ADATools: free and easy-to-use tools for semi-automatically extracting and analysing multitemporal interferometric displacement maps

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Abstract

The availability of displacement maps based on Multi-Temporal Satellite SAR Interferometry (MT-InSAR) has greatly increased, particularly since the launch of the Copernicus Sentinel-1 satellites in 2014. These satellites provide open and free data, leading to services like the European Ground Motion Service (EGMS) which offers highly detailed displacement maps across Europe. Despite their potential for territorial management and risk assessment, the use of these maps is limited due to the complexity of the data and the lack of experience in interpreting MT-InSAR results. Projects such as RASTOOL and SARAI aim to address this by developing automated tools that simplify and expedite the analysis of EGMS data. The ADATools suite, including ADAFinder, ADAClassifier, and ADAImpact, automates the identification, classification, and impact assessment of active deformation areas (ADAs). These tools facilitate the use of displacement data for non-experts, supporting better management of territorial and infrastructural risks. Examples of ADATools applications to EGMS data highlight their strengths and future development potential, as part of the SARAI project.

1. Introduction

The availability of displacement maps in extensive areas based on Multi-Temporal Satellite SAR Interferometry (MT-InSAR) techniques has significantly increased in recent years (Crosetto et al. 2017, Crosetto and Solari, 2023). The launch of Copernicus Sentinel-1 satellites in 2014 marked a turning point in both the exploitation and application of these techniques thanks to a policy of global and regular acquisition and open and free data distribution. An example of this progress has been the development of regional, national, and continental services, providing displacement maps with very detailed information on both natural and anthropogenic processes. Since 2022, the European Ground Motion Service (EGMS - https://egms.land.copernicus.eu/) has been providing billions of updated displacement measurement points (MP) annually, covering almost the entire European territory and characterized by their high reliability. Despite the potential utility of these maps for territorial management and risk assessment, their use is lower. The main cause of this is precisely the large volume of information they contain and the lack of experience in interpreting MT-InSAR results. There is a critical need for automated tools that can simplify and accelerate the processes of extraction, analysis, and interpretation of EGMS information (Barra et al. 2017). The production of simplified and ready-to-use maps is crucial for the adoption of EGMS products by non-expert users in MT-InSAR.

In response to this need, projects such as RASTOOL (DG-ECHO, UCPM-PJG-101048474) and SARAI (MCIN/AEI) focus their activity on exploring methods of artificial intelligence and deterministic approaches. This work presents the ADATools (Active Deformation Areas Tools) tool. This tool is designed to be flexible, adaptable, and easy to use. It aims to support territorial and risk management, paying special attention on its compatibility with EGMS data format. The tool has different functionalities. ADAFinder allows for the automatic extraction and selection of the most important ADAs. After identifying areas in motion or ADAs, the ADAClassifier enables a preliminary assessment of the nature of the movement and a temporal characterization based on the automatic analysis of the time series of all MPs within each ADA. Finally, an initial classification of the ADAs is provided, considering their potential impact on structures and infrastructures, using the ADAImpact. In this work, we describe the main parts of the ADAtools and we show some examples of results of applications of ADATools, emphasizing strengths and outlining perspectives for future improvements. This work is part of the SARAI project, PID2020-116540RB-C21, funded by MCIN/AEI/ 10.13039/501100011033.

2. Methods

This work aims to present ADAtools, a tool for the automatic analysis of terrain displacement maps obtained through MT-InSAR. This simplified analysis focuses on three basic pillars: (i) Automatic identification of areas with movements; (ii) Automatic classification by type of movement: nature and temporal behaviour; (iii) Identification of urban areas exposed to potential damage. Figure 1 shows the flowchart of the methodology. The input data consist of a movement map obtained using MT-InSAR techniques.

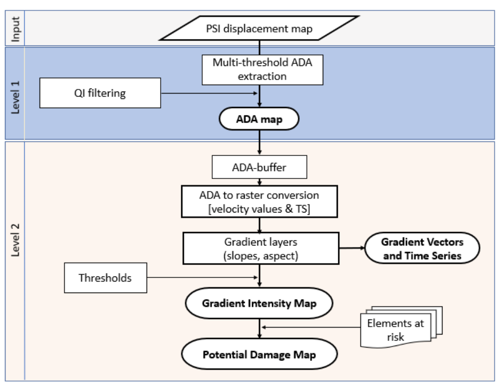

Figure 1. Flowchart of the methodology. In bold, the main results (Barra et al. 2022).

2.1 ADA Finder

The ADAFinder allows for the extraction of the most significant detected ADAs, substantially reducing the time required for the analysis of extensive displacement maps. This tool provides an ADA map that serves a dual purpose: it offers a global-scale overview to visualize and locate detected active areas, while summarizing key information such as average annual velocity, accumulated deformation, and a Quality Index (QI) that indicates the reliability of each detected ADA. For a complete description of the ADAFinder algorithm, refer to Barra et al., 2017 and Navarro et al., 2020.

The ADAFinder allows users to optionally filter input data and extract ADA polygons by simply adjusting a few user-defined parameters, enhancing the tool’s flexibility and usability.

When specifically focusing on ADA extraction, not filtering, the main parameters to configure are:

- *Velocity threshold.* This parameter sets the minimum velocity value (in absolute terms) required to consider each MP as active. It is important to note that MPs falling below this threshold may not inherently be stable but are excluded from active categorization.
- *Neighbourhood radius.* This parameter sets the distance between two points necessary for them to be considered neighbours, forming a cluster.
- *Minimum number of active and neighbouring MPs.* This parameter dictates the minimum count of active and neighbouring MPs essential to designate an area as ADA.

These parameters collectively guide the extraction process, identifying areas as ADA polygons where at least a specified minimum number of active and neighbouring MPs converge.

2.2 ADA Classifier

The ADAclassifier begins where ADAfinder ends. It takes the ADAs produced by ADAfinder and performs a series of tests to determine which type of ground movement process likely caused each ADA. Using auxiliary inputs, it verifies up to four different processes: subsidence, settlement, sinkhole, and landslide.

The auxiliary inputs include slope and aspect maps derived from the DEM, geological maps, inventories (for landslides, sinkholes, subsidence, settlement), and values of horizontal and vertical velocity components (VV and VH). As illustrated in Figure 2, these inputs are mandatory or optional depending on the specific phenomenon, and they complement the information from the ADAs, such as the average velocity in the satellite's line of sight (LOS). While some inputs, like slope and aspect derived from the DEM, ADA polygons, and MPs belonging to the ADAs, are always mandatory, others, like inventories, are optional as they may not be available for all areas.

Compared to the old tool (Navarro et al., 2019, 2020; Tomás et al., 2019), the new ADAclassifier features an algorithm with a completely new approach. This new methodology employs a scoring system to categorize ADAs into specific deformation phenomena, whether confirmed or potential. Like the previous version, various thematic and auxiliary inputs are used in the screening process, but in this case, each input is analysed with a separate and independent decision tree. Figure 3 shows, as an example, the tree used by the landslide classification process to determine if the intersection of an ADA with an inventory polygon exceeds a user-provided threshold (THLA02). Based on the existence or absence, and whether the

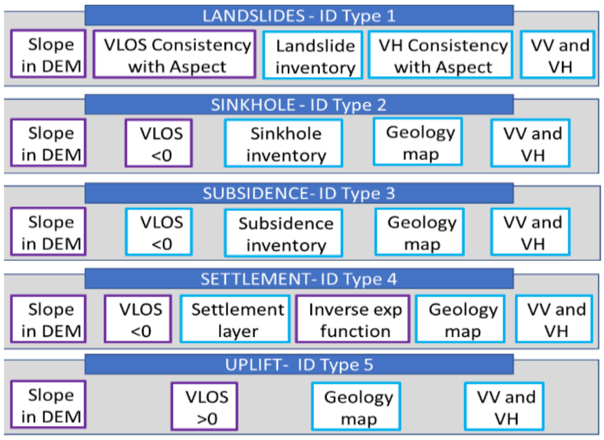

Figure 2. List of auxiliary inputs analyzed for each process. Mandatory inputs are highlighted in purple, optional inputs in blue.

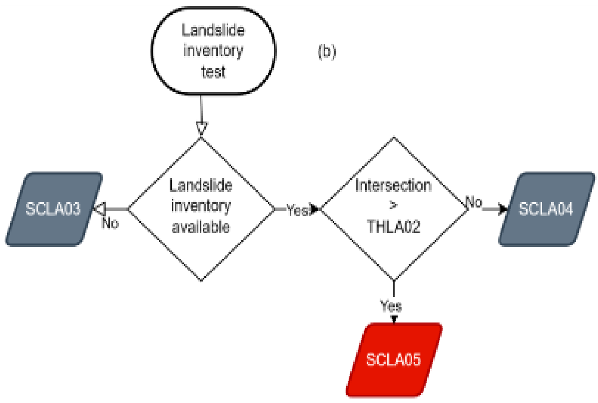

Figure 3. Example of a decision tree used by ADAClassifier to analyze the inventory input in the assessment of landslide processes. SCLA0X: output points of the tree. THLA0X: threshold percentage of intersection with a landslide inventory polygon.

intersection percentage exceeds THLA02, the tree assigns a score (SCLA0x). Through these trees, points are added or subtracted to the final decision of the process. The final points of each process indicate how confidently we can say that each ADA is or is not caused by this process. This allows for a final classification, attributing the process with the highest score. As an example, Figure 4 shows an example of ADAs extracted and classified in an area of approximately 4600 km², covering the Upper Guadalentín Basin (Spain). This region is particularly susceptible to subsidence, mainly caused by extensive groundwater extraction.

2.2.1 TS Classifier

The last version of the ADAtools includes a Python tool developed with the aim of classifying the TSs from the EGMS and quickly detecting whether the movement within the data is accelerating, maintaining constant, or decelerating.

The TS_Classifier allows users to perform analysis on each individual TS or aggregate and analyse the average TS of active MPs belonging to each ADA, enabling a temporal classification of each ADA based on its average temporal behaviour. Using the concept of moving windows to reduce noise influence, the TS_Classifier segments TS data into temporal windows for analysing overall trends as well as behaviour within and

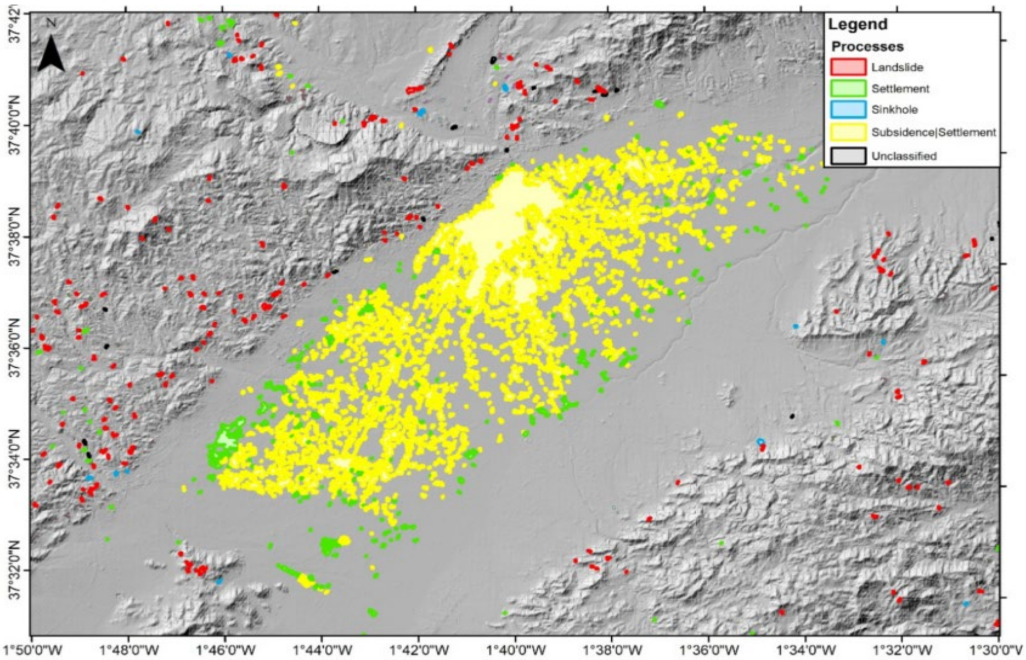

Figure 4. Example of classified ADAs over the Alto Guadalentín region.

between specific time intervals. The tool calculates the average velocity within time windows and evaluates the acceleration or deceleration occurring in the latest period relative to preceding behaviour. Users can define the duration of the time interval that defines the temporal window.

Figure 5 shows an example of average time series of two different ADAs, automatically classified into deceleration classes (top, TS_Class=1) and acceleration classes (bottom, TS_Class=3).

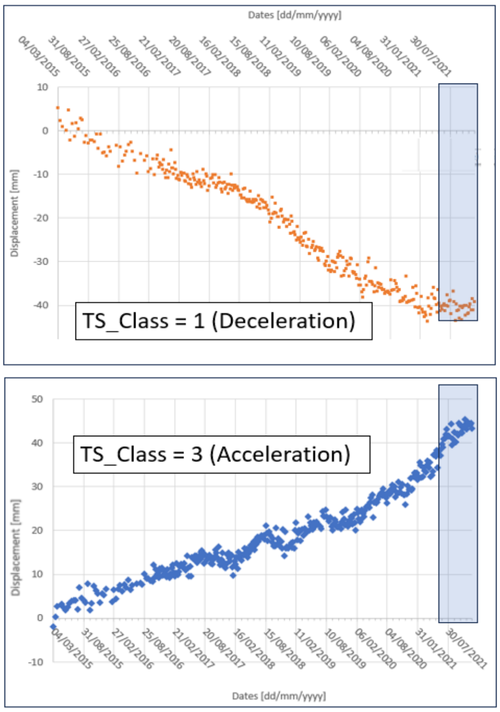

Figure 5: Example of TS classified with the TS_Classifier, the top one classified as deceleration and the bottom one as acceleration. The blue rectangle indicates the last period used to determine the class (6 months).

2.3 Potential damage maps

The final step, the estimation of potential damages, is carried out at the ADA level within a surrounding buffer. Velocity values within the ADA buffers are rasterized, and ultimately a slope map of velocity values is calculated. The classified slope serves as input for the main outcome of the methodology: the Potential Damage Map. Additionally, additional information is derived for deeper analysis and interpretation: gradient vectors, representing the direction of gradients, and the time series of gradients.

To assess potential damage to structures, at least three elements are required: identification and definition of parameters affecting structures, building characteristics, and the correlation between parameter intensity and damage levels. Commonly used parameters include total displacement, differential displacement, spatial gradient of displacement, inclination, displacement velocity, and depth of sliding surface. Building characteristics such as construction materials, geometry, foundations, age, and maintenance status are also considered.

The correlation between displacement parameter intensity and damage levels depends on the characteristics of exposed elements. This approach uses the spatial gradient of displacements as the primary inducing factor for damage. The goal is to evaluate gradient intensity and assign potential damage levels to buildings. The process follows a multi-scale perspective and is conducted in several stages, from obtaining a displacement map to generating gradient intensity and potential damage maps, purely based on earth observation data.

The objective is to identify areas susceptible to be affected by movement intensity, providing direct support to risk management and territorial planning.

3. Results

The proposed methodology is applied in an area of approximately 705 km² (Figure 6) located in the districts of Almuñécar and Salobreña, in the province of Granada (Andalusia, southern Spain).

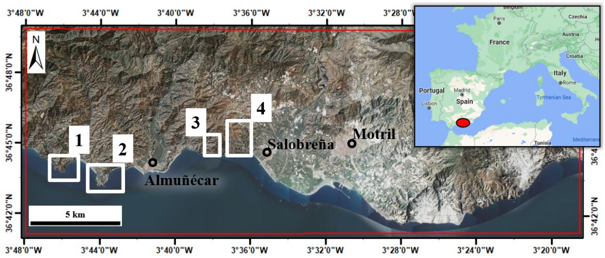

Figure 6. The upper figure shows the western coastal edge of Granada, which corresponds to the study area. Square 1 outlines the Cerro Gordo tourist complex. Zones 2, 3, and 4 show other areas affected by land movements.

This area is affected by numerous ground movement phenomena including landslides and subsidence (Chacón et al., 2006; Notti et al., 2016; Mateos et al., 2016; Reyes-Carmona et al., 2020, 2021). Since the late 1960s, these districts have undergone significant urban development (Chacón et al., 2014, 2016, 2019). This rapid territorial development has often resulted in the reactivation of pre-existing coastal landslides (Notti et al., 2015) or even triggered new ones (Chacón et al., 2014). Currently, many urban areas and several tourist complexes suffer damage and economic losses due to slope movements.

The areas marked by numbers 1 to 4 are zones affected by landslides along the area of interest. The analysis of potential impact focuses on the urbanization of Cerro Gordo (1). This urbanization was built on a coastal slope affected by a known landslide. Studies suggest that urban development triggered the reactivation of the landslide, experiencing accelerations during periods of heavy rainfall. Severe urban damage occurred after a series of intense rains recorded in the winter of 2009-2010. Cerro Gordo was partially evacuated and declared in a state of emergency in 2015 and is currently under legal proceedings.

MT-InSAR processing based on Sentinel-1 data allowed obtaining a displacement map consisting of approximately 215,000 measurements (Figure 7, top). For each point, the average annual velocity and the displacement time series are available. The estimated accuracy of the velocities is 2.9 mm per year. This value is used to assess the overall noise level of the displacement map, considering that changes in noise level within the Area of Interest (AOI) depend on local surface conditions and terrain cover characteristics.

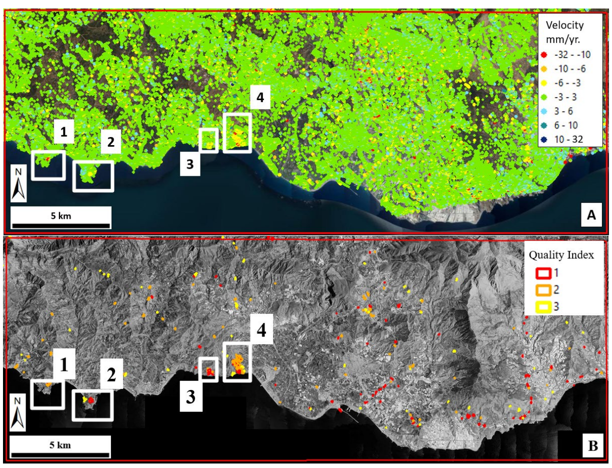

Figure 7. The upper figure shows the deformation velocity map in the study area. Reddish and yellowish tones can be seen in squares 1-4, indicating movement. The lower figure shows the detected ADAs. The colors classify them based on the quality of the measurements they comprise, with 1 being high and 3 being low.

From this map, the extraction of Active Deformation Areas (ADAs) was performed (Figure 7, bottom). In total, 175 ADAs have been identified. Each ADA is accompanied by a Quality Index (QI) that informs about the spatio-temporal consistency of the points within it.

Out of the 175 ADAs, 55 have a maximum quality value, indicating reliable ADAs, 72 have a medium value, interpreted as ADAs needing further detailed analysis, and 48 have a low level, reserved for ADAs where the temporal series cannot be exploited. ADAs with lower quality indices were discarded during classification.

Figure 8 shows a zoomed-in view of the Motril and Salobreña area with the ADA-Classifier results for the landslide class, although the results for the different classes are also discussed below. For this analysis, only one acquisition geometry (ascending) and a DTM, slope, and aspect were used. For this reason, it was only possible to obtain results labelled as "potential" at most for both landslide and subsidence phenomena. The minimum slope angle to consider a possible landslide has been set at 5 degrees, while the maximum slope angle to consider possible subsidence has been set at 10 degrees. It is noted that the slope considered is the average slope value within the ADA. The different slope thresholds allow a dual classification of the ADAs that are on the borderline between the two possible phenomena. An ADA is classified as possible subsidence only if it is on quaternary lithology.

Regarding consolidation settlement due to new constructions, 6 ADAs have been classified as settlement due to the clear inverse exponential trend of the average time series and the intersection with polygons related to infrastructures and urban areas. One ADA has been classified as possible settlement because it shows an inverse exponential trend but does not overlap with any polygon from the cadastral inventory.

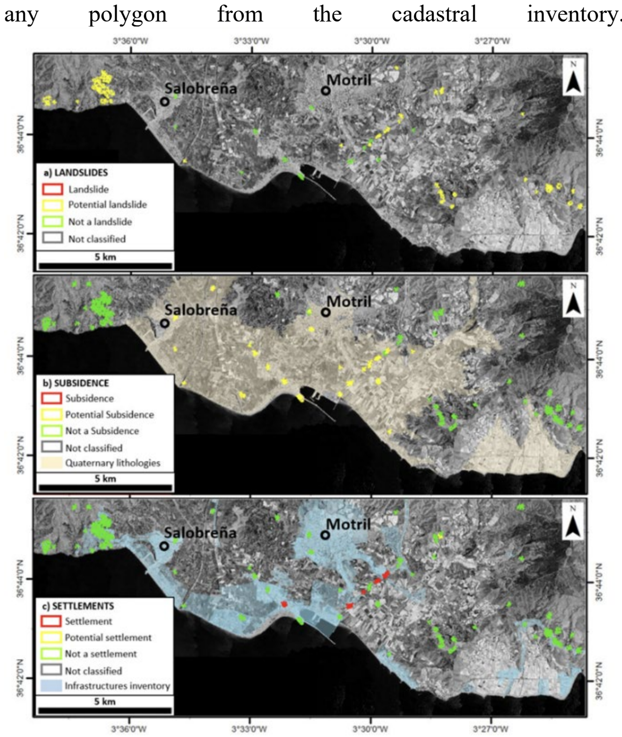

Figure 8. Classification according to the different types of phenomena in the area around Motril.

Among the settlement ADAs, 5 are on the newly constructed A-7 and one is on a building near the port of Motril; both structures were built between 2014 and 2015.

As for the ADAs classified as possible landslides, some of them are already known slope instabilities affecting the coast of Granada, such as the movements affecting the Los Almendros and Alfamar urbanizations. These are the areas 3 and 4 in Figures 6 and 7.

The last step of the procedure is to perform an analysis of the displacement gradients at the ADA level. The objective of this analysis is to evaluate the potential damage that a building or infrastructure will suffer over time. This analysis is performed considering only the intensity of the differential displacements affecting each structure. Figure 8 shows the potential damage map obtained for the Cerro Gordo Urbanization and some intermediate results. The colour assigned to each building represents the different levels of potential damage considering the intensity of the differential displacements affecting the building. Red represents the highest level of probability of suffering damage over time, while green signifies a very low probability.

Figure 8 c shows a damage map obtained from on-site inspection. The yellow circle shows an example of a time-related discrepancy between potential damage and what is visible in the field at the time of inspection. Comparing our damage inventory map (July 2020) with the one produced by Mateos et al., 2016 (January 2016), we see that the same building was classified with moderate damage severity in 2016, while it showed no damage in 2020. Therefore, the damage state has likely changed due to stabilization or reconstruction interventions carried out between 2016 and 2020, now counted as a false positive. Damage to roads or low walls, which have a direct response to differential movements, overlaps quite well with areas classified with moderate, high, or very high gradient intensity, often found near false positive predictions. The blue box in Figure 5 shows a case of a false negative: in this case, it is justified as a residual area of the analysis with little information to produce a reliable prediction.

It is important to note that these potential impact maps are derived using only movement information. They can serve as a first approximation for detecting critical areas. Factors such as the type of deformation, type of construction, and others are important for a real risk assessment.

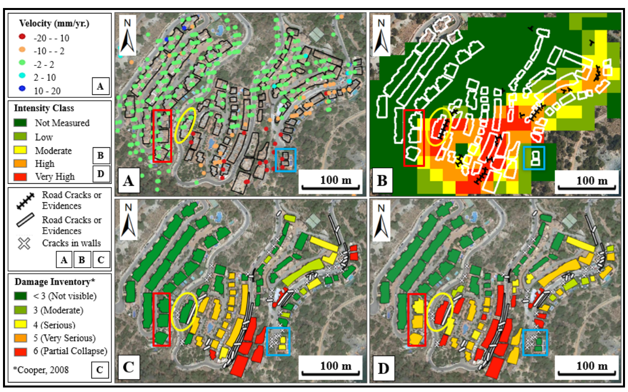

Figure 5: Results in Cerro Gordo. A) PSI displacement velocity map (input of the methodology); B) Gradient Intensity Map (result of the methodology), overlaid with building polygons (white) and cracks in the road mapped in the field (black lines); C) Damage inventory map created through field survey; D) Potential Damage Map (result of the methodology). (Source: Barra et al. 2022)

4. Conclusion

The implemented methodology detects, and analyses ground displacements based on satellite InSAR techniques and ADAtools. This article presents a description and analysis of the results obtained for an area located on the coastal zone of Granada (Spain). The work demonstrates the capabilities of ADAtools to support the analysis of displacement maps generated by InSAR. On the one hand, InSAR techniques can provide displacement measurements over large areas at a low cost, but the difficulty in interpreting these results by non-expert users hinders their use in decision-making. On the other hand, ADAtools enable the semi-automatic identification of critical areas affected by instability, i.e., the ADAs, and provide a preliminary assessment of the nature of the movement process. An integrated analysis of the deformation velocity map and the time series of each ADA can provide critical information on the potential effects of movement on buildings and infrastructures.

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