Geo-structural monitoring with long-gage interferometric Sensors

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ABSTRACT

The monitoring of geotechnical structures like piles, anchors and tunnels requires the measurement of deformations over bases of a few meters to a few tens of meters. The SOFO monitoring system, based on the use of long-gage low-coherence interferometric sensors therefore presents interesting application opportunities in this domain.
The SOFO system was installed in a number of piles to monitor their short and long term deformations, to evaluate the lateral friction and to asses their ultimate bearing capacity.
The sensors were also installed inside anchor cables to measure the deformations of the rock in the free and in the anchored parts. Additional sensors were installed directly on single cable strands.
This paper presents the sensor installation and the results from selected applications in the monitoring of piles and anchors.
Keywords: Deformation sensors, Structural Monitoring, Geotechnical Structures, Piles, Anchors, Fiber Optic Sensors.

1. INTRODUCTION

The management and the security of civil structures, in particular or geotechnical type, require periodic monitoring to allow the planning of maintenance interventions and possibly of repairs. Excessive and non stabilized deformations are often observed. Even if they do not influence the structural security, these deformations can lead to durability problems. Furthermore, an accurate knowledge of the structural behaviour becomes more important as new construction techniques and technologies are introduced and the existing structures are called to serve well beyond their designed lifespan. Monitoring during construction and in the long term, gives quantitative information that can be directly used to reduce the uncertainty on the structural performance and allow an efficient management of the structures.
As geotechnical times are usually relatively long and degradations can appear only after years, it is important that the used monitoring systems are reliable and offer excellent long-term stability in their readings. Fiber optic sensors are ideal candidates for that task, provided that their packaging and installation procedures are adapted to the use in the demanding environment of geotechnical applications.

2. SOFO: STRUCTURAL MONITORING WITH FIBER OPTIC SENSORS

In the last few years, fiber optic sensors have become a reality in the domain of structural monitoring and are now no longer a scientific curiosity but rather a complement to traditional instruments. Their ease of use, non-conductive nature, high sensitivity and dynamic range, insensitivity to external perturbation like temperature, humidity and electromagnetic fields, make them the ideal choice of many applications.
SMARTEC SA in cooperation with the IMAC laboratory at the Swiss Federal Institute of technology in Lausanne, has developed a monitoring system for the long-term monitoring of deformations over long measurement bases. This system, called SOFO, has been used with success for the monitoring of more than 100 structures including bridges, dams, tunnels, historical monuments, nuclear power plants, laboratory models and geotechnical structures (as we will see in this paper).

The SOFO monitoring system

The functional principle of the SOFO system is schematized in Figure 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, being attached at two anchorage points and pre-stressed in-between. The other fiber, called the reference fiber, is placed loose in the same 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 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 exactly compensates the length difference between the fibers in the structure.

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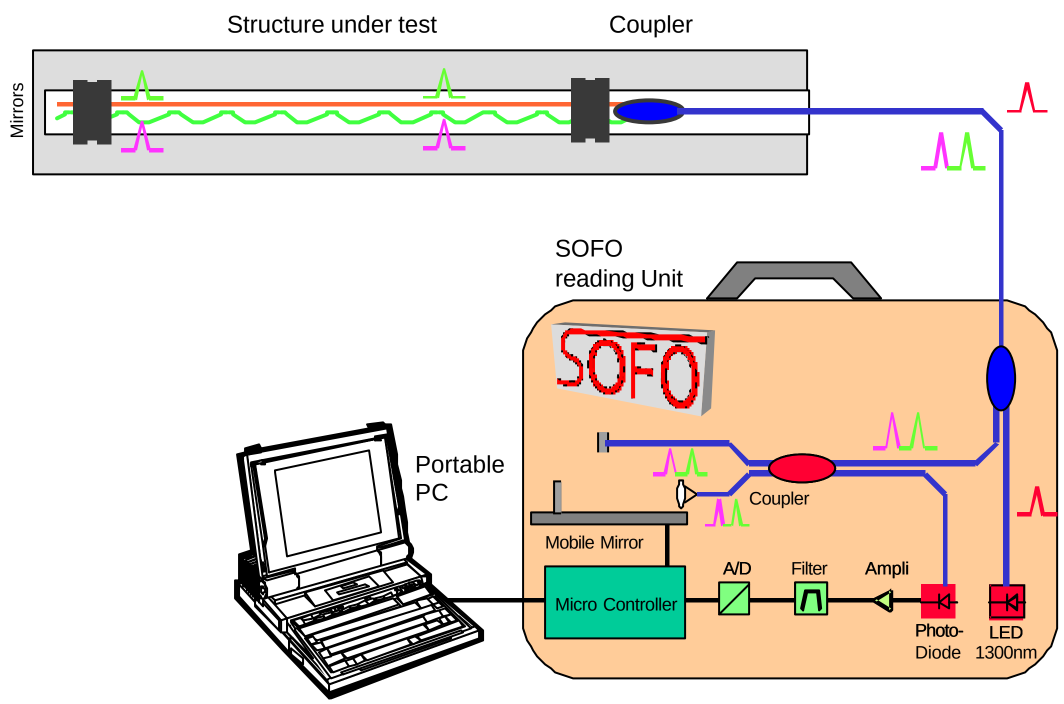

Figure 1 Setup of the SOFO system

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 SOFO Sensors installed on a rebar

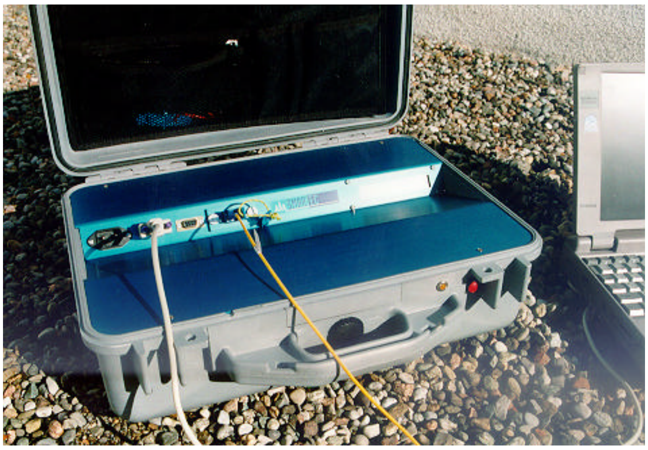

Figure 3 SOFO Reading Unit

Figure 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 (see Figure 3) 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.

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. GEOSTRUCTURAL MONITORING WITH SOFO® SENSORS

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

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 4. 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.

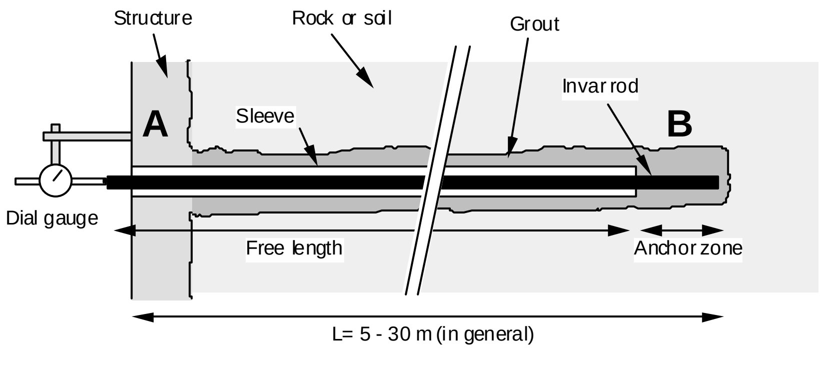

Figure 4 Schematic representation of a conventional extensometer; the measurement will give the relative displacement between points A and B

The instrumentation of a borehole with a long fiber optic sensor is similar to the old system (see Figure 5). 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.

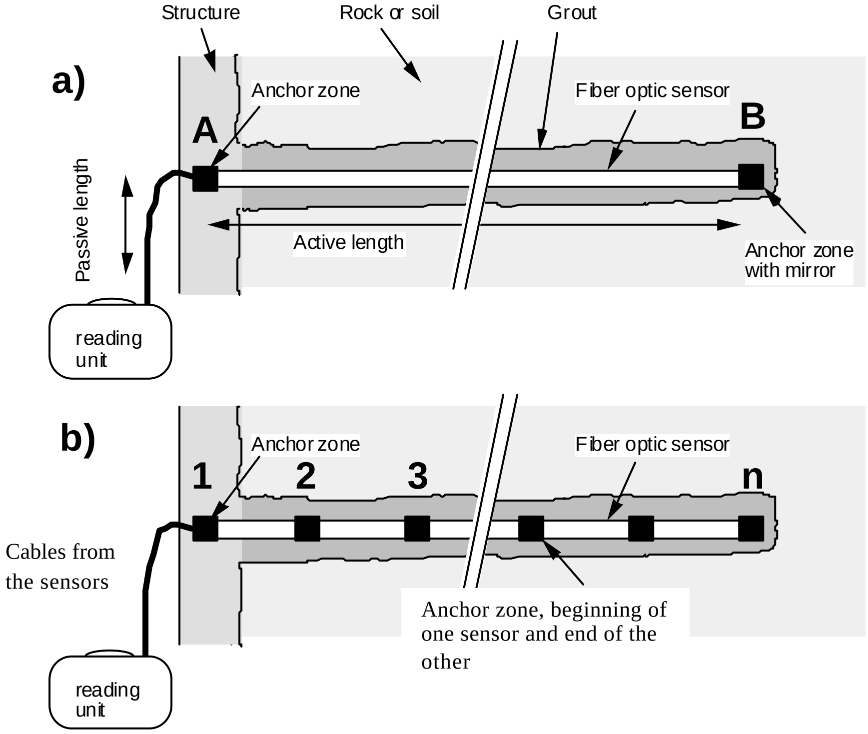

Figure 5 Schematic representation of our fiber optic extensometer;
a) single length set-up: the measure gives the relative displacement between points A and B.
b) multi-point set-up: the measurement gives the relative displacement between points 1 and 2, 2 and 3, and so on.

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. The cables can be protected with shotcrete and there is no need to keep a direct access to the top of the extensometer.

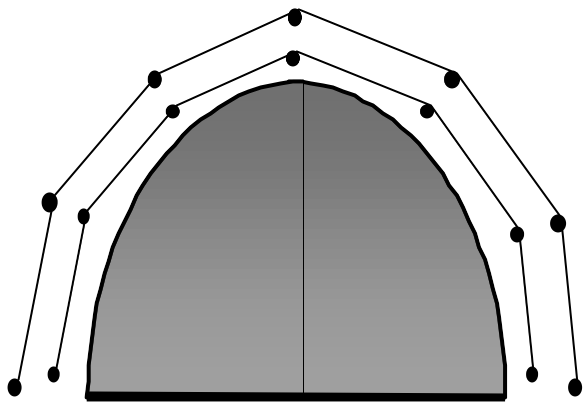

Figure 6 Installation of sensors for curvature measurement and convergence analysis.

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 possibility of performing automatic and remote convergence measurements and in the ease of installation and measurement.

Concrete and shotcrete deformation analysis

One of the main interests of the SOFO sensors consists in its ability to be embedded 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 EXAMPLE: THE MONT 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 7).

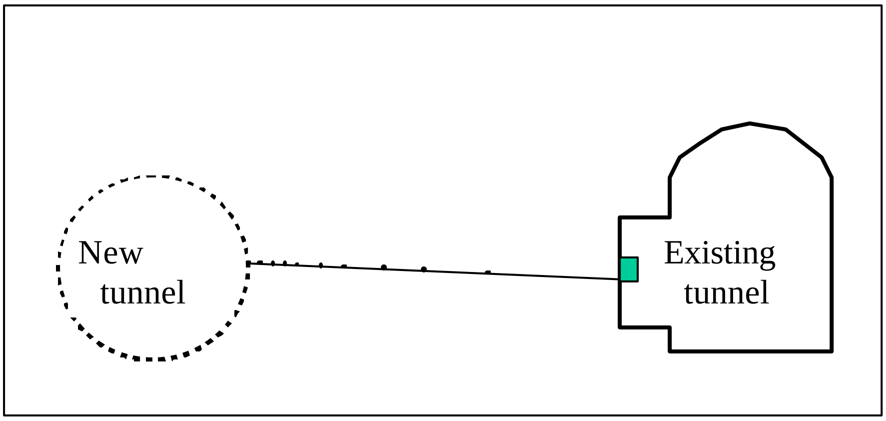

Figure 7 Sensor installation in the Mt. Terri tunnel.

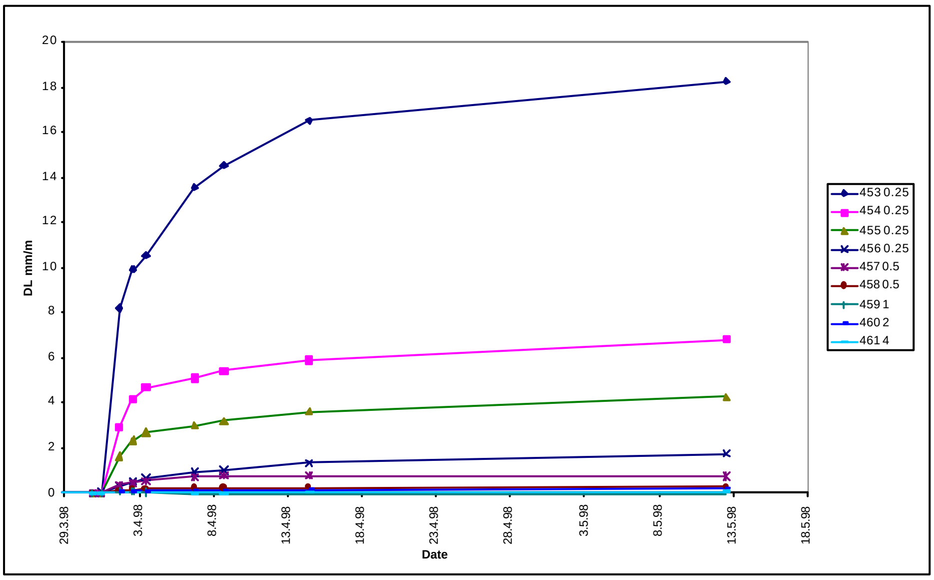

Figure 8 Strain measurement in the Mt. Terri Tunnel.
The fist sensor (453) is placed the closest to the new tunnel.

Figure 8 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 application 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.

Lugano lakeshores anchors

The stability of the lakeshores of Lugano is compromised over a distance of about 150m. This particular condition is related to the local geology formed by a succession of layers of lake deposits (mostly slime with high organic contents) and patches of river deposits (sand and gravel). Furthermore, the shore has been extended towards the lake at the beginning of 1900 by depositing materials of different nature and with extremely high slopes.

As part of a larger project aiming to increase the security of the shores in this zone, the engineer has designed a pile diaphragm with head anchors. The installation of anchors in this type of soils presents certain unknowns and the engineer has decided to proceed with a number of laboratories and filed tests to refine his design. In particular it was necessary to characterize the most critic stratifications (in particular the slimes), evaluate the ongoing movements and evaluate the feasibility of the anchors.

Test anchors were installed with the aim to optimize the anchored length, verify the ease of boring and ascertain the ultimate load bearing capacity of the different types of anchor. In particular, anchors with bulbs of different types and realized in different layers were tested.

The financial constraints and the limited space available have allowed the perforation of only 4 anchors with an anchored length of 10 m each an subdivided has follows (see also Figure 9):

A) Anchored part realized with multiple injections in sand and gravel
B) Anchored part realized with multiple injections in lake deposits
C) Anchored part realized with jetting column in sand and gravel
D) Anchored part realized with jetting column in lake deposits

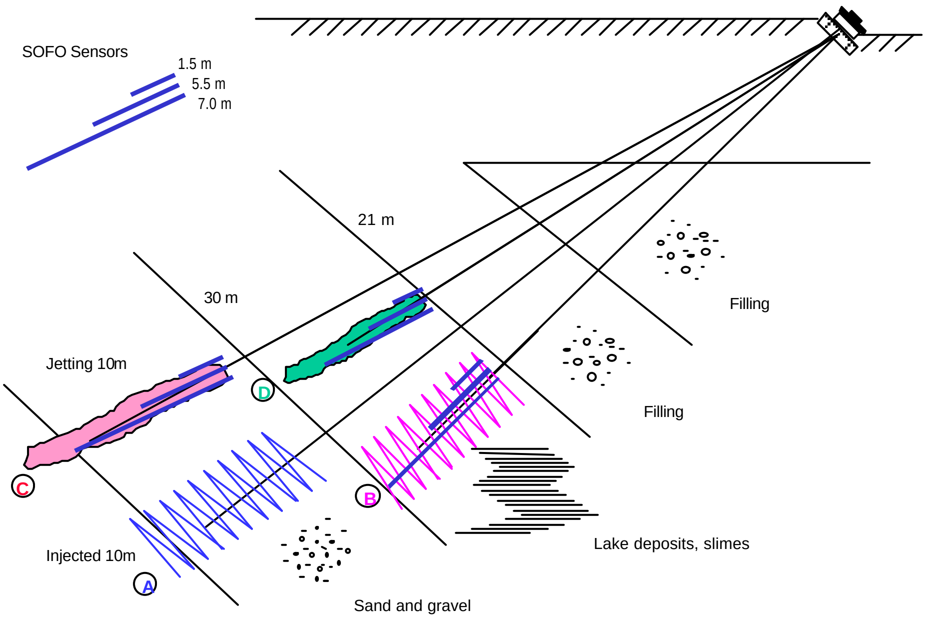

Figure 9 Schematic representation of the 4 test anchors (B, C e D have been instrumented with SOFO sensors)

The SOFO sensors have been installed in the anchor part to verify the ideal length of the anchored pert, allowing the investigation of the force transmission from the anchor to the soil, in the short and long term. The test also aims to compare the efficiency of the different types of bulbs in the different types of soil.
In each of the three instrumented anchors (anchor A has not been instrumented since its behaviour is already well known) was provided with three SOFO sensors having the beginning of the anchored part as reference point and extending to 1.5 m, 5.5 m and 7 m, respectively. The measurements were performed during the load test and a few weeks after to correlate the loss of force with the deformations in the bulb.

Anchor B, injected bulb in slimes:
There is a layer of filing material above the anchored part. Figure 10 shows the deformations measured in anchor B during the load test. The first sensors (sensor 685) shows a compression in the first 1,5 m of the anchored part. The fact that sensor 680 and sensor 682 show a very similar results indicates that the part of the bulb beyond 5.5m does not transmit a significant force to the ground.
The few measurements at 300 kN show a decrease in the slope of the elongation of the two longer sensors. This could be an indication of a pull-out of the anchor at high loads. The measurement time was however insufficient to give clear results.

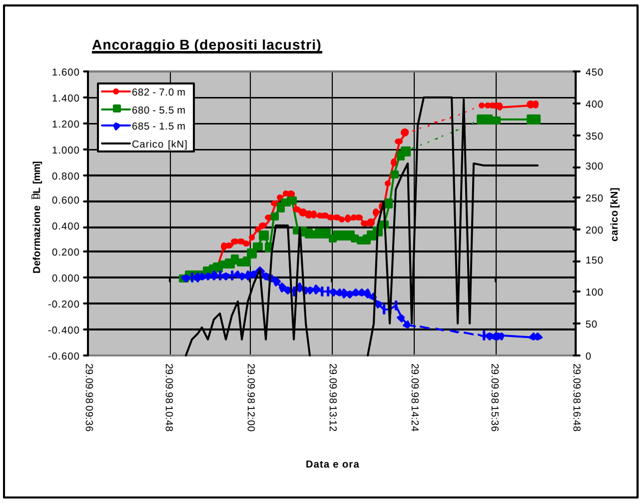

Figure 10 Load test on anchor B

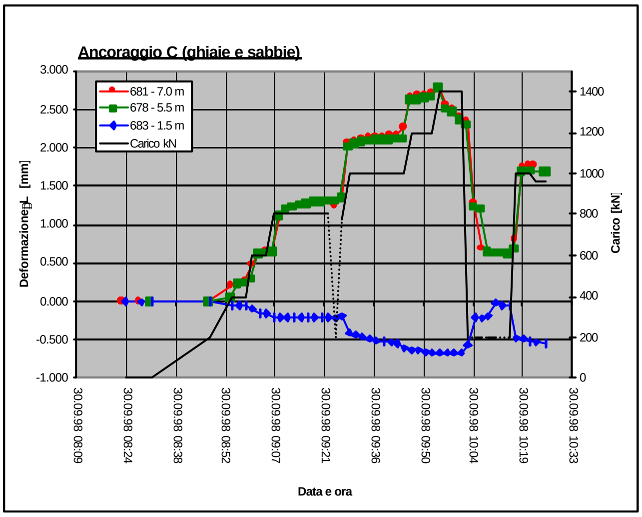

Figure 11 Load test on anchor C

The measurement made two weeks later show an increase in the compression of the first sensor (the tip load towards the filling layer increases), while the sensors in the lower part of the anchor show a decrease in the deformations indicating a reduction in the transmitted load to the surrounding soil. The presence of the filling layer above the anchor zone could therefore influence the load-bearing capacity of the anchor.

Anchor C, jetting bulb in sand and gravel:
Above the anchored part we find the slimes layer with much worse mechanical characteristics than the sand in which the jetting bulb was executed.
The jetting column was 10 m long and could therefore terminate in the lower slime layer. We will therefore disregard the bottom 3 m of the anchored part as they might not be representative. Figure 11 shows the deformations during the load test. The compression in the first 1.5 m and the tension in the lower part shows a linear response to the load. Once again we find no difference between the 5.5 m and the 7 m long sensors.
The highest load step from 1'200 kN and 1'400 kN shows a rapid decrease in the elongation of the longer sensors, indicating that the lateral friction of the column has been exceeded. The tip of the column continues to resist even for an higher load.
The measurements performed two weeks later show a relaxation of all deformations indicating a decrease in the lateral friction and a penetration of the bulb in the upper slime layer.

Anchor D, jetting bulb in slimes:
Above the anchored part we find the slimes layer with much better mechanical characteristics than the sand in which the jetting bulb was executed. Once again we disregard the last 3 of the column as non representative.
Figure 12 shows the deformations measured during the load test (see Figure 13). The first sensor shows again a compression proportional to the applied load, but the deformations are not reversed when the load is released. The 5,5 m long sensors first show an elongation that however becomes a compression for higher loads. At the same time the longest sensor shows a sudden elongation, probably indicating the start of an upward movement of the first part of the anchor.
It should be noticed that the first sensors has exceeded its dynamic range in the second part of the test and the measured values are therefore smaller that the real ones.

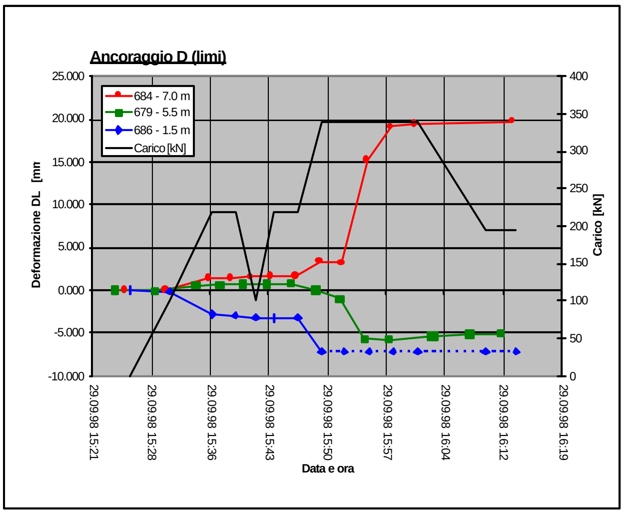

Figure 12 Load test on anchor D

Figure 13 Load test setup

The measurement made after 2 weeks indicate a decrease in the compression of the column tip and of the 5.5 m sensor. The longer sensor shows an important decrease of the deformations that we are not able to explain.

5. STATIC LOAD TEST ON PREFABRICATED PILES

A static loading test on three piles was performed in Spier (canton of Lucerne, Switzerland) in the framework of the preparatory works for the construction of a cut-and-cover tunnel. The piles are prefabricated concrete columns with a diameter of 450 mm. They are hammered in a soil composed of lake deposits, clay, slime, sand and gravel and are designed to carry the load mainly by lateral friction (floating piles). The aim of the test was the determination of the lateral friction as a function of the depth in the ground. This measurement is important in order to determine the optimal length of the piles and the number of piles required to support the tunnel load.
A chain of 7 or 8 SOFO sensors with a measurement basis of 3 m each was introduced in the central hole of each pile and than injected with an expansion and low modulus mortar.

The SOFO sensor was selected because of its precision, ease of installation and the possibility of measuring automatically. Furthermore the use of the SOFO sensors simplified the loading setup, since no direct access to the pile head was required and the loading jack could be installed directly on top of the pile (see Figure 14).

Figure 14 Pile loading setup

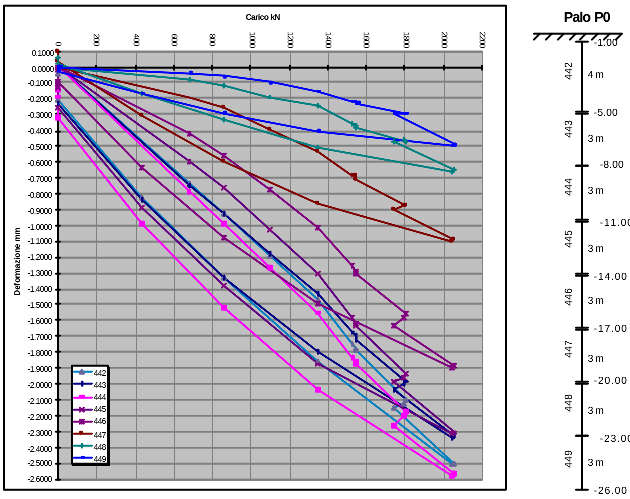

Figure 15 Measurement results

Before, during and after the load test of each pile, the sensors were measured automatically at pre-defined intervals and just after a change in the applied load. Figure 15 shows the results on one of the piles. Each curve represents a sensor. The sensors near the top of the pile measure a larger load. Since the lateral friction decreases the force in the pile for increasing depths, the deformations in the pile also decrease. If we assume that the elastic modulus of the pile is constant over the whole length (a good assumption for prefabricated piles) we can use the pile as a force sensor. A large decrease in the deformations between two successive depths is an indication of an high lateral friction.
The measurements were used to determine the lateral friction as a function of the depth, the tip force as a function of the load, the ultimate load bearing capacity ad the optimal length of the pile.

6. CONCLUSIONS

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. In geotechnical applications, the sensors can be used to monitor the free and anchored part of an anchor, to measure the deformations of piles and in general to measure the deformations of the rock soil and any load-bearing structure.
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, geotechnical structures as 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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For further information on the SOFO system look at the following home pages: \\www.smartec.ch and \\imacwww.epfl.ch.