MEASURING DEFORMATIONS OF LARGE STRUCTURAL SYSTEMS

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KEY WORDS: Structural Health Monitoring, Fiber Optic Sensors, GPS, SAR

ABSTRACT:

The paper discusses some peculiar aspects of the measurement of deformations of large structural systems like breakwaters, embankments, dams, long bridges, tunnels and lifelines. These systems, indeed, may extend for several kilometers in length. Apart from the use of conventional topographical survey, modern techniques have made available a variety of non-conventional methods that have been proven to be very useful in assessing the state of deformation of the above mentioned structural systems. In particular, GPS station networks, satellite radar imagery, long-base and distributed fiber optic sensors are described in the first part of the paper. Some examples of application of these techniques are then presented in the second part of the paper. Among these applications, the settlement monitoring of the "Duca di Galliera" breakwater in the Port of Genoa, performed from 2002 to 2005 with GPS sensors, and a few cases of deformation monitoring of dams, levees and tunnels with distributed fiber optic sensors are described in detail. Some aspects of the engineering interpretation of the data obtained from the measurements are also discussed.

1. INTRODUCTION

Monitoring the in-service response of structural systems has become a very important tool for assessing the structural integrity of infrastructure and for providing the basis of knowledge for efficient implementation of maintenance strategies. Indeed, infrastructure maintenance represents a very challenging problem for modern societies as replacement costs may not be viable in many instances. On the other hand, the need of ensuring safety for users and general population of old infrastructure has raised significant problems that modern engineering community has been forced to face.

To this purpose, in the last 15 to 20 years a great deal of research efforts has been dedicated to the development of Structural Health Monitoring (SHM) techniques, as witnessed by the activity of several international technical associations like SPIE, IASCM, IABMAS or ISHMII and by the increasing support that infrastructure owners and public bodies are giving to the subject.

Research in SHM has included the development of new sensor technologies as well as new applications of existing ones, data acquisition and data processing techniques, data fusion and data mining techniques, condition (damage) identification procedures, residual life estimation and decision support systems. Practical applications are also developing quite rapidly although the effectiveness of SHM procedures will take a long time to come into evidence, as ageing and degradation phenomena of structural systems are slow and very complex in nature.

The focus of the present paper is related to the application of SHM techniques to large structural systems, ranging from several hundred meters to several kilometres in size, where the problem of assessing the safety conditions involves the knowledge of the displacement and deformation states in very many, if not in all the structural sections as well as in the system as a whole. In addition, the interpretation of the monitoring data requires complex reasoning schemes and involves the use of behavioural models that often are not restricted to the structural system itself but also includes the response of the surrounding fields.

The discussion that is presented in the first part of the paper concerns in particular with the use of different sensing technologies, like GPS station networks, satellite and terrestrial radar imagery, long-base and distributed fiber optic sensors, that have been proven to be suitable for the application on such structural systems.

Some examples of application of these techniques are then presented in the second part of the paper. Among these applications, the settlement monitoring of the "Duca di Galliera" breakwater in the Port of Genoa, performed from 2002 to 2005 with GPS sensors, and a few cases of deformation monitoring of dams, levees, and tunnels with distributed fiber optic sensors are described in some detail. Some aspects of the engineering interpretation of the data obtained from the measurements are also discussed.

2. SENSING TECHNIQUES

The sensing techniques that are described in this paragraph are restricted to the ones that have been used in the examples. Some of them, in particular GPS, synthetic aperture radar (SAR) interferometry and laser scanners, are well know in the present context and therefore the specific features and arrangements subsequently used are only briefly described.

Some more information is however given on long-gage and distributed fiber optic sensing techniques, as their use is assumed to be less common.

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2.1 Global Positioning System

GPS technique has proven to be very effective in displacement monitoring of very flexible structures (Fuggini, 2009). Static and dynamic response measurements on long bridges and tall buildings have been successfully performed. In these cases, the displacements relative to an initial position of the measurement points only is of interest. On the contrary, for large structural systems like dams, breakwaters and levees, the state of displacement of several points with respect to a common fixed reference shall be traced. This is obtained by utilizing nets of GPS antennas distributed on the structure and on the surrounding area, these latter serving as reference stations. In the example described in the following paragraphs, a commercial system called MMS (Knecht & Manetti, 2001) has been used (Figure 1).

Figure 1 – The MMS System

The system consists in a set of autonomous mobile stations comprising power supply, GPS antenna, local processing and transmission logics, plus a Central Control Unit. The communication between mobile stations and control stations is guaranteed by a GSM or radio connection. The Control Unit provides for full automatic operation and remote control of operational aspects of the structure (defining measurement timing and intervals, alarm setup, inclusion or exclusion of a measurement station, and also control battery charge level, temperature, etc….). The software is also able to manage possible discontinuity of the measurements automatically and remotely. The software is divided into three main components:

- measurement station manager: communicates with the measurement stations and logs any sensor or link malfunction;
- baseline processor: is responsible for post-processing the raw measurement data;
- internet server, for making processed data available on the web to selected users.

Accuracies of the order of a few millimeters on the vertical axis can be achieved.

2.2 Radar Interferometry

Among radar sensors for infrastructure monitoring, a key role is played by spaceborne sensors on-board the main European, US and International Space Agency Platforms. Promising results have been obtained by means of the ERS-1/2 sensors, the ASAR sensor of the ENVISAT platform, the German TERRASAR-X, the Italian COSMO-SkyMed, etc.

SAR interferometry is a well known remote sensing tool, useful for many applications in geomatics and other earth sciences. Applications for movement control of large or highly diffused structural systems have also been proposed. Some of the applicable technologies take advantage of reflecting devices positioned on the ground or on the structural surface. Other techniques actually do not need discrete reflectors, as the movement of any point on the surface can be traced with sufficient accuracy. In the case study described, the Permanent Scatterers Technique (Ferretti et al., 2001) has been used.

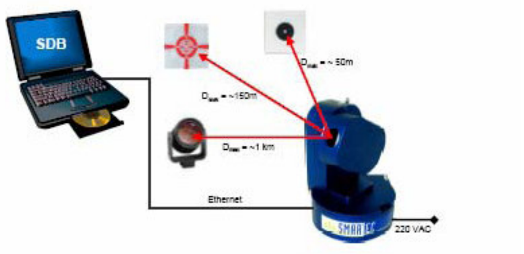
The extension of space-based radar products to airborne and land observations has also been largely pursued. While camera-based acquisition campaigns are conventional land mapping tools, the use of radar techniques is quite innovative. In the recent years radar sensors for commercial lightweight aircrafts and for terrestrial use have been developed and tested in prototypical applications. The promising results can definitely lead to wide exploitation to this technology thanks to its low cost and the enormous capability in terrain observation and data collection.

2.3 Robotized Laser Scanners

Representations of structural surfaces similar to the ones obtained by using microwaves (radar) can also be gathered by means of automated laser scanners, either fixed or mounted over vehicles. If the movements of only a fixed number of points on the structure's surface are to be taken under control, robotized measuring stations positioned at selected locations can be very effectively used.

One of such systems is for example the ROBOVEC automated programmable position measuring station provided by SMARTEC S.A. and is represented in Figure 2. By fixing targets on the structure surface or on significant points of the surrounding terrain, the station can be instructed to measure the distance from the targets at fixed time intervals. The measured data are stored in the local memory and transmitted to a central data acquisition unit.

Figure 2. The ROBOVEC laser distance measuring station



2.4 Fiber Optic Sensors

In the last ten to fifteen years, the development of fiber optic sensing techniques has received considerable attention both for research and applications in many different fields; in particular, very interesting sensory systems have been developed in the field of Structural Health Monitoring (Glisič & Inaudi, 2007).
An innovative technique based on distributed fiber optic sensors (Figure 3a) can be used in particular to identify and localize behavioural anomalies (damage) in structural systems, even extending for several kilometres in length.

Different techniques are used to measure temperature and/or temperature and strain along the fiber (Inaudi & Glisič, 2005). In a few words, one can say that the method for temperature measurements uses Raman-scattering of light in silica optical fibers. The Raman back-scattering depends on the local temperature of the fiber, so that studying this phenomenon one can obtain information on the thermal behavior of the structure around the fiber. By identifying thermal anomalies it is possible to detect leakages in pipelines, earth or concrete structures or correlate temperatures with displacement or strain measurements for engineering interpretation. Other distributed fiber optic sensing techniques based on Brillouin scattering allow the measurement of distributed strain and can be used to detect and localize defects such as cracks or settlements.

Finally, long gauge sensors, such as SOFO sensors (Inaudi & Glisič, 2002), can be used to measure deformations over long measurement bases (Figure 3b), effectively performing as long extensometers (Figure 3c).

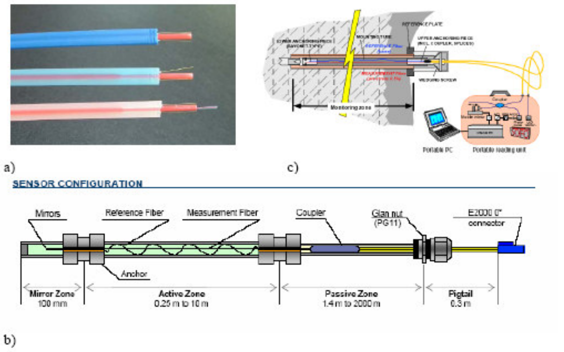


Figure 3. Fiber optic sensors: a) distributed sensor, b) SOFO deformation sensor, c) long-base extensometers.

3. CASE STUDIES

Some case studies illustrating the application of the above described techniques are presented in the following.

3.1 Breakwater deformation monitoring

In the following example, an application is shown concerning a displacement monitoring application of an old breakwater, entitled to the Duke of Galliera who sponsored its construction, existing in the Port of Genoa, Italy, during refurbishment of the outer jetty (Del Grosso et al., 2003, 2008). The monitoring was performed by a set of ten GPS stations placed on the breakwater and two reference GPS stations on firm ground. Measurements were taken from February 2002 to January 2005.

The Duca di Galliera breakwater is the main structure protecting the old basin of the Port of Genoa; it was constructed between 1877 and 1888. It is a rubble mound, crest walled structure that suffered significant damages because of the storms and seepage occurred during its life. In 1928 the Port has been widened, adding a new basin and a new breakwater on the west; the configuration of the original structure was changed opening the first part of the breakwater to realise a navigation channel. The structure actually under consideration is only the longest part of the ancient breakwater, spanning 845 m in length.

Due to severe damages induced by more recent storms, the Genoa Port Authority decided to carry out a refurbishment program in order to avoid the risk of a complete collapse of the structure. The works were aimed at reducing the action of the waves by transforming the existing breakwater into a berm breakwater: the wave motion will indeed model the jetty until an equilibrium configuration is reached. More than a million tons of stone material have been added to the outer jetty.

Figure 4 depicts the positioning of the ten GPS sensors on the breakwater and of the two reference stations on firm ground.

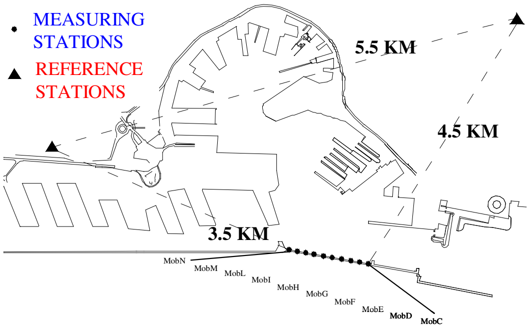


Figure 4 – The GPS network

Measurements were taken every four hours with some discontinuity due to interruptions in works, by polling the stations from the control unit using GSM telephone links. A plot of the measured vertical displacements in the ten sections of the breakwater at different times is shown in Figure 5.

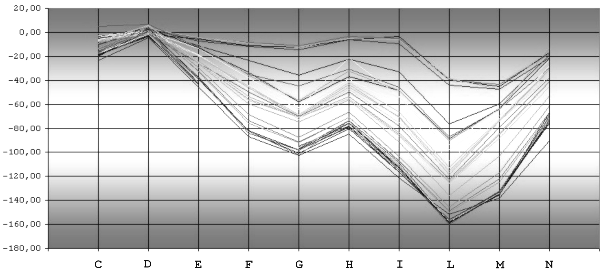


Figure 5 – Vertical displacements of the Breakwater

The measured data, that show significant differences in the settlements of the structure, together with other historical information have been used to construct a finite element numerical model of the settlement behaviour of the structure. The model has also been validated by reproducing the settlements that have been recorded during the life of the breakwater.

The results of the numerical model were well in accordance with the measured data but also indicated that some small settlements were probably already taking place before the refurbishment interventions.

The measured settlements were thus integrated with a settlement analysis performed on the whole area of the Port of Genoa by means of the Permanent Scatterers Technique by using SAR images over some years before the works. Figure 6 represents a combination of the settlements obtained from SAR interferometry and the settlements measured with the GPS system.

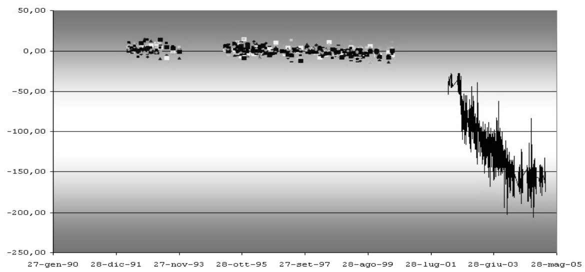


Figure 6 – Combined SAR and GPS settlements

The plot shows that there is a continuity in the settlement behaviour of the breakwater.

From the comparison of the two satellite techniques, some considerations can also be done. GPS system has the advantage to reliably have a vertical precision of 5-10 mm and to give 3D displacements in near real-time; the precision is independent on environmental conditions but strictly related to the quality of the satellite signal. On the other side, PS analysis is more useful for the monitoring of large areas and can give a long historical database of the movements of significant features like man-made structures. Vertical displacements can be measured with a precision of 1-3 mm but only long-period movements can be measured. As a conclusion, the combined utilization of both satellite systems has demonstrated to be a valid tool for the monitoring of large structural systems.

3.2 Dam monitoring

Some applications of fiber optic sensing techniques to the monitoring of dams are shown in this subparagraph (Del Grosso et al., 2010).

A first example is represented by the Emosson shell dam, where two long-gage fiber optic sensors have been used to replace traditional extensometers. The Emosson Dam is situated in the Swiss Alps, near the French border, 1930 meters above sea level, near the Swiss town of Martigny. Completed in 1975, the dam is 180 m high and at its coping is 554 m long with a thickness varying from 9 m (coping) to 48.5 m (footing). Two long SOFO fiber optic sensors, have been used in order to replace two traditional rod extensometers (Figure 7). The long sensors, 39 m and 30 m long respectively, are mounted side by side with the rod extensometers. The monitoring started in October 1996.

The 30 m long sensor is placed close and parallel to the 60 m long extensometer. The sensor was installed in October 1997. Its measurement data as well as the measurement data of the extensometer, the difference between the long sensor and the extensometer and the stored water level altitude are represented in Figure 8. The measurements are performed periodically once a month, with, however, some exceptions. It can be noticed that the two measurements are in very good agreement.

Figure 7 – A long sensor on its transporting spool

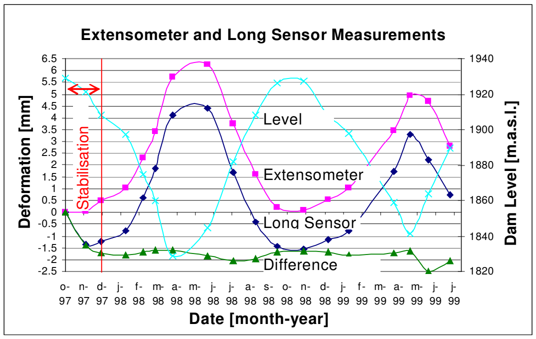


Figure 8 – Comparison between SOFO end traditional extensometers

A second example is related to the use of distributed temperature sensors in detecting leakage through dams. As a matter of fact, leakage is one of the major causes of distress in earthfill and rockfill as well as in concrete dams and its presence can influence the state of displacement and deformation. Characterization of leakage phenomena is therefore very important in engineering interpretation of displacement data, both during construction and in-service life of a dam.

The reported case concerns the Koudiat Acerdoune dam. SMARTEC SA supplied a DTS (Distributed Temperature System), installed in different horizontal layers distributed over the whole height of the Koudiat Acerdoune dam (Fig. 9), a RCC (Roller Compacted Concrete) dam situated in Algeria. The temperature gradient and seepages values for each level are acquired by a DiTemp readout unit and saved on a server.

The scanning is automatic and scheduled at customizable frequency. Figure 10 shows a typical graphic representation of the instrumentation's output.

DiTemp is able to work in single ended or loop configuration. Leakage is monitored continuously and automatically and a reliable alert system is also active for abnormal temperature increase.

Figure 9 – The Koudiat Acerdoune dam under construction

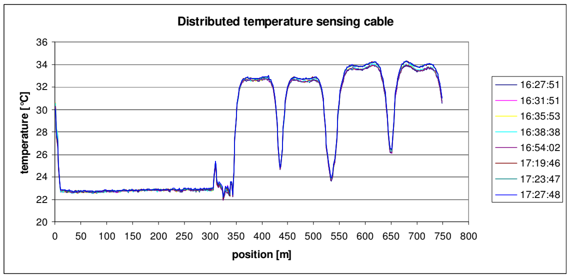


Figure 10. Temperature values for 750 m of distributed cable, different temperatures correspond to different levels

3.3 Monitoring of Levees

The combination of temperature and deformation measurement with distributed fiber optic sensors can play a very important role in stability monitoring of long dykes, where critical sections cannot be easily established a priori (Inaudi & Belli, 2011).

Dykes are frequently founded on a soil with relatively bad mechanical properties. They have a trapezoidal cross-section, being very wide at the base and relatively narrow at the top. The angles of the slopes depend on the construction material and are imposed by stability conditions. Being a barrier for large water accumulations, in order to increase safety awareness and insure structural reliability, dykes shall be monitored. The main aims of monitoring levees are early detection of slope instability, uncontrolled seepage and piping or internal erosion due to seepage. Uncontrolled seepage can be a consequence of cracking in the concrete jacket or clay core generated by water pressure combined with long-term settlement of dyke materials. That is why the deformation in the jacket, core and soil must be monitored.

The stability of slopes depends mainly on the construction material, the water level table in the dyke itself and the pore pressure in the soil. Pore pressure, therefore, is an important parameter to be monitored.

The combined distributed sensing system is mainly intended to provide for crack detection and average strain monitoring, and can replace discrete deformation and temperature sensors. Schematic positions of the distributed sensors in the cross-section are presented in Figure 11.

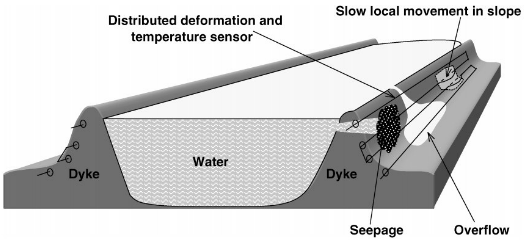


Figure 11 - Schematic representation of distributed deformation and temperature FOS locations in a levee

The distributed systems offer the unique capability of monitoring both strain and temperature simultaneously: distributed deformation FOS can provide for detection and localization of slow movements in the slopes; at the same time distributed temperature FOS can provide for seepage or overflow detection. Seepage or overflow changes the thermal properties of the soil, which are detected by the temperature sensor; the slow local movement of a slope puts the deformation sensor in tension. In both cases, localization and evaluation of the size of the area involved can be performed. The principles are also shown schematically in Figure 11.

Combined temperature and deformation FOS have been recently inserted in geotextiles (SMARTGeoTex). The choice of a SMARTGeoTex solution beside the monitoring capabilities can provide reinforcement capabilities thus leading to a double benefit and a better safety.

3.4 Monitoring of Tunnels

If the monitoring of large structures resting on the earth surface can be performed by remote sensing, as described in the previous subparagraphs, there are less alternatives for the monitoring of underground structures. However, when they represent critical facilities, underground structures shall be usually monitored during their entire lifespan.

As concerning tunnels, the selection of suitable monitoring instrumentation as well the sensors location shall be done accordingly to tunnel typology, soil mechanical quality and purpose of the tunnel. The main goal of tunnel monitoring is to achieve a better knowledge of the structure behaviour in order to plan effective maintenance and prevent major damages.

Beside traditional monitoring techniques and point-wise FOS to monitor convergence, local strain and temperature, the innovation is the use of distributed FOS for average strain, temperature and integrity monitoring. A distributed monitoring system is, by its own nature very suitable and efficient for the monitoring of tunnels where total lengths can reach several kilometers.

Distribuited FOS are installed on the walls and vaults, depending on the tunnel typology and shape, in longitudinal and tangential directions (Figure 12). These sensors provide for crack detection and localization and for detection of local average strain changes due to damage or ground settlement.
Moreover the distributed sensors provide for average strain distribution and temperature monitoring.

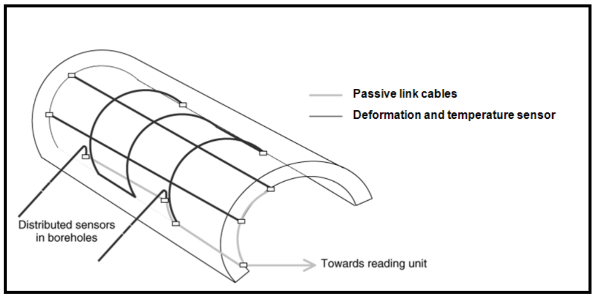


Figure 12. schematic example of tunnel integrity monitoring

With proper installation, FOS can be even used for fire detection. Taking into account the number of monitoring parameters and tunnel dimensions, distributed sensing techniques represent convenient, cost effective and multi-purpose solution. SMARTEC has recently developed a monitoring solution for a railway tunnel where the FO DiTeSt and SMARTprofile solution were selected.

In order to insure structural safety during construction works in a critical area affected by soil settlement, 15 km of SMARTprofile sensors have been installed at 5 different locations around the tunnel section, 2 locations on each vertical wall and 1 in the horizontal deck between the 2 railway lines. Installation was carried out by surface clamping the SMARTprofile FOS to the concrete walls (Figure 13).

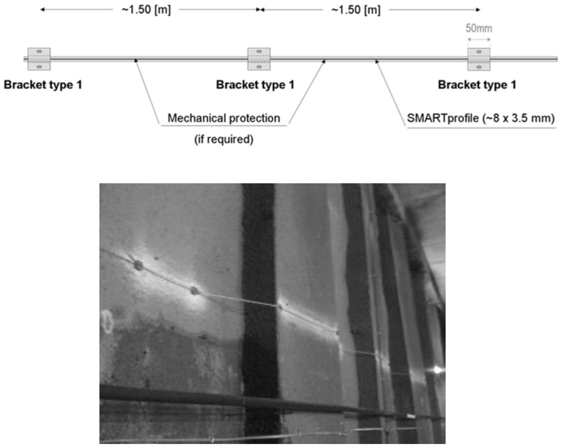


Figure 13. SMARTprofile FOS surface installation

4. CONCLUSIONS

Structural Health Monitoring of large structural systems requires quite different approaches than other systems. In this paper some of present-day sensing technologies have been briefly introduced and discussed and some examples of application have also been presented.

In particular, remote sensing techniques and recent developments of fiber optic sensors have been considered in detail. The examples shown demonstrate the usefulness of these techniques in complex structural problems.

It has to be pointed out that engineering interpretation of displacement and deformation monitoring of such structures usually requires the construction of complex behavioural models. For existing structures, especially for those interacting with the surrounding territory, model validation and interpretation often requires reconstruction of the past behavior.

In these cases, available satellite imagery records can provide a very valuable tool to perform this latter task.

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