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DAMS REGIONAL SAFETY WARNING USING TIME-SERIES INSAR TECHNIQUES

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Abstract. *Accurate and frequent monitoring of dams and its surroundings is an extremely important task to ensure the safety of settlements located downstream. Time-series InSAR techniques are a cost-effective way for measuring millimeter-level displacements on the Earth surface, at a regional scale, and can be used as an early warning system for the safety of structures and their surroundings. This study presents the application of one of these techniques to Álamos I, Álamos II (earth) and Alqueva (concrete) dams, in Portugal. The results obtained for Álamos I and Alqueva were compared to geodetic measurements and it was verified that the maximum difference of the average displacement rate between the two techniques is 3.2 mm/yr.*

1 INTRODUCTION

Dams are important infrastructures for a country's economy due to the several purposes they may serve, such as hydroelectric power generation or irrigation of agricultural fields. Nevertheless, they represent a risk for the populations living downstream. The Malpasset dam, in France, collapsed in 1959 due to excessive rainfall, resulting in several casualties and damages, such as the destruction of a bridge that was being built downstream of the dam[1]. However, the accidents related to dams do not always concern the structure itself. In 1963, in Italy, approximately 2000 people died in the vicinity of the Vajont dam, due to the flood caused by a massive rockslide into the reservoir[2]. Recently, a tragic event happened in Portugal during the construction of the Foz Tua dam, where a rockslide killed 3 workers, in 2012.

The main causes of dams collapsing are earthquakes and heavy rainfall, especially those occurred during the first filling. Accurate monitoring operations of structures and their surroundings are of major importance in order to identify instability in time of taking prevention actions. However, the monitoring operations imply sending a team to perform field-work which is time consuming and limited to small areas. A cost-effective

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way to regionally monitor dams and their surroundings would allow an efficient planning of more localized monitoring tasks.

Space-based Radar interferometry is a technology that uses microwave active sensors carried in satellites to image Earth surface. The sensor emits microwave radiation towards the planet which is reflected and returns to the sensor. Both amplitude and phase information are registered for each resolution cell, forming Synthetic Aperture Radar (SAR) images. Images of phase difference between two epochs are called interferograms, in which the presented values depend on the acquisition geometry, terrain displacement, different atmospheric conditions, and noise[3]. If the images are acquired in distant epochs, changes occurred in the terrain cause decorrelation, resulting in lack of information. Decorrelation also occurs if the images are acquired from points in space separated by a distance larger than a critical one. Besides, the different atmospheric conditions in each acquisition epochs cause different delays in the radiation propagation, which cannot be estimated from only two or three images. Time-series Interferometric SAR (InSAR) techniques provide a way to estimate displacements at millimeter-level[3] from using a series of SAR images with the same acquisition geometry – an interferometric stack. These techniques search for points which keep a stable (or partially stable) reflective behavior during large time intervals and for large distance between acquisitions. The high frequency of atmospheric contribution in time and low frequency in space enables the estimation of Atmospheric Phase Screen (APS) for each image. Therefore, using an interferometric stack of SAR images, it is possible to separate all components of the interferometric phase (phase difference) and obtain for each stable point a time-series of displacements during the considered time period.

This paper proposes a method to evaluate dam and its surroundings safety by using a time-series InSAR technique for an *a priori* evaluation of displacements. This evaluation would allow the identification of possible instable regions in an early stage, working as a safety warning system and pointing which areas would require more accurate and localized monitoring operations. The permanent scatterers InSAR technique (PSInSAR)[3] was applied to two datasets of Envisat ASAR images, freely provided by the European Space Agency (ESA). The considered study areas are the earth dams Álamos I, II, and III and the concrete arch dam Alqueva, in Portugal. Data from geodetic monitoring were available for Álamos I and Alqueva dams and were used to validate the results achieved through PSInSAR.

The following section presents the study area and the data used in this study, while the third section shows the methods applied. Section 4 presents the results achieved, their validation and discussion. The last section contains the main conclusions of the study.

2 STUDY AREA AND DATA

The Alqueva infrastructures were selected for testing the capabilities of PSInSAR for dam safety warning. Alqueva is a concrete arch dam located in Alentejo region, Portugal, finished in 2002. It has the largest reservoir in Western Europe, spanning 250 km^2. Being one of the most recent and important concrete dams in the country, the Alqueva dam is also one of the most well equipped and monitored dams. Besides the hydroelectric power generation, Alqueva has an important task on irrigating one of driest regions in Portugal as well. The Alqueva dam is connected to a network of smaller earth dams which spreads the water through the whole region (Figure 1). The Álamos dams, finished in 2006, are three earth dams linked to Alqueva, which ensure the water transportation to another earth dam, Loureiro.

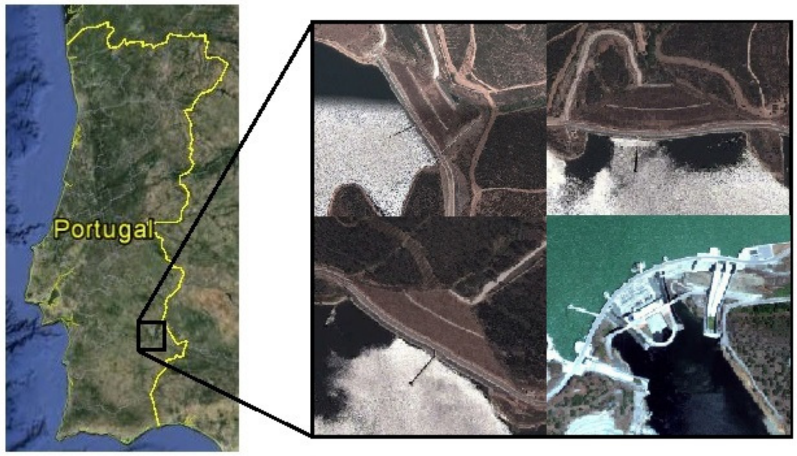

Figure 1: Location of Álamos and Alqueva dams (© Google Earth); Álamos I (top left), Álamos II (top right), Álamos III (bottom left) and Alqueva (bottom right).

The SAR images freely provided by ESA and used in this study were acquired through the sensor Advanced SAR (ASAR) on board the satellite Envisat, which was active from 2002 to 2012. This sensor imaged the Earth in the C-band of microwaves, with a wavelength of 5.6 cm. Its resolution cell spans around 20 m in range direction (across track) and 4 m in azimuth direction (along track). For monitoring the Alqueva dam, a datastack of 16 images acquired between 2004 and 2010 were used. Nevertheless, this dataset has many lacunae in data acquisition, including gaps of one year without a single image, particularly, after 2006. Therefore, the dataset is very weak for processing the earth dams which were built later. Instead, a dataset of only six images, acquired in 2011 and 2012 were used for the Álamos dams.

A Digital Elevation Model (EU-DEM), freely provided through Copernicus (a program from the European Comission, DG Enterprise and Industry), with a spatial resolution of 25 m, was used.

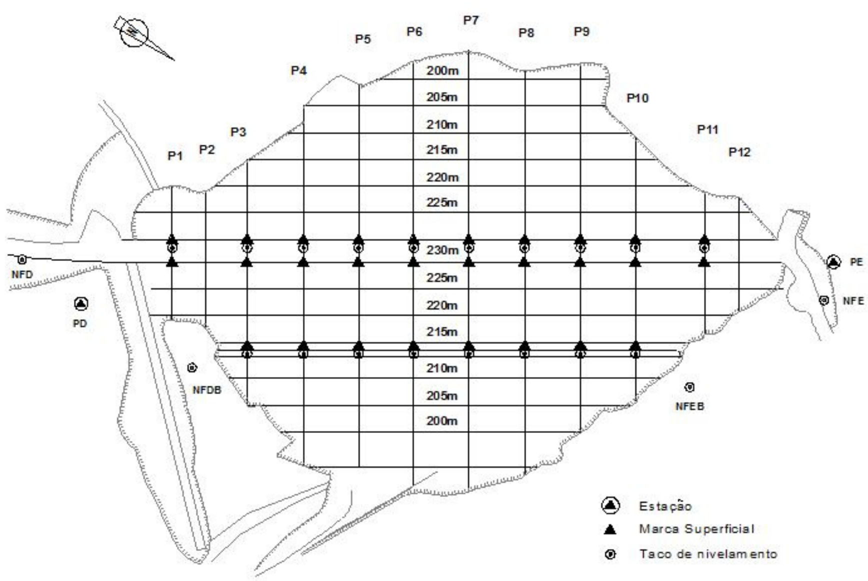

Figure 2: Location of the points from the geodetic network in the Álamos I dam.

The Applied Geodesy Division of the National Laboratory for Civil Engineering, from Portugal, performs geodetic monitoring on the Alqueva dam at least once every year since its construction. The geodetic network contains eight points located in the dam crest and six points in the banks (three reference points and three for auxiliary purposes)[4]. Geodetic measurements for Álamos I are performed by EDIA – Empresa de Desenvolvimento e Infra-estruturas do Alqueva, S.A. (Figure 2). There are three geodetic networks: one for planimetric displacement monitoring formed by 19 points in the dam crest and eight points in the dam banquette and two other networks for evaluating vertical displacements. The first one is in the dam crest formed by 19 points and the second one in the dam banquette with eight points. Each geodetic network has two additional points for reference, one located in each bank. The geodetic data from the two dams were used to validate the PSInSAR results, however for Álamos I only the vertical displacements were considered as the relative displacements between reference points are not known and, therefore, it is not possible to link the three networks and perform a 3D analysis.

The software used for applying time-series InSAR techniques is SARPROZ[5], developed by Professor Daniele Perissin.

3 METHODS

Before applying any time-series InSAR techniques, the images were corregistered with respect to a reference image (the master image), meaning that the resolution cells from each image corresponding to the same geographical location were superimposed. This operation was performed through a first approximation using information from the satellite orbits, and later refined. A Ground Control Point was used to geocode the resulting interferometric stack. One of the most critical steps in InSAR processing is the estimation of APS. A correct estimation requires at least 15 images, but as independent processing is being performed for each dam, the considered area is small enough for the APS to be neglected. Therefore, the dataset composed of six images could be used for the earth dams, which would not be possible if APS had to be estimated.

The interferograms can be used in order to evaluate the possibility of extracting information from the data. The interferograms from every possible pair of images were analyzed for each dam. Besides the calculation of phase differences, the contribution of flat terrain and of topography were removed and a Goldstein filter with a 10 pixel x 10 pixel was applied.

For the earth dams, it was verified that both Álamos I and II had several interferograms with information, while Álamos III presented mostly noise. Thus, only the first two dams were selected for further processing. For the Alqueva concrete dam, several interferograms presented information on the infrastructure location. Thus, although the available interferometric stack presents several gaps in the acquisition time-series, it was considered acceptable for InSAR processing.

Similar methods were applied for the three dams. For each one of them, a small area containing only the structure and its neighborhood was considered. Points presenting high average amplitude values during the time period being analyzed were selected as candidates to permanent scatterers (PSs). One of those points, located outside the dam and on an area known to be stable, was selected as reference point. Particularly, for the Alqueva dam, as many changes occurred in its neighborhood in the last years, such as the construction of a second hydroelectric plant, the reference point was selected in the bank in which fewer changes occurred. Residual height values (ellipsoidal height of the candidate points with respect to the reference one, estimated from the images) were calculated through the time-series InSAR technique Quasi-PSInSAR[6]. The obtained quasi-permanent scatterers (points that only have a stable reflective behavior in some of the image acquisition dates) showed residual height values consistent with the local topography, including even on the dams. To be noted that, since the study area is small, the geoid undulation can be considered to be constant.

The residual height values were used in the second part of the processing, where another time-series InSAR technique, the PSInSAR[3], was used to evaluate each point displacement. The EU-DEM was used as external DEM and the option to determine non-linear movements was selected. A quality control was performed on the PSs, in which only those presenting high coherence values (measure of the fit between the model and the observations[7]) were considered for further analysis, thus resulting in a small number of available points.

4 RESULTS AND DISCUSSION

4.1 Earth dams

From the application of the PSInSAR algorithm over the earth dams Álamos I and II, it was verified that few PSs were identified on the dams (Figure 3). This was already expected, since the method was applied on C-band SAR images with a small wavelength that usually does not perform well on vegetated areas such as those under study. The most appropriate SAR images for the purpose of this analysis would be the Japanese ALOS-1 PALSAR, which are acquired in L-band, with a wavelength of 23.6 cm and are not sensitive to plant leaves, thus identifying a higher number of stable points.

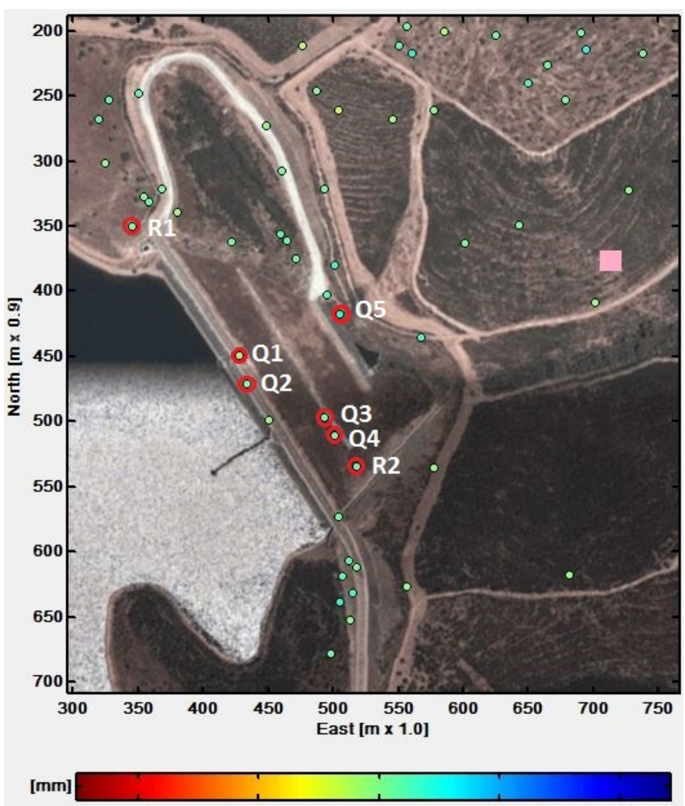

Figure 3: Cumulative displacement for permanent scatterers in Álamos I.

In the few permanent scatterers identified in Álamos I, negative values of displacement rate along the sensor line-of-sight (LOS) were identified in the crest, with an extreme negative value of -4.7 mm/yr for point Q1, meaning that the points are moving away from the sensor. However, points located in the dam foundation present positive values (they are getting closer to the sensor), with extreme positive displacement rate along LOS of 7.6 mm/yr for point Q5. These results can be either explained by the possible instability of the reference point (pink square in Figure 3), which may be subsiding, or movements in the horizontal direction of the dam. However, the small number of points does not enable a global idea of the phenomenon in the whole dam and the number of images available is not enough to allow a clear interpretation of the results.

A few PSs were obtained in locations close to points belonging to the geodetic networks (Q1, Q2, Q3, Q4, R1, and R2), in which R1 and R2 are coincident to reference points. The displacements obtained through PSInSAR for Q1 and Q2 were calculated with respect to R1 and those from Q3 and Q4 were calculated with respect to R2, similarly to the geodetic observations. PSInSAR displacements were evaluated with respect to the acquisition date of the first image. The vertical displacement obtained from the geodetic observations was projected in LOS and compared to the LOS displacement from PSinSAR. It was observed that the difference between the average displacement rates obtained from the two techniques ranged between 0.2 mm/yr to 3.2 mm/yr. Table 1 presents the differences between the average displacement rates for each point and Figure 4 presents the displacement time-series from both techniques for Q1. The high differences obtained may be explained by the fact that planimetric displacements are not being considered in the analysis while they are a significant part of the points' total displacement and by the small number of images used.

Point ID	Difference (mm/yr)
Q1	0.2
Q2	3.2
Q3	1.4
Q4	1.7

Table 1: Difference in average displacement rate for points in Álamos I.

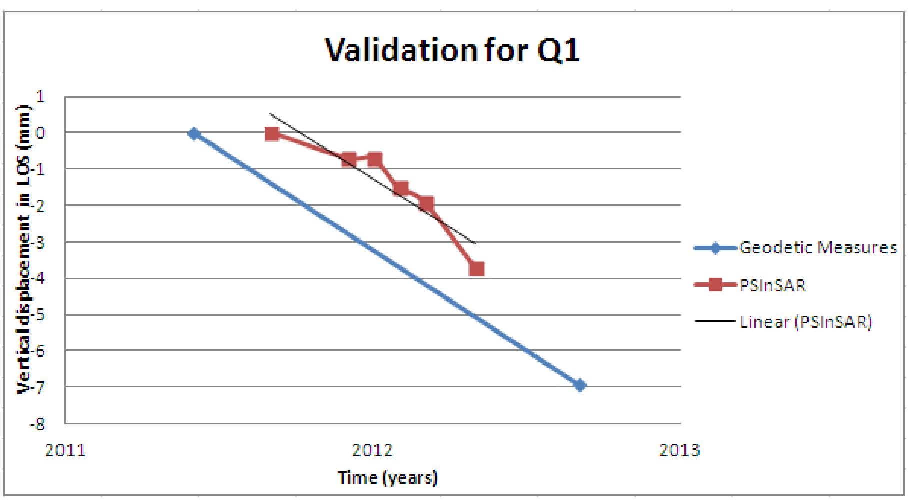

Figure 4: Displacement time-series for Q1 acquired with geodetic and PSInSAR techniques.

For the Álamos II dam, the few PSs detected on the structure were close to the crest and all of them presented subsidence behavior (Figure 5). The point closer to the crest center, Q6, had the lowest displacement rate value of all: -15.4 mm/yr along LOS. As the horizontal component of LOS is parallel to the dam, it is not likely that any horizontal movement was detected by PSInSAR, since it is expected to occur in the direction orthogonal to the dam. Therefore, the displacement detected along LOS was considered to be only in the vertical direction, meaning that Q6 is subsiding with a displacement rate of -16.7 mm/yr (calculated considering a radiation incidence angle of 23º). Besides, it was observed that the PSs located downstream of the dam also present a subsiding behavior, which may be explained by possible instability of the reference point. It would had been interesting to analyze the banks of the whole reservoir in order to identify if the subsiding pattern is also verified in other areas, however the study area would be too large for neglecting APS estimation and the number of available images is not enough for that operation.

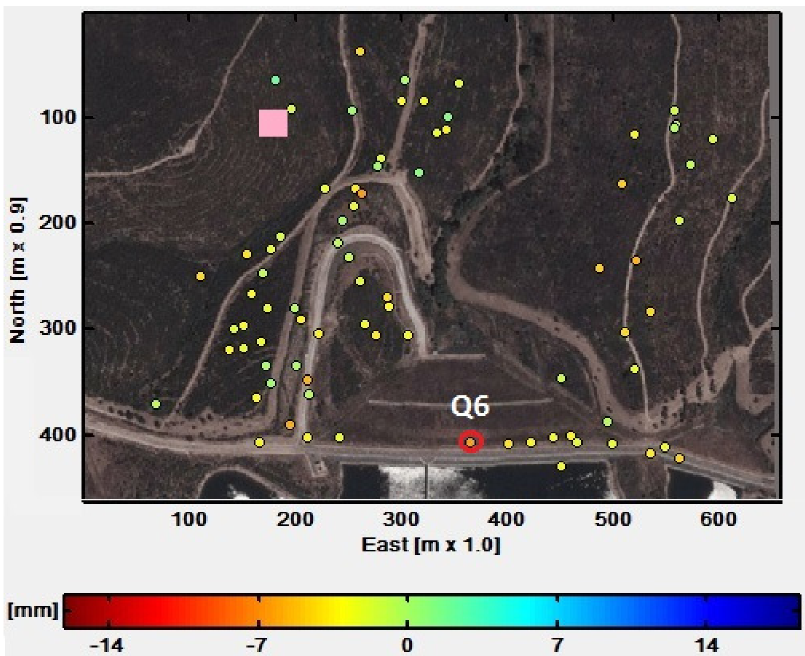

Figure 5: Cumulative displacement for permanent scatterers in Álamos II.

4.2 Concrete dam

A few PSs were detected on the downstream wall of the Alqueva dam and none of them presented meaningful displacement values (Figure 6). However, it should be noted that not all the dam was covered by PSs, namely, the spillway closer to the left bank, which is known to be located on a seismic fault.

The Alqueva dam is monitored by the National Laboratory for Civil Engineering since its construction, through both embedded equipment and geodetic measurements, allowing the comparison between the results achieved through PSInSAR and geodetic measurements contemporary of the SAR images. Three PSs were identified to be close to the locations of points from the geodetic network: P6, P8 and P9. As the first two points are located in the dam crest and the last one is on the bank, P9 was selected as reference. The displacements of P6 and P8 were calculated with respect to P9 and to the first epoch with observations from both techniques (Figure 7). PSInSAR technique only enables the detection of displacements along the sensor LOS. In order to compare the results, the planimetric and altimetric displacements from the geodetic measurements of P6 and P8 were projected in LOS direction using Equation 1:

$$d_{PS}=d_V \cdot \cos\theta - \sin\theta \cdot (d_N \cdot \sin\beta + d_E \cdot \cos\beta) \quad (1)$$

where d_{PS} is displacement in LOS direction, d_V is vertical displacement, d_N is displacement in northing direction, d_E is displacement in easting direction, θ is the radiation incidence angle and β is the angle on the horizontal plane between the easting axis and LOS.

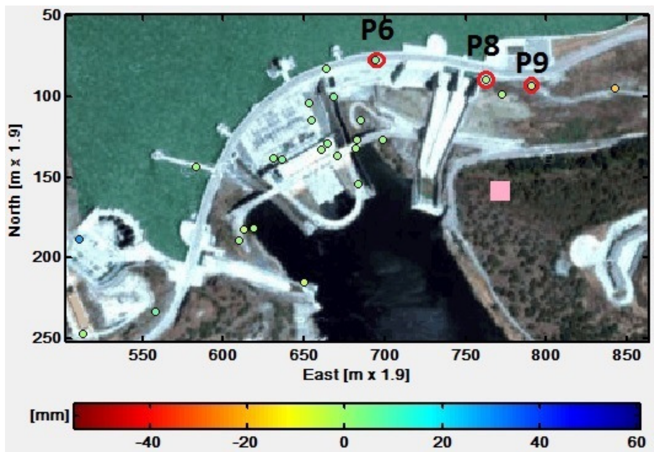

Figure 6: Cumulative displacement for permanent scatterers in Alqueva.

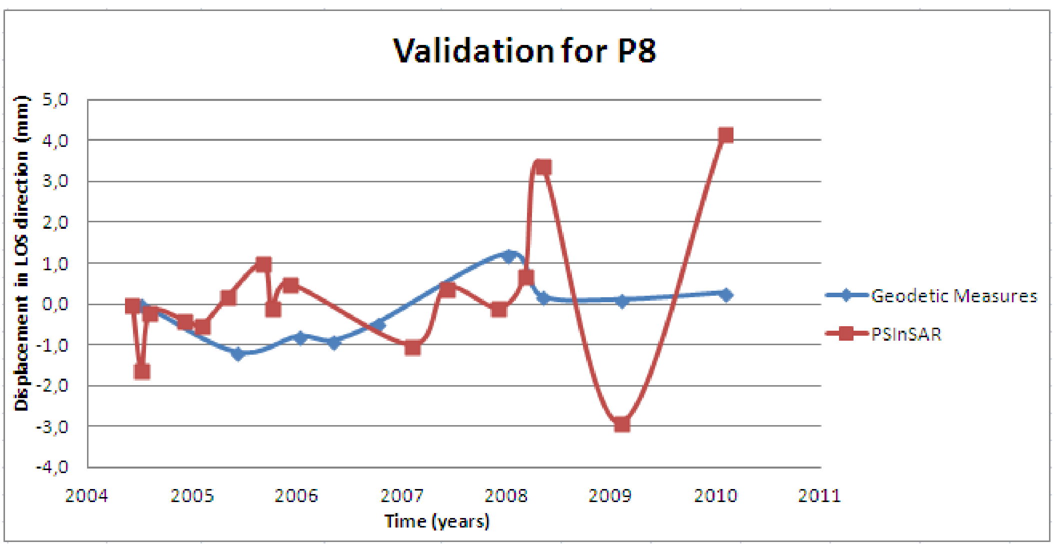

Figure 7: Displacement time-series for P8 acquired with geodetic and PSInSAR techniques.

For P8, it was observed that between 2004 and 2006, the PSInSAR displacements were close to the geodetic measurements (maximum difference of 2.2 mm); however from 2006 onwards, the PSInSAR results presented large oscillations, probably caused by the lack of images in the time-series acquired in this period. Concerning the average displacement rates, there is a difference of 0.1 mm/yr between the results from both techniques. For P6, between 2004 and 2006, the PSInSAR displacement values oscillated around those from geodetic measurements, but after 2006 the difference between the displacements obtained from both techniques increased, reaching 6.5 mm. The difference between average displacement rates from both techniques for P6 was 0.7 mm/yr.

When thinking of monitoring dams using PSInSAR technique, several aspects must be considered. The dam orientation with respect to the sensor LOS is one of the most important, since PSInSAR only enables the detection of movement in this direction. For example, for the Alqueva dam, if an ascending pass had been used, fewer points would had been detected, as that acquisition geometry performs a worse illumination of the dam downstream wall. Besides, if LOS is orthogonal to the direction of movement, PSInSAR will not detect it. The wavelength of the microwave radiation is another critical variable. For a concrete dam such as Alqueva, it would be desirable to use images acquired in X-band (wavelength of 3.1 cm). Those images enable the detection of smaller displacements and have larger spatial and temporal resolutions, which would allow a more detailed analysis than with C-band. As for the earth dams and the reservoirs banks, images from L-band (wavelength of 23.6 cm) would be a better option, since they are less sensitive to the presence of vegetation than C-band. However, while C-band images are freely provided by ESA, X- and L-band data are commercialized at high prices by the spatial agencies responsible for their acquisition.

5 CONCLUSION

In this study, time-series InSAR techniques were applied to two datasets of SAR images presenting the earth dams Álamos I and II and the concrete arch dam Alqueva, in Portugal. A few permanent scatterers were identified in the dams and in their surroundings. Subsiding phenomena were identified in both earth dams, with extreme negative displacement rates of -4.7 mm/yr for Álamos I and -15.4 mm/yr for Álamos II along the sensor line-of-sight. Comparison to geodetic measurements presented differences on average displacement rate between the two techniques ranging from 0.2 mm/yr to 3.2 mm/yr. The discrepancy observed is probably due to neglecting the planimetric displacements and to the usage of a small number of images for PSInSAR processing. For the concrete dam Alqueva, agreement between the InSAR results and the geodetic measurements was found for the time period between 2004 and 2006. The discrepancy observed from 2006 onwards is believed to be caused by the gaps in the image acquisition. However the average displacement rate determined through PSInSAR is close to that from geodetic measurements (maximum difference of 0.7 mm/yr).

Although the proposed technique presents several limitations concerning dam monitoring, such as the adequacy of the acquisition geometry and wavelength, it enabled the identification of the displacement trend in the dams. This trend can be useful to an *a priori* analysis to verify the dam stability and decide if more precise geodetic monitoring should be performed.

For future work, the installation of artificial corner reflectors in critical areas where PSs were not available is planned. These structures assure that the point presents a stable reflective behavior, being identified as a PS and allowing the analysis of its displacement.

Data from the ESA satellite Sentinel-1A will be available for free, starting from 2015, through the European program Copernicus. This dataset will have a higher time resolution than that provided by the previous ESA satellites, being expected that more reliable time-series will be obtained.

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