Analysis of Long-term Deformation Data from the San Giorgio Harbor Pier in Genoa

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ABSTRACT

In the framework of a large-scale monitoring program conducted by the Port Authority of Genoa, the east quay wall of the San Giorgio pier has been equipped with an array of more than 60 SOFO fiber optic sensors for continuous monitoring. These sensors allow the measurement of the pier displacements during the dredging works, ship docking and in the long term. The sensors measure the curvature changes in the horizontal and vertical planes and allow a localization of settlements with a spatial resolution of 10 m over a total length of 400 m.

The system is in operation since fall 1999, and data has been collected automatically and continuously since then. This paper is intended to present the first analyses and interpretations performed on the monitoring data. Correlation of raw data and curvature analysis to environmental conditions is also presented. .

INTRODUCTION

A large-scale monitoring programme is being conducted by the Port Authority of Genoa to assess safety and degradation of existing structures and to keep records of the effects of service conditions as well as of the effects of retrofitting activities.

In the framework of this programme, the first realisation has been the installation of a monitoring system composed by more than 60 SOFO fibre optic long-base sensors along the east quay wall of the San Giorgio pier. Originally designed for detecting possible disruption of the wall caused by nearby dredging, the system will remain in place for a long-term monitoring experiment. The system is operational since fall 1999, and analysis and interpretation of the first series of data is presently under way.

Data show to be reach of information concerning the real structural behaviour but recognition of the mechanical phenomena taking place in the structure is proving to be a challenging problem.

Attempting to correlate simple inputs to a characteristic structural response, environmental temperature variation has been recognised to be the leading cause of structural deformation. In the paper, the approaches to data analysis and interpretation that have been applied yet are presented and discussed, together with their correlation to temperature data.

As a conclusion, strategies for the development of the system and further processing of the data are discussed.

MEASURING PRINCIPLE: THE SOFO SYSTEM

SOFO [1] sensors are fibre optic sensors, able to detect deformations between any two points of a structure. This method has the advantage of allowing the measure of small deformations with very high precision (2 microns independently on the base length) over long periods of observation and, in addition, allows continuous and automatic monitoring of internal strains with a very good spatial resolution. These sensors are based on low coherence interferometry principles [2], giving high sensitivity non-incremental measures, without the need of continuous connection with the reading unit.

A sensor is composed by two optical fibres inside a protection tube; one of the fibres is connected to the structure at both ends and the other one serves as a reference fibre, to compensate temperature effects. Measuring takes place through a

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coupled path interferometer, composed by a first interferometer measuring the difference between the optical path in the two fibres, and by a second one that translates the first interferogram into a displacement.

The system is insensitive to external environmental disturbances like temperature, eddy currents, electromagnetic fields, corrosion, humidity and vibrations [3].

DESCRIPTION OF THE MONITORING PROJECT

The San Giorgio pier is used for coal import and it has been recently subjected to a retrofitting programme, partly under way. The facility has been realised in the 20's and the vertical walls delimiting the quays are made of heavy concrete blocks; more recently, a further section has been added to the pier in order to increase berthing space and actually the pier measures 400 metres in length. Planned developments consist in dredging of the east basin from the actual 11 m to a water depth of 14 m, to allow berthing of bigger ships: this work has been planned for 2001, and has required the strengthening of the east wall (Figure 1).

Retrofitting of the wall has been performed in 1998; to avoid disruption of the wall during dredging, the structure has been underpinned with jet-grouting columns up to the depth of 18 m, and the blocks have been connected by means of vertical steel rods. Stability has been improved with permanent active tendons installed along the entire length of the pier. After execution of the consolidation works, the east wall has been equipped with a system of sensors in order to study the structural movements over a long period of time [4]. Monitoring has the objective of detecting deviations from normal structural behaviour that may indicate a state of damage in the structure. Therefore, monitoring is organised in distinct phases: the first phase, before dredging operations, has the aim of determining what a *normal* structural behaviour can be; a second phase, during dredging, will be intended to detect potential damaging of the wall caused by the works and, finally, a third phase will involve health monitoring in the long term.

The quay wall has been equipped with 72 SOFO sensors (67 of them continuously functioning), installed in such a way to have 3 sensors for each measuring section (Figure 1). All sensors have an active length of 10 metres; sensors have been positioned at the 3 vertices of the service gallery located in the crown blocks, except in the last extension part, where no gallery was built: therefore in the last 5 sections only a pair of sensors have been installed in the upper surface of the crown block, underneath the pavement. Cabling of sensors has been organised in three groups (A, B, C, starting from the sea side), each one controlled by a junction box collecting 24 optical cables. The junction boxes are in turn connected to the reading unit by means of cables located in an underground duct. The reading unit is connected to the sensors through a programmable optical switch. Data are collected and stored in a computer database (SOFODB). In the next future, the reading unit will be connected to the Port of Genoa Information Network and the database will be made available on-line.

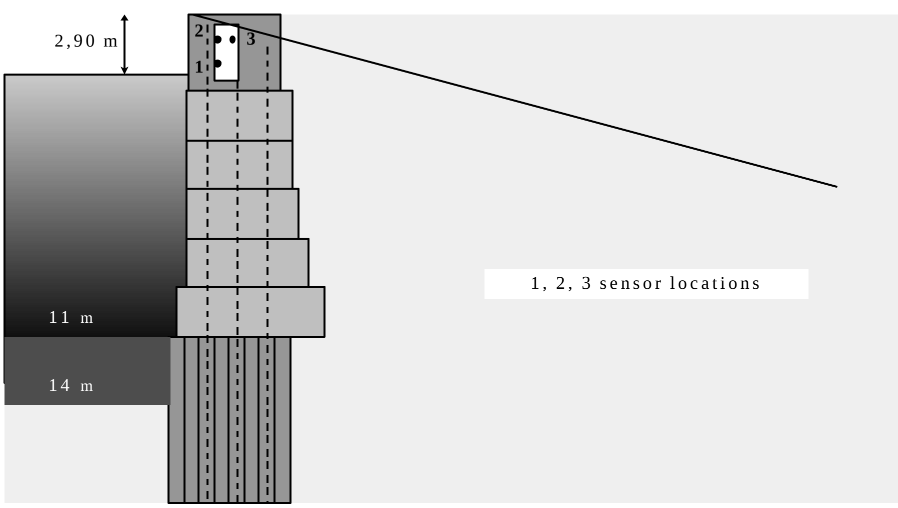

Figure 1: Quay wall cross-section; strengthening works and sensor locations.

DATA ANALYSIS AND INTERPRETATION

SOFO sensors have been extensively applied in the monitoring of bridge girders in Switzerland. To carry out interpretation of the readings and correlation with the mechanical behaviour of the structure, a computer method has been implemented at IMAC, Polytechnic of Lausanne. The algorithm, named SPADS, has been successfully tested both in laboratory experiments and in the field.

According to this algorithm, developed by S. Vurpillot [5], the structure is subdivided into *macro-elements*, each one containing several *cells* in which the sensors are installed. Readings are collected through *data acquisition campaigns*. From the data of each campaign, an average curvature is computed for every cell, both in the vertical (C_z) and in the horizontal (C_y) planes. Computation is performed from the equation of plane deformation for two-way bending, using the sensor position matrix **X** and the measurement matrix Q:

$$(1) \qquad \begin{pmatrix} c \\ a \\ b \end{pmatrix} = \left(\mathbf{X}^T \cdot \mathbf{X}\right)^{-1} \cdot \mathbf{X}^T \cdot \mathbf{Q} \qquad \Rightarrow \qquad C_z = -\frac{b}{L_{cells}} \qquad C_y = -\frac{a}{L_{cells}} \qquad (2)$$

where a,b,c are the equation coefficients. A polynomial fitting of the curvatures for each cell is then computed for every macro-element:

$$(3) \qquad P_n(x) = \sum_{i=1}^{n} a_i \cdot x^i$$

In the case of displacement analysis for beams, double integration of these polynomials gives the deformed shape of the structure.

This procedure is not completely applicable in the case of the quay wall, because it does not behave as a flexural element. However, the concepts of macro-elements and cells have been retained in data analysis, to transform sensor strain data into curvatures.

After a few months, needed for the tuning of the system, the data have been permanently stored in the data base starting from 30 November 1999; acquisition campaigns have been programmed four times a day, each campaign elapsing 15 minutes to completion. Monitoring has been therefore addressed to characterise a long-term structural response. It is planned to analyse short-term phenomena, like crane operations, at a later stage.

For the analysis of the data, the structure has been divided into 24 cells. The analysis of raw data has shown that the 3 sensors included in each standard cell give very similar relative displacements during time, with differences of the order of 1mm/100, i.e. of the same order of magnitude of the sensor precision.

Among the various environmental sources causing long-period displacement of the wall, it has been found that temperature is playing the most important role. No apparent influence of the amount of coal stored in piles on the quay has been found. Correlation to environmental temperature has been therefore studied to a greater extent.

In all the cells, it has been apparent that response to environmental temperature variations is delayed by a few days, due to the thermal inertia of such a massive structure.

Sensor readings can be put in strict correlation with temperature variations, but different sections may respond to temperature in a different way. In particular, cells containing joints in the crown blocks give responses out-of-phase with respect to temperature variation, while monolithic cells give responses in-phase.

The plots in Figure 2 and 3 show the different behaviour of the two types of cells. The difference is visible considering biweekly thermal variations (shown in tenth of degree Celsius) as well as in the complete observation period (winter cycle and beginning of summer cycle).

The analysis has been repeated in terms of curvatures. The horizontal and the vertical curvature have been determined applying equations (1) and (2) in a simplified form, because each cell contains only three sensors at the corners of a triangle.

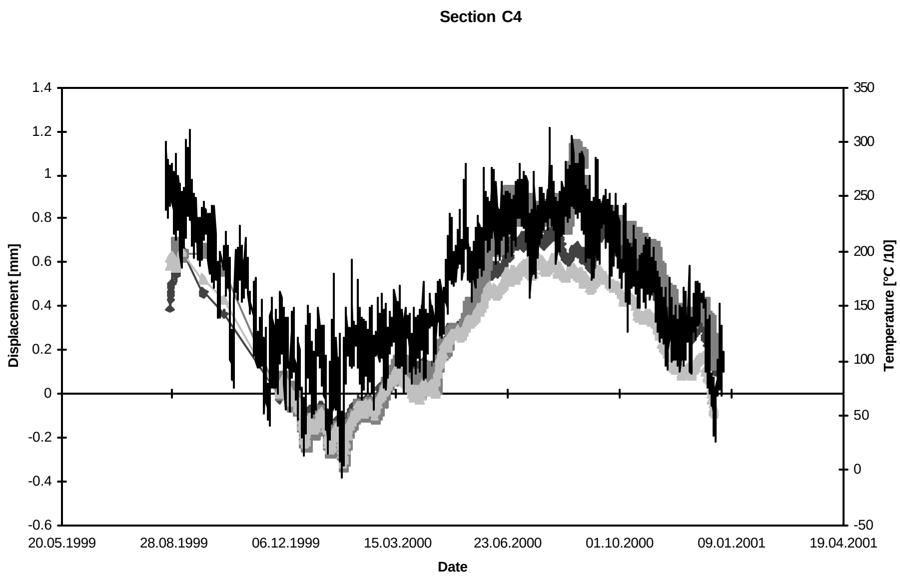

Figure 2 : Time-strain-temperature plot for a section in-phase with thermal variations.

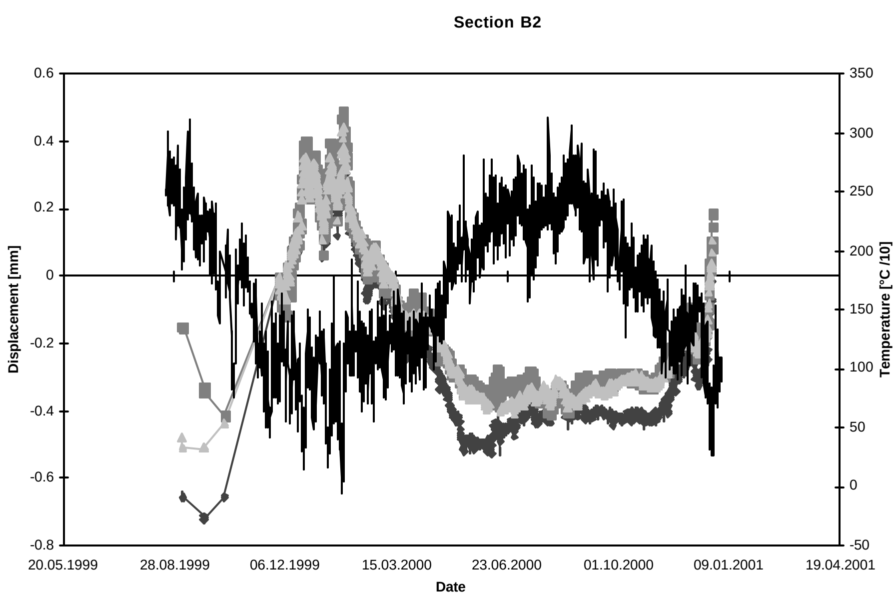

Figure 3 : Time-strain-temperature plot for a section out-of-phase with thermal variations.

Curvatures have also been correlated to temperature variations. In terms of curvatures, the response of the structure is smoother but the most important information is retained. In particular, the response of a cell is still influenced by the presence of joints, but no clear information on discontinuity is detectable from the curvature plots.

Figure 4 shows the recorded deformation as a function of the ambient temperature. A correlation is clearly visible and a thermal expansion coefficient of about 25 10^{-6} /°C can be found. The plot presents a large dispersion; this is due to the response time of the structure that creates a hysteretic curve. In the near future it is planned to measure the concrete block temperature instead of the ambient temperature, as this first should be better correlated with the pier deformations.

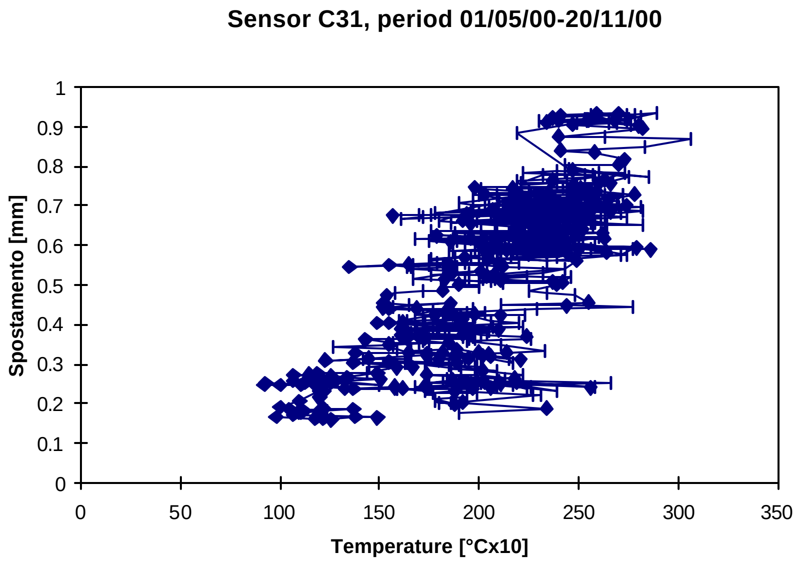

Figure 4 : Displacement-temperature correlation for one Sensor

Figure 5 illustrates the plots of the time history of the curvature in a typical section, compared with the time history of the environmental temperature.

Time-delay due to the thermal inertia of the structure is visible from the plots.

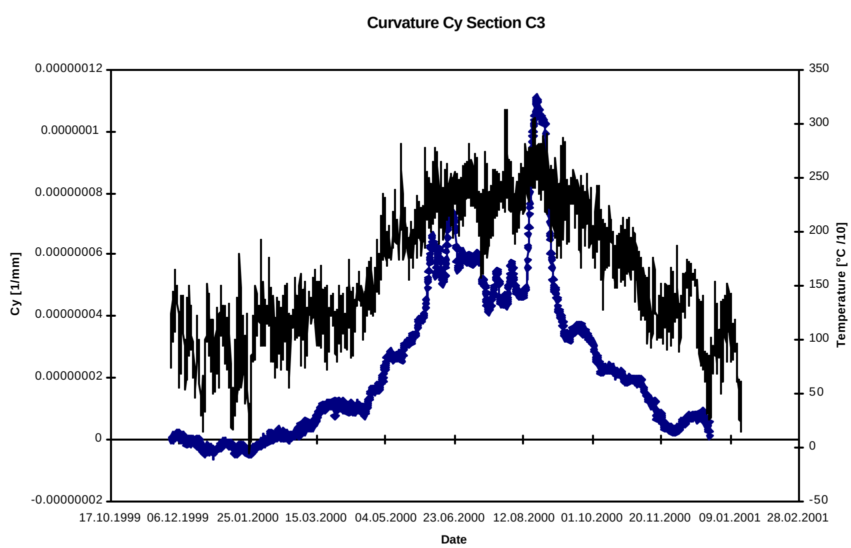

Figure 5 : Time-curvature-temperature plot.

Since thermal effects have resulted to be the most important factor influencing the monitored response of the quay wall, more detailed analyses have been carried out. In particular, the comparisons have been repeated taking into consideration only the campaigns performed at the same hours. These comparisons have led to observe that, during the day, anomalies appear in the correlation between temperature variations and observed response. An attempt has been made to attribute such *disturbances* in the response to terminal operations. However, no correlation has been found between such disturbances and the presence of ships at the berths.

Figure 6 shows a typical plot of the curvature versus time and temperature, derived from the readings of a cell taken at the same time of the day.

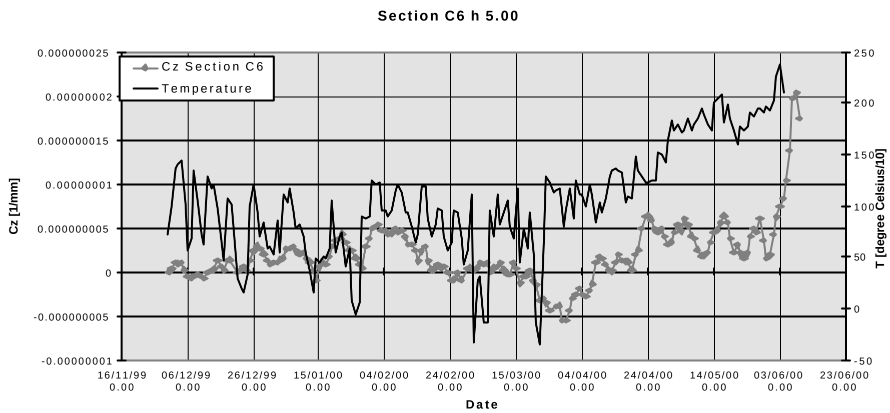

Figure 6 : Time-curvature-temperature plot for the same hour.

To conclude the presentation of curvature analysis, a global view of the quay wall response, in terms of curvature as a function of space and time, is presented in Figure 7. It is observed that the response close to the pier root (left) is smoother than the response derived from the sensors located at the sea-side end. In particular, the sensors located on the surface of the blocks seem to give a less significant response.

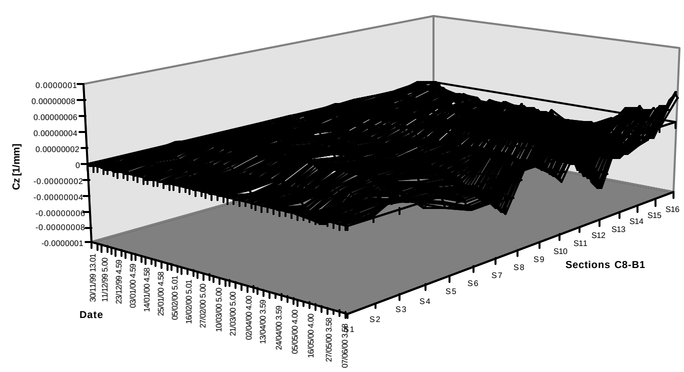

Figure 7 : Time-curvature-space plot for the entire wall.

STATISTICAL CORRELATION ANALYSIS

A further step in data analysis and interpretation has been performed by applying a signal processing technique, called *proper orthogonal decomposition* [6]. This technique has the aim of filtering out the noise from the signal and has been used to obtain *clean* space-time responses in terms of strains and curvatures. In general terms, a signal can be decomposed in the sum of an average value in time and of a zero-average time fluctuation. It is then possible to compute the correlation matrix of the data, and perform an eigenvalue analysis. The time-invariant eigenvector associated to the maximum eigenvalue represents the dominant trend in space of the data, corresponding to the time function with the maximum variance. The analysis performed on strain and curvature responses has confirmed that such filtered time history of the strains and curvatures is still correlated to the variation of the temperature in time.

CONCLUSIONS

A first analysis and interpretation of the data collected from the long-term monitoring system of the San Giorgio pier has shown that the structural behaviour can be characterised in terms of its response to environmental temperature variations. Other informative observations will be obtained from the short-term monitoring experiments planned in the next future. During these experiments, the campaigns will concern only part of the sensors, to observe the structural response during unloading of ships and manoeuvring of the cranes.

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