

Differential SAR Interferometry for surface monitoring of an Earth Dam

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Abstract – Surface dam monitoring has been always based on traditional surveying techniques that are time consuming and characterized by some limitations in space coverage and frequency. More recently DInSAR (Differential Synthetic Aperture Radar Interferometry) satellite-based technologies allow us to integrate and improve the monitoring capabilities provided by ground-based methods, thanks to their effectiveness to measure displacements on reflecting elements of the structure, acting as non-destructive control points. Therefore the availability of a large number of measurements points distributed along the whole structure and the capability of observing displacement rates of few millimeters per year furnish useful information for the calibration of numerical models simulating dam behavior under stress conditions, thus improving the maintainance of safety standards. The aim of this work is to show how DInSAR technique integrated with the traditional measurements was adopted to analyse the long-term displacements of an earth dam in Genzano di Lucania .

I. INTRODUCTION

The safety of large civil structures is assured not only by reliable design and construction approaches but also by a constant control of its behavior in different stages of operation. Specifically, it is fundamental to measure the real values of the displacements to be compared with the expected ones estimated during the design stage. Displacements can be compared with the results of numerical modeling, in order to identify the presence of anomalies and avoid the achievement of Limit States. Traditional topographical techniques provide measurements on a limited number of control points that are usually not enough to describe the overall deformation pattern and not even adequate to verify the effectiveness of a structural models. On the contrary, the use of automated total stations or satellite-based techniques allows a systematic and distributed control of structural movements, without any need to access the structure [1]-[2]. A example of application of the

satellite-based SAR interferometry technology to the monitoring of a large earth dam located in Genzano di Lucania (Italy) is described in the following.

II. DINSAR DATA ANALYSIS

An advanced DInSAR technique based on the Small Baseline Subset (SBAS) algorithm [1]-[4] was applied to estimate average displacement rates (mm/year) and to extract the displacement time series of a number of control points (persistent scatterers) measured on the Genzano di Lucania dam. In particular, for our purposes we benefited from the multi-sensor full-resolution SBAS approach [4]. Such a technique, by jointly processing data acquired by different SAR sensors, as in the case of ERS-1/2 and ENVISAT acquisitions, allows us to generate very long deformation time series, spanning almost 20 years, with an accuracy of about 5 mm [5].

The key point of the multi-sensor SBAS technique is the selection criteria of the SAR data pairs used for generating the interferograms. In order to mitigate the noise (i.e., the decorrelation phenomena) affecting the interferograms, and to maximize the reliable measure points, only SAR data pairs characterized by small spatial and temporal separation (baseline) between the satellite orbits are processed. Moreover, no cross interferogram between images acquired by different SAR sensors is generated, and only ERS-ERS and ENVISAT-ENVISAT interferometric pairs are selected.

A SAR dataset formed by 77 ERS-1/2 and ENVISAT scenes, from descending orbits acquired every 35 days between 1992 and 2007 over the Murge area (Southern Italy), was selected. More than 200 ERS/ERS and ENVISAT/ENVISAT interferograms were generated, characterized by maximum spatial and temporal baselines of about 400 m and 1500 days, respectively. In addition, precise satellite orbital information obtained by the Delft Institute for Earth-oriented Space Re-search (DEOS), and topographic information retrieved from the Digital Elevation Model (DEM) with a 3-arc-second spacing (approximately 90 m × 90 m) produced by the Shuttle Radar Topography Mission (SRTM) in February of 2000 have been used for the correct co-registration of the SAR images [6] and for the interferograms generation.

III. TEST SITE

A. Geological setting of Genzano di Lucania dam (Potenza, Italy)

The Genzano di Lucania Dam (Fig.1) is located in the Bradano River valley (Italy), within the Subappennine Argillaceous of the Upper Pliocene. The basin geomorphology is characterized by a line of clayey hills gradually sloping towards the lake. Immediately below the dam, the Bradano River flows over an ancient calcareous substratum dating from the Cretaceous along a deep depression (gravina) excavated by the erosive action of stream water.

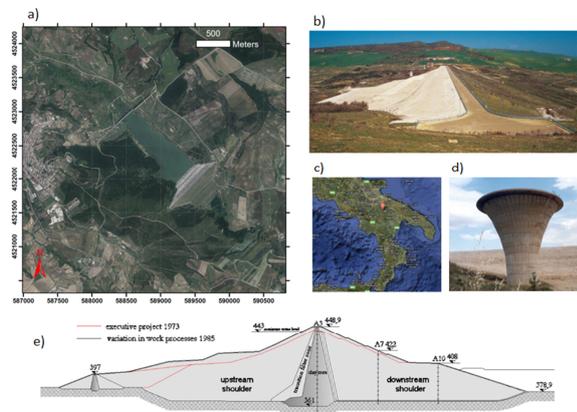


Fig.1. a) Orthophoto of the Genzano di Lucania reservoir (UTM WGS84: 589521.03 E, 4521935.12 N) — b) View of the embankment — c) Location of the dam — d) shaft spillway — e) main cross section of the dam (modified in December 1985 from the initial configuration indicated by red lines).

The surface terrains in the catchment basin are the effect of the sedimentary cycle of Bradanic trench and are formed essentially, from the oldest to the most recent, by:

- blue or yellowish altered clays;
- limestone quartz yellowish sands;
- polygenic conglomerates with pebbles also made by crystalline rocks and interbedded with lenses of sandy and clay.

As envisaged in the preliminary plan, geotechnical investigations and geological surveys evidenced at the foundation section the presence of blue clays at depths varying between 10 and 20 m; clays are covered by a thin layer of altered dark clay.

B. Hydrological setup

The hydrographic network of the Basilicata region (Fig.2) is based on five main rivers (Bradano, Basento, Cavone, Agri, Sinni) flowing into the Ionian Sea, one (Ofanto) flowing into the Adriatic Sea and two (Sele and

Noce) flowing into the Tyrrhenian Sea. Besides the rivers, there is an extensive network of small waterways and numerous springs.

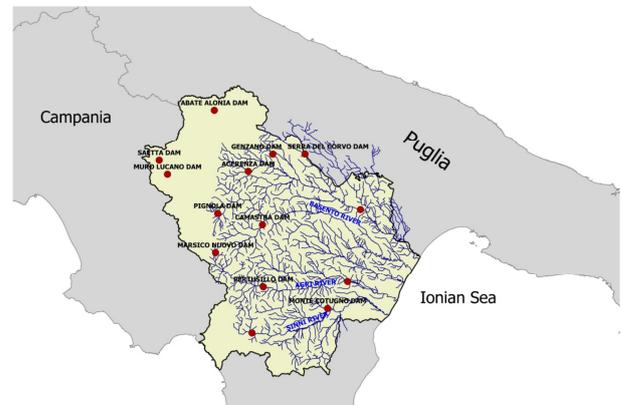


Fig.2. Primary system of water infrastructure and dams in Basilicata region.

The hydrographic network of the Basilicata region is regulated by a complex hydraulic system composed by dams, crosses, spring and groundwater collectors, supply networks and distribution systems. This infrastructure system was developed between 1950 and 1960 and later integrated through the construction of new infrastructures, in order to potentiate the industrial plants water supply and hydroelectric power also to the neighboring regions, Puglia and Calabria.

C. The Genzano di Lucania dam

The Genzano dam is a 88 m-high zoned earthfill dam. 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, typical of the Ofanto River valley. The project of the construction (Ing. Baldovin, Servizio Tecnico Ingegneria dell'Ente, 1973) is dated December 1973. The dam was built between July 1979 and January 1993. During this period, due to the Irpinia earthquake (November 23, 1980) and to the issuing of the new Italian building code (D.M.LL.PP. 24-03-1982-“Technical standards for the design and construction of dams”) a modification of the project was required (December 1985) to change the geometry of the cross section. The main changes were the elevation of crest dam, from 445 to 448.9 m a.s.l, and the increase of the width of crest dam from 8 to 10 m [3] (Fig.1e).

D. Instrumental monitoring data

The deformation monitoring system of the dam includes different sensors: 51 vibrating wire piezometers, 18 pressure cells, 9 open standpipe piezometer, and 13 extensometers USBR model (U.S. Bureau of Reclamation), 5 located inside the core and 8 inside the downstream bank (Fig. 3). Reservoir level, precipitation and air and water temperature are also recorded.

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.



Fig.3. Position of the installed extensometers USBR model (green circles) and piezometers (blue circles) on the dam.

The measurements are repeated every three months. Benchmarks are located on the dam 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);

Two points used as reference (point 1 and 2) (Fig.4.).

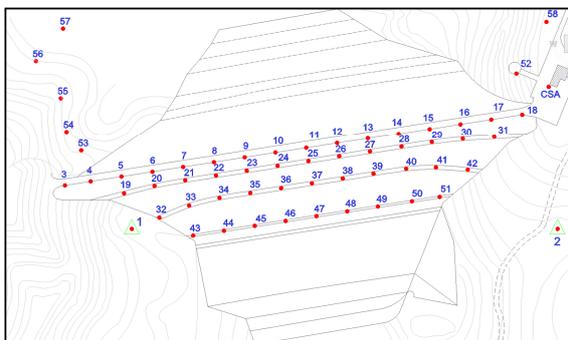
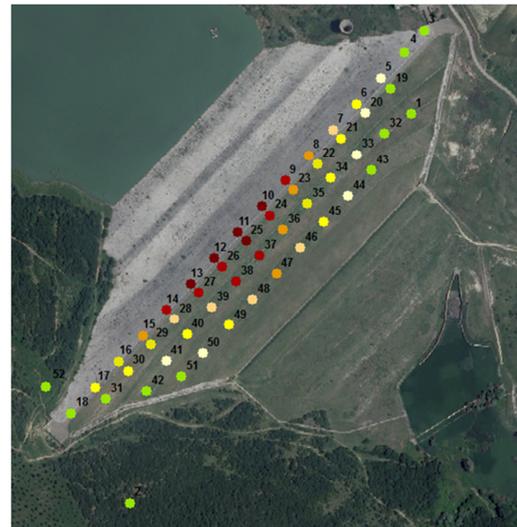


Fig.4. Leveling surveying: location of the benchmarks.

Analyses of the geomatic monitoring data (since no leveling is available until July 1999) at the benchmarks evidenced relevant vertical displacements. Figure 5 shows that the maximum cumulated displacement is measured (from July 1999 to October 2010) along the first alignment (crest of the dam) at the benchmark 11 reaches a value of 180 mm. The graph shows similar deformation trends are observed for all the alignments.



velocity (mm/year)

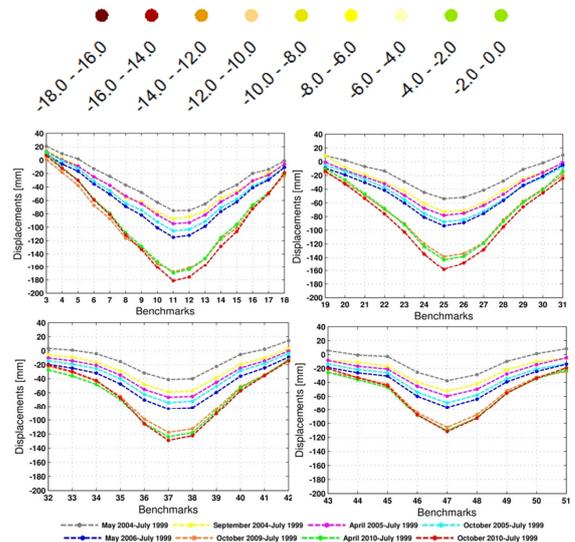


Fig.5. Results from the leveling surveying: on the top, the location of the benchmarks classified by their average velocity; bottom, cumulated displacements along the 4 benchmark alignments, divided for subsequent period.

Figure 6 shows the evolution of the dam construction, the piezometric levels and the reservoir water level. The plot shows that the dam construction started in 1981 and was completed in 1993. The piezometers investigated, placed in the foundation of the downstream dam (P1-P2-P3-P4) showed in the Fig. 4 (blue circles), exhibited a pore pressure growth related with increased total stresses caused by an increased dam weight with a maximum pressure coinciding with the completion of the dam. After dam construction, the piezometers showed a continuous decrease due to the gradual reductions in excess pore pressure. This long-term deformations might be expected due to soil consolidation processes.

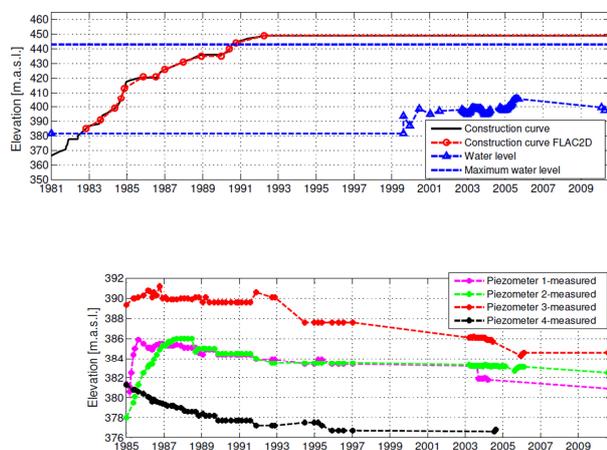


Fig.6. Dam construction curve b) Piezometer measurements.

IV. DINSAR AND TRADITIONAL MEASUREMENTS

DInSAR data analyses, covering a period of 15 years (1992-2007) was carried out on the Genzano Dam. The comparison between the results provided by the DInSAR technique and the ones from traditional methodologies usually applied for the dam monitoring is discussed in the following. The output from the SBAS-DInSAR analysis were analysed using GIS spatial analysis tool, displacement velocity maps and time series were adopted to provide an overall description and quantify the settlements between 1992 and 2007. The DInSAR measurements are only available on the crest of dam and on the upstream slope, covered with rip-rap material. Due to the presence of vegetation and to the consequent lack of coherent scatterers, it was not possible to examine the downstream slope.

Figure 7 clearly evidences that the investigated portion of the dam underwent a lowering process, with a

maximum average velocity of 15.5 mm/year as showed in the Tab.1.

The displacements (almost fully ascribed to the vertical component) reached a maximum values of 24 cm in the 1992-2007 period along the crest of the dam, while was quite negligible at the toe of the structure. Figure 7 shows the average LOS displacement velocity (projected along vertical direction) for each measurement point obtained for the descending geometry. Negative velocities represent displacements away from the satellite (subsidence) while green color indicates stable areas.

The comparison with extensometers and leveling measurements (Fig.8 and 9, Tab.2 and 3) are in very good agreement with the DInSAR results.

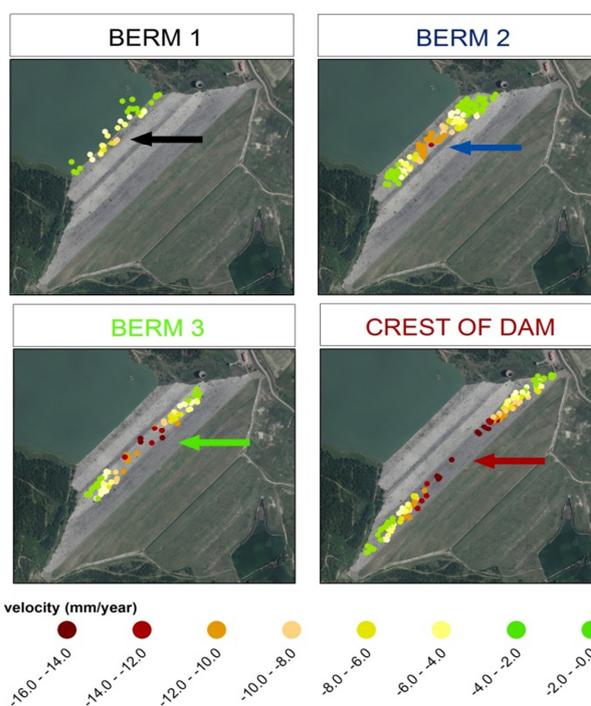


Fig.7. DInSAR measured displacements over the dam embankment classified by average velocity.

Table 1. DInSAR average displacements.

Position	Average velocity (mm/year)
Berm 1	8.6
Berm 2	13.3
Berm 3	14.6
Crest of dam	15.5

As showed in the graphs in Figure 8, displacements measured by USBR1, USBR3 and USBR4 extensometers in the period 1992-2006 were compared with the time series of the corresponding DInSAR measurement points.

Similarly, leveling data collected in the period 2004-2006 were compared to DInSAR data (Fig.9). Three leveling benchmark were selected on the crest of the dam and compared to a displacement time series obtained for the average of the most proximal DInSAR points.

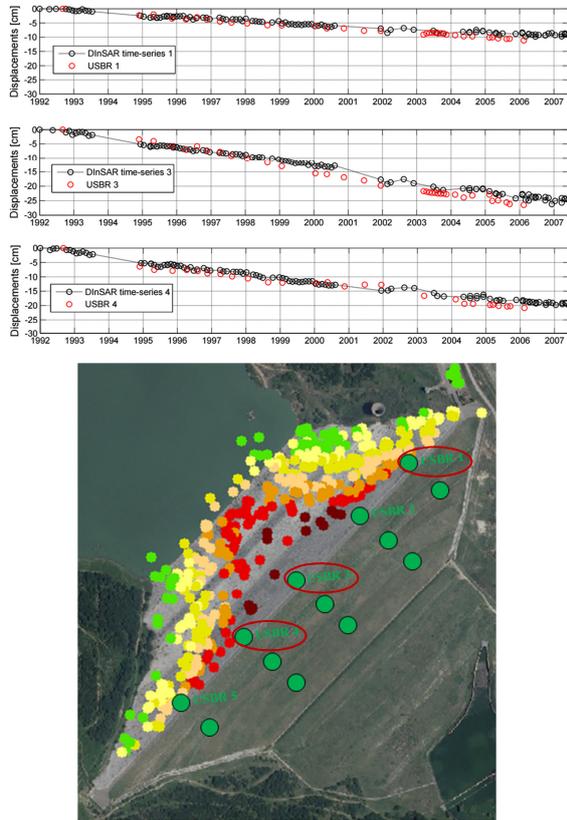


Fig.8. Comparison between the time-series obtained by: DInSAR (dashed black line) and in-situ extensometers measurements (red circles) on the crest of the dam

Table 2. SAR vs extensometer

Position	Vel (cm/year)	
	USBR	SAR
1	0.76	0.66
3	1.64	1.96
4	1.32	1.39

The extensometer and the leveling sensors evidenced a good agreement both for each single measurements and for the long-term trends. As showed in Tab.2 and Tab.3, the angular coefficient of the regression trend line (i.e. the mean velocity of displacement) is very close to the values obtained, from extensometers and levelling data respectively.

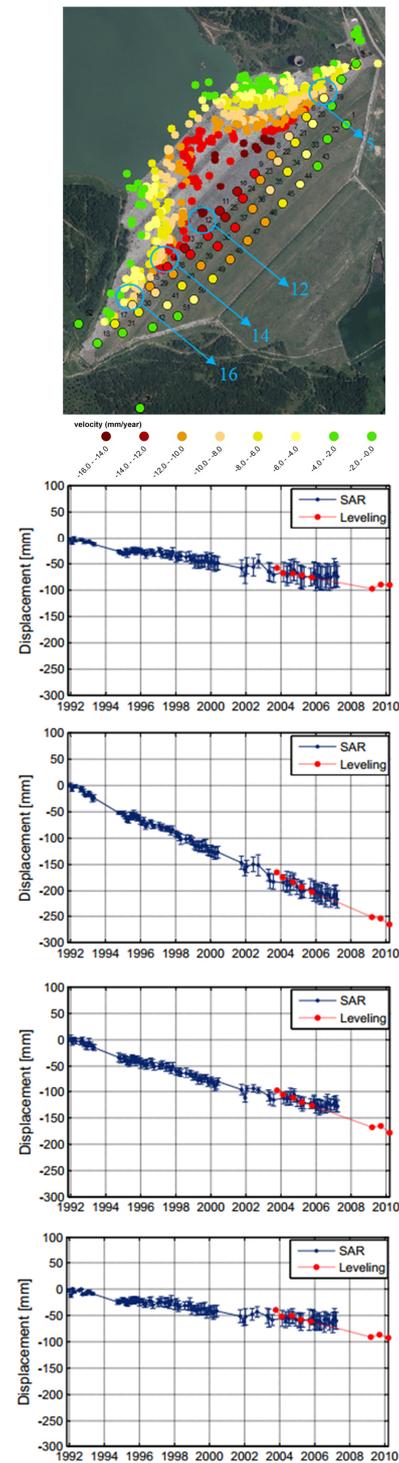


Fig.9. Comparison between the time-series obtained by: DInSAR (blue line) and leveling measurements (dashed red line) on the crest of the dam

Table 3. SAR vs levelling

Position	Vel (cm/year)	
	Benchmark	SAR
5	0.48	0.47
12	1.49	1.40
14	1.18	0.84

V. CONCLUSIVE REMARKS

The SBAS-DInSAR analysis provided data useful to describe the behavior of the dam since 1992, permitting to perform back analyses also in the periods in which other monitoring data were not available. The collected data can be profitably employed 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 very 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 present 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.

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