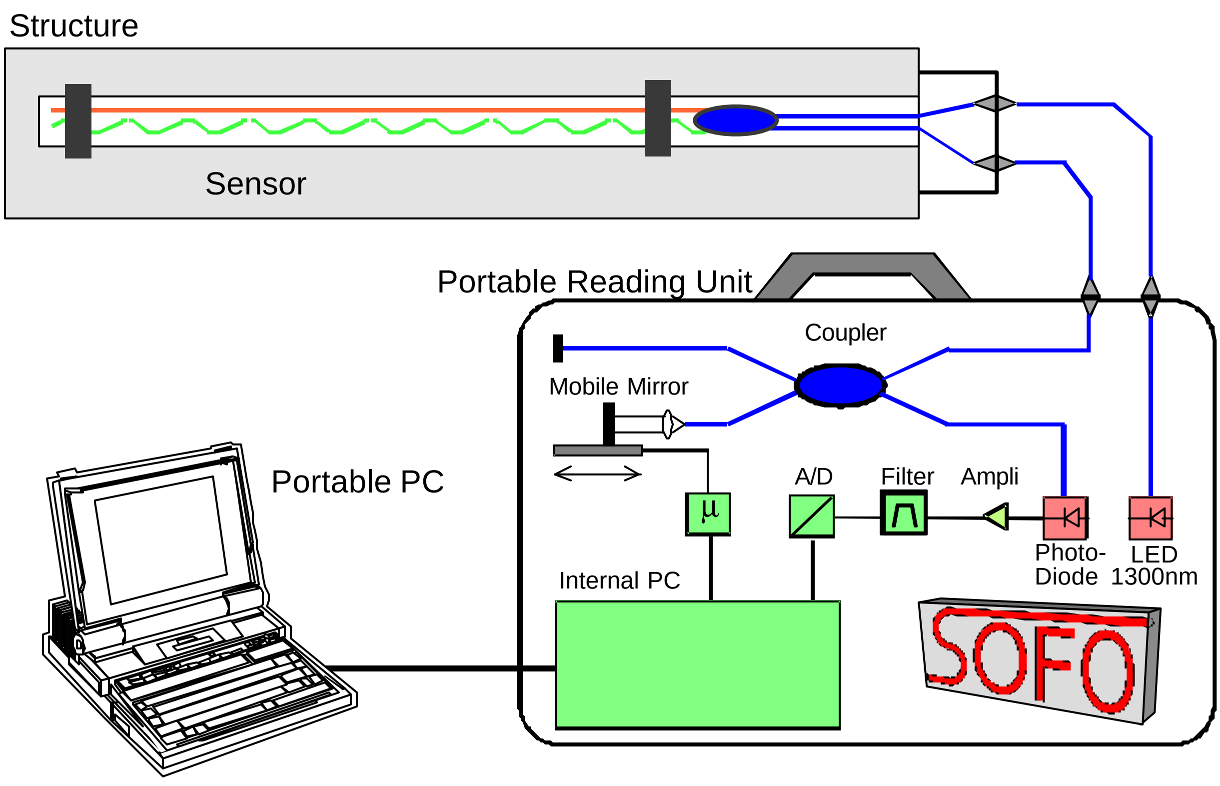

Figure 2.1: Setup of the SOFO system

If this measurement is repeated at successive times, the evolution of the deformations in the structure can be followed without the need of a continuous monitoring. This means that a single reading unit can be used to monitor several fiber pairs in multiple structures.

The signal detected by the photodiode is pre-amplified and demodulated by a band-pass filter and a digital envelope filter.

The precision and stability obtained by this setup have been quantified in laboratory and field tests to 2 micron (2/1000 mm), independently from the sensor length over more than four year. Even a change in the fiber transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity.

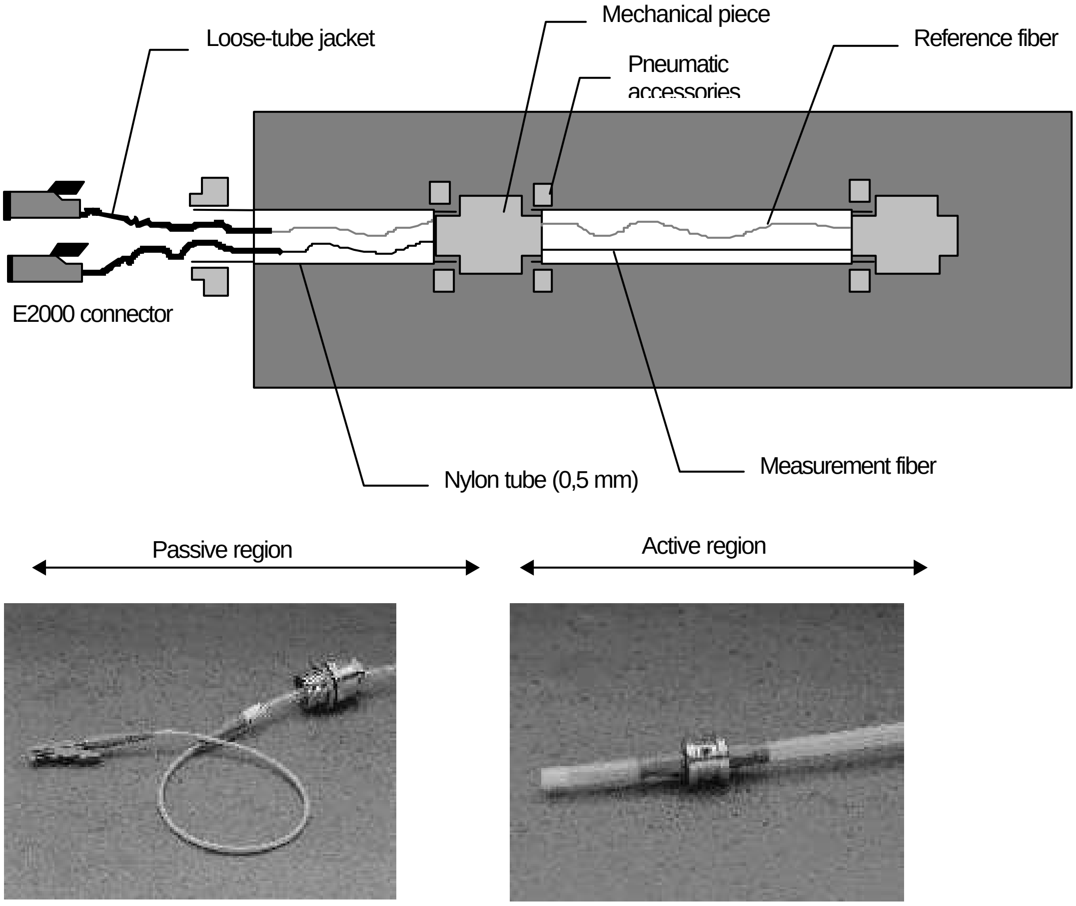

Figure 2.2: SOFO fiber optic deformation sensor

Figure 2.2 shows a typical sensor for length up to 10 m. This sensor is adapted to direct concrete / grout embedding or surface mounting on existing structures. The passive region of the sensor is used to connect the sensor to the reading unit and can be up to a few kilometers long.

The reading unit is portable, waterproof and battery powered, making it ideal for dusty and humid environments as the ones found in most building sites. Each measurement takes about 10 seconds and all the results are automatically analyzed and stored for further interpretation by the external laptop computer.

The measurements can either be performed manually, by connecting the different sensors one after the other, or automatically by means of an optical switch. Since the measurement of the length difference between the fibers is absolute, there is no need to maintain a permanent connection between the reading unit and the sensors. A single unit can therefore be used to monitor multiple sensors and structures with the desired frequency.

2.2 Data Analysis Algorithms

The data analysis packages interpret the data stored by the acquisition software in the database. Some of these packages are general and can be used with each type of structure, while others are aimed to a precise structure or structure type. Examples of such tools are:
Displacement evolution analysis: This general-purpose package extracts the results concerning a single sensor and displays them as a function of time or load. The data can than be exported to other software packages, like spreadsheets or other graphical tools for adequate representation.
Curvature: In beams, slabs, vaults and domes, it is possible to measure the local curvature and the position of the neutral axis by measuring the deformations on the tensile and compressive sides of a given element. In many cases, the evolution of the curvature can give interesting indication on the state of the structure. For example, a beam, which is locally cracked, will tend to concentrate its curvature at the location of the cracks. Furthermore, by double integration of the curvature function, it is possible to retrieve the displacements perpendicular to the fiber direction. This is particularly interesting since in many cases the engineers are interested in deformation that are at a right angle to the natural direction in which the fiber sensors are installed. For example: in a bridge fibers are installed horizontally, but vertical displacement are more interesting. In a tunnel the fibers are placed tangentially to the vault, but measurement of radial deformation is required. In a dam the fibers are installed in the plane of the wall but displacements perpendicular to it have to be measured.
Statistics: Another software package allows the analysis of deformation data from structures undergoing statistically reproducible loads (such as traffic).

3 Tunnel monitoring with SOFO sensors.

The SOFO sensors can be applied to the monitoring of different types of deformations encountered in typical tunnel applications:

3.1 Multi-point optical extensometer

In geostructural and tunnel engineering it exists a need for measuring relative displacements instead of local values of strains. For example, one wants to monitor the horizontal displacement of a slurry trench wall, or the vertical heave of a tunnel base. Conventional geodetic techniques are not always a good solution mainly due to access difficulties (think of underground structures in general) and to a lack of accuracy. Conventional techniques will estimate settlements or displacements with an error of as much as ±1 mm. For some applications, this precision can be sufficient but in general the interest - especially in the first phase of a construction - is the first sign of a movement. And this sign can only be detected with high precision measurements with a accuracy of 10 to 100 µm.
To measure the relative displacement of two distant points, the conventional technique used in geotechnical engineering consists of anchoring a long Invar rod in a borehole, at a distant

sufficient to be outside of the zone of influence of the structure (up to several tens of meters), see Figure 3.1. The rod can slide freely between the anchoring zone and the structure to be measured. The measure is simply done by measuring with a dial gage (or an electronic LVDT transducer) the relative displacement between the rod head and the structure.

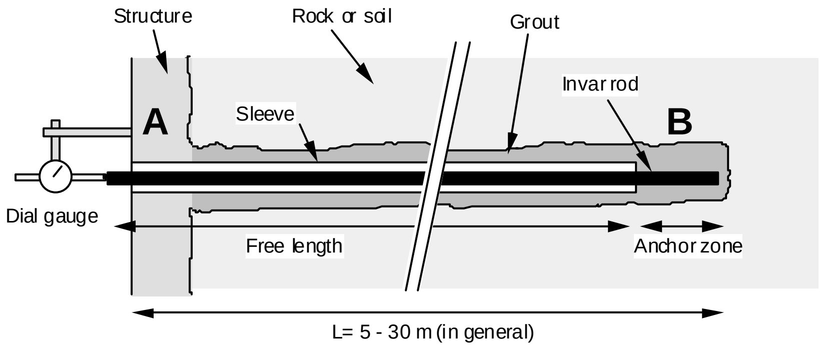

Figure 3.1: Schematic representation of a conventional extensometer; the measure will give the relative displacement between points A and B

The instrumentation of a borehole with a long fiber optic sensor is similar to the old system (see Figure 3.2) Note that the fiber is not only used to measure the displacement in the so-called « active zone » but is used to transmit the signal to the remote reading unit.

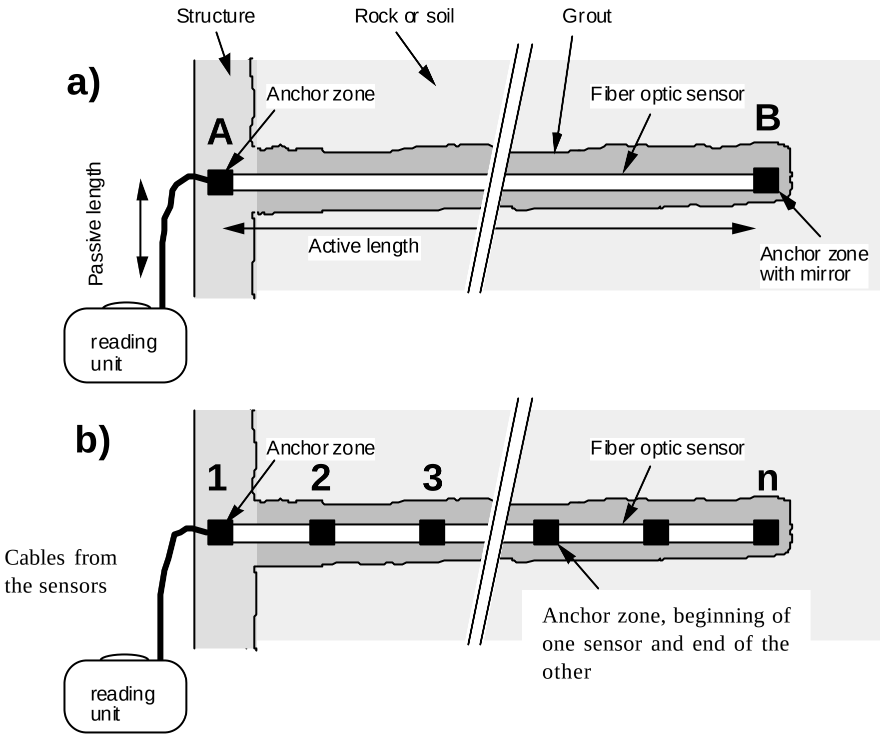

Figure 3.2: Schematic representation of our fiber optic extensometer; a) single length set-up: the measure gives the relative displacement between points A and B. b) multi-point set-up: the measurement gives the relative displacement between points 1 and 2, 2 and 3, etc..

The main advantage of the SOFO sensors when compared to the conventional extensometer reside in their higher resolution and precision, in the possibility of installing a large number of sensor sections in a relatively smaller borehole, in the absence of any transducer at the head of the extensometer, in the possibility of measuring them automatically and remotely (up to 5 km away) and in the simplicity and rapidity of both the installation and the measurements.

3.2 Vault curvature measurements

Pairs of SOFO sensors can be used to obtain the average local curvature variation in a vault. In this case, the sensors are installed in two parallel layers at the intrados and extrados of the vault. It is interesting to notice that the sensors do not need to be installed in a straight line, but can follow the natural bending of the tunnel. If a sufficient number of sensors is available, it is possible to retrieve the convergence of the tunnel by performing a double integration of the measured curvatures. This technique was often used for the calculation of vertical displacements of bridges from horizontal deformations measurements. Thanks to the high resolution of the SOFO system, it is expected that for typical tunnel sections, the precision of the convergence calculation will be in the 0.1-1 mm range. The main advantage of this technique resides in the absence of obstructions in the tunnel cross-section, in the possibly of performing automatic and remote convergence measurements and in the ease of installation and measurement.

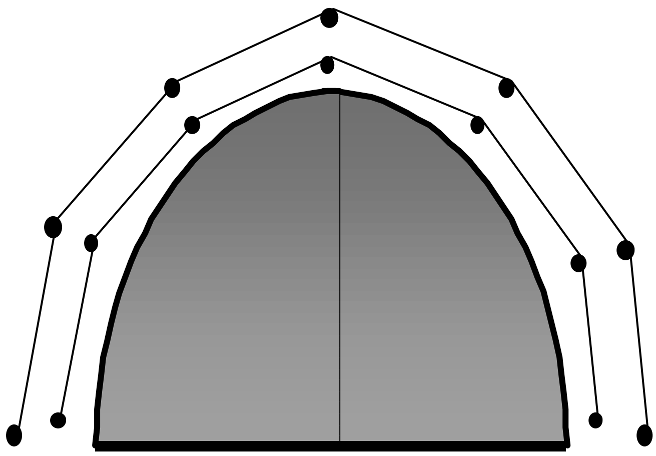

Figure 3.3: Installation of sensors for curvature measurement and convergence analysis.

3.3 Concrete and shotcrete deformation analysis

One of the main interests of the SOFO sensors consists in its embeddability in concrete, shotcrete and mortars. This allows a measurement of the concrete deformations right after pouring and in the long term. The sensors can measure the thermal swelling due to the setting reaction, the thermal shrinkage, the drying shrinkage and the deformations due to external loads. The SOFO sensors are also used to evaluate the adherence between material with different properties and ages such as rock-concrete, masonry-shotcrete, old-new concrete and steel-concrete. The measurements can be used to optimize the concrete mix in order to reduce or eliminate the build-up of self-tensions and the formation of cracks.

4 Application examples: short and long term monitoring

In the next paragraphs, we will present a choice of applications of the SOFO system for different monitoring purposes in tunnel building and maintenance.

4.1 The Luzzone Dam Tunnel

The Luzzone dam tunnel (Switzerland) serves as expansion chamber for the pressurized conduit of the Luzzone hydroelectric power station. Since the dam was raised by 17 m to increase the reservoir capacity, it was also necessary to extend the chamber. The excavation was performed with conventional blasting techniques and was realized in for successive section as shown in Figure 4.1. The final section has a width of about 10 m and a maximal height of about 6 m.

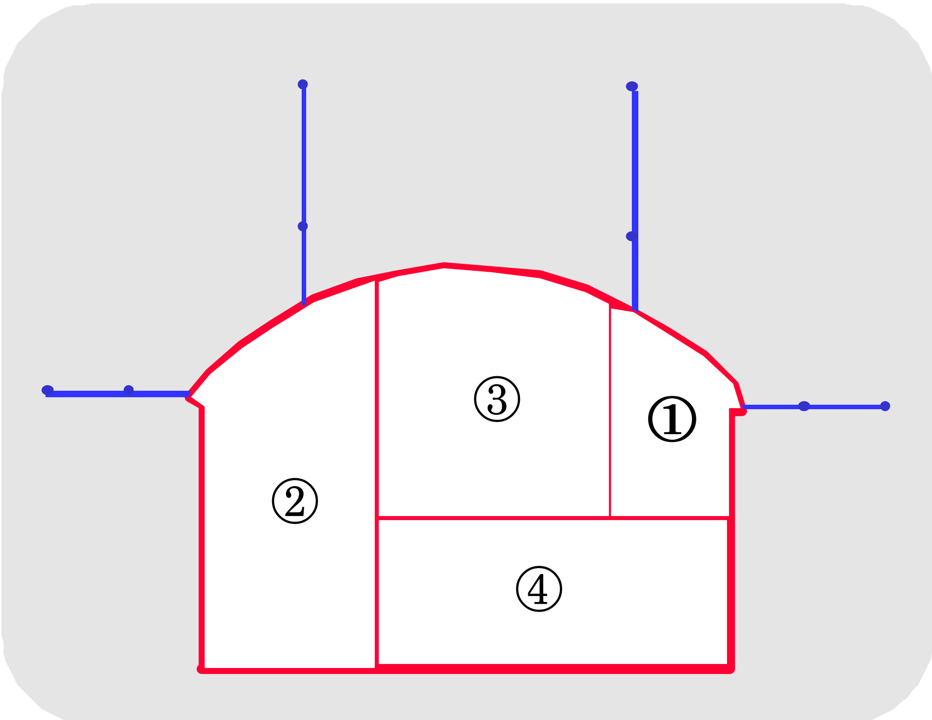

Figure 4.1: Cross section of the Luzzone tunnel with excavation section and SOFO sensors emplacement.

After the excavation of section 1, two multi-point SOFO extensometers were installed vertically and horizontally in the rock to measure its displacements. The sensors had different length between 2m and 8m and were assembled in a strand, inserted in the borehole and grouted (see Figure 4.2). The passive cables were than protected with shotcrete and routed to a convenient measurement location. The exit point of the cable are therefore not exposed nor even visible after the sensor installation.

Figure 4.2: Installation of the SOFO sensors in section 1.

When section 2 was excavated, it was possible to measure small (<0.1 mm/m) deformations on the already installed sensors. At that time, two additional multi-point sensors were installed in the wall and vault of section 2. The most interesting operation consisted in the removal of the central section 3. The measurements showed a maximal convergence of only a few mm. This was well below the expected value and the engineer felt confident to optimize the thickness of the final shotcrete lining according to the measurements.

4.2 The N5 Cut and Cover tunnel

In this case the fiber optic sensors were used to evaluate the swelling and shrinkage of a complete section in a cut and cover tunnel. The whole N5 (Switzerland) tunnel section is cast in a single operation, but because of the different thickness of the basement and walls, a differential shrinkage will occur and induce bending and tension in some of the elements.


Figure 4.3: Sensor installation and concrete pouring at the N5 tunnel.

The sensors were simply installed along the rebars and the concrete pouring could be carried out without any particular attention (see Figure 4.3).

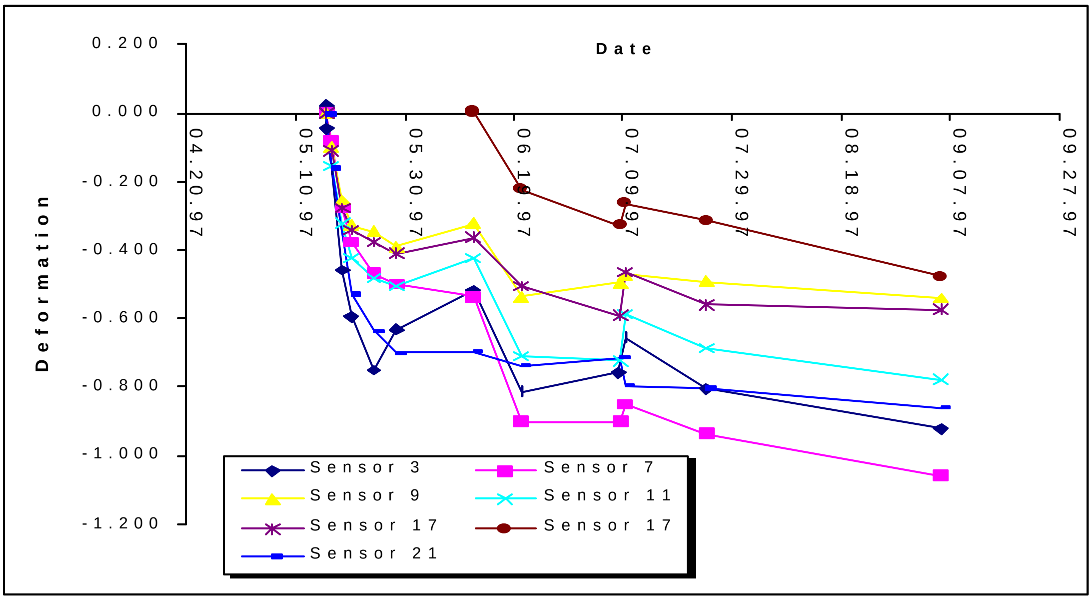

Figure 4.4: Shrinkage measurement on the N5 cut and cover tunnel.

Figure 4.4 show the measurements obtained during the first few months after pouring. The concrete shrinkage is clearly identified as well as the different behavior of different zones in the cross-section. Environmental changes like humidity and temperature variations are also easily spotted.

4.3 The Mt. Terri tunnel

SOFO sensors were installed in the Mt. Terri tunnel to evaluate the rock decompression during excavation with a tunnel-boring-machine. The general aim of the experiment is the study of the rock (opalinus clays) cracking and its loss of impermeability. This data is particularly important to evaluate the suitability of such rock formations for the storage of nuclear waste.

Nine sensors were installed by grouting in a borehole executed from an existing tunnel parallel to the new one. The active length of the sensors was chosen to have a higher data density in the proximity of the new tunnel. The first four sensors are 250 mm long, the next two are 500 mm long and the other are 1m, 2m and 4m long. All the sensors and cabling could be comfortably installed in the same 100 mm borehole (Figure 4.5).

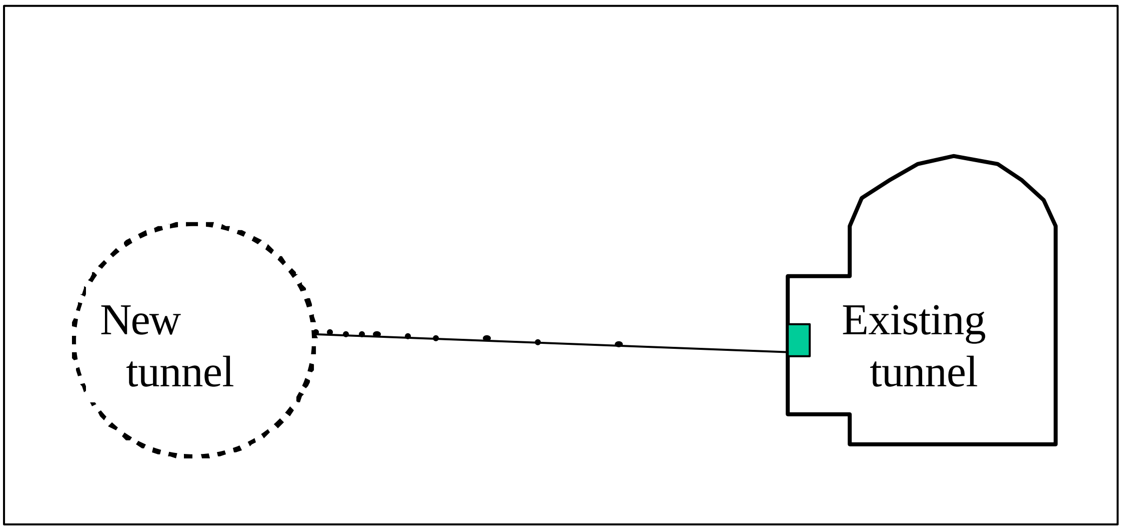

Figure 4.5: Sensor installation in the Mt. Terri tunnel.

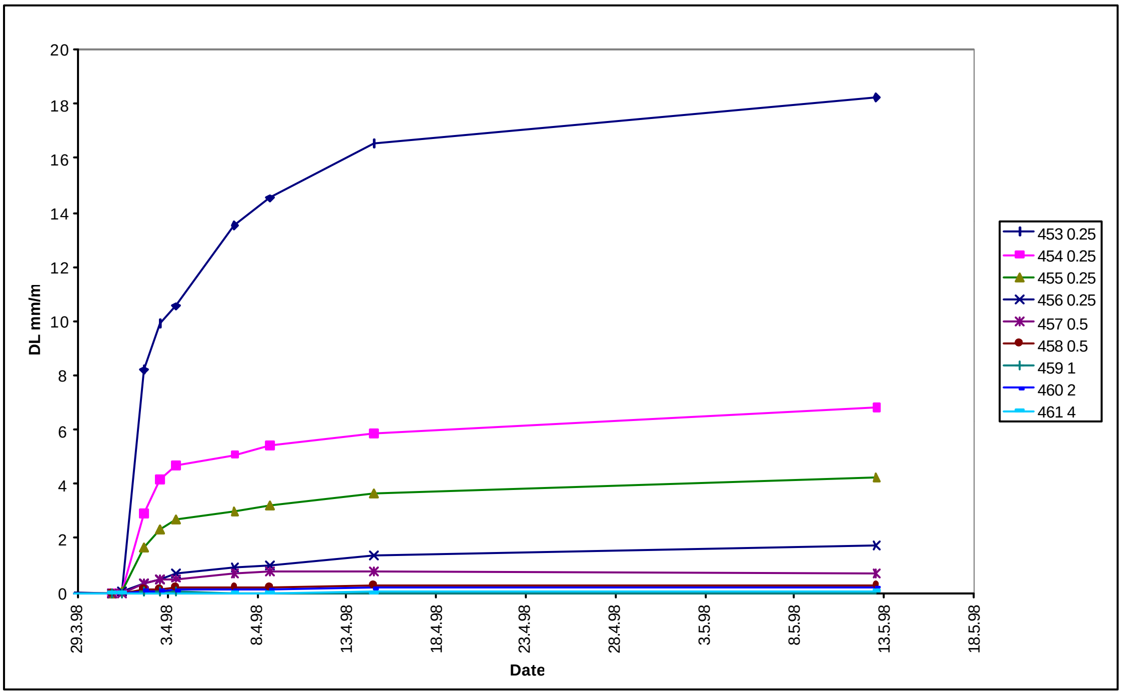

Figure 4.6: Strain measurement in the Mt. Terri Tunnel

Figure 4.6 shows the observed strains (given by the measured deformations divided by the sensor's active length). It can be seen that no significant deformation was measured before the arrival of the tunnel-boring-machine at the location of the extensometer. After the passing of the machine, large strains are measured on the first 4-5 sensors, while the other show much smaller (but still easily measurable) strains. The large value registered on sensor 453 can be explained with the formation of a crack.

This applications takes advantage of some peculiarities of the SOFO sensors. On one hand, it is possible to adapt the active length to the phenomenon to be observed. On the other hand, the high precision and the dynamic range of the system allow the measurement of deformations over a large spectrum of magnitudes and little a-priori knowledge on the expected deformations is required. Finally, the absence of moving parts in the sensors greatly reduces the risk of sensor malfunctioning in the case of large transverse deformations.

5 Conclusion

The benefits of structural monitoring during construction and in the long-term are obvious. A continuous or at least regular monitoring of a structure can increase the knowledge on its behavior, help to guarantee its safety and to plan for maintenance interventions.

Long-gage length deformation sensors can give important information on the global behavior of the structure. In the case of tunnels, it is possible to use them as radial multi-point extensometers, for convergence monitoring by double-integration of the vault's curvature variations and for the evaluation of concrete and shotcrete properties.

The SOFO monitoring system is composed of a portable reading unit (adapted to field conditions), a series of sensors (that can be either embedded into concrete or surface mounted on metallic and other existing structures) and of a software package (allowing the treatment of the large data-flow resulting from the measurements). This system has been applied to a number of tunnels ad well as to new and existing bridges, dams and other civil structures in order to monitor their short and long-term behavior.

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