The role of structural monitoring in the management of risks associated to dams

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ABSTRACT: In many countries, the presence of a large number of dams deriving from mining and agricultural activities, creation of water resources and energy production is generating a diffused state of risk, the characteristics of which are not very well known. Many dams are equipped with instrumentation systems, sometimes according to local standards, but analysis and interpretation of the data is not always appropriately or timely performed. Recent developments of Structural Health Monitoring (SHM) techniques provide a very useful tool to better characterize and manage this risk. With special reference to earth and rock fill dams, the paper summarizes the major risk-originating mechanisms, the control parameters of which are identified and the capabilities of traditional and innovative instrumentation systems are reviewed in the light of defining effective monitoring systems that can be used to improve the level of control over the associated risks. As concerning sensor technologies, fiber optics and remote sensing will be specifically addressed. Some real-case applications of such technologies in dam engineering are illustrated. The characteristics of a data management system suitable to be used at a regional scale and capable of providing different data interpretation schemes, automatically raising warnings and alarms and supporting engineering decisions are also presented.

1 INTRODUCTION

In many countries, the presence of a large number of dams constructed for agricultural and mining activities or for the production of energy and to provide water supply to urban areas is generating a source of risk to life and properties, especially in seismic prone regions, that sometimes is not very well defined or understood. As a matter of fact, many of such dams have been constructed a long time ago and, especially for the smallest ones, maintenance and safety control is often not being performed in a timely and efficient manner.

In the history of modern industrialized countries, many severe dam accidents have occurred, creating large disruptions and loss of lives. More than 150 more or less severe accidents, including failures, have been reported in the U.S. from 1874 to date (Association of State Dam Safety Officials, 2009). In the Alps, during the last half of the past century, some very severe accidents have also occurred. The first one was the Malpasset concrete dam failure, in South-Western French Alps, occurred on December 2, 1959, and killing possibly 500 people. A second case is the Vajont Dam, in the Eastern Italian Alps, where a giant landslide felt into the lake (Fig. 1) causing a wave to overtop the arch dam and devastate the area downstream with at least 1960 casualties.

Figure 1 – View of the Vajont Dam landslide area as it appears today (http://www.bellunovirtuale.com).

As concerning tailing basins created for mining activities several failures have also been reported, the most dramatic of them being probably the event occurred in the Eastern Italian Alps (Tosatti & Lucchi, 2008), where on July 19, 1985, a set of two ponds collapsed one over the other, causing the village of Tesero and other buildings in the Stava Valley to be invested by the mud flow with 268 reported casualties (Fig. 2).

Figure 2 – The Stava tailing basins before (upper) and after (lower) collapse (http://www.stava1985.it)

According to the 2007 update of the National Inventory of Dams, there are more than 80,000 dams in the United States; approximately one third of these pose a high or significant hazard to life and property if failure occurs (FEMA, 2009). China has a long history of dam construction: An-Feng-Tang dam with a 10m height was built 2600 years ago, but only 22 dams with a height greater than 15m were existing up to 1950, according to the statistic of International Committee on Large Dams. However, dam construction went very fast after 1950: in the period from 1951 to 1977, China built 420 dams per year. In 1982 there were 18,595 dams in China. The number of dams with a height over 15m raised to 22,000 and, according to recent statistics (Jia et al. 2005), in 2005 in China there were 4,860 dams with a height over 30m which had been built or under construction. 2,865 of them are soil and rock fill dams, 545 are gravity dams, 391 are rock filled dams, 729 are arch dams. As concerning the height of those dams, one is over 300m high, 8 are 200~300m high, 22 are100~150m high, 422 are 60~100m high, and 4,308 are 30~60m high. Actually, the Three-Gorges Dam represents the world's largest reservoir.

So only looking at two of the major today's world economies - but big numbers are also found for Europe, South Asia, Africa and South America - the hazard related to the presence of dams is very diffused.

However, despite of risk related aspects, the maintenance and further development of water reservoirs is a key issue in power generation from renewable sources and in providing new water resources for economic growth and social improvement in many countries. Because of that, innovations leading to a safer and more efficient construction and management of dams and similar structures can be very important.

New monitoring technologies are amongst such innovations, and this paper is devoted to illustrate some of them and their applications in taking control over the development of risky situations both during construction and operation of dams.

A short discussion of the phenomena leading to potential dam failures and of the consequent monitoring objectives will be presented first.

2 CAUSES OF DAM FAILURES AND MONITORING OBJECTIVES

The causes leading to dam failures are very complex and sometimes depending on external events like floods and earthquakes. Dam failures have some precursors like cracking, large displacements or slope instability and overtopping, but dam failure can also occur with little warning.

An analysis performed on dam failures reported in the U.S. (Association of State Dam Safety Officials 2009) has revealed that approximately 34% of registered dam failures were due to overtopping caused by inadequate spillway design, debris blockage of spillways or settlement of the dam crest. Foundation defects, including settlement and slope instability, caused about 30% of dam failures. Another 20% of dam failures have been caused by piping (internal erosion due to seepage). Seepage often occurs around hydraulic structures, such as pipes and spillways; through animal burrows; around woods and woody vegetation; and through cracks in dams, dam appurtenances, and dam foundations. Seepage is also one of the major problems in earth and rock fill dams. Other causes of failure include structural failures of the materials used in dam construction and inadequate maintenance.

Mitigation of risk would therefore follow in conjunction with the identification of the behavior of the dam in response to environmental conditions and of optimized maintenance plans.

The establishment and exploitation of automatic, real-time monitoring techniques would allow feeding static and dynamic structural models, thus improving sharply the capability of predicting damages and collapses. It is well known that static monitoring is normally conducted in advance with respect to seismic or dynamic monitoring. The former allows assessing the safety level of the dam and identifying potential deficiencies in performance and stability. Multiple techniques are used for this purpose and include all traditional sensors and measurements techniques widely used in civil and geotechnical engineering. As dynamic monitoring is concerned, the use of strong-motion accelerometers is usually preferred with accurate positioning of the sensors on the dam infrastructure (both at the foot and on the uppermost section). This second class of sensors aims at characterizing seismic loads that affected the dam, hence at understanding the potential mechanisms for dam deterioration.

A fundamental prerequisite for using mathematical models and ensuring the full adherence of the results to the real dam conditions is the availability of precise and dense observations, either from a geometric point of view or about boundary conditions.

Several monitoring techniques contribute to this goal by relying on geodetic measurements and intrinsic capabilities for measuring local deformations, rotations, and displacements. The selection of optimal monitoring sensors for a given condition and their spatial/temporal configuration is the key issue addressed by the Monitoring System engineering discipline, which aims at identifying the correct response to user needs in the light of performance, risk in operative conditions, costs and technological readiness levels.

In any case the dam monitoring process represents a crucial process nowadays: rules and recommendations on dam safety put pressure on the creation of monitoring systems that efficiently support geotechnical and structural engineers and decision makers.

For any dam to be monitored – independently from the site and its executive design – routine (i.e. periodic) monitoring or specific inspection procedures (i.e., after a seismic event) should be aimed at assessing:

(i) damages, fractures and water infiltration for the dam structure;
(ii) displacement, damages, rocks movement for the dam supporting structures
(iii) breaking or damages for the draining sub-system;
(iv) structural health and any displacement of the ancillary structures;
(v) landslides, rocks movement, superficial fractures of the ground surrounding the basin;
(vi) anomalies of the resident instrumentation for site monitoring and alarm generation.

It is worthy to mention that software for anomalous event detection is an integral part of current generation monitoring sensors. Not only does the software support real-time monitoring capabilities: it also employs several built-in modules for pre-event warning and event effects assessment. This information may be monitored on site or at any remote location with terrestrial cables, line of sight radio or satellite internet access using secure connection. This approach fully integrates most recent findings in ICT (Information & Communication Technology) solutions, which allow wide and prompt exploitation of such tools at reasonable costs.

In the design of a dam monitoring system, the specific characteristics of the dam are to be properly considered for the optimal choice of sensors and the installation configuration. Key features are several, since dams might largely differ in nature, width, and level of risk.

As a general indication, monitoring requirements for the different classes of dams may be listed as represented in Table 1

Table 1 – Monitoring requirements for different classes of dams

	Arch or Multiple-Arch Dams	*Gravity Dams (Concrete)*	*Earth and Rockfill Dams*
Objective	- Measure stress condition and the absence of tension zones - Monitor cracking and determine the causes	- Verify general stability of structure - Verify the efficiency of impervious seals - Monitor fissuring	- Verify general stability of structure - Ensure that seepage doesn't cause internal erosion
Measured Parameters	- Stress - Temperature - Deformation	- Fissuring - Temperature - Deformation - Displacement	- Pore pressure within the core and core permeability - Total and differential dam deformation.
Controlled Area	- Dam structure - Foundations - Shoulders - Basin Area	- Dam structure - Foundations - Shoulders - Basin Area	- Dam structure - Foundations - Shoulders - Basin Area

3 INNOVATIVE MONITORING TECHNOLOGIES

A complete description of the instrumentation that is or may be used in the monitoring of dams is outside the scope of the present paper.

The issues of monitoring displacements, deformations and leakage phenomena will however be considered because the availability of innovative technologies as fiber optic sensing and remote sensing allow very efficient and cost-effective solutions to the corresponding measurement problems.

Such innovative technologies will be briefly presented and some significant projects involving their use will be also described in the next paragraph.

3.1 *Fiber optic sensors*

Amongst the causes that may originate dam failures, leakage is one of the most dangerous and at the same time difficult to detect in its early stages.

An innovative technique based on distributed fiber optic sensors can be used to identify and localize leakages through dams. Over the last years, different techniques (V-Notch weir, toggle-switch, colored tracer, piezometer etc) and technologies (water level indicator by pressure or ultrasound transducers, magnetic reed, visual inspection etc) have been applied to identify seepage flows. All of them provide information on global water flow and are usually restricted to the surface or inspection galleries; whilst technology based on distributed sensing (Inaudi & Glisič 2005) is able to study seepages in the whole body of the dam, including under the foundation.

In a few words one can say that the method is based on temperature measurements using Raman-scattering in silica optical fibers. The Raman backscattering 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 it. By identifying thermal anomalies it is possible to detect leakages in earth, rock fill or gravity dams.

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, effectively performing as long extensometers.

3.2 *Remote sensing techniques*

In parallel to optical sensors exploitation, new radar techniques have gained relevance in Structural Health Monitoring applications, since they offer innovative features and added value capabilities that well complement traditional devices, GPS-based measuring systems, and fiber-optic sensors.

Radar instruments for SHM applications simultaneously measure the displacement of the entire scenario illuminated by the antenna beam (from hundreds of meters to hundreds of kilometers), hence providing a continuous mapping of displacements of the site. The attractiveness of radar monitoring techniques lies in the capability to monitor the generalized movement of a dam site with a general accuracy of tenths of millimeters and a measurement rate that ranges from minutes to months.

Site includes the infrastructure itself and all the surrounding elements (terrain, supporting infrastructure, basin banks). Continuous monitoring over long periods allows retrieving the so-called historical picture of the interested area (i.e., displacement trends due to slow phenomena, both natural and human induced), which is meant to support the interpretation of the traditional measurements of the dam control points.

Among radar sensors for infrastructure monitoring, a key role is played by spaceborne sensors onboard 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.

Space radars can potentially provide an image of the dam of interest and the surrounding area at each satellite passage over the entire lifecycle of the satellite. From an adequate number of satellite images of the area of interest, the deformation history of specific ground points can be estimated, also extending back in the past if past observations are used. This is the basic principle on which Subsidence Monitoring is founded; this has been recently extended to manmade structures monitoring for health status checking. It is worthy noting that purchasable satellite images date back to the launch of each satellite, since they are properly archived by the satellite owner or data provider. Therefore, the building of new constructions or the analysis of existing structures can be supported by a backward analysis of the interested terrain and areas in terms of natural or man-induced movements.

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.

3.3 *Integration of monitoring systems and data processing*

An integrated Dam Monitoring System can be considered as being composed by the following main building blocks (Fig. 3):

- Local and Distributed Monitoring Sensors, including the necessary Reading/ Interrogation Units
- Innovative Monitoring Sensors, often remotely located;
- Data Control Centre, with the necessary subsystems for data collection, archiving, and assimilation;
- System Command & Control Unit, often located in the Data Control Centre and supported by ad hoc command transmission network;
- Data Processing Unit, located at the central "node" of the network, which implements data analysis and data fusion techniques for properly combining and interpreting the multi-sensor data;
- Data Interpretation Unit based on mathematical models to derive the cause-effect relationship, to forecast the status conditions, and to simulate the effect of intervention works;
- Monitoring data transmission network, linking the sources of information to the Data Control Centre;
- Early Warning Unit which allows Alarm generation in correspondence of configurable thresholds.

Local Monitoring Sensors include traditional, GPS and fibre optic sensors (e.g., temperature, strain, fibre Bragg grating, SOFO and DITEST). Innovative Sensors include radar techniques, which are proposed nowadays as added value components of Integrated Monitoring Systems.

Local sensors are controlled by the reading or interrogation unit, which collects measurements over time with a given interrogation frequency and transmits them to the Control Centre. Data transmission means are normally designed on the basis of the system installation plan and the overall data rate between the measurement points and the Control Centre. It can be implemented via GPRS, WiFi/WiMax, dedicated radio link, fibre optic cables, or satellite communications.

Innovative sensors are characterized by specific carriers: radars used for structural monitoring can be installed on space, air or ground-based platforms.

Innovative sensor data need to be validated and transformed before ingestion either in the conventional monitoring data base or in the structural mathematical model. This process is called data assimilation, and it is commonly based on the mathematical representation of the radar sensors.

All collected data are stored in the Data Control Centre and processed in order to best combine the multi-source information. The goal is to extract the relevant engineering parameters (Data Processing Unit) to feed the structural models (Data Interpretation Unit). In the meantime, the measurements are continually analyzed and compared with threshold values generating alarms (Early Warning Unit).

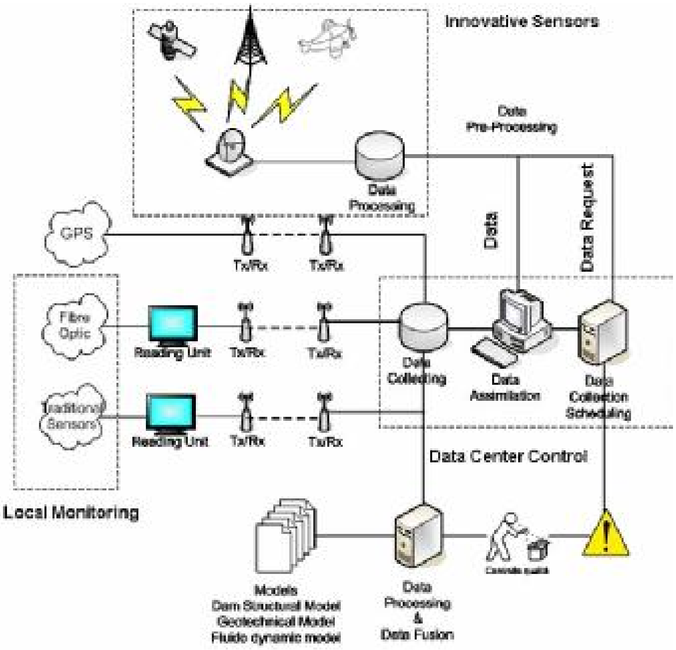

Figure 3 – Monitoring systems architecture

4 CASE STUDIES

Some applications of the previously described technologies are presented in this paragraph. More detailed information can be obtained from the SMARTEC web site (www.smartec.ch).

4.1 *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. 4), 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 5 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 4. Koudiat Acerdoune under construction

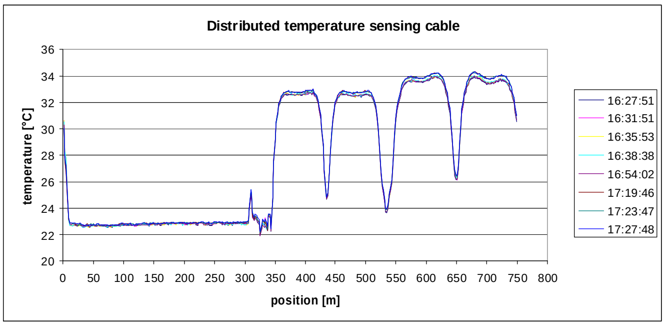

Figure 5. Temperature values for 750 m of distributed cable, different temperatures correspond to different levels

4.2 *In Nam Ngum 2, CFRD dam in Laos*

In Nam Ngum 2, CFRD dam in Laos, a heated distributed monitoring system has been installed at the plinth level (Fig. 6).

Figure 6. Men at work at dam's plinth to install the blue distributed sensing cables

In this application, a distributed armoured multifiber cable was selected. This cable has two major advantages. Firstly, it offers a greater mechanical strength during the installation and operation. Secondly, it allows obtaining leakage information even when seeping water has the same temperature as the parts in contact with the fibre (e.g. soil, concrete, etc.). Slightly rising the temperature of the armoured cable for a few minutes with an electrical current and then releasing the heat supply, allows the detection of flow around the cable that would have been impossible without heating. Figure 7 graphically shows this concept.

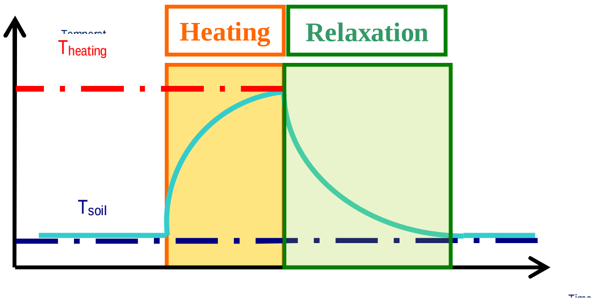

Figure 7. Heating cable procedure. The relaxation time depends on the water flow rate around the cable

Distributed sensing shows several advantages in comparison with the other existing seepage monitoring methods. Fiber optic sensors are immune to electromagnetic fields, corrosion and are rodent resistant. The distributed temperature sensing cable can cover a distance up to 30km with one channel and provide one temperature value every one meter. Embedded sensors do not require any maintenance over the years. Actually there is no practical limit to their life expectancy.

4.3 *Luzzone Dam Temperature monitoring*

Distributed temperature measurements are highly interesting for the monitoring of large structures. In the present application, SMARTEC and EPFL used the DiTeSt system to monitor the temperature development of the concrete used to build a dam.

The Luzzone dam was recently raised by 17 meters to increase the capacity of the reservoir (Fig. 8). The raising was realized by successively concreting 3m thick blocks. The tests concentrated on the largest block to be poured, the one resting against the rock foundation on one end of the dam. An armored telecom cable installed in serpentine during concrete pouring constituted the Brillouin sensor.

The temperature measurements started immediately after pouring and extended over 6 months. The measurement system proved reliable even in the demanding environment present at the dam (dust, snow, and temperature excursions). The temperature distributions after 15 and 55 days from concrete pouring are shown in Figure 9. Comparative measurements obtained locally with conventional thermocouples showed agreement within the error of both systems.

This example shows how it is possible to obtain a large number of measurement points with relatively simple sensors. The distributed nature of Brillouin sensing make it particularly adapted to the monitoring of large structures were the use of more conventional sensors would require extensive cabling.

Figure 8: Luzzone Dam raising works

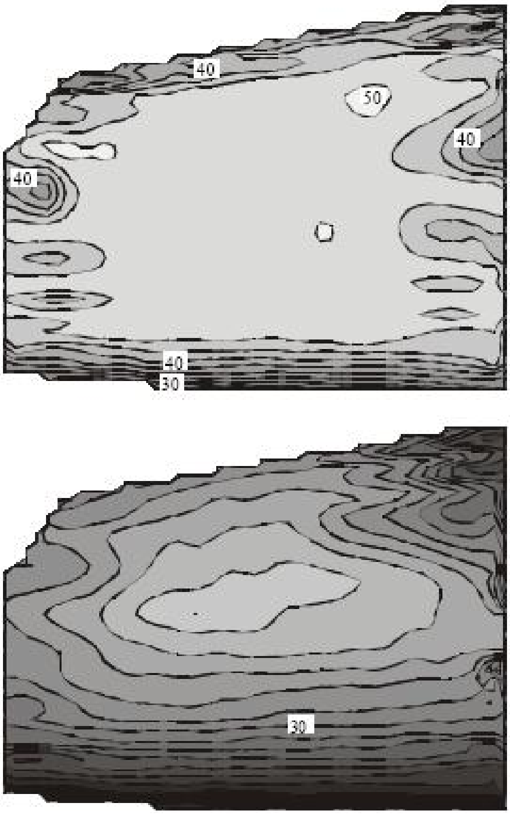

Figure 9: Temperature measurements in the Luzzone Dam 15 and 55 days after concrete pouring (courtesy of L. Thévenaz)

4.4 *Plevinu Dam joint monitoring*

Plavinu is a dam belongs to the complex of three most important hydropower stations on the Daugava River in Latvia (Fig. 10). In terms of capacity this is the largest hydropower plant in Latvia and is considered to be the third level of the Daugavas hydroelectric cascade. It was constructed 107 km distant from the firth of Daugava and is unique in terms of its construction - for the first time in the history of hydro-construction practice; a hydropower plant was built on clay-sand and sand-clay foundations with a maximum pressure limit of 40 m. The HPP building is merged with a water spillway. The entire building complex is extremely compact. There are ten hydro-aggregates installed at the hydropower plant and its current capacity is 870,000 kW.

Figure 10: Plavinu dam in Latvia

One of the dam inspection galleries coincides with a system of three bitumen joints that connects two separate blocks of the dam. Due to abrasion of water, the joints lose bitumen and the redistribution of loads in concrete arms appears. Since the structure is nearly 40 years old, the structural condition of the concrete can be compromised due to ageing. Thus, the redistribution of loads can provoke damage of concrete arm and as a consequence the inundation of the gallery. In order to increase the safety and enhance the management activities it was decided to monitor the average strain in the concrete arm next to the joints. A threshold detection software with SPST (open-ground) module was installed in order to send pre-warnings and warnings from the DiTeSt instrument to the Control Office.

4.5 *Emosson shell dam*

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 (Fig. 11).

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 12. The measurements are normally performed once a month. It can be noticed that the two data sets are in very good agreement.

Figure 11: Long Sensor on Transporting Spool

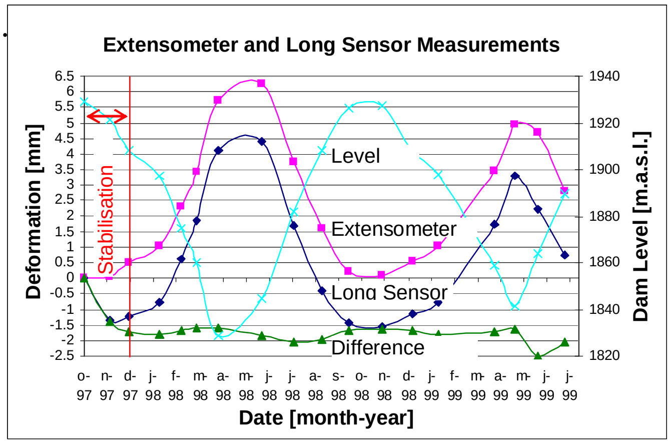

Figure 12 – Comparison between long-sensor and extensometer

4.6 *Breakwater monitoring in the Port of Genoa*

In the following example an application is shown concerning a displacement monitoring application of an old breakwater existing in the Port of Genoa, Italy, during refurbishment of the outer jetty (Del Grosso et al. 2003). The monitoring was performed by a set of ten GPS stations placed on the breakwater an two reference GPS stations on firm ground (Fig. 13). Measurements were taken from February 2002 to January 2005.

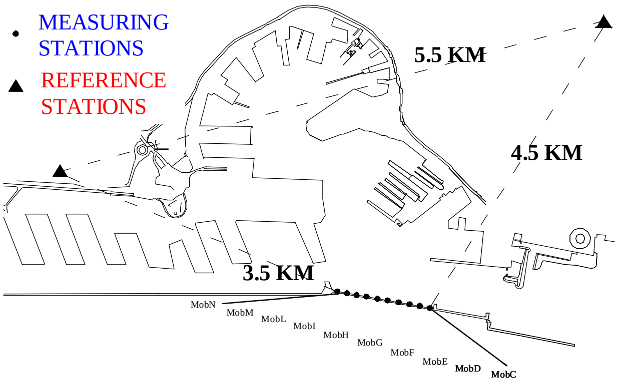

Figure 13 – GPS System in the Port of Genoa

A plot of the measured vertical displacements in the ten sections of the breakwater is shown in Figure 14.

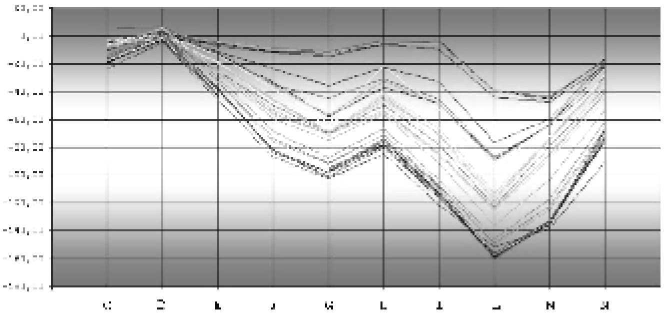

Figure 14 – Measured vertical displacements of the breakwater

The measured data, together with other historical information have been used to construct a numerical model of the settlement behavior of the structure. The results of the model have then been compared with the data obtained from the GPS systems and by processing of satellite SAR images using the permanent scatteres technique. The plot of Figure 15 shows the combined data from satellite radar and GPS. A very good agreement with the numerical model was found.

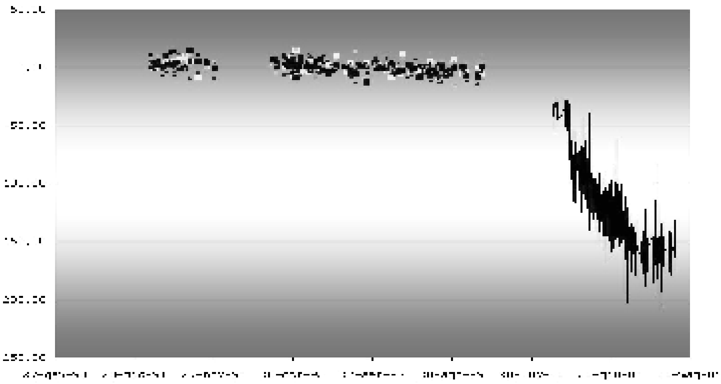

Figure 15 – Combination of SAR and GPS settlement data

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