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Benedetta ANTONIELLI

NHAZCA S.R.L., SPIN-OFF OF “SAPIENZA” UNIVERSITY OF ROME

ITALY

Paolo CAPOROSSI

“SAPIENZA” UNIVERSITY OF ROME, DEPARTMENT OF EARTH SCIENCES

ITALY

Paolo MAZZANTI

NHAZCA S.R.L., SPIN-OFF OF “SAPIENZA” UNIVERSITY OF ROME
“SAPIENZA” UNIVERSITY OF ROME, DEPARTMENT OF EARTH SCIENCES

ITALY

Serena MORETTO

NHAZCA S.R.L., SPIN-OFF OF “SAPIENZA” UNIVERSITY OF ROME

ITALY

Alfredo ROCCA

NHAZCA S.R.L., SPIN-OFF OF “SAPIENZA” UNIVERSITY OF ROME

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Benedetta Antonielli [a], *Paolo Caporossi* [b], *Paolo Mazzanti* [a,b], *Serena Moretto* [a],
Alfredo Rocca [a]

[(a)] *NHAZCA S.r.l., spin-off of "Sapienza" University of Rome, Via Vittorio Bachelet 12, Rome, 00185, Italy*
[(b)] *"Sapienza" University of Rome, Department of Earth Sciences, P.le Aldo Moro 5, Rome, 00185, Italy*

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ABSTRACT

This paper is focused on the use of InSAR (Synthetic Aperture Radar Interferometry) and PhotoMonitoring^{TM} techniques for dams and reservoir slopes monitoring.

The technological and scientific advances in the field of remote sensing have allowed the spread of different technologies that currently represent powerful tools for the surficial monitoring of ground and infrastructures. This paper allows to circulate and to make known the capabilities of these technologies for dams monitoring applications. In particular, Terrestrial and Satellite SAR interferometric techniques and the innovative remote sensing approach called PhotoMonitoring^{TM}, are introduced highlighting their potential and the possible applications for dams and reservoir slopes monitoring. Furthermore, two example of applications based on Terrestrial and Satellite SAR interferometric techniques have been described.

1. INTRODUCTION

Remote sensing techniques can be a powerful tool for structural health assessment of dams and for reservoir slopes monitoring. The evolution of traditional technologies and the development of emerging technologies (e.g., satellite and terrestrial radar technologies and PhotoMonitoring^{TM}) offer a wide spectrum of monitoring solutions. These technologies find application during different stages of the life cycle of a dam (e.g., design, construction, operation and maintenance) and can be applied effectively in several crucial operations, such as (i) dam reservoir site selection, (ii) reservoir catchment management, (iii) detection and control of geohazard-prone areas, (iv) structural health monitoring (SHM) of dams, (v) risk management and risk-informed decision-making.

Over the last decades, several monitoring approaches have been adopted, ranging from visual inspection to instrumental continuous monitoring [1-4]. At this regard, Satellite and Terrestrial SAR Interferometry can be an effective tools for the engineers in charge of SHM [5,6], representing a unique solution in the monitoring of structures, such as the capability to provide information about the ongoing and past deformations with millimeter accuracy.

As regards the radar-based technologies, satellite and terrestrial SAR (Synthetic Aperture Radar) interferometry represents one of the most advanced and effective techniques for monitoring deformation of both ground and man-made structures.

The main strengths of satellite SAR interferometry are the capability of monitoring large areas with high accuracy and the ability to perform historical analyses (thanks to archive satellite SAR images available from 1992). These characteristics allow to observe and measure reservoir slopes and to detect potentially unstable slopes at reservoir scale, in order to undertake the appropriate risk management strategies.

Terrestrial SAR interferometry, on the other hand, thanks to its high sampling frequency of data collection (in the order of few minutes or even seconds) and its high accuracy of displacement measurement (up to decimal millimeter order), has proven to be effective for local-scale, real-time slopes and structures monitoring, currently considered a proper technology for early warning purposes.

In addition to radar-based technologies, cutting-edge solutions like the PhotoMonitoring^{TM} are now available for dams and reservoir slopes monitoring. The concept PhotoMonitoring^{TM} refers to different image processing techniques, used for geotechnical and structural monitoring purposes. Among these techniques are included the digital image correlation (DIC), the change detection and the 3D photogrammetry.

In the following paragraphs, the description of the techniques and an overview of some projects carried out by NHAZCA S.r.l. using terrestrial and satellite SAR interferometry and PhotoMonitoring^{TM} techniques are presented.

2. TERRESTRIAL SAR INTERFEROMETRY

2.1. BASIC PRINCIPLES AND APPLICATIONS

Terrestrial SAR Interferometry (TInSAR) is an all-time (night and day), all-weather, non-contact, high-accuracy and fully remote sensing technique based on an active radar sensor that emits microwaves and receives the return of scattering objects. The final output is a 2D displacement map of the investigated scenario along the instrumental Line of sight (LOS), i.e., the path between the sensor and the target. In addition, for every measurement point characterized by high backscattering features, it is possible to obtain the time series of displacement.

The SAR principle is achieved by moving the sensors along a rail and by combining the backscattered signals using focusing algorithms, that allow to obtain high resolution 2D images in range (sensor-target direction) and cross-range (orthogonal to the range; [7]) directions. The length of the rail determines the cross-range resolution of the acquired images (i.e., the longer the rail, the higher the cross-range resolution), while the distance between the instrument and the observed scenario determines the range resolution [8].

By the comparison of the phase value of SAR images collected at different times, sub-millimeter accuracy measurements can be obtained (interferometric principle). According to the site-specific conditions, the system's accuracy can range between some tenths of a millimeter, in the optimal monitoring conditions (very high signal to noise ratio values), to some millimeters (Figure 1).

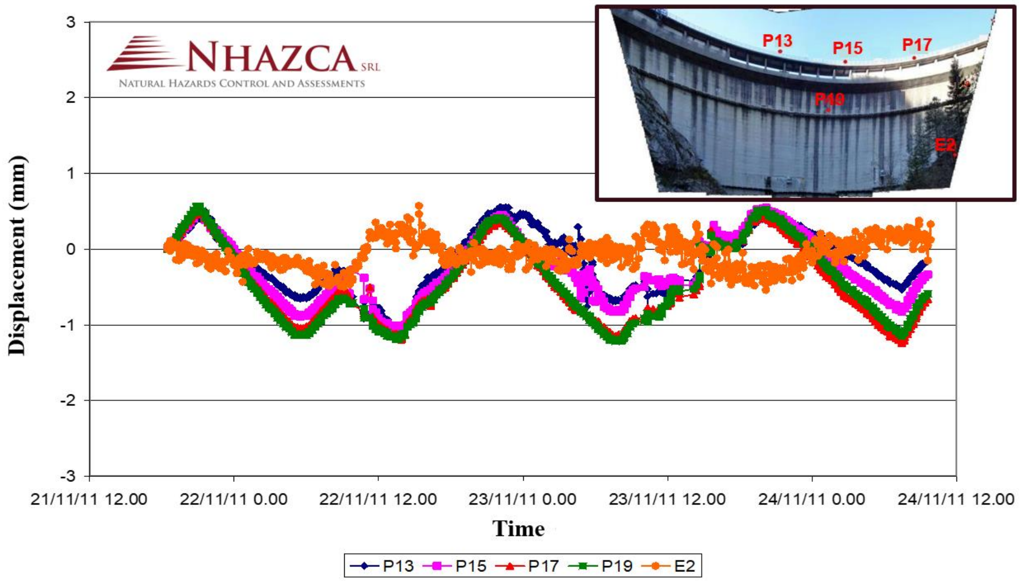

Figure 1. Example of time series of displacement (in millimeters) obtained with TInSAR in correspondence of a concrete arch dam in Northern Italy. The high accuracy of the collected displacements (up to a few hundredths of a millimeter) allowed to capture the thermal deformation behavior of the concrete dam.

Thanks to the active nature of the sensor, the TInSAR instrument does not need artificial reflectors, allowing to monitor the deformational behavior of ground and structure/infrastructure from a completely remote point of view. However, in particular conditions, artificial reflectors on the ground (i.e., the so-called corner reflectors) would allow to improve the data accuracy and the density of measurement points.

The high data sampling frequency (up to 30 seconds), the high spatial resolution, the continuous monitoring capabilities (both in time and in space) and the high accuracy in terms of displacement monitoring, make TInSAR a suitable instrument for different applications and purposes such as [9]:

- knowledge monitoring, to characterize and assess the processes under investigation in ordinary operational conditions;
- control monitoring, to quantitatively check the evolution of known issues;
- emergency monitoring, in order to provide alert in case the risk become unacceptable.

An example of application of the TInSAR technique for the monitoring of the right flank of an earth dam is reported in paragraph 2.2.

2.2. TINSAR MONITORING OF AN EARTH DAM

In the frame of the engineering works for the stabilization of the right flank of an earth dam in Central Italy, a continuous 24/7 TInSAR monitoring has been setup. The activity has been performed for the following purposes: i) early warning for the safety of workers and ii) improvement of knowledge about the deformational behavior of the slope, also thanks to the correlation of TInSAR data with weather data and information from other monitoring instruments.

The measurements have been acquired in continuous, with a sampling period of few minutes. The data have been pre-processed on site through suitable algorithms and then transferred to the NHAZCA monitoring center, where they have been processed using a semi-automatic software. A phase of automatic image processing and internal alarms notification was performed to guarantee the early warning purposes. In case defined thresholds were exceeded, after the data validation performed by an expert user, the alarm procedure is activated.

During the 2 years of monitoring, localized surface displacements have been observed in the central part of the slope (Figure 2). In particular, more than 300 mm of displacements have been detected on the right flank of the earth dam. However, the deformations were ascribed to anthropic work activities and shallow debris movements correlated with rainfalls that did not cause concerns among the decision makers.

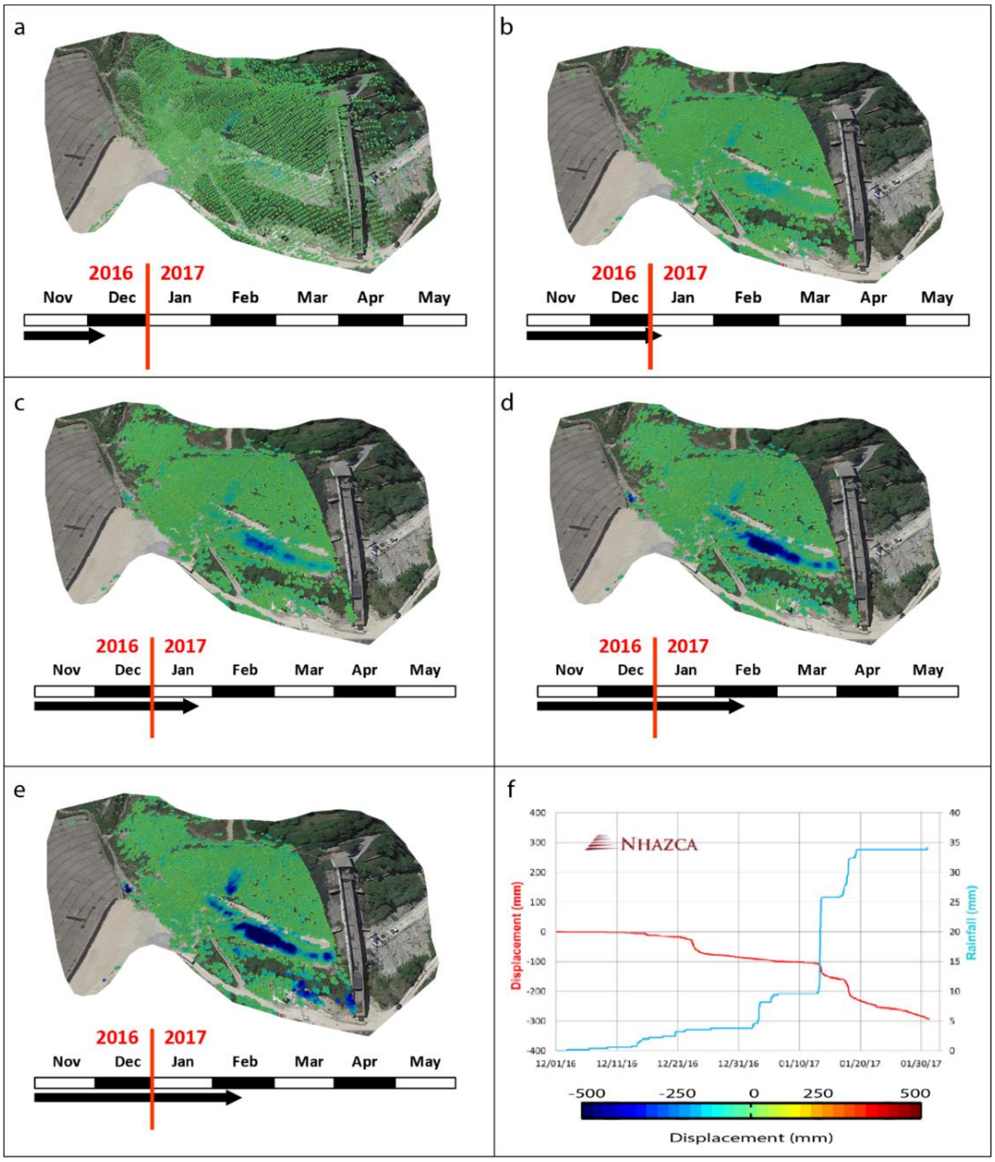

Figure 2. a - e) TInSAR multi-temporal deformation maps in tridimensional view; f) time series of displacement of one of the measured point inside the moving area and the relation between rainfall and displacements can be observed. The color of the points indicates the intensity and the direction of displacements. Specifically, negative values (light blue to dark blue) are points with deformation direction towards the sensor, while positive values (yellow to red) refer to points moving away to the sensor. Green points are considered stable.

3. SATELLITE SAR INTERFEROMETRY

3.1. REPEAT PASS SATELLITE SAR INTERFEROMETRY

Satellite Synthetic Aperture Radar (SAR) Interferometry has proved its capability in monitoring the ground and structures deformation with high accuracy

[10-14]. With respect to other traditional methods, this technology can work at all-time, with all-weather conditions and it is suitable for both wide areas and site-specific applications. A further relevant characteristic of Satellite SAR Interferometry is the possibility to retrieve information on the deformation history of the area of interest, looking back in time using the SAR data archives of the Spatial Agencies. In fact, the first global systematic acquisition of SAR imagery started in the early 1990s, with ERS-1 and -2 satellites (European Space Agency). Since then, images have been collected in several parts of the world with revisit times of the order of some days (for examples the Envisat-ASAR sensor had a revisit time of 35 days, while the recent Sentinel-1 constellation has a revisit time of only 6 days).

A SAR image consists of a matrix of resolution cells (i.e., pixels) that contain the information about the satellite-target distance. Surficial deformations can be investigated through to the Differential InSAR (DInSAR) methodology, that is based on the phase difference between two SAR images collected in different times (computing in the so-called interferogram), allowing to estimate the displacement occurred between the two acquisitions. In order to overcome the major limitations of the DInSAR technique, like the influence of the atmospheric phase screen (APS), long time series of SAR images are used in the Advanced Differential InSAR (A-DInSAR) technique. This latter take advantage of several SAR images collected in the same area over time to perform deformation measurements [10, 11]. A-DInSAR methodology allows to obtain the displacement-time information of natural targets on the ground, which are measured along the satellite Line of Sight (LOS).

The Persistent Scatterers Interferometry (PSI) is one of the most effective A-DInSAR techniques, based on the analysis of specific targets on the Earth's surface (called Persistent Scatterers, PSs) characterized by long time-coherent behavior [10, 12].

The main outputs of a PSI analysis are: i) the trend of deformation during the investigated time period; ii) the time series of displacement, with an accuracy up to few millimeters; iii) the height of the target on the ground; iv) cyclic (non-linear) deformation due to several factors (e.g., temperature variations).

3.2. A-DINSAR HISTORICAL ANALYSIS OF 2 ROCK-FILL DAMS

A preliminary site-specific PSI analysis has been carried out for two rock-fill dams in USA (Figure 3a, b). The two reservoirs serve as terminal basins for the water supply of Colorado Springs and surrounding municipalities.

The A-DInSAR historical analysis has been performed using a stack of 114 high-resolution COSMO-SkyMed (form Italian Space Agency, ASI) scenes collected in the time span ranges between 2011 and 2016, in the ascending geometry of acquisition.

The multi-image processing technique allowed the analysis of the past deformational behavior of the dam bodies. The velocity measurements have been obtained with millimeter accuracy in the LOS direction (the average velocity map is showed in Figure 3c). The measurement points in correspondence of the dam flanks show a general stability, while constrained ground deformations have been observed in the lower portion of the dam '*b'* in Figure 3c, where linear deformation behavior has been observed during the 5 years monitoring period, with an average velocity trend ranging between 3 and 7 mm/year.

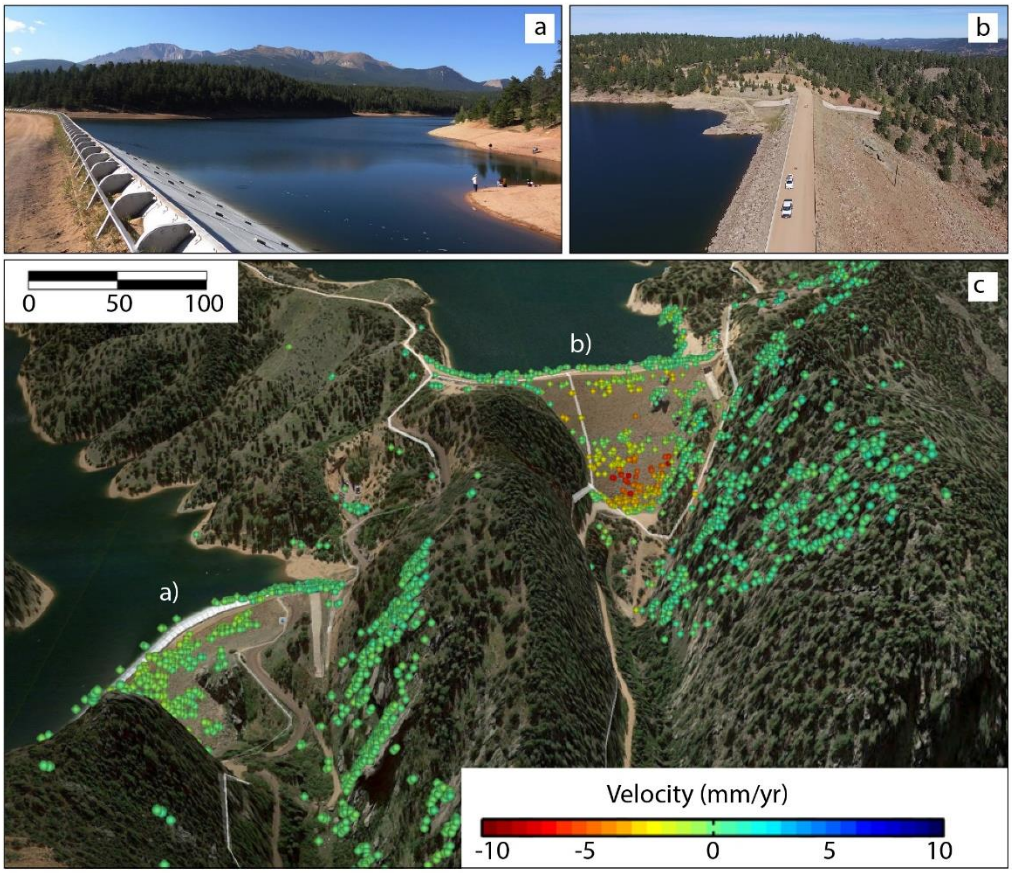

Figure 3. The two dams under investigation (a, b) and A-DInSAR results (c). For every measurement point, it is possible to observe the displacement rate in mm/year. Negative values (yellow to red) are points with deformation rate away from the satellite, while positive values (light blue to dark blue) are points that move towards the sensor. Green points are stable. (COSMO-SkyMed Product - ©ASI - Agenzia Spaziale Italiana – (2017). All rights reserved).

4. PHOTOMONITORING^{TM}: AN INNOVATIVE MONITORING SOLUTION

In addition to radar-based technologies, cutting-edge solutions are now available for dams and reservoir slopes deformation analyses. PhotoMonitoring^{TM} is one of the most innovative remote sensing solutions, useful for geotechnical and structural monitoring.

The increasing number of satellite-based, airborne and ground-based optical and radar sensors, have greatly increased the potential of PhotoMonitoring^{TM} for engineering applications. Ranging from very high resolution (VHR) optical and/or multispectral cameras to low-cost and low resolution sensors, today an incredible amount of source of information can be exploited using the PhotoMonitoring^{TM} approaches.

The approach of PhotoMonitoring^{TM} is based on the integration of different remote sensing measurement techniques that allow to identify, analyze and quantify the surface changes/variations over time by processing two or several optical or multispectral images (e.g., satellite, aerial imagery or simple photos), collected at different times over the same area (www.photomonitoring.com).

Specifically, Change Detection (CD), Digital Image Correlation (DIC) and 3D Photogrammetry techniques can be combined, also with other remote or contact instruments for dams and reservoir slopes monitoring. In fact, it is possible to retrieve quantitative and qualitative measurement of surface changes on the investigated object (e.g., the surface of a concrete or earth dam, unstable reservoir slopes) with both Change Detection and Digital Image Correlation techniques. If Change Detection technique allows to identify, describe and quantify any changes of the area of interest, Digital Image Correlation technique allows the measurement of "full-field" deformation on the surface of investigated area. This is possible through the correlation of co-registered images, collected at different time intervals [15-19] (Figure 4).

The great adaptability of the technique makes PhotoMonitoring^{TM} appropriate for several kinds of dam related applications. PhotoMonitoring^{TM} can be an effective solution at different scales of investigation, from the single crack measurement to the reservoir scale.

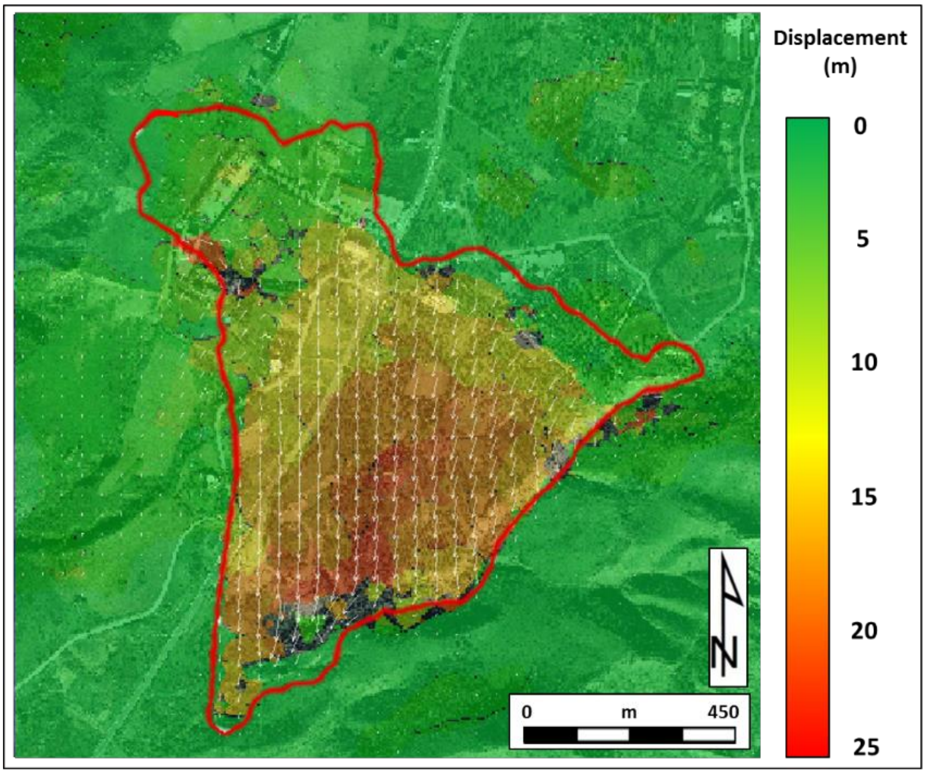

Figure 4. Example of 2D displacement map retrieved by DIC analysis performed on very high-resolution optical imagery. Here it is reported the displacement related to a large earth-slide, occurred in Italy. The landslide boundary is highlighted in red, while the displacement field is highlighted with white arrows.

In fact, satellite multispectral and/or radar images can be exploited with PhotoMonitoring^{TM} approach for big scale application in order to investigate the stability of reservoir slopes and identifying insights of slope instability processes, thanks to the application of semi-automatic digital image analysis techniques. At the same time, terrestrial instrument based on the acquisition and processing with CD and DIC techniques of high-resolution photos can be installed for local-scale analysis, in order to monitor the 2D displacement field of the dam body or of a slope of interest. The accuracy in displacement measurement strictly depends on the kind of sensor used, the distance between the target and the collecting instrumentation and the environmental features, reaching a theoretical accuracy of 1/10 of pixel [20-24]. The terrestrial instrument, known as Virtual Digital Extensometer (VDE), can be completely managed from a remote location, allowing considerable advantages during emergency scenarios, where a quickly monitoring service is required and when traditional geological, geotechnical and structural monitoring techniques (such as inclinometers, strain gauges, crack-meter, etc.) cannot be applied avoiding risks and logistical problems.

3D Photogrammetry technique allows the reconstruction of 3D digital models, by using optical images with a high percentage of overlapping and through the implementation of Structure from Motion (SfM) algorithms. This latter can be the most suitable solution to have a comprehensive three-dimensional overview of the dam of interest [25-28]. As reported also in Buffi et al. (2017) [25], the 3D Photogrammetry technique, integrated with an UAV-based platform (Unmanned Aerial Vehicle) and traditional topographic techniques, can be the most suitable solution for the reconstruction of a 3D model of a dam. In addition, through the digital analysis of the three-dimensional model, it is possible to perform an accurate virtual inspection of the dam, even in correspondence of inaccessible or dangerous dam sectors.

5. CONCLUSIONS

This paper showed the potential of three different remote sensing monitoring solution for dams surveillance: Terrestrial SAR Interferometry (TInSAR), Satellite SAR Interferometry and PhotoMonitoring^{TM}.

The main capabilities of TInSAR (i.e., the high sampling frequency and the high accuracy of measurements) make it possible to use the technique to improve the knowledge about a deformation process, to control it over time and for emergency applications.

Satellite SAR Interferometry, and in particular, A-DInSAR technique, allows to perform both wide areas investigation and local scale analysis with high accuracy in terms of displacement measurements. The large-scale analysis can be very useful in order to investigate the state of activity of reservoir slopes, possibly detecting deformation anomalies where to focus the attention, allowing decision makers to plan further investigations. On the other hand, site-specific investigations can be carried out on localized area or structure, allowing to characterize and monitor the possible occurrence of deformations. The peculiarity of satellite InSAR is the possibility to perform historical analyses, exploring the deformation processes occurred in the past in order to improve the know-how about the investigated phenomena.

The PhotoMonitoring^{TM} is an emerging group of technologies, which can be effectively used for long term monitoring surveys but also for quick analyses, taking advantage of the relatively low-cost of the technology.

In conclusion, the aforementioned remote sensing technologies represent powerful tools for several applications at different stages of the life cycle of a dam (design, construction and operation), such as: the reservoir catchment management, the structural and health monitoring of dams, geo-hazard monitoring and risk management.

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KEYWORDS

Monitoring, Control, Landslide.