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Monitoring of an embankment dam in southern Spain based on Sentinel-1 Time-series InSAR

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Abstract

Deformation monitoring is a common practice in most of dams to ensure their structural health and safety status. Systematic monitoring is frequently carried out by means of geotechnical sensors and geodetic techniques that, although very precise an accurate, can be time-consuming and economically costly. Remote sensing techniques are proved to be very effective in

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assessing deformation. Changes in the structure, shell or associated infrastructures of dams, including adjacent slopes, can be efficiently recorded by using satellite Synthetic Aperture Radar Inteferometry (InSAR) techniques, in particular, Muti-Temporal InSAR time-series analyses. This is a mature technology nowadays but not very common as a routine procedure for dam monitoring. Today, thanks to the availability of spaceborne satellites with high spatial resolution SAR images and short revisit times, this technology is a powerful cost-effective way to monitor millimeter-level displacements of the dam structure and its surroundings. What is more, the potential of the technique is increased since the Copernicus C-band SAR Sentinel-1 satellites are in orbit, due to the high revisit time of 6 days and the free data availability. ReMoDams is a Spanish research project devoted to provide the deformation monitoring of several embankments dams using advances time-series InSAR techniques. One of these dams is The Arenoso dam, located in the province of Cordova (southern Spain). This dam has been monitored using Sentinel-1 SAR data since the beginning of the mission in 2014. In this paper, we show the processing of 382 SLC SAR images both in ascending and descending tracks until March 2019. The results indicate that the main displacement of the dam in this period is in the vertical direction with a rate in the order of -1 cm/year in the central part of the dam body.

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1. Introduction

Dam monitoring is an essential component of modern-day safety programs in the world. Reports of structural failures that led to collapse of structures, causing significant material and economic losses and large number of fatalities date back from the construction of the first dams highlighting the need of monitoring. As a response to those catastrophic failures, improvements in design and changes in inspection programs were developed. Structural Health Monitoring (SHM) is founded on the experimental identification of relevant dynamic properties of large structures, such as dams[1,2].

In the last decades, civil structures have become even more complex leading to the use of in-built geotechnical/structural sensors for structure parameters monitoring. Each sensor focuses on a specific area of the dam, the slopes surrounding the reservoir, or the structures of public services. The purpose of monitoring is not only to early warn about a future collapse but also to provide useful information to verify the design parameters, investigate the reasons that may cause deformation processes, and extract necessary lessons that can be implemented in future projects. Moreover, dams undergo phenomena that are only detectable by long-term observation due to the characteristics of parameters behavior, very difficult to observe by means of conventional sensors. The definition and objectives of SHM have been changing through time as technologies evolve, including as main components: real-time monitoring, in-service structures, and array or network of sensors to collect data and represent changes in the condition of a structure over time[3,4].

Monitoring systems of the dam structure and surrounding areas include classical geodetic networks (triangulations/trilaterations and leveling), GNSS networks as well as other remote sensing techniques from ground-based and satellite platforms, such as terrestrial laser scanning (TLS), ground-based synthetic aperture radar (GBSAR), or spaceborne SAR interferometry (InSAR)[5,6]. Classical geodetic techniques, although very precise and accurate, are time-consuming and very expensive. The evaluation of space sensors for dams monitoring are proved to provide useful information to detect deformations on critical structures such as dams[7]. Modern space-borne SAR sensors provide spatial resolutions of the order of a meter. Additionally, high-resolution SAR data (TerraSAR-X, COSMO-SkyMed, PAZ,…) allow monitoring small dams by a large number of pixels. SAR data have been tested for structural health monitoring (SHM) applications with very satisfactory results[8,9,10,11,12,13]. The new generation of high-resolution radar imagery acquired by SAR sensors and the development of advanced Multi-temporal InSAR (MT-InSAR) algorithms[14,15] such as Persistent Scatterer (PS) and Small BAseline Subsets (SBAS) methods, that retrieve deformation time series and velocity maps from a stack of SAR images acquired in different time over a region, have enhanced our capabilities in recent years in using MT-InSAR techniques for high precision deformation monitoring related to engineering infrastructures.

In order to demonstrate the potential and reliability of MT-InSAR technique in dam monitoring, RemoDams initiative, a Spanish project, is testing several real case studies in coordination with dam property and managers. One of these dams is the Arenoso dam, an embankment dam located in southern Spain. Since 2014, Sentinel-1 monitoring is being routinely applied to this dam. In this paper, we present the results of this monitoring which includes 2014-2019 ascending and descending data sets demonstrating the potential the of the MT-InSAR with C-band imagery as a feasibly technique for the continuous surveillance of this civil infrastructure.

The paper is structured as follows. Section 2 includes a general description of the Arenoso dam. Section 3 describes the SAR data used in this study as well the processing methodologies carried out. An outline of the deformation results is presented in Section 4, and thus the main conclusions are derived.

2. The Arenoso dam

The Arenoso dam (Montoro, Cordova, S Spain) is an embankment dam located in the Arenoso riverbed, a tributary of the Guadalquivir River with a capacity of 167 hm^3 and a basin of 405 km^2 (Fig. 1). The dam has a maximum height of 80 m, a crest length of 1.481 m and a coronation width of 11,30 m with impervious core, filters and rock fill shoulders[16] (Fig. 2). More than 3 million m^3 of materials were used for the construction, which started in April 2004 and finished in November 2006 with the first filling of the dam. It is used both for irrigation and energy production in the Guadalquivir basin. The Arenoso reservoir belongs to the Confederación Hidrográfica del Guadalquivir (CHG).

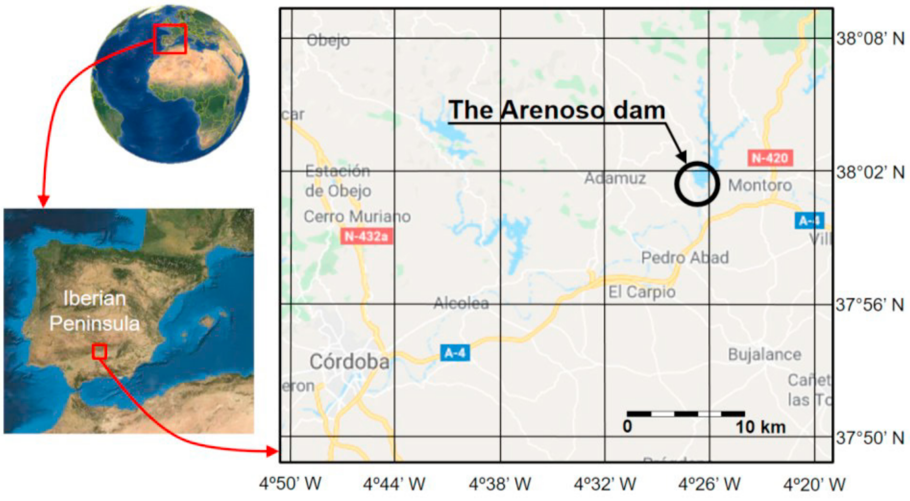

Fig. 1. Location of The Arenoso dam in Montoro, province of Cordova (southern Spain).

3. Data and Method

In this section, we present the different SAR data sets and describe the processing methodology.

3.1. Data

In our study, we used the Copernicus Sentinel-1A/B C-band SAR data from the European Space Agency (ESA) and the European Commission (EC). Sentinel-1A and -1B are two twin satellites that provide SAR images with a short revisit time of 6 days when they are combined. Following the Copernicus policy, these data are free and openly accessible. Our SLC SAR data are from the Interferometric Wide (IW) swath mode acquired using the Terrain Observation with Progressive Scan that allows wide area coverage with a size of 240 km x 170 km per image. We selected the vertical polarization VV and processed two independent sets of Sentinel-1A/B SAR images acquired along ascending and descending orbits. The ascending set is from Track 74 and sub-swath 3. It is composed by 194 SAR images (120 S1A and 74 S1B) from March 3rd, 2015 to February 28th, 2019. On the other side, the descending set belongs to Track 81 and sub-swath 3 as well. It is composed by 188 (116 S1A and 72 S1B) SAR images acquired from November 16th, 2014 to March 1st, 2019. The perpendicular baselines were smaller than 150 m according to the satellite parameters (Fig. 3). The incidence angles in both sub-swaths are close to 44° with a heading azimuth of 189.5156° for the ascending orbits and 350.5042° for the descending ones. The spatial resolution for these SLC IW images with this incidence angle is 3.4 m x 22 m (range x azimuth) with a ground sampling of 3.3 m x 13.9 m (range x azimuth).

Fig. 2. 3D view of the reservoir and the Arenoso dam. (Source: Google Earth).

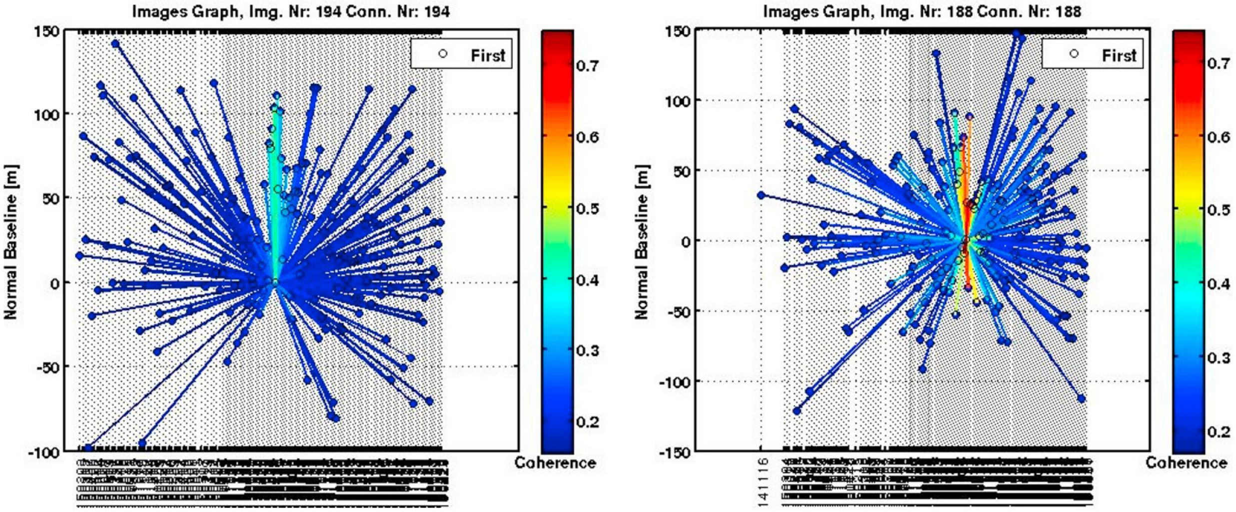

Fig. 3. Normal vs. temporal baseline plots for the ascending Track 74 (left, 03/03/2015-28/02/2019) and descending Track 88 (right, 16/11/2014-01/03/2019) showing the average spatial coherence for each interferogram with the color bar. The shorter spatial/temporal baseline usually the higher spatial coherence.

3.2. Multi-Temporal InSAR

MT-InSAR techniques were developed to overcome the temporal and geometrical decorrelation of DInSAR. These techniques identify coherent radar signals from incoherent contributions, the so-called Permanent or Persistent Scatterers (PS), which are isolated targets physically meaningful with interpretable phase characteristics in time. Methods for identifying and isolating these PS pixels in interferograms have been developed using a functional model to map deformation variation with time. The methods have been very successful in identifying PS pixels in both urban and non-urban areas undergoing primarily steady-state or periodic deformation. In this work, we used the standard linear PS-InSAR technique[17,18] to generate time series of deformation as implemented in SARPROZ[19]. In the PS-InSAR technique, N-1 single look co-registered differential interferograms are formed from N SAR images in each data set using a single-master configuration. For the ascending one, the master image was selected on 27th April 2017 and for the descending one on 7th October 2017. They were automatically selected by the software in the middle of the stack to minimize spatial and temporal decorrelations. First, the N images are co-registered to the master image using Precise Orbit Ephemerides (POE), then the initial differential phase is extracted. The topographic phase component was removed using the 1-arcsec SRTM DEM. The selection of the PS was based on different parameters such as Amplitude Stability Index (ASI), spatial coherence, and reflectivity. Different processing tests were carried out in the ascending and descending data sets considering and estimating the Atmospheric Phase Screen (APS) for removal the atmospheric component from de initial differential phase and without its estimation, considering a small area processing. For a small area processing, the APS can be neglected as the correlation distance of APS is less than few kilometers. Finally, we selected the results from the small area processing, that is, a small crop centered in the dam, selecting the PS pixels with temporal coherence above 0.7. For each PS pixel, the height, LOS velocity, and displacement time series were estimated adopting a linear trend model.

4. Results and conclusions

Due to the characteristics of theregion, fully covered by olive-tree plantings, almost no PS pixels were detected in the area surrounding the dam body, but a considerable density of coherent PS points over the dam allows the establishment of a long-term MT-InSAR monitoring system:. Fig. 4 shows the mean LOS velocity maps for both ascending and descending data sets. The general picture is quite similar. According to the depicted patterns, both tracks indicate the presence of a subsiding sector in the crest of the dam reaching linear values of the order of –(8-10) mm/year which represent cumulative displacement in the LOS direction up to about -40 mm in 4 years.

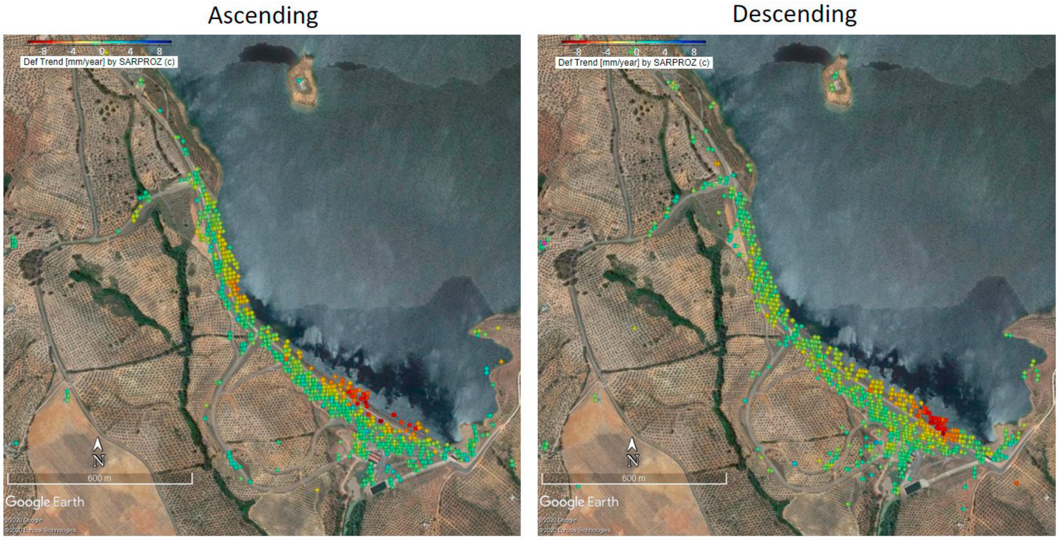

Fig. 4. Mean LOS velocity maps for the ascending and descending Sentinel-1A/B data sets.

The reference area, that is, the area assumed with zero deformation, was selected 600 m NW away from the dam, over a stable area according to different tests, being the same reference for both data sets. The standard deviations of the LOS velocities are lower than ±1 mm/year indicating a good quality control of the technique. As both LOS velocity maps show a similar pattern, it could indicate that the main movement of the dam is in the vertical direction with little horizontal component, what is coherent with dam typology. Combining both ascending and descending LOS velocity maps, the displacement vector can be decomposed in the true horizontal E-W and vertical components. This decomposition can be seen in Fig. 5 confirming that the main movement component of the dam is in the vertical direction.

Previous geodetic works were carried out to establish some control points on the dam leaded by members of the "Microgeodesia Jaén" research group of the University of Jaén[20,21]. The sites were measured using high-precision leveling and GNSS during seven surveys: February and July 2008, March and July 2013, August 2014, September 2015, and September 2016, initiating the measurements after the first filling of the dam in 2006. The accumulated vertical movements from leveling reached to maximum values of –16 cm in the crest of the dam during the period 2008-2016, showing a decrease in the settlement velocity in the last surveys and thus confirming the stabilization trend of the dam. Horizontal movements from GNSS show differential movements between the different surveys, more than 4 cm in 2008 and decreasing with time to a few millimeters when comparing with the last surveys.

Our SAR measurements started at the end of 2014 and the beginning of 2015, after these previous geodetic works, so not it is not possible a full comparison with these data. Currently, a mathematical modeling of the dam is being elaborated to investigate the expected theoretical subsiding behavior due to materials consolidation through time. In addition, the analysis of the dam's property geodetic data will provide us with new information that will allow us to compare and validate our time-series measurement from SAR data.

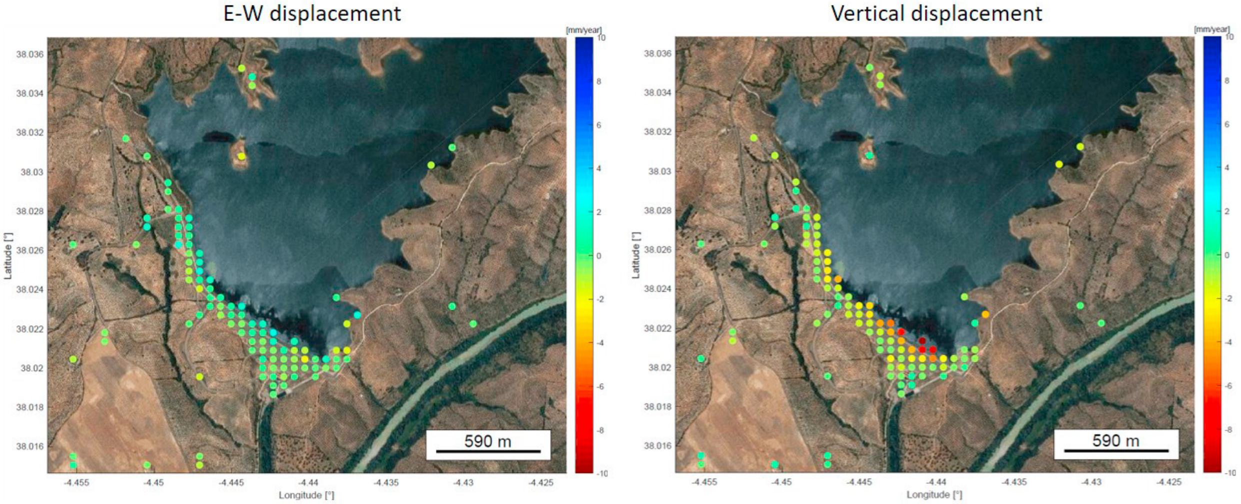

Fig. 5. Mean velocity maps for the E-W and vertical displacements of the Arenoso dam in the period November 2014 - March 2019.

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