ICONHIC2022
3rd International Conference on Natural Hazards & Infrastructure
5-7 July 2022, Athens, Greece

Application of ADAtools tools for InSAR based ground displacement map analysis: the coast of Granada

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ABSTRACT

Satellite interferometry (InSAR) has become a consolidated technique for ground displacement detection and monitoring in the last years. InSAR based techniques allow to process large areas, providing numerous displacement measurements at low cost. This consolidation is confirmed by the emergence of regional, national, and European programs to monitor ground displacements using InSAR data. However, the interpretation of the outputs provided by such techniques is sometimes difficult and time-consuming. This is particularly critical for users who are not familiar with radar data. In this context, the development of tools and methods to automatize the retrieval of key information and to ease the interpretation of the results is needed to improve its operational use. A series of tools developed in the framework of different projects (MOMIT, SAFETY, U-Geohaz) is presented and an example of use in the project RISKCOAST is shown. The ADA (Active Displacement Areas) tools have been developed with the aim of easing the management, use and interpretation of InSAR based results. Specifically, the ADAFinder tool allows a semi-automatic extraction of the most significant Active Displacement Areas (ADas) detected by the InSAR analysis. We show its application to one of the test sites of the project Riskcoast, the coast of Granada. These tools have been developed to improve the exploitation capabilities of the European Ground Motion Service (EU-GMS), which will provide consistent, regular, and reliable information on natural and anthropogenic ground motion phenomena all over Europe.

Keywords: Ground displacements, InSAR, Natural Hazards, Satellite Imagery.

INTRODUCTION

Satellite interferometry (InSAR) has become a consolidated technique for ground movement detection and monitoring. InSAR based techniques are able to provide numerous ground displacement measurements at different scales; from regional/national up to very detailed such as single buildings (Carla et al. 2019,Galve et al. 2017, Crosetto et al. 2016). The availability of Sentinel-1 data free of charge with continuous acquisition policy worldwide since 2014 has marked a significant step forward for such techniques. In particular, the range of applications of InSAR based techniques for risk management activities expand from the scientific field to operational use. This tendency has been institutionally reinforced with the launch of several regional, national, and European programs to investigate and improve the processing performances and broaden the operational use and application of InSAR to monitor ground displacements (Crosetto et al. 2020).

However, the products provided by InSAR techniques are usually not easy to understand. Its interpretation demands a level of expertise which might turn out to be a time-consuming for users who are not familiar with radar data (Barra et al. 2017). In this context, the development of methodologies and tools to automatize the retrieval of information and to ease the interpretation of the results is required to improve its operational use. In this work, a series of tools developed in the framework of the projects MOMIT, SAFETY, U-Geohaz and RiskCoast is presented. Their use is illustrated on one of the test sites of the project RiskCoast, the coast of Granada. Riskcoast focuses on the development of tools, methodologies and innovative solutions aimed at the prevention and management of geological risks on the coast linked to climate change.

The presented work is an example of multi scale (medium to large) application of InSAR for geohazard detection and monitoring. The results are an example of use of the ADA (Active Displacement Areas) tools [4] developed with the aim of facilitating the management, use and interpretation of InSAR-based results. The velocity of deformation map and the displacement time series have been estimated over the test area of Granada (Spain) by processing Sentinel-1 (A and B) SAR images. From these initial InSAR outputs, a semi-automatic extraction of the most significant ADAs is carried out using the ADAFinder tool [4]. These tools have been developed to increase the exploitation capabilities of the European Ground Motion Service (EU-GMS), which will provide consistent, regular, and reliable information on natural and anthropogenic ground motion phenomena all over Europe (Crosetto et al. 2020).

METHODOLOGY

This section briefly describes the data and the methodology used in this study to generate the ADA maps. The methodology applied is a multi-step processing procedure which includes two main stages: InSAR processing and ADAs extraction. Figure 1 shows the flow chart of the procedure.

Dataset

A stack of 210 co-registered SAR Sentinel-1 Wide Swath Single Look Complex (SLC) images acquired in Ascending geometry during the period May 2017 to March 2021 has been processed at full resolution. The resolution of Sentinel-1 data is approximately 4×14 m^2. Specifically, two swaths and eight bursts have been processed to cover the area of interest. Images from Sentinel-1A and Sentinel1-B satellites have been exploited with a minimum temporal sampling of 6 days. The SRTM Digital Elevation Model provided by NASA was used to process the interferometric products. Finally, a set of 985 redundant wrapped interferograms were generated with a maximum temporal baseline of 30 days.

InSAR processing

The goal of the InSAR processing stage is to derive the deformation information of the area of interest from SAR data. The Persistent Scatterer Interferometry chain of the Geomatics (PSIG) Division of the CTTC described in Devanthery et al. 2014 has been used in this study. The main steps of the InSAR processing carried out are: (1) interferogram generation; (2) interferogram network selection performed with a statistical evaluation of the coherence of the study area to locate and remove those interferograms characterized by low coherence (e.g., snow periods in mountain areas); (3) selection of points based on the dispersion of amplitude; (4) estimation of the residual topographic error and subsequent removal from original SLC interferograms; (5) 2+1D phase unwrapping to obtain the stack of unwrapped phases which are temporally ordered in correspondence with the dates of the SAR images processed, hereafter referred as time series of deformation (TSD); (6) atmospheric phase screening estimation using spatio-temporal filters and removal from the TSDs generated in the previous step; (7) estimation of the velocity of deformation from the TSDs and; (8) geocoding of the results.

The output of the InSAR processing stage is a ground displacement map composed of a set of selected points, called Persistent Scatterers (PSs), with information on the estimated ground displacement velocity and the accumulated deformation at each Sentinel-1 image acquisition time, i.e. TSDs.

ADAs extraction

The main goal of this stage is the identification and mapping of those areas where ground displacement has been measured in the previous stage. The ADAfinder tool [4, 6, 8] has been used with that purpose. The input of this stage is the deformation map of the area of interest generated in the previous step. ADAfinder includes the option to filter the input deformation map from isolated or potential outlier PSs, which has been done in order to ease the detection of ADAs and avoid spurious results in the final ADA map. The ADA finder

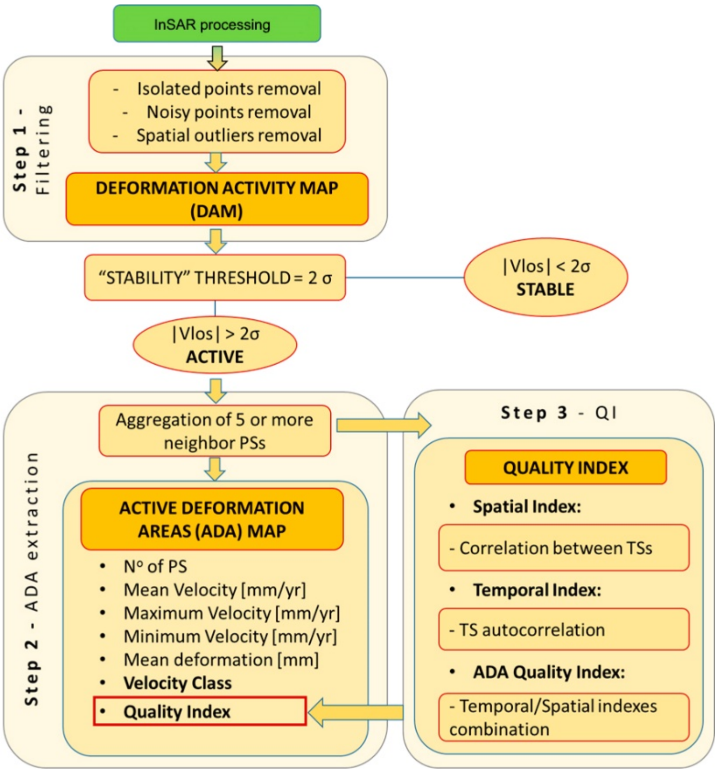

Figure 1: *Flow chart of the applied procedure (source [4]).*

employs the information contained in the filtered deformation map to define each ADA on the basis of their location and density of PSs, i.e. some thresholds as the minimum number of PSs making an ADA or the area of influence of each PS need to be defined. The minimum number of PSs making an ADA was set to 5 and the area of influence of each PS was set to 26 m. A quality index describing the noise level and the consistency of the displacement TSDs of the PSs contained at each ADA is calculated. The QI ranges from Class 1, which represents the ADAs characterized by very high quality TSDs, to Class 4. Specifically, Class 1 means reliable ADA and TSD; Class 2 means reliable ADA, but a further analysis of the TSD is recommended; Class 3 means reliable ADA but TSD cannot be exploited; and Class 4 denotes a not reliable ADA. For detailed information regarding the procedure to identify the ADAs and assess their quality please refer to (Barra et al. 2017, Navarro et al. 2020).

The outputs of the ADA extraction stage are two shapefiles containing the filtered ground displacement map and the ADA map. Regarding the former map, the user can decide whether to keep all the filtered PSs available in the area under study or just keep the PSs included in the extracted ADAs. The ADA map contains the polygons defining the boundaries of the ADAs. Each polygon contains a set of parameters about the displacement such as average velocity, average TSD or maximum measured displacement.

RESULTS

This section describes and analyses the results in two critical infrastructures located in the area under study: a section of the A-7 highway (Figure 2) as it passes through Granada County (Spain) and the Rules Reservoir (Figure 5), due to their relevance in the communications and water supply in the area.

Section of the A-7 highway

Figure 2 shows the obtained ground displacement velocity map in a section of the A-7 highway. Specifically, a section of approximately 40 km between La Gorgoracha and La Rábita (both located in Granada County, Spain). The green points indicate stability, the red colours indicate movements away from the satellite and the blue colours movements towards the satellite. A total of 6850 PSs were measured in that section of the A-7 highway. Several road sectors affected by deformation phenomena have been detected. These unstable areas are located in the cut slopes or the pavement of the A-7 highway as can be seen in Figures 3 and 4.

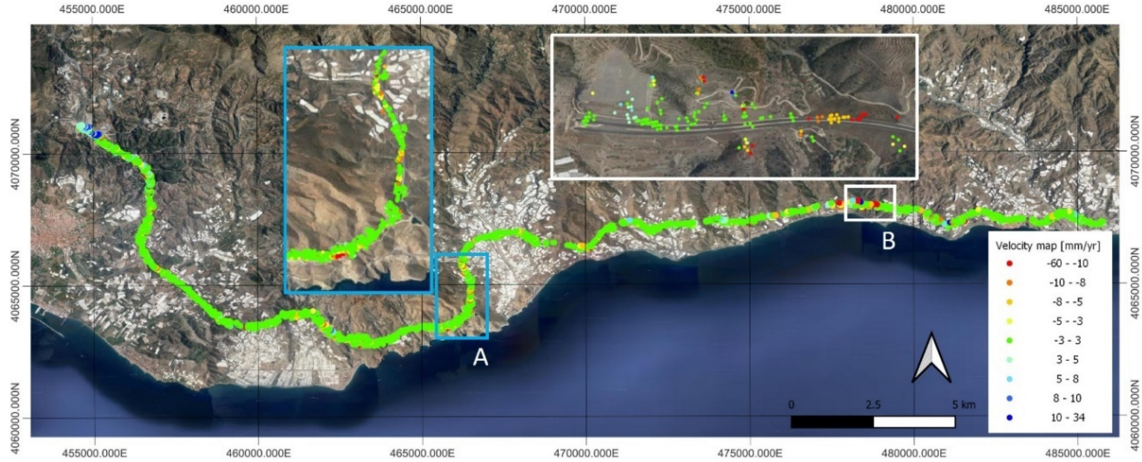

Figure 2. Deformation velocity map of the section of the A-7 highway between La Gorgoracha and La Rábita (Granada County, Spain). The areas A and B, amplified in the blue and white highlighted areas, show the test sites displayed in Figures 3 and 4, respectively

The ADAfinder tool extracted 29 ADAs in the 40 km section of the A-7 highway under study, of which 15 display QI=1, 3 exhibit QI=2, 3 correspond to QI=3, and 8 to QI=4. Figure 3 shows seven ADAs extracted in a section of the A-7 under study that exhibit different QI values, and thus different levels of reliability. For example, ADA (a) is a reliable ADA as indicates its QI=1. In this case, the TSDs (Figure 3a) shown as example display a low level of noise and display a consistent behaviour with movements away from the satellite of up to -60 mm. On the contrary, ADA (b), with a QI=4, represents the lowest quality of ADA that can be extracted. The TSDs of three of the PSs (Figure 2b) located at this ADA show a higher level of noise and different behaviour. In this case, TSD3 exhibits a near linear movement away from the satellite that seems to stabilize at the end of the observation period with a maximum displacement of up to -70 mm, TSD4 displays stability at the beginning of the observation period followed by a small window of time where there is movement away from the satellite and then stability with a maximum displacement of -40 mm, and finally TSD5 shows a smaller movement away from the satellite at the beginning of the observation period and then remains more or less stable compared with the other two TSDs.

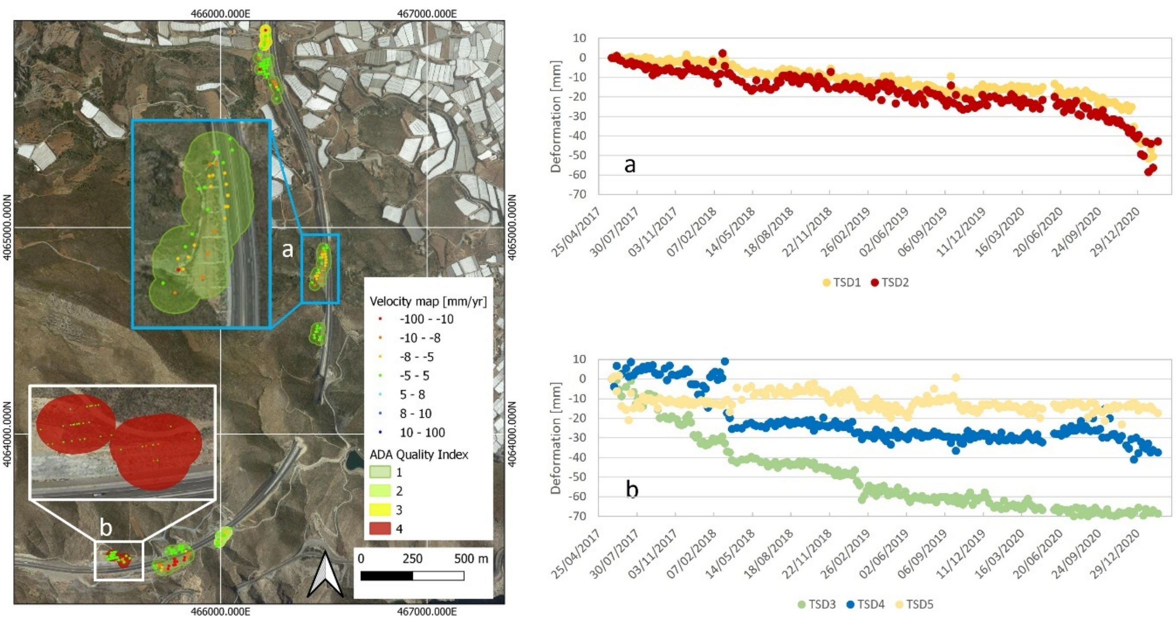

Figure 3. ADA map of the area A highlighted in blue in Figure 1, with two amplified ADAs (a and b) affecting two sectors of the A-7 highway. The velocity of deformation of the active PSs showing instability are displayed in this map. Stable PSs have been filtered out by the ADAfinder tool. Several time series of deformation (TSD) are displayed for each sector as example.

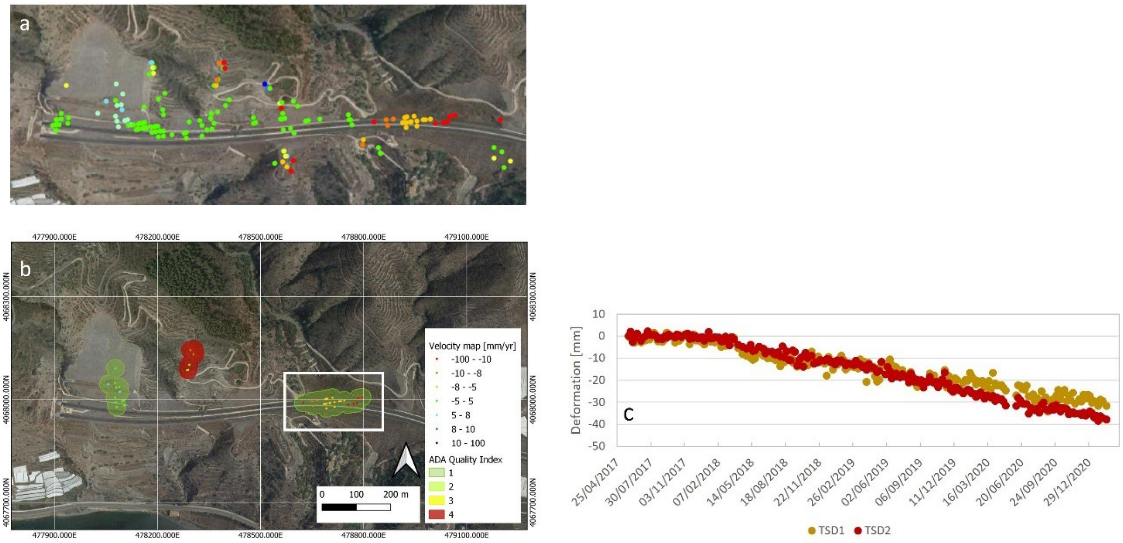

Figure 4. *Velocity of deformation map (a) and ADA map (b) of the area B highlighted in white in Figure 1. Two ADAs with QI=1 and one with QI=4 have been extracted in this area. Stable PSs have been filtered out by the ADAfinder tool in (b). (c) Time series of deformation (TSD) of two of the PSs making the ADA highlighted in white are displayed as example.*

Figure 4 illustrates another sector of the A-7 highway where three ADAs have been extracted (Figure 4b), two of them displaying QI=1 and the other QI=4. The TSDs (Figure 4c) shown as example display a low level of noise, similar behaviour but different maximum displacement. This is a good example to show the filtering approach of the ADAfinder. Figure 4a show the InSAR generated displacement velocity map and Figure 4b only those PSs kept after filtering the PSs showing stability (green points) and isolated PSs or those that do not meet the 5 PSs criteria set to make an ADA.

Rules Reservoir

The Rules reservoir is the second critical infrastructure located in the area under study that will be further analysed in this work due to its relevance to the water supply in the area. Figure 5 illustrates the ADA map generated for the reservoir and its surroundings. A total of 24 ADAs have been detected in this area with different levels of QI. Due to their significance, we focus of two ADAs detected over a viaduct and in the slope located on the southwestern part of that viaduct (Figure 5b).

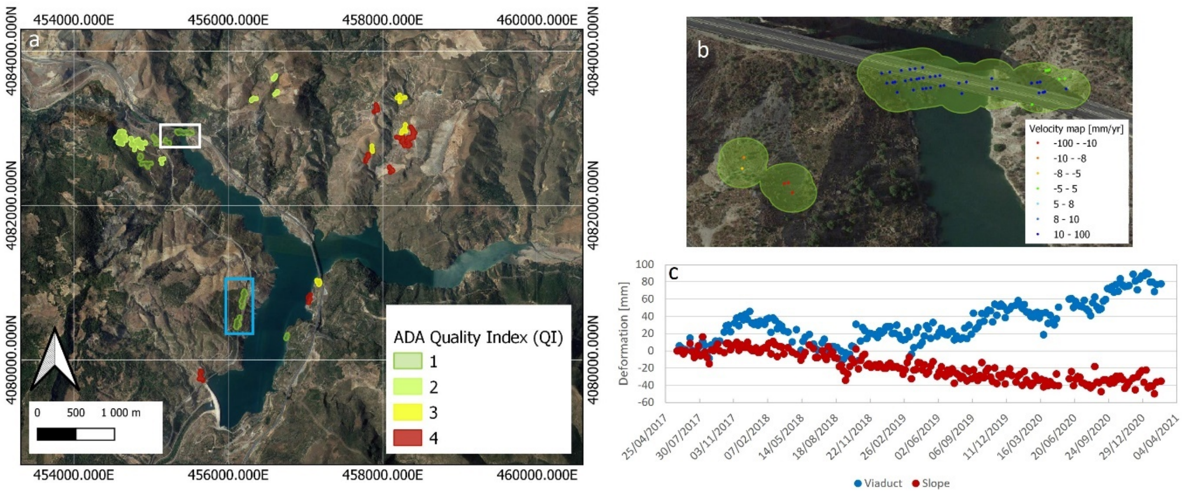

Figure 5 *(a) ADA map of the Rules reservoir with two areas highlighted in white and blue (shown in Figures 5b and 6). (b) Amplification of the area highlighted in white in (a). (c) Time series of deformation (TSDs) of a PS located in the ADA extracted on the viaduct (b) showing movements towards the satellite (blue line) and a PS located in the ADA detected on the slope located in the southwestern part of (b) displaying movements away from the satellite (red line).*

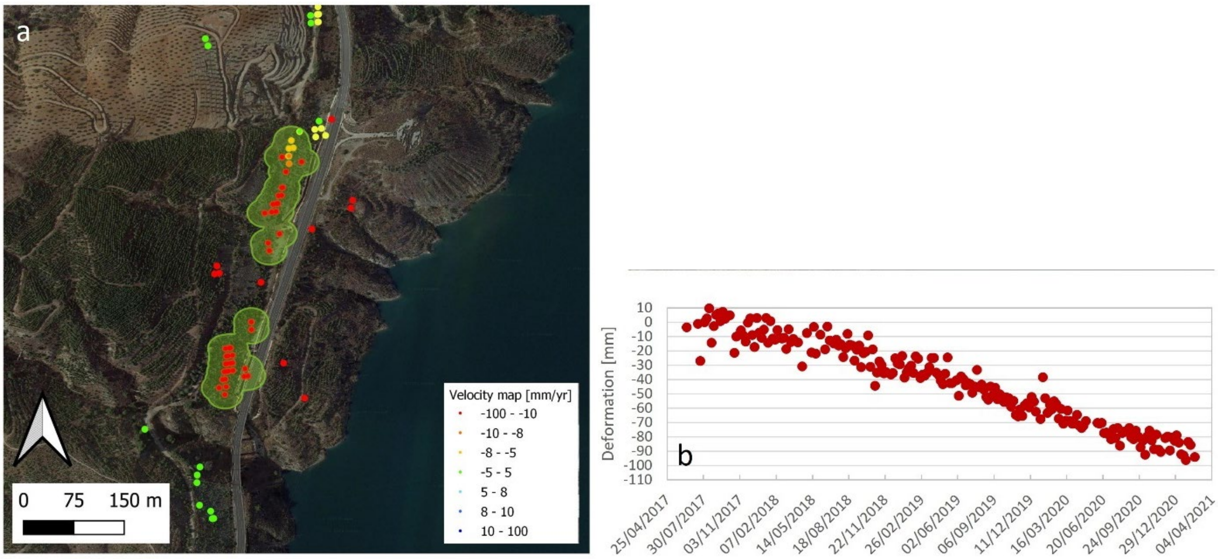

Figure 6*: ADA map and deformation velocity map of the area highlighted in blue int Fig. 5. Two ADAs with QI=1 are displayed.*

All the PSs belonging to the ADA located over the viaduct (Figure 5b) show movements towards the satellite (blue points) while the PSs located in the ADA on the slope display movements away from the satellite (red points). The TSDs of the PSs located in each ADA provide very useful information on the deformation phenomena that is occurring in those areas. A representative TSD of the PSs making each of the two ADAs is shown in Figure 5c.

The TSD of the viaduct, represented with blue points, show a seasonal displacement that might be compatible with a thermal expansion phenomenon characteristic of the viaducts and an uplift displacement beginning at the end of 2018. The PS located on the ADA extracted on the slope (red points) shows a displacement away from the satellite starting in the same period that the uplift movement detected on the viaduct.

Furthermore, Figure 6 shows two ADAs detected in the cut slopes of a road that surrounds the reservoir. A TSD representative of the displacement detected by the InSAR processing is shown in Fig. 6b. This TSD shows a linear movement away from the satellite with displacements of up to 100 mm. The movement detected in these ADAs is compatible with a landslide that might pose a risk to the road.

DISCUSSION

The work illustrates how ADAfinder tools can be used to ease the analysis of ground displacements measured with PS-InSAR data. The main goal of such tools is to simply and ease the interpretation of the ground displacement velocity map and TSDs resulting from the PS-InSAR. ADAfinder tools semi-automatically identify unstable areas or ADAs. It is worth emphasising that the ADA detection does not overcome the intrinsic limitations of the InSAR techniques, i.e. the absence of ADAs does not necessarily imply stability since it could also mean non-detectable movement due to unfavourable geometry (Ferretti et al. 2007) or lack of information due to low coherence.

Two regions of interest, located in Granada County (Spain), have been analysed due to their significance in the communication and water supply in the region. The first one corresponds to a section of approximately 40 km of the A-7 highway that has been affected by landslides and cut slope failures in several sections of its path as it passes through the territory of Granada County (Spain). InSAR and the ADAfinder tool have been exploited to assess and monitor road stability. In this area of interest, a total of 29 ADAs have been detected, of which 18 display QI 1 or 2, and 11 QI 3 or 4. An experienced user might be able to exploit information from the TSDs associated to the PSs belonging to low quality ADAs, i.e. QI 3 and 4. However, for non-expert users, the information provided by the QI related to the reliability of the extracted ADAs might prove useful to decide to contemplate, for example, only ADAs displaying QI 1 and 2, while disregarding QI 3 and 4. In any case, the methodology exploited in this work has been able to detect, with a high degree of reliability, 18 sectors of the A-7 highway characterized by instability which might pose a risk to the communications in the region and passing by drivers. Furthermore, a thorough analysis of the remaining 11 ADAs indicate that the information contained in some of the TSDs of the PSs making that ADAs might be exploited by experienced interpreters.

Regarding the Rules reservoir, several areas around this reservoir are known to be affected by instability processes. In this region, 24 ADAs displaying different levels of QI have been detected. Specifically, 14 of them have QI 1 or 2 and the other 14 QI 3 or 4. Many of the ADAs extracted in this region are in isolated slopes that might not pose too much risk. However, a few of them affect two relevant infrastructures, a viaduct and a road.

The results obtained demonstrate that the method applied in this work might prove useful for a fast and semi-automatic detection of geohazards. The ADAfinder tool provides an approach to rapidly assess the InSAR products to detect critical unstable areas that can be easily used by Civil Protections and Geological Surveys.

CONCLUSIONS

The methodology implemented to detect and analyze ground displacements based on satellite InSAR techniques and the ADAfinder tool, and a description and analysis of the results obtained for a regional area located in Granada County (Spain) have been presented. The complementarity of the PSIG InSAR technique and the ADAfinder tool have been demonstrated. On one hand, InSAR techniques are able to provide displacement measurements over large areas at low cost, but the difficulty to interpret those results by non-expert users hamper their use by decisions makers. On the other hand, the ADAfinder tool allows a semi-automatic identification of critical areas affected instability, i.e. the ADAs, satisfying the need for post-processing tools that ease the interpretation of the InSAR based outputs. The ADA tool might be exploited to rapidly obtain a set of deformation areas. However, an advanced analysis and interpretation is possible with the combination of all outputs as presented in this work. An integrated analysis of the velocity of deformation map, the TSDs and the ADA map might prove very useful to interpret the geological and geotechnical processes affecting wide areas. Furthermore, this set of techniques will support the exploitation of the European Ground Motion Service (EU-GMS), which will provide consistent, regular and reliable information on natural and anthropogenic ground motion phenomena all over Europe.

ACKNOWELEDGEMENTS

This work was mainly supported by the European Regional Development Fund (ERDF) through the project “RISKCOAST” (SOE3/P4/E0868) of the Interreg SUDOE Programme.

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