Looking below the Surface

Structural monitoring is seen as integral to successful maintenance programmes for both new and aging structures.

Daniele Inaudi, Smartec SA, Lyesse Laloui and Gilbert Steinmann, LMS – EPFL, Switzerland, ***describe a fibre optic monitoring system that promises improved performance in the monitoring of piles.***

The safety of civil structures requires periodic monitoring, maintenance and restoration. Excessive and destabilised deformations are often observed and although they rarely affect the security of the global structure, they can lead to maintenance deficiencies. Furthermore, accurate knowledge of real behaviour is becoming more important as new structures become lighter and as an increasing number of existing structures are required to remain in service beyond their theoretical service life. Monitoring, both in the long and short term, helps to increase knowledge of the real behaviour 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. Monitoring transducers currently available, such as inductive and mechanical extensometers, GPS, microbending sensors or accelerometers, are not always sufficiently stable or require extensive maintenance reducing their usefulness. The result is that fibre optic sensors have gained in importance for 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 percent.

The IMAC laboratory (EPFL) has developed a non-incremental long term monitoring system based on low coherence interferometry, which has already been applied successfully in several bridges, dams and other civil engineering structures. This system is named SOFO, the French acronym of 'Surveillance d'Ouvrages par Fibres Optiques' (or structural monitoring by optical fibres).

The SOFO system

The SOFO sensor consists of a pair of single mode fibres installed in the structure to be monitored (Figure 1). One of the fibres, called a measurement fibre, is contained in a pipe, attached at the two ends of the measurement zone and pretensioned in between. The other fibre, called a reference fibre, is placed loose in the same pipe. All deformations of the structure will then result in a change of length difference between these two fibres.

To make an absolute measurement of this path imbalance, a low coherence double Michelson interferometer is used. The first interferometer is made of the measurement and reference fibres, 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 imbalance between its two arms.

Because of the reduced coherence of the source used (the 1.3 micron radiation of an LED), interference fringes are detectable only when the reading interferometer compensates for the length difference between the fibres in the structure to better than a few microns.

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

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 years. Even a change in the fibre transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity.

The sensors are adapted to direct concrete/grout embedding or surface

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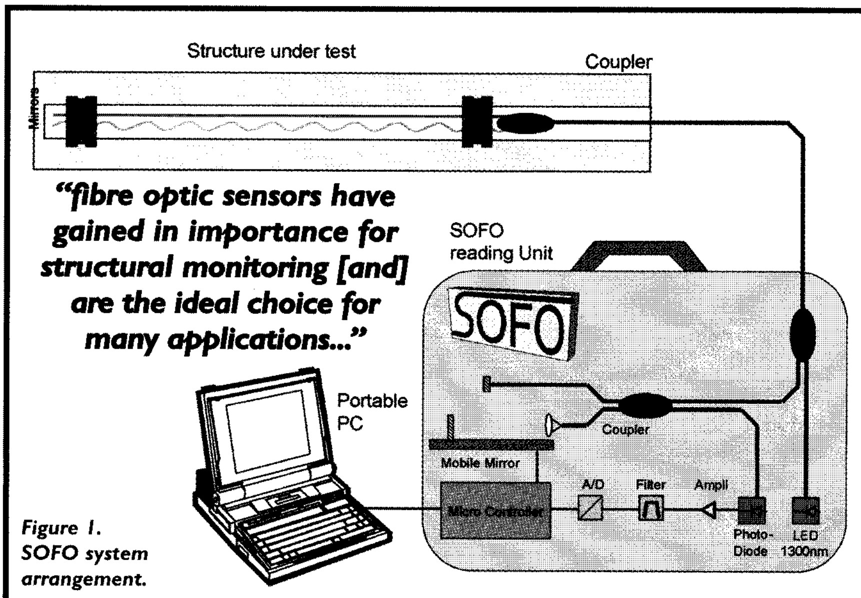

Figure 1. SOFO system arrangement.

Figure 2. Preparation of the sensors for installation in the centrifuged piles.

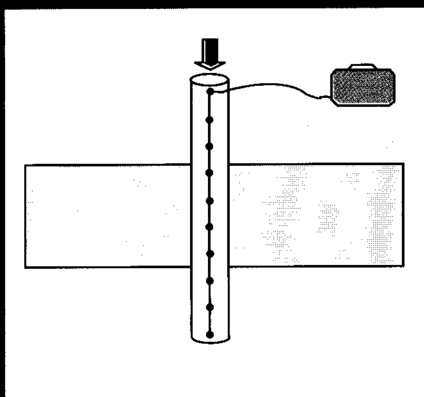

Figure 3. Sensor position in the pile.

Figure 4. Setup for the pile loading test.

mounting on existing structures. The passive region of the sensor is used to connect it to the reading unit and can be up to a few kilometres long. The reading unit is portable, waterproof and battery powered, making it ideal for dusty and humid environments as found on most building sites. Each measurement takes about 10 s and all the results are automatically analysed and stored for further interpretation by the external laptop computer.

The measurements can be performed either 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 fibres 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 at the desired frequency.

Precast pile

In preparation for the construction of a cut and cover tunnel in Spier (Lucerne, Switzerland), three prefabricated concrete floating piles were tested. The centrifuged piles had a diameter of 45 cm, a length between 22 - 26 m and were hammered into a soft soil composed of layers of lake deposits, silt, sand and gravel. The fibre optic sensors were installed in the central hole of each pile and injected with an expanding, low modulus grout (Figure 2). The sensors had lengths of 3 and 4 m, covering the whole length of the pile (Figure 3). The aim of the measurements was the determination of the lateral friction and of the ultimate capacity of the piles subjected to loads up to 2000 kN.

The SOFO system was selected because of its reliability, precision, ease of installation and the possibility of performing unattended creep measurements. The loading jack could be installed directly on top of the pile (Figure 4) while the sensor cables exited from the side of the pile.

Before, during and after the loading test, the sensors were measured automatically with a pre-fixed interval and at additional times selected by the operator (for example when the load was changed). Figure 5 shows the recorded deformations as a function of the applied load and for sensors placed at different depths. It can be seen that for an equivalent load level, the deformations reduce with increasing depths. It can also be noticed that the first four sensors nearer to the top of the pile measure almost the same deformation, indicating an extremely low lateral friction. Further down, the deformation decreases rapidly, indicating a much higher friction. Finally, the last two sensors measure a rather small deformation, indicating that there is almost no load left in the pile at that depth. This is the result of the loading transfer to the soil by the lateral friction of the pile. From the rate of load reduction, it is therefore possible to evaluate the lateral friction for the different geological layers.

This data was used to determine the optimal length and number of piles used to support the newly built cut and cover tunnel.

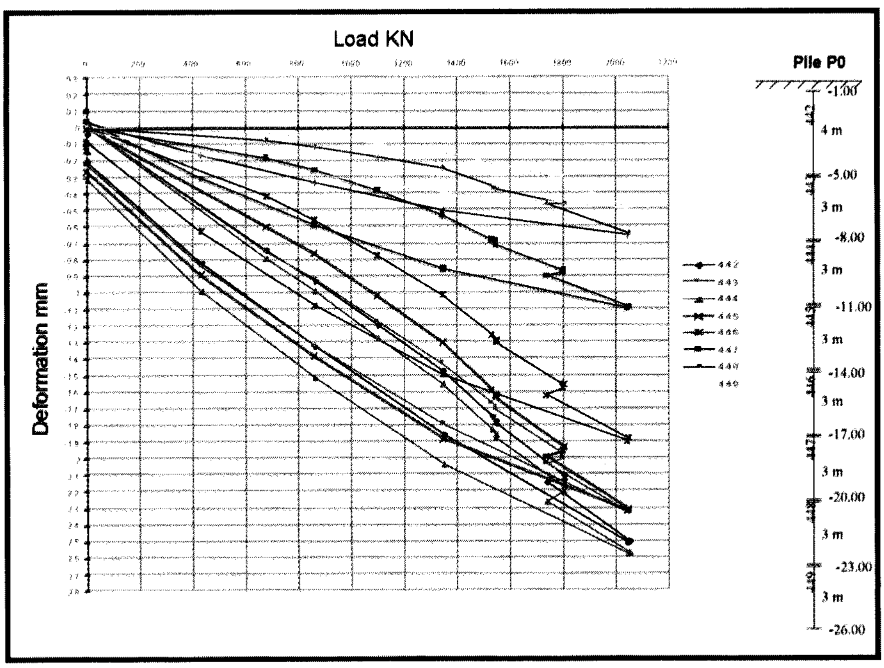

Figure 5. Deformation as a function of the applied load for sensors installed at different depths

Heat exchanger pile

A heat exchanger pile is a pile foundation equipped with a channel system, so that a heat carrier fluid can be circulated in order to exchange heat with the surrounding soil (Figure 6). Coupled with a heat pump for heating and/or cooling purposes, the advantage of such a system is its ability to use the shallow geothermal resources (in fact solar energy) at a reasonable cost.

The two main functions of the heat exchanger piles are to support the loads of the building and to serve as a heat exchanger with the ground. The heat exchanger piles are connected together hydraulically and coupled to a heat pump. During the winter, the heat pump extracts thermal energy from the ground and provides heat to the building. As a result, part of the heating requirement is covered by energy that originates from the ground. If large enough, a regional ground water movement will provide a thermal regeneration of the ground volume which contains the piles from year to year. If not, cooling of the ground takes place, which is actually an advantage during the summer when the heat exchanger piles are used for direct cooling realised by directly connecting the pile flow circuit to the cold distribution without a cooling machine in between. In other words, part of the thermal loads generated in the building are directly injected into the ground through the heat exchanger piles. Direct cooling enables a thermal regeneration of the ground and is beneficial to heating the next winter.

The principal constraint on the system is the thermal disturbance withstood by the piles that should not affect their mechanical properties, that is their ability to support the loads of the building. This problem represents the main objective of this experiment.

This insitu test was set up to determine the thermo-mechanical behaviour of a heat exchanger pile. The pile tested is one of those in the foundations of a new building (100 m long x 30 m wide) with five floors at the QN-EPFL (Swiss Federal Institute of Technology at Lausanne, Switzerland). This pile is 25.8 m long and 880 mm in dia. It has been equipped with a pipe system for the thermal disturbance and with 58 sensors: one load cell, 29 SOFO optical fibre sensors for deformation and 28 conventional extensometers for deformation and temperature. The sensors were installed on the rebar cage before lowering into the borehole (Figure 7).

Precision levelling enables the vertical pile head displacement to be measured. All these sensors allow data to be acquired for the analysis of the behaviour of the pile submitted to the thermo-mechanical loading. The mechanical loading is imposed by the increasing weight of the building, whilst the thermal loading is imposed by an electric heater. From the practical point of view, the coupled thermo-mechanical loading is obtained by imposing a cyclic thermal variation (heating and relaxation) after the construction of each floor of the building (Figure 8). In these conditions, there are eight thermo-mechanical tests. The static loading is imposed on the pile by the building. Knowing the pile's diameter and its elastic modulus, four deformation sensors at the top of the pile

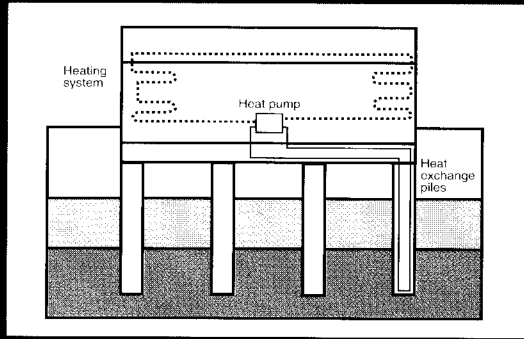

Figure 6 (above). Heat exchanger pile system.
Figure 7 (right). Sensor installation on the rebar cage. Additional circumferential sensors are also shown.

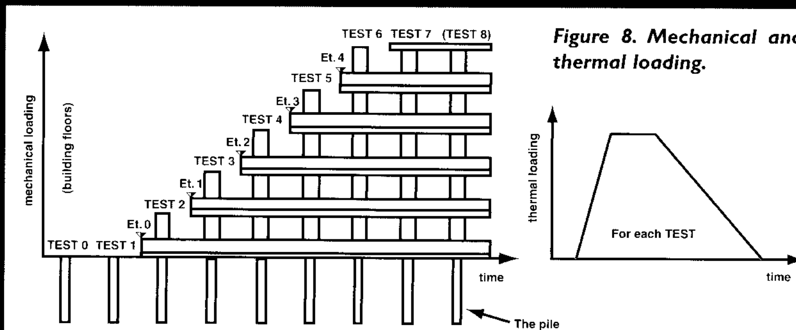

Figure 8. Mechanical and thermal loading.

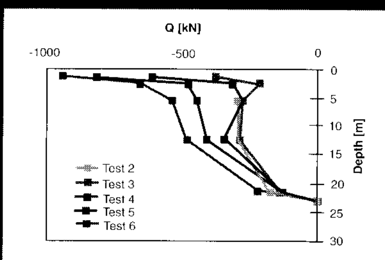

Figure 9. Load distribution in the pile after construction of each floor and for different depths.

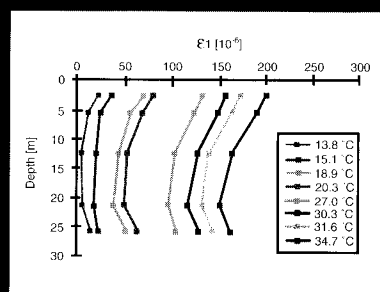

Figure 10. Strain vs. depth for different temperatures.

allow this loading to be estimated. The measured load as a function of the depth in the ground is shown in Figure 9, while Figure 10 shows the strains measured at varying temperatures.

The results show that thermal variation has two effects on the mechanical behaviour of the pile. The first effect is that lateral friction is increased with temperature loading. The second effect is that a thermal compressive stress is added in the pile. These two effects should be taken into account in the design of foundations with any heat exchanger pile, especially if a summer thermal injection (solar collector) is used. However, in this case, the integrity of the pile and thus of the building have never been threatened by thermal solicitations.

Conclusion

The benefits of structural monitoring are obvious. A continuous, or at least regular, monitoring of a structure can increase knowledge about its behaviour and help to guarantee its safety and to plan for maintenance interventions. Besides short gauge strain sensors that measure the local properties of the construction materials directly, long gauge length deformation sensors like SOFO can give additional and complementary information on the global behaviour of a structure.

The SOFO monitoring system has been applied to the monitoring of piles as well as to other civil structures such as bridges, tunnels and dams, in order to monitor their short and long term behaviour.

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