Satellite Techniques: New Perspectives for the Monitoring of Dams

M.Corsetti, P.J.V.D'Aranno, F.Giancola, M.Marsella, S.Scifoni, A.Sonnessa
DICEA-Dipartimento di Ingegneria Civile e Ambientale,
Sapienza Università degli Studi di Roma – Via Eudossiana 18, 00184 Roma

M. Manunta
IREA – CNR, Istituto per il Rilevamento Elettromagnetico dell'Ambiente
Via Diocleziano, 80124 Napoli

Abstract. The improvement of the methods for dam deformation monitoring represents a growing issue among the community that deals with the safety of critical infrastructures. Although dam failures are usually sudden, in the majority of cases it is possible to understand in advance when structural damage conditions might evolve in a dangerous process. Nowadays, the development of innovative methodologies for the static and dynamic structural modeling allows to sharply improve the capability of predicting collapses, thus preventing and reducing the associated risks. With respect to this issue, several geomatic techniques can be profitably exploited for the implementation of analytical and mathematical models. This is accomplished by benefiting from the availability of dense and accurate displacement measurements provided both by satellite data and ground sensors having high temporal and spatial coverages.
As for satellite-based technologies, the improved capability relies on the detection of accurate ground displacements on the whole infrastructure with no need to install locally control points. The availability of spatially dense deformation measurements is of crucial importance for structural modeling because it allows us to overcome the drawbacks of traditional monitoring systems, which provide high accuracy measurements only on a limited number of points.
The aim of this work is to show the results on two case studies: the Genzano di Lucania earth dam and at Corbara gravity dam relevant to the monitoring of the dams. In particular, we show how satellite measurements can be profitably exploited and effectively integrated with the traditional measurements, in order to improve the current monitoring systems and increase the safety of dams. The results look very promising and open new perspectives for static analysis of large dam behavior as well as of large infrastructures.

Keywords. earth dams, gravity dams, Differential Interferometric Synthetic Aperture Radar (DInSAR), monitoring of subsidence

1 Introduction

The safety of great civil engineering projects, also known as "risk of considerable accident", is assured not only by reliable design methods and a right execution, but also by a constant control of the behavior of the structures in different stages of operation. Particularly, knowing the real values of the strains with precision, to be compared with the expected values (project values) is of primary importance. Strains can be compared with the results of numerical modeling, in order to identify the presence of anomalies and avoid the achievement of Limit States. Generally, the topographical techniques and sensors currently used for this purpose allow the monitoring of a limited number of control points. This lack of information represents a disadvantage for structural modeling, especially when we want to compare the expectations of the theoretical analysis with the real deformations. The classical topographic techniques suffer of two major drawbacks: the impossibility to provide a complete information about the deformation of the project and the difficulty to work, as often as it's necessary, in areas where the access is not easy. New Ground-Based techniques overcomes these drawbacks, allowing a whole and continuous control of structural movement through satellite or terrestrial sensor stations, without any need to access the structure [2]-[3]. As hereafter presented, the SAR interferometry technology was applied at the monitoring of two test cases: the first is a large earth dam Genzano di Lucania, the other one is a mixed dam of Corbara (part in concrete and part in earth).

2 TEST SITE *A* : GENZANO DAM

2.1 The dam

The Genzano dam is a 88 m-high zoned earthfill dam with impervious core and upstream and downstream soil embankments in rock fill. Between the core and the embankments there is a transition upstream zone and double-layer filters on the downstream. The cofferdam is made of rockfill material with an impervious core. The entire scheme is completed by bottom and surface discharge channels, including natural and artificial tunnels. The dam is founded on the blue-gray clay formation which is, as stated above, typical of the Ofanto River valley. The dam was built between July 1979 and January 1993.

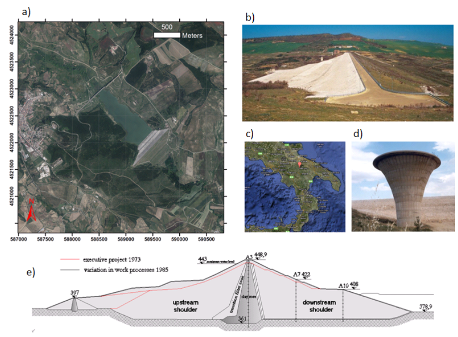

Fig.1. a) Ortophoto of Genzano di Lucania reservoir. b) View of the. c) Localization of the dam. d) Shaft spillway. e) The main cross section of the dam

2.2 Instrumental monitoring data

The geodetic monitoring system consists in 49 retro reflective prisms placed on the structure in order to monitor the deformation of the dam body along the crest and on the downstream face, by measuring the prisms coordinates with a TCA-2003 total station. The measurements are repeated every three months. Benchmarks are located as indicated

- 16 at the crest of dam (from 3 to 18);
- 13 at the first downstream berm (from 19 to 31);
- 11 at the second downstream berm (from 32 to 42);
- 9 at the third downstream berm (from 43 to 51);

and two points used as reference (point 1 and 2) (Fig.2.).

Analysis of the geomatic monitoring data (since no leveling is available since July 1999) at the benchmarks evidence an important vertical displacements.

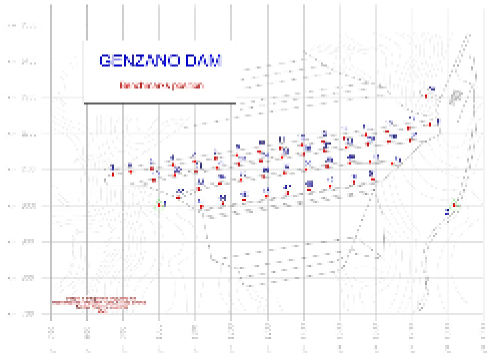

Fig.2. Leveling surveying: location of the benchmarks.

The Fig.3 shows that the maximum cumulated displacement (from July 1999 to October 2010) is measured at the first alignment (crest of the dam) at the benchmark 11 with a value of 180 mm. The graph shows that all alignments measured is present a deformation trend, with an average velocity of 18 mm/year for the benchmark 11.

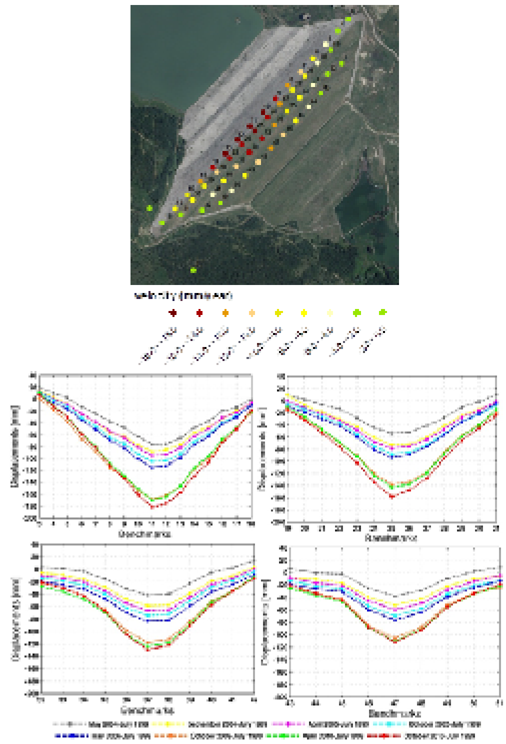

Fig.3. Results from the levelling surveying: on the top, the location of the benchmarks classified by their average velocity; bottom, cumulated displacements along the 4 benchmark alignments divided for subsequent period.

2.3 DinSAR processing results and traditional measurements comparison

In this work, we applied the multi-sensor SBAS technique to a SAR dataset of 77 ERS-1/2 and ENVISAT scenes, acquired from descending orbits between 1992 and 2007 over the Murge area (Southern Italy). The output from the SBAS-DInSAR analysis were processed in a GIS environment, where both the annual velocity maps and the deformation time series were analyzed, describing the settlements observed on the Genzano dam between 1992 and 2007. The annual average velocity map is available on the crest of dam and on the upstream slope.

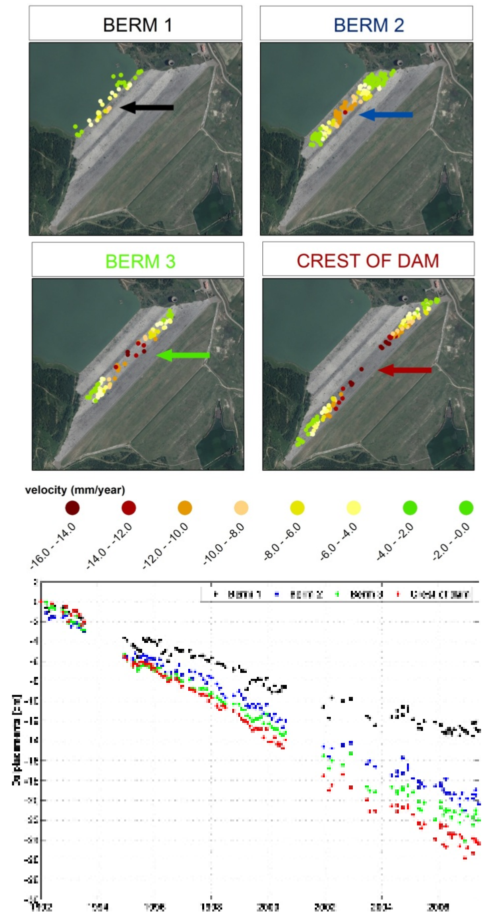

Fig.4. DInSAR measured displacements over the dam embankment classified by average velocity, on the top; DInSAR time-series displacements from 1992 to 2007, bottom.

Due to the presence of vegetation and the consequent lack of coherent permanent scatterers, point belonging to the downstream slope were excluded from the processing. DInSAR data analyses, covering a period of 15 years (1992-2007), clearly evidence the portion of the dam that is lowering (Fig.4), with a maximum average velocity of 15.5 mm/year.

Results show that vertical displacements reached maximum values of 24 cm for the 1992–2007 period along the crest of the dam, while they are almost terminated at the toe of the structure. In Fig.4 negative velocities represent displacements away from the satellite (subsidence) while green color indicates stable areas. The comparison of satellite measurements with conventional methods (assestimetric measurements) confirms the reliability of the SAR technique (Fig.5). As showed in the graphs in fig.9, displacements measured by USBR1, USBR3 and USBR4 assestimeters in the period 1992-2006 were compared with the time series of the corresponding PS obtained by the DInSAR data.

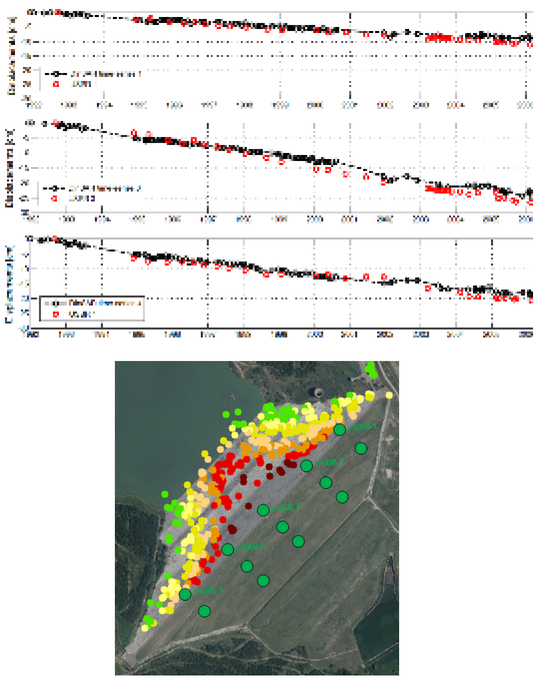

Fig.5. Comparison between the time-series obtained by: DInSAR (dashed black line) and in-situ assestimetric measurements on the crest of the dam

3 TEST SITE *B* : CORBARA DAM

3.1 The dam

The Corbara dam is a gravity dam located in the city of Corbara(TR) and it was built between 1959 and 1963 to block the Tevere river. It's reservoir has the volume invaded of $192 \cdot 10^6$ m^3 and its function is to regulate the flow for hydroelectric and lamination purposes. The dam is high 51m and it's composed by a part in concrete (416m length) and a part in earth (224m length).

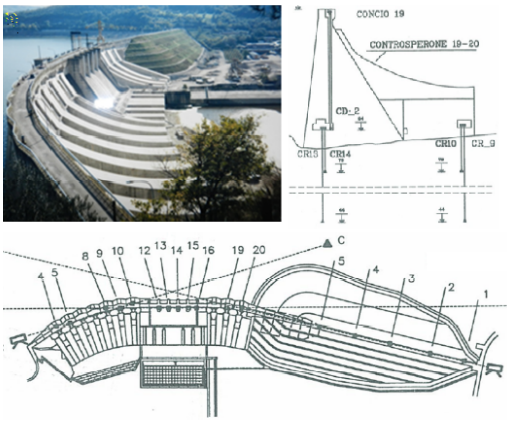

Fig.6. a) View of the Corbara dam. b) Central section. c) Plan

3.2 Instrumental monitoring data

The dam has a strong monitoring system consisting in traditional instruments, like optical collimator, pendulum, clinometric, ecc. For this work we are focusing on the leveling measures installed on the concrete dam's side. The leveling network consists of 28 benchmarks located as shown in fig. 7. The benchmarks 4 (left side), 11 (center) and 19 (right side) were chosen to compare leveling measures with the time series of the corresponding PS obtained by the dinsar data.

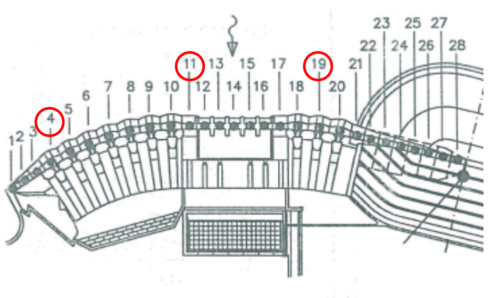

Fig.7. Leveling surveying: location of the benchmarks.

3.3 DinSAR processing results and traditional measurements comparison

In this work, we applied as first study the multi-sensor SBAS technique to a SAR dataset images *ERS- ENVISAT low resolution ascending and descending 1992 – 2010* (source IREA –CNR). The fig.8 shows the annual average velocity map ascending (fig.8a) and descending (fig. 8b), but owing to low images resolution ERS-ENVISAT (spatial resolution 25m) and for small planimetric extention of the crest of the dam, few points were identified.

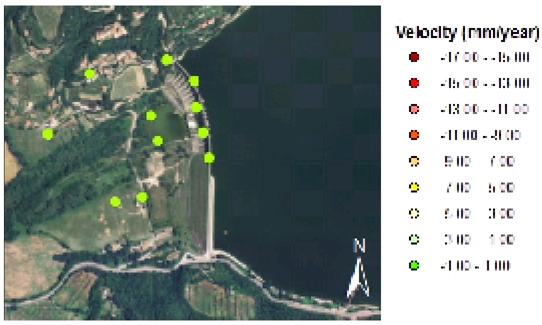

Fig.8.a Annual average velocity map ascending ERS-ENVISAT (1992-2010)

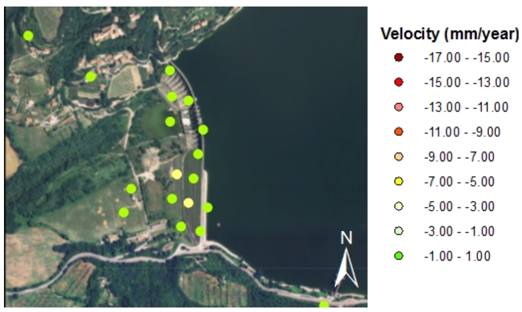

Fig.8.b Annual average velocity map descending ERS-ENVISAT (1992-2010)

The new generation of satellite sensors SARwith high resolution allows to obtain a remarkable increase of measured points .The fig.9a shows a coherence map obtained between two acquisitions SAR-COSMO Skymed where it is clearly visible the dam body and a bridge near the dam.

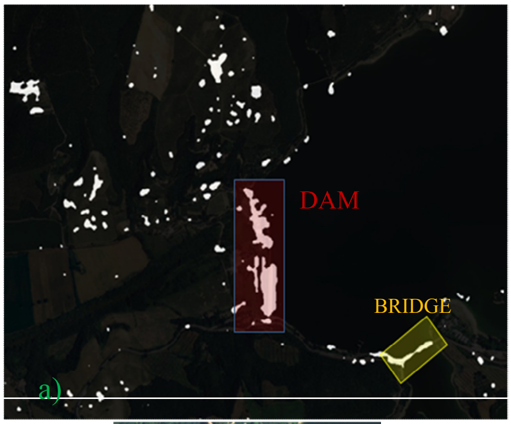

Fig.9.a/b Coherence map and DInSAR measured displacements over the dam classified by average velocity of Corbara dam obtained by COSMO SkyMed images.

A dataset of 35 images of Corbara dam was acquired including in the period 2010 - 2014 with the COSMO SkyMed sensor (source ASI) that will be processed with DInSAR technique.
The fig.9b shows the results of the processing as annual average velocity map; it is obvious that with the COSMO SkyMed sensor the identified points are increased, in order to carry out a better analysis. The fig.9b shows also that all the points have a velocity between -1.00 and 1.00 mm/year.
The dam does not present significant vertical displacements during the analyzed period, but there are only small periodical displacements due to changes in the reservoir level and temperature changes.

4 CONCLUSIVE REMARKS

In both cases SBAS-DInSAR analysis provided data useful to describe the behavior of the dams, permitting to perform back analyses also in periods in which other monitoring data were not available (site A), and allowing to implement a calibration procedure to set up a reliable numerical model. This paper compares the displacement measurements acquired by traditional and innovative monitoring techniques. As evidenced in the analysis, SBAS-DInSAR results are in good agreement with the ground based measurements. This monitoring approach is mainly valuable for large dams where a sufficient number of coherent points are detected by the SAR sensors. Artificial targets built on purpose can be established and positioned in the most significant parts of the structure in order to improve the capability of the method.
The availability of last-generation VHR images acquired by TerraSAR-X, COSMO-SkyMed and SENTINEL constellations will hopefully allow to obtain better results in terms of ground resolution and revisiting-time by means of algorithms that produce increasingly reliable results as demonstrate for the site B.
Besides, dataset that will be provided by the SENTINEL sensor, will permit to easily correlate the new acquisitions with the images acquired by the ERS/ENVISAT missions, due to the comparable resolution.
SAR techniques can be then recommended for monitoring movements of concrete dams and surrounding slopes and, due to its very high sensitivity, it can precisely estimate influence of various deformation sources, such as pressure of water in dammed reservoir. Using appropriate dataset (COSMO, etc), in terms of temporal and spatial resolution of data as well as orientation of satellite line of sight towards the dam, it is possible to accurately identify dam movements, both continuously graduating as well as periodical.

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