

Landslide Monitoring by Radar Permanent Scattered Remote Sensing Technique in Tangier

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Abstract. In northern Morocco, local authorities in Tanger commonly map landslide susceptibility to support effective land use management and urban planning. The area's complex geology leads to significant land surface displacement, resulting in instability phenomena such as landslides and block falls. This study utilizes Persistent Scatterer Interferometric Synthetic Aperture Radar (PSinSAR) techniques with Sentinel-1 data in Interferometric Wide (IW) mode to evaluate ground deformation in Tanger from 2021 to 2023. We focused on mapping surface displacements in the radar line-of-sight direction by identifying persistent scatterers. The findings enhance the understanding and monitoring of slow deformation phenomena in the region, providing essential insights for land management and infrastructure planning.

Keywords: Tangier, landslide susceptibility mapping, PSinSAR, land-use planning, subsidence rate.

1 Introduction

Landslides are significant natural hazards with a global impact, causing substantial human and economic losses [1, 2]. Defined as the movement of a mass of rock, debris, or soil down a slope due to gravity [3], landslides can be triggered by various natural phenomena such as earthquakes, heavy rainfall, volcanic eruptions, or anthropogenic activities [4]. Large-scale construction, temperature increases, extensive development of road and rail networks, and heightened traffic flow also contribute to land subsidence [5].

Extensive research has been conducted on landslide detection using Persistent Scatterer Interferometric Synthetic Aperture Radar (PSinSAR) [6]. PSinSAR is a long-term, multi-temporal technique that produces a series of deformation measurements over natural or anthropogenic targets by analyzing a sequence of SAR images over time [7, 8]. This method identifies pixels with stable phase and high coherence, on interferograms generated using a master image [9, 10]. This paper focuses on the detection and measurement of subsidence and landslides and the subsidence velocity with centimeter-per-year accuracy through stable point detection. Reliable and accelerated PS points are identified to enhance the

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understanding of the location's kinematics. This study employs the new persistent scatterer technique, PSInSAR, in the Tangier region of Morocco, utilizing complex SLC data from Sentinel-1 in Interferometric Wide (IW) mode with VV and VH polarization from 2021 to 2023. The objective is to investigate landslide occurrences and their environmental impacts in Tangier.

1.1 Study Area

1.1.1 Geological, structural, and hydrogeological setting of the area

The study area for this research is situated in Tangier, located in Northwest Morocco at $35^{\circ}45'34.074''$ N, $5^{\circ}50'2.234''$ W, approximately 14 km from the southern Spanish coast (Figure 1). Tangier lies at the northwestern tip of the Rif Mountain range and extends along the southern shore of the Strait of Gibraltar. Positioned on the Rif Mountain range's western edge, Tangier marks the Maghrebian Alpine chain's western extremity, which extends along the North African Mediterranean coast from Calabria to the Gibraltar Arc [11]. The city is bordered by distinctive geographical features: to the north by the Strait of Gibraltar, to the west by the Atlantic Ocean, to the south by Asila, and to the east by the internal Rif formations near Tétouan. The region's relief is shaped by complex tectonic movements during the Oligo-Miocene, forming distinct strata in the mountains [12]. These movements have resulted in low massifs and hills surrounded by notable sandstone formations of the Numidian nappe, often seen at higher altitudes. The hinterland of Tangier is characterized by the stacking of four layers of flysch resting on the Tangier unit: Melloussa, Béni-Ider, Tisirène, and the Numidian layer [13]. This specific geology enriches the region's landscape and natural environment. Tangier's dense hydrographic network comprises four main temporary wadis, each draining a specific part of the region: Boukhalf, Bougadou, Mharhar, Lihoud, Souani, Moghogha, and Mellaleh. These watercourses are vital elements of the local ecosystem and have shaped the environment over time. The rugged relief of the Tangier peninsula, exposed to three coastal fronts (Atlantic, Strait of Gibraltar, and Mediterranean), bears witness to the complex geological and geographical influences of the region [14]. The area's subsequent evolution, marked by significant neotectonic activity, has added dimension to its geological and environmental dynamics [15]. Landslides are a significant natural hazard in Morocco, particularly in the Rif region. They have caused substantial environmental and socioeconomic losses in recent decades, including road cuts (34%), road subsidence (18%), habitat destruction (18%), railway collapses (12%), and the destruction of numerous hydraulic infrastructures [16].

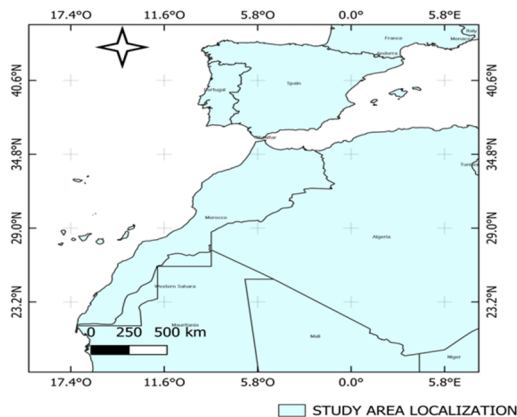


Fig. 1. Study Area

2 Materials and methods

2.1 Sar radar interferometry principle

They should be centered above the tables and flush left beneath the figures Repeating satellite passes in synthetic aperture radar interferometry (InSAR) potentially offers a unique, cost-effective tool for monitoring surface deformations over large areas [17, 18, 19,20]. This well-known technique involves comparing interferometric phases of SAR images acquired at different times and with different baselines, providing millimeter-scale accuracy for terrain deformations. To achieve this, Permanent Scatterers Synthetic Aperture Radar Interferometry (PSInSAR) data can be effectively utilized, particularly in slow or very slow landslide case studies [21, 22]. The PSInSAR method analyzes a backscattered signal from multi-temporal and co-registered SAR images to identify highly reflective ground elements known as Permanent Scatterers (PS).

PSInSAR techniques identify these persistent scatterers on interferograms generated using a master image [23, 24]. This approach efficiently eliminates atmospheric effects and temporal/geometric decorrelations, allowing for millimeter-level precision in measuring terrain deformation.

2.2 Sentinel 1A and 1B images

We utilized a total of 15 images spanning from April 5, 2021, to September 10, 2023, to track ground displacement within the study area and detect potential slope movements. (Table 1) below is a concise overview of the acquisition years, satellites, sensors, product types, polarizations, and acquisition modes of our dataset. To conduct interferometry and obtain high-quality interferograms (Figure 4), it is essential to work with images that have parallel polarization. However, in our region, we only have access to IW data with dual polarization (VV and VH). Notably, the VV polarization is more responsive to vertically oriented structures, such as vegetation and urban areas, compared to HH polarization. This discrepancy may result in a potential lack or loss of Persistent Scatterers (PS) in our final results.

Table 1. Description of images used for the PSI method of the study area

Satellite	Years of acquisition	Sensor	Type of product	Polarization	Mode of acquisition
Sentinel 1-A Sentinel 1-B	2021-2022 2023	SAR-C	SLC	VV -VH	IW

2.3 Pre-processing and processing

The SLC images are divided into 3 sub-swaths for each image, and bursts of interest (4 and 5) have been selected from the IW3 sub-swath (Figure 3). The master image is selected in a way that minimizes the distribution of values along the perpendicular baseline and maximizes the (expected) coherence of the interferometric stack. The images must be co-registered to

become superposable. The first chosen image will be the master image (20220319 in our case). This master image was selected using the 'INSAR STACK OVERVIEW' tool. Removal of horizontal black bands – Debursting eliminates the black bands. It is applied to the stack of interferograms obtained in the previous step and to the stack of co-registered images. Atmospheric and topographic corrections were used to ensure the accuracy and reliability of the interferometric results. The atmospheric correction (Figure .6) accounts for the influence of weather and atmospheric conditions on the radar signal, while the topographic correction (Figure .5) adjusts for the effect of the Earth's surface features, such as elevation and terrain variations, on the radar data. Both corrections were crucial for improving the precision of the displacement measurements and ensuring the integrity of the final results.

2.3.1 Preparation with Python script

We have developed the coregistration and interferogram creation steps using the graph processing tool library and based on the Snap2Stamps module. The coregistration and interferograms have been developed within a single Python code, but the exportation requires two inputs, which prompted the separation of the code into coregistration and interferogram creation components (Figure 3).

2.3.2 Processing with STAMPS

Processing with STAMPS (Stanford Method for Permanent Scatterer) is a software package that uses spatial phase correlation in interferograms to find phase-stable pixels.

2.3.3 Processing with MATLAB

To prepare MATLAB, you would first call the script 'mt_prep_snap.py' located in the results folder obtained during the STAMPS export.

2.3.4 Processing with Snaphu

After phase filtering, the unwrapped interferograms generated a height map by calculating the vertical displacement

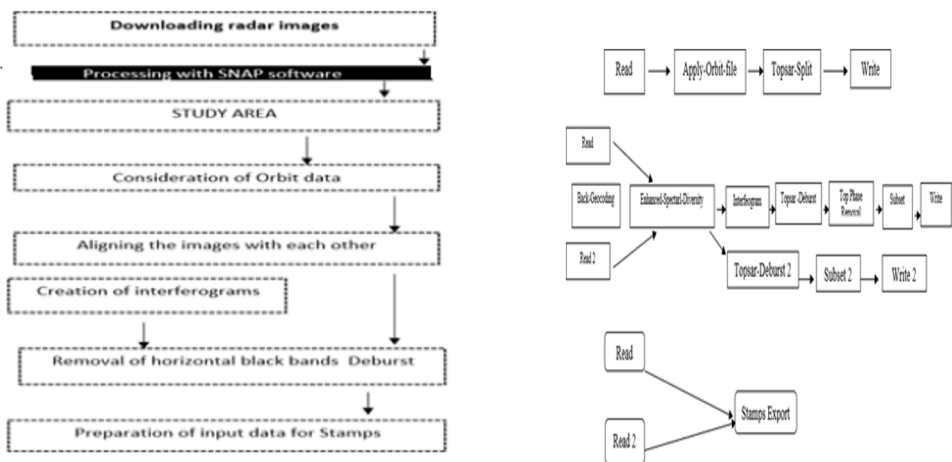


Fig. 2. Workflow of the Study.

3 Results and discussion

The ground movement speed in the selected area varies between 9.8 mm and -12.3 mm from April 5th, 2021, to September 10th, 2023. Overall, there is a growing trend of subsidence towards the east of the study area, particularly in the Achakar region, where it reaches -12.3 mm/year (-1.23 cm), and towards the west (Figure 7). Conversely, we observe a progressively stronger uplift speed at the center of the study area, reaching 9.8 mm/year. In addition to the spatial distribution of PSs identified by radar and their Line of Sight (LOS) velocity, it is possible to visualize a chronological series of displacement data for each PS (Figure 8). Each point contains a temporal record of deformation. Some PSs have been identified in the city of Tangier during the period 05/04/2021- 10/09/2023, and three of them are labeled with different colors. These PSs respectively show an average velocity of -0.5 mm/year and 2.5 mm/year. The displacement value for each PS is expressed as a velocity in millimeters for a year and has a negative sign if the target moves away from the sensor (ground subsidence) or a positive sign if the target approaches the sensor (ground uplifting) (figure 9). We exported all the results in Kml format to achieve a 3D visualization using Google Earth Pro. The PS was exported using the command ">ps scatter" in Matlab.) Using the Stamps commands in Matlab, we exported the PS into Kml format to visualize them in Google Earth, aiming for a comprehensive 3D view of their dispersion about the displacement results ((Figure 10).

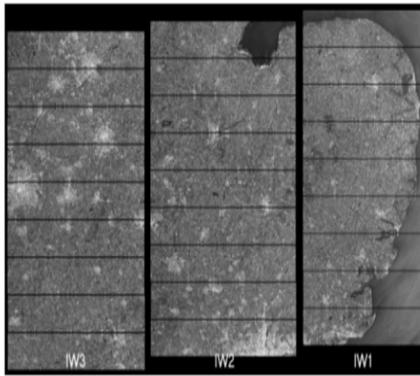


Fig. 3 . Subdivision of an SLC image

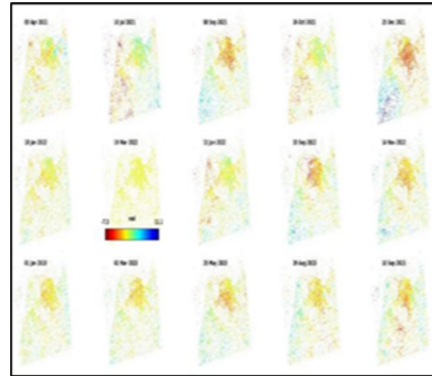


Fig. 4. Interferograms

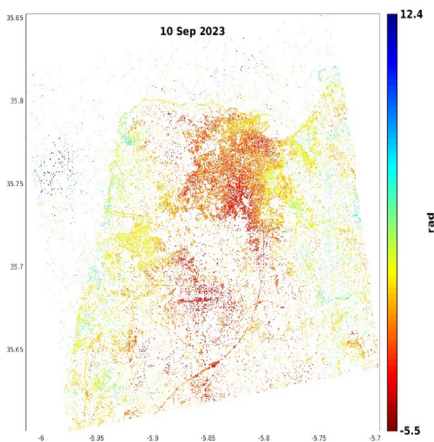


Fig. 5 . Atmospheric corrections

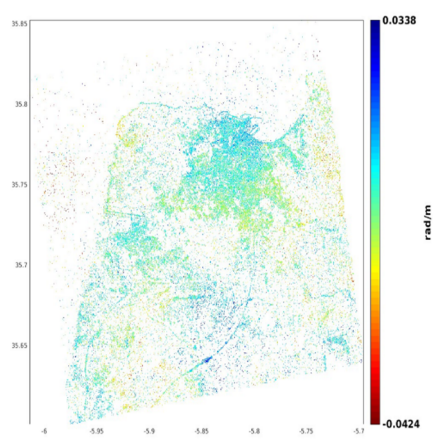


Fig. 6. Contribution of topography



Fig.7. Visualisation of PS in the study area

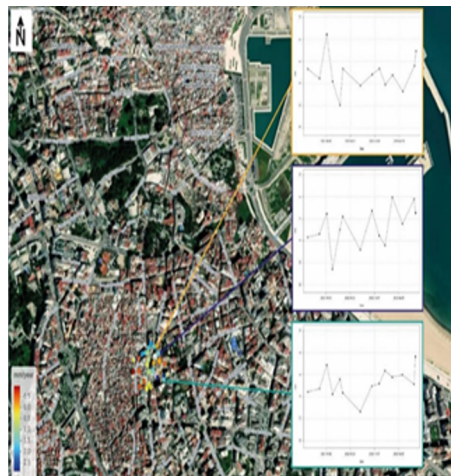


Fig.8. Chronological series of displacement data for each PS



Fig. 9. Google Earth visualization of PSs

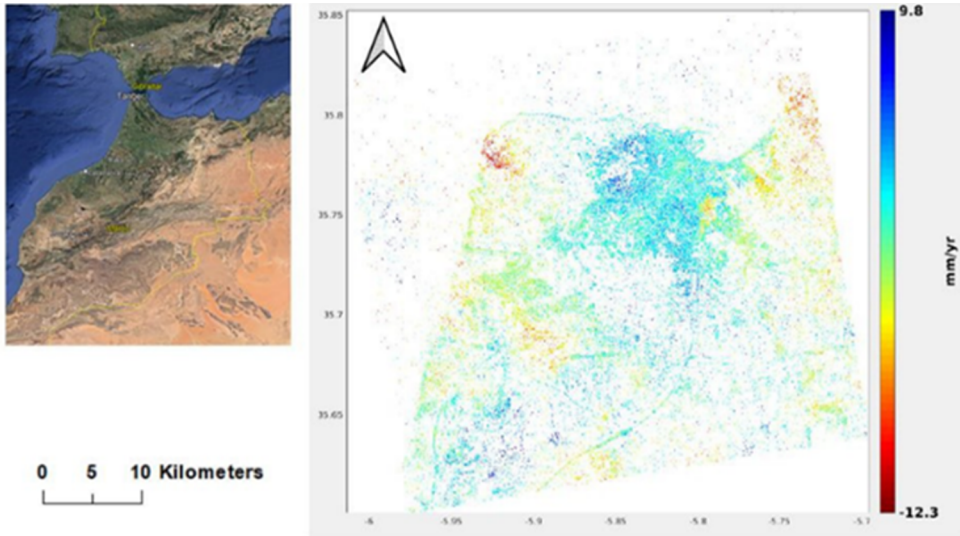


Fig. 10. Map of ground displacement velocity between 2021 and 2023 in the Tanger area in mm/year

4 Conclusion

In conclusion, this study investigated landslide phenomena in Tanger over two years from 2021 to 2023 using the PSInSAR method. Our analyses revealed significant ground movements, particularly in Achakar and the city center, with displacements ranging from - 12.3 to 9.8 mm/year. These findings underscore the extent of landslide risk in these urban areas, highlighting Tanger's vulnerability to this natural phenomenon. Accurate identification of landslide-prone areas is essential for urban planning and natural disaster management. Our conclusions provide a solid foundation for developing prevention and risk mitigation strategies, such as implementing soil stabilization measures, ongoing landslide monitoring, and raising awareness among local populations. However, it is important to note some limitations of this study, including the limited spatial resolution of PSInSAR data and the need to complement these results with other data sources for a comprehensive assessment of landslide risks in Tangier. In the future, it is crucial to continue research in this field by refining monitoring and analysis methods and assessing the potential impact of climate change on the frequency and intensity of landslides. By integrating this knowledge into land use policies and emergency plans, we can contribute to strengthening Tanger's resilience to natural hazards and ensuring sustainable urban development in the region.

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Author Contribution

All authors (Ali Hadek, Miriam Wahbi, Mohammed Hlal, Mustapha Maatouk, Hakim Boulaassal, Omar El Kharki, and Otman Yazidi Alaoui) reviewed and approved the final manuscript. Ali Hadek and Mohammed Hlal contributed to developing the methodology, analyzing the data, and addressing the research problem. Miriam Wahbi, Mustapha Maatouk, and Hakim Boulaassal contributed to the supervision and revision of the paper, ensuring its coherence and overall quality. Omar El Kharki participated in developing the methodology, while Otman Yazidi Alaoui was involved in reviewing the article.

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

All authors have agreed to publish this article.

Competing Interests

The authors declare that they have no competing interests.

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