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STRUCTURAL HEALTH MONITORING OF HARBOUR PIERS

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Abstract

The evolution of container and bulk ships involves the need of increasing the water depth in ports and the loads sustainable by quay walls and piers. Consequently, existing ports are facing expensive interventions to dredge navigation channels and berths and to strengthen or replace structures that have already been subjected to degradation. The paper will present some experiences that have been or are being conducted in the Port of Genoa in installing and managing instrumental monitoring systems on piers with the aim of performing short to medium and long-term control of the efficiency and safety conditions of such structures. In particular, two examples of monitoring the walls underlying existing piers that have been subjected to strengthening and dredging of the contiguous basins will be discussed, in view of the validation of the efficiency of the refurbishment works. Another example, consisting of the monitoring of a prestressed concrete pier, will also be presented. In all the cases, the monitoring systems are based on fibre-optic deformation sensors. The efficiency of the monitoring systems will be discussed considering the aspects of durability and maintainability for long-term operation in severe environments. The issues of data interpretation will also be addressed.

INTRODUCTION

Structural health monitoring of aging infrastructure has become a very popular issue in applied civil engineering research, because managing constructed facilities has shown to be more critical than building new ones. In particular, the detection of structural integrity of bridges has been most often the subject of investigation although buildings, dams and offshore platforms have also received considerable interest.

The use of monitoring systems, as well as of sophisticated data processing and interpretation techniques, has been studied to a great extent. A variety of innovative approaches is therefore available to set up the basis for large-scale application projects. However, despite the very large amount of work dedicated to other infrastructure systems, a limited number of applications have been developed for port structures.

A review of the most important aspects of infrastructure condition monitoring in the marine environment has been presented by one of the authors [1]. As reported in this reference, infrastructures interacting with the marine environment represent a very significant case-study, because of their extreme economical importance and because of the concern about the effects that these facilities may produce on the natural environment.

In particular, internal structures in a port environment (such as piers, docks, berths, dolphins and transportation facilities) represent an important aspect in the management of harbour infrastructures. Aging and physical degradation due to fatigue, corrosion and material degradation for chemical and biological phenomena is very severe in the marine environment. Indeed, corrosion and concrete degradation is one of the major causes of repair, especially after the diffusion of precast prestressed concrete elements that has taken place in the recent years for the construction of pier slabs, and because of the harsh microclimatic environment that sometimes is established between the slabs and the water surface.

Internal structures can also be subjected to obsolescence related to technologic, regulatory and economic changes that impose new requirements and adjustments on infrastructures [2]. The increase in maritime commerce involves the need of improving and expanding port facilities to meet the growing demands of the commercial shipping industry. For these reasons existing ports are facing expensive interventions to strengthen or replace facilities that have already been subjected to extensive degradation, as well as to dredge navigation channel and berths.

In a large port, monitoring of facilities by direct inspection involves important resources and is very difficult to perform. Great interest is therefore raised by the potential use of instrumental monitoring to control the safety conditions of structures and the efficiency of the refurbishment works. Some experiments of large-scale structural monitoring projects are already being performed.

This paper presents the ongoing project started a few years ago by the Port Authority of Genoa, in co-operation with the University of Genoa. Different piers are being subjected to maintenance and refurbishment programs. These programs involve large investments and have suggested the opportunity of launching a structural monitoring project, with the scope of experimenting over a large scale the application of instrumental monitoring in the realization of a computer-aided procedure for the planning of maintenance and retrofit operations over the port facilities. The implementation of the monitoring project is evolving in accordance with the programmed works.

SHM EXPERIENCES IN THE PORT OF GENOA

Monitoring Network

A fibre-optic data and communication network existing inside the wide port area has formed the basis for the development of the monitoring system architecture [3]. The network is providing a variety of information services for the automation, management and control of port operations. The network is composed of four separate fibre-optic ATM carriers interconnected by microwave bridges. A database, updated on a real-time basis, is providing information to the community of port operators, enabling in principle effective decision-making.

While the development of the global monitoring network and the decision-making system are still underway, the installation of monitoring systems on single piers is going on. Figure 1 illustrates the location of the structures already under control and those for which the instrumentation design and installation have been completed and the initiation of monitoring activities is foreseen in the next future. In particular, San Giorgio pier and Etiopia pier have been subjected to strengthening of the walls and dredging works of the contiguous basin, while Colombo and Assereto piers have been expanded and totally redesigned, although the installed monitoring system is not yet operative. A long-term GPS-based monitoring system has also been installed on the ‘Duca di Galliera’ breakwater, in order to keep under control the settlements of the structure during refurbishment works. This latter application is presented in another paper in the same conference [4].

Different sensor technologies have been adopted and integrated in the various applications but the core of all the installed monitoring systems are fibre-optic deformation sensors. A brief description of the efficiency of the chosen monitoring systems is given in the following, taking into consideration the aspects of durability and maintainability for long-term operation in severe environments.

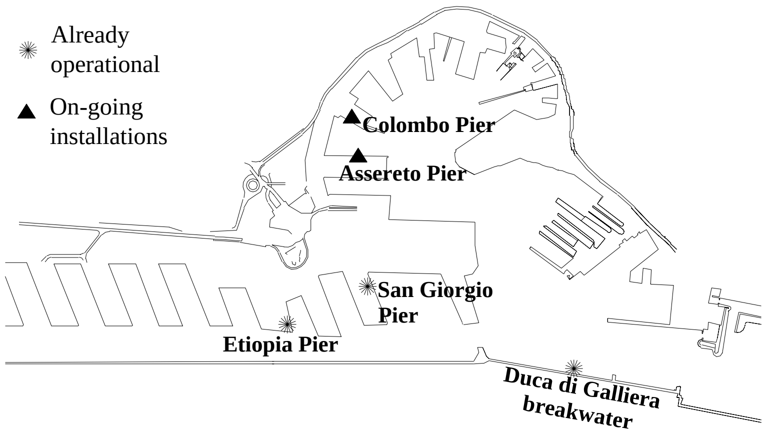

Figure 1. Monitoring systems installed in the Port of Genoa.

Fibre-Optic Sensors for Long-Term Monitoring in Severe Environments

Fibre-optic measurement systems used in all the monitored piers in the Port of Genoa are based on low coherence interferometry. It was introduced by SMARTEC and it is widely used for structural health monitoring (SOFO system [5]). To date more than 3500 sensors have been installed in various types of buildings, ranging from power plants to highway bridges.

The sensors were specially designed to be embeddable into concrete, but are also mountable on the surface of a structure. Initially, the SOFO system was developed for long-term monitoring within a wide temperature range. Thus issues like temperature insensitivity and long-term stability are of great importance. In most applications the temperature dependence of the reading unit has shown to be much smaller than the temperature induced movement of the structure and thus it can be neglected. However, for high-precision measurements, the temperature of the reading unit should be measured and a correction function should be applied. If a linear correction function is used, a precision of 2μm can be achieved within a temperature range of -10°C to 40°C. Further, it is demonstrated that the accuracy of the reading unit is stable for at least 1½ years, also in severe environments.

In order to verify the specifications of the Producers, detailed investigations were carried out in a temperature-controlled laboratory and on site [6]. The results have shown that long-term stability, durability, independency on electrical disturbances, and capability of being used in largely distributed networks, render this technique superior to other sensing devices. For these reasons, fibre-optic sensors look to be very suitable for application in marine and harsh environment. Indeed, in addition to deformation sensing, fibre-optic sensors can be developed for chemical, temperature, and other processes, thus allowing a high degree of integration of the data acquisition system.

San Giorgio Pier

The first realization of the global project has been the long-term monitoring program of the San Giorgio pier [7, 8]. The San Giorgio pier is used for coal import and it has been recently subjected to a retrofitting program. The facility was built in the 1920s and the vertical walls delimiting the quays are made of heavy concrete blocks. More recently, a further section was added to the pier in order to increase berthing space and the pier now measures 400 metres in length. The evolution of bulk ships has created the need to increase the water depth in the adjacent basin and dredging activities were programmed to increase the actual water depth from 11 m to 14 m. The planned works have required strengthening of the wall. 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 (see Figure 2).

The east quay wall of the San Giorgio pier was equipped in 1999 with an array of 72 SOFO fibre-optic linear deformation sensors (67 of them effectively installed and functioning), in order to detect possible distress caused by the dredging activity. The sensors are located in a service tunnel along the top blocks, in such a way to have three sensors in 24 measuring sections (see Figure 2). All the sensors have an active length of 10 metres. The sensors have been positioned in triplets for a set of measuring sections, in order to derive the curvatures in the vertical and in the horizontal planes. The optical fibres are routed from the sensors to the measurement system located in a close-by building. Measurements are stored into a relational database that can be remotely accessed for processing through the data network.

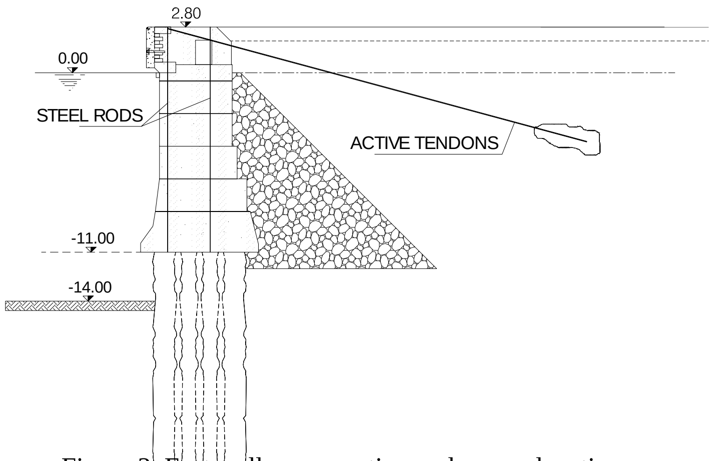

Figure 2. East wall cross-section and sensor location.

After a few months, needed for the tuning of the system, data have been permanently stored in the data base beginning in 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, in order to identify a normal structural behaviour before dredging works.

After five years of continuous monitoring, the time histories of the working sensors have been plotted (see Figure 3). It is clear that there have been two long periods in which the system wasn't operative. At the present time the system needs maintenance intervention. The analysis of the measurements has requested particular attention because the pier is a non-homogeneous structure which doesn't necessarily deform like a continuous beam. Several joints are placed along the pier; this means that the cross-section is not uniform. In a first phase of data interpretation, it has been found that temperature plays the most important role among the various environmental sources causing long-period displacement of the wall. No correlation has been found to the activities taking place at the terminal such as coal load, ship docking and crane position. The measurements in each section are well correlated, indicating that the main deformation is a uniform elongation or shortening. The recorded displacements follow the temperature changes within a response time of a few days, indicating the large thermal inertia of the structure. The analysis has also been performed in terms of vertical and horizontal curvatures. 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.

The analysis has shown that interpretation of the mechanics of the wall is very cumbersome due to the complexity of the interaction among blocks and the uncertainties in the conditions of joints. For this reason deeper investigations seem to be necessary. In particular, data interpretation is being performed with signal processing techniques, such as correlation analysis. The algorithm calculates the correlations on all sensor pairs for a reference period with the aim to quantify the tendency of measurements to change in similar ways. After the initialization, all the correlations are calculated at each step of measurements to determine the presence of anomalies in the evolution of monitoring. Anomalous behaviour is observed through correlations lying outside the thresholds defined during the initialization phase. Displacement time histories for the San Giorgio pier have shown to be well correlated but the statistical analysis are still under study.

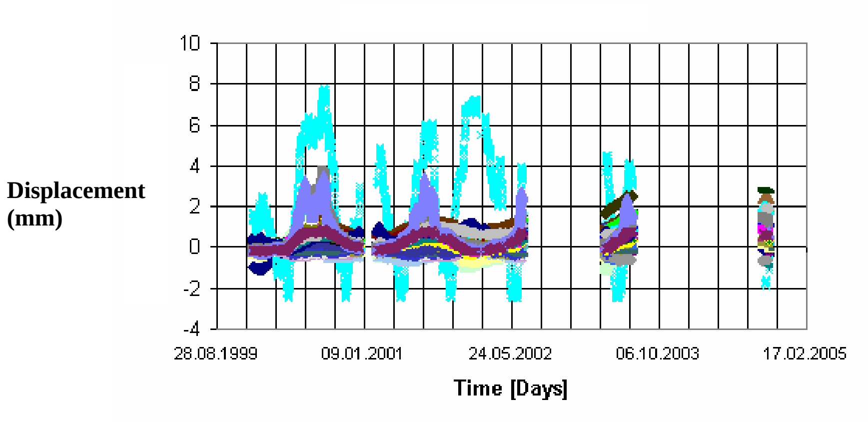

Figure 3. Displacement time histories (in mm) for all the working sensors for the period November 1999 – December 2004.

Etiopia Pier

The Etiopia pier was built in the 1920s and the vertical walls delimiting the quays are made of heavy concrete blocks. It is used for container dumping and has been recently subjected to a similar retrofitting program as the San Giorgio pier. The programmed dredging works have required strengthening of the wall. The solution adopted for the San Giorgio pier has also been performed for the Etiopia pier except for the presence of tendons (see Figure 4).

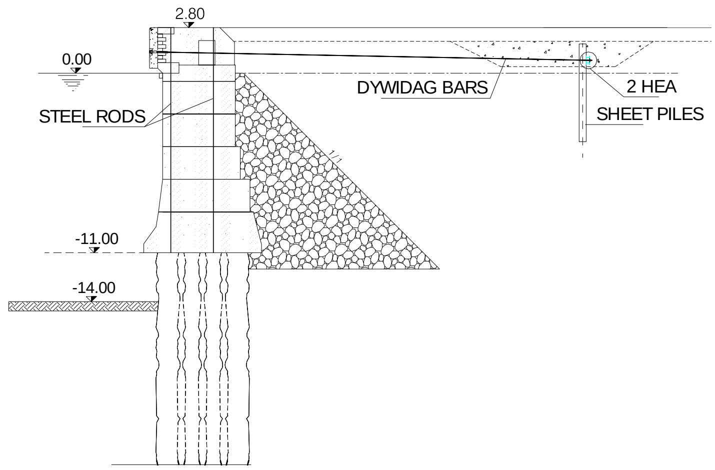

Figure 4. Wall cross-section and strengthening works.

Only the corner south-east of the quay wall was initially instrumented in order to validate the efficiency of the monitoring system on a test zone of limited extension. The system will be tested during the dredging works in front of the instrumented zone. A different monitoring system was installed in 2006 due to the inaccessibility of the service tunnel. Eight passive tendons have been equipped with fibre Bragg grating sensors with an active length of 0.25 m. This type of sensor has the high-resolution of the fibre-optic deformation sensors but they can measure strain as well as temperature, useful to control tendon strains. Monitoring system has been completed with three couples of high-resolution inclinometers mounted into suitable holes along the pier (see Figure 5). Optical fibres are routed from the sensors to the measurement system located in a close-by building. Signals from inclinometers are transformed locally into digital formats by ADAM modules, and routed through fibere-optic cables to the reading unit. Measurements are stored into a relational database that can be remotely accessed for data processing and interpretation.

The monitoring system has been operative since April 2006 for the inclinometers and since June 2006 for the fibre-optic sensors. This was due to the difficulties encountered in the tuning of the sensors. Acquisition campaigns have been programmed four times a day. Dredging works started in August 2006 and have been realized in two phases. At the present time they are not completed; a water depth of -12 m has been obtained.

Strain data have been obtained combining elongation and temperature measurements. All measurements are relative to a reference measurement corresponding to the starting of each phase of the dredging works. The induced strains on the tendons are of the order of 200 microstrains (see Figure 6). Also the inclinometer's measurements show a substantial stability of the pier during the works. Deeper considerations on the efficiency of the strengthening and on the stability of the pier will be possible after the conclusion of the dredging works.

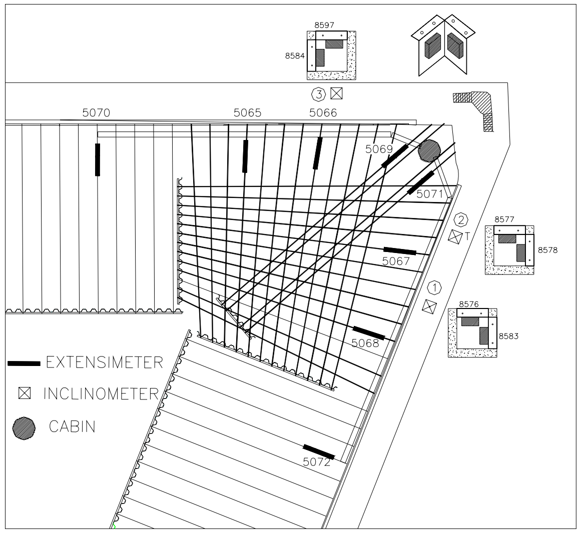

Figure 5. Fibre Bragg grating on the tendons and location of inclinometers in the south-east corner of the pier.

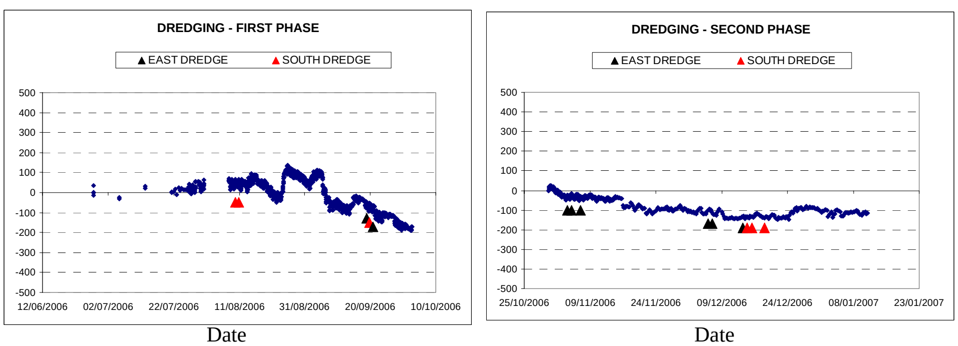

Figure 6. Strain variation (in microstrain) of a tendon in the corner during the two phases of dredging.

Colombo Pier

Another application will be started soon, involving monitoring of a prestressed concrete pier slab with fibre-optic deformation sensors and conventional sensors for moisture content, inserted in the beams at critical locations.

The section of the port comprising Colombo and Assereto piers is used for operation of the fast ferries directed to the major Mediterranean islands, Spain and North Africa. The evolution of this type of ship and the expected increase in traffic is demanding substantial redesign of the existing facilities. In particular, access malls shall be widened to accommodate larger numbers of boarding vehicles; piers shall allow berthing of longer and taller ships, and the effects of the maneuvers performed by the ferries using on-board jet propellers shall be accounted for.

In the framework of these refurbishment works, it has been planned to install, on both piers, an instrumental monitoring system aimed at detecting the displacements of the structures (front quay walls and mooring piers) induced by external events (ship maneuvers). The mooring piers are formed by prestressed reinforced concrete decks simply supported by small caissons. It is therefore planned to detect also the physical parameters (humidity, temperature, corrosion potential) important for the durability of the deck elements.

Figure 7 shows the positioning of sensors that has been studied for typical pier spans. System architecture is based on the capabilities of the measurement unit of the SOFO fibre-optic system to integrate data originated by different types of fibre-optic sensors as well as by conventional sensors, storing them in the same measurement data base. Signals from conventional sensors are transformed locally into digital formats by ADAM modules, and routed through fibre-optic cables to the reading unit. The instrumentation has been installed in the recently finished pier but it is not operative yet.

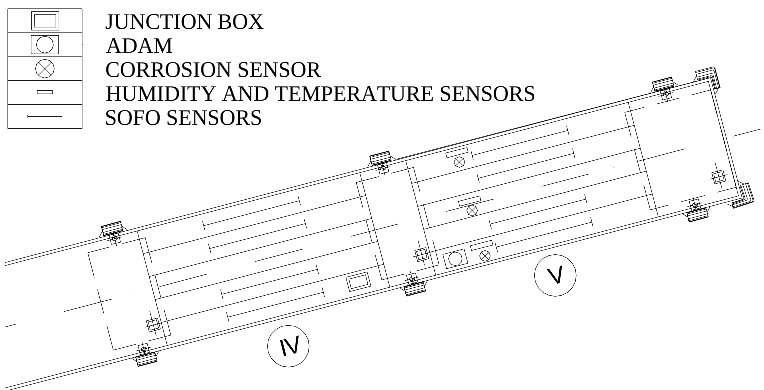

Figure 7. Location of sensors in typical pier spans.

CONCLUSIONS

The paper has presented some experiences conducted in the Port of Genoa in installing and managing instrumental monitoring systems on piers. The purpose of the monitoring is to realize a large-scale management program to perform short to medium and long-term control of the efficiency and safety conditions of port facilities. Fibre optic sensors have been chosen for their good performance and stability in long-term monitoring and severe environment.

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