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Study of spatiotemporal evolution of landslides along the El Jebha-Amtar Corridor (Morocco) using InSAR techniques

Estudio de la evolución espaciotemporal de deslizamientos a lo largo del Corredor El Jebha-Amtar (Marruecos) utilizando técnicas InSAR

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ABSTRACT

The El Jebha-Amtar corridor in northern Morocco experiences frequent landslides that threaten critical infrastructure, including the RN16 highway. This study employs Persistent Scatterer Interferometry (PSInSAR) with Sentinel-1 data (January–December 2019) to map ground deformation in the region, identifying displacements ranging from 20.71 mm uplift to -21.57 mm subsidence, especially concentrated near El Jebha. Analysis of rainfall data reveals its significant contribution to slope instability, with deformation patterns strongly influenced by the area's complex geology, characterized by fractured metamorphic rocks and active faulting. This integrated approach offers valuable insights for developing targeted landslide risk assessment and mitigation strategies specific to the El Jebha-Amtar corridor.

Key-words: *Landslides, PSInSAR, El Jebha-Amtar Corridor, Rainfall, RN16, Hazard Assessment.*

RESUMEN

El corredor El Jebha-Amtar en el norte de Marruecos enfrenta deslizamientos de tierra frecuentes que amenazan la infraestructura crítica, incluida la carretera RN16. Este estudio emplea la Interferometría de Dispersores Persistentes (PSInSAR) con datos de Sentinel-1 (enero-diciembre de 2019) para mapear la deformación del terreno en la región, identificando desplazamientos que van desde 20.71 mm de elevación hasta -21.57 mm de subsidencia, especialmente concentrados cerca de El Jebha. El análisis de datos de lluvia revela su contribución significativa a la inestabilidad de las pendientes, con patrones de deformación fuertemente influenciados por la compleja geología del área, caracterizada por rocas metamórficas fracturadas y fallas activas. Este enfoque integrado ofrece información valiosa para desarrollar estrategias de evaluación y mitigación de riesgos de deslizamientos de tierra específicas para el corredor El Jebha-Amtar.

Palabras clave: *Deslizamientos de tierra, PSInSAR, Corredor El Jebha-Amtar, Lluvia, RN16, Evaluación de riesgo.*

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Introduction

Landslides are a major threat to the El Jebha-Amtar corridor in the Rif Mountains of northern Morocco, particularly affecting the RN16 highway that links Tétouan to Al Hoceima (fig. 1). The region's steep topography, complex geology, and frequent seismic activity make it highly susceptible to landslides, rockfalls, and mudflows, resulting in costly disruptions to transportation (Rmili and Janati, 1995; Lacroix, 1985; Fonseca et al., 2014). Despite slope reinforcement and road rehabilitation efforts, the risks remain substantial (Dardori, 1995; El Kharim, 2002).

El Jebha, a crucial port town along this route, faces frequent road closures due to landslides. Fractured rock formations, combined with heavy rainfall, exacerbate slope instability, endangering infrastructure and local communities (El Kharim et al., 2021; Obda et al., 2022). The high velocity and long runout distances of rockfalls and avalanches pose significant hazards (Palma et al., 2012; Cignetti et al., 2021), highlighting the importance of thorough hazard assessments (Aleotti & Chowdhury, 1999; Dai & Lee, 2002; Van Westen et al., 2008; Mastere et al., 2013).

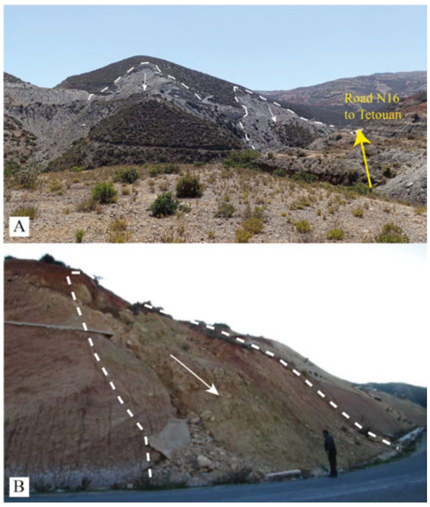

Fig. 1.- Landslide on El Jebha road (RN16). See color figure in the online version.
Fig. 1.- Deslizamiento de tierra en la carretera El Jebha (RN16). Ver figura en color en la versión web.

This study uses Persistent Scatterer Interferometry (PSInSAR) and Sentinel-1A satellite data to monitor ground deformation in the El Jebha-Amtar corridor. By analyzing displacement patterns and correlating them with rainfall data from 2019, the research aims to enhance landslide hazard assessments and inform mitigation strategies to safeguard the RN16 highway and nearby infrastructure (Meziane et al., 2018; Ghzala et al., 2019; Muhire et al., 2018).

Geological framework

The study area covers approximately 80 km², extending from El Jebha to Am-

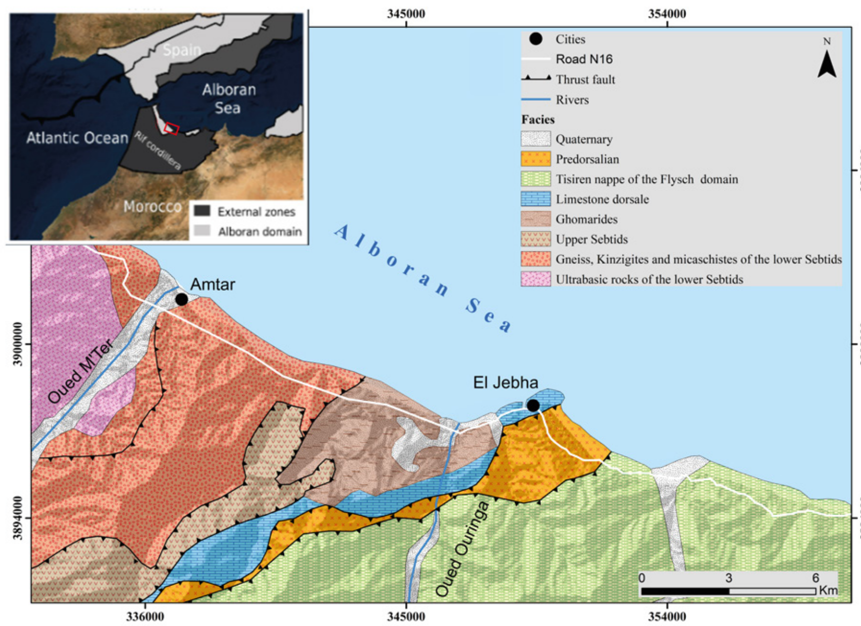

Fig. 2.- Geological map of the study area (modified from DIR. GEOL. MAROC, 2011; Kornprobst & Wildi, 1980). See color figure in the online version.

Fig. 2.- Mapa geológico del área de estudio (modificado de DIR. GEOL. MAROC, 2011; Kornprobst y Wildi, 1980). Ver figura en color en la versión web.

tar along the Mediterranean coastal road N16 (fig. 2). This region forms part of the Rif chain, which spans the northern coast of Africa and constitutes the southwestern end of the Betic-Rif-Tell orogeny. The mountain system has been uplifting over the past 70 million years due to the convergence of the African and Eurasian plates (Fonseca, 2014; Morel & Meghraoui, 1996).

The Rif chain is subdivided into three structural zones: internal; flysch nappes and external zones (Delga et al., 1962; Didon et al., 1973). The internal units, composed of a stack of allochthonous units from the Alboran domain, were overthrust on the African and Iberian borders (Chalouan et al., 2008).

Our study is situated in the internal zones where the Sebtides unit consists of micaschistes, migmatite and granulite associated with mantle peridotite (fig. 2). This unit is overthrust through a regional detachment by the Ghomarides, which include schist and greywacke affected by Variscan metamorphism and by weak Alpine recrystallization (Chalouan et al., 2001; Chalouan & Michard, 1990).

Climate

The climate of the El Jebha region is Mediterranean, with rainfall of 300 mm on average, occurring on the wet season from October to April, and peaking on November and December. June, July and August are dry months, occasionnaly including thunderstorms which bring heavy torrential downpours (fig. 4). The occurence of these downpours in rather warm seasons enhance the infiltration of water into the fractured marl, limestone, and clay formations. Rains are, however, often torrential in nature even in wet seasons (Tag et al 2023). Average temperatures typically range between 20 and 32°C in summer and 7 and 22°C in winter.

Methodology

1. Persistent scatterer interferometry (PS-InSAR)

Data Collection

The SAR images used in this study were obtained from NASA's Alaska Satellite Facility (ASF) archive (https://search.asf.alaska.edu/). A total of 24 Sentinel-1A SAR images were acquired, with 12 images in ascending mode and 12 in descending mode, covering the period from January to December 2019.

PS-InSAR Technique

Persistent Scatterer Interferometry (PS-InSAR) is a powerful remote sensing technique used for monitoring ground deformation with high precision and temporal resolution. Unlike traditional InSAR methods, PS-InSAR focuses on identifying and analyzing stable scatterer points (persistent scatterers, PS) that exhibit coherent radar reflections over time. These points are typically associated with stable features such as buildings, rocks, and infrastructure, allowing for the detection of subtle ground movements (Ferretti et al., 2001).

In the context of landslide monitoring, PS-InSAR provides valuable insights into the spatial and temporal evolution of ground deformation (Singhroy et al., 2013; Cigna et al., 2019). By analyzing displacement time series derived from interferometric pairs, PS-InSAR can delineate areas prone to landslide activity and quantify displacement rates, aiding in understanding the underlying factors triggering landslides.

Data Processing

Interferometric and time series analysis

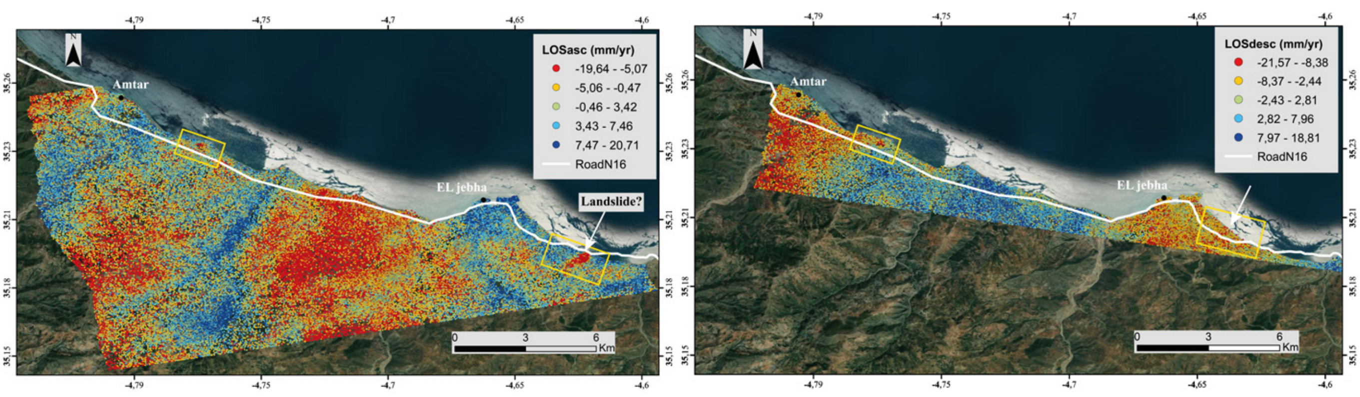

Fig. 3.- Average Line-Of-Sight velocities for Ascending (A) and Descending (B) mode during 2019. See color figure in the online version.

Fig. 3.- Velocidades medias de la Línea de visión para el modo Ascendente (A) y Descendente (B) durante 2019. Ver figura en color en la versión web.

were performed using the SNAP, SNAP2StaMPS, and StaMPS/MTI software packages (Delgado Blasco et al., 2019; Foumelis et al., 2018; Hooper et al., 2012). A master image for each mode (22/06/2019 for ascending, 10/08/2019 for descending) was selected based on minimal perpendicular baseline values and high interferometric coherence. Images were cropped using the TopSAR Split operator, and precise orbit files were applied for accurate satellite position correction.

Co-registration was completed using the Back Geocoding operation with a 30-meter SRTM DEM. The images were then debursted and merged where necessary. Interferograms were generated and processed in StaMPS (Hooper et al., 2010) to identify persistent scatterer points based on phase noise characteristics. Phase unwrapping and corrections for look angle errors were applied, followed by atmospheric filtering to enhance accuracy.

The final displacement data were exported to QGIS for visual representation, and time series analyses were conducted using R/RStudio to produce the results.

2. Rainfall data

Rainfall data covering the period from January to December 2019 was obtained from the University of California, Irvine's Center for Hydrometeorology and Remote Sensing (CHRS) database (https://chrsdata.eng.uci.edu/). This data is pivotal in assessing the influence of precipitation on landslide occurrences in the study area.

Results and discussion

The InSAR analysis revealed significant displacement patterns across the El Jebha corridor. In the ascending mode, a total of 102,258 Persistent Scatterer (PS) points recorded line-of-sight (LOS) displacement values ranging from 20.71 mm of uplift to -19.64 mm of subsidence. In contrast, the descending mode analysis, which captured 41,174 PS points, detected displacements between 18.81 mm of uplift and -21.57 mm of subsidence (Fig. 3). These displacement patterns are predominantly concentrated in tectonically stressed regions, particularly the Ghomarides and Upper Sebtides units, with significant activity observed around El Jebha (Fig. 2).

The daily precipitation data for El Jebha in 2019 (Fig. 4) provides critical insights into the temporal evolution of ground displacement. Notably, periods of heavy rainfall in November and December corresponded with substantial increases in subsidence, especially during the months when precipitation levels exceeded 30 mm per day. This saturation of fractured rock formations, particularly in the Upper Sebtides and Ghomarides units, intensified landslide activity. Additionally, the Oued Outinga and Oued M'Ter river systems, mapped within these

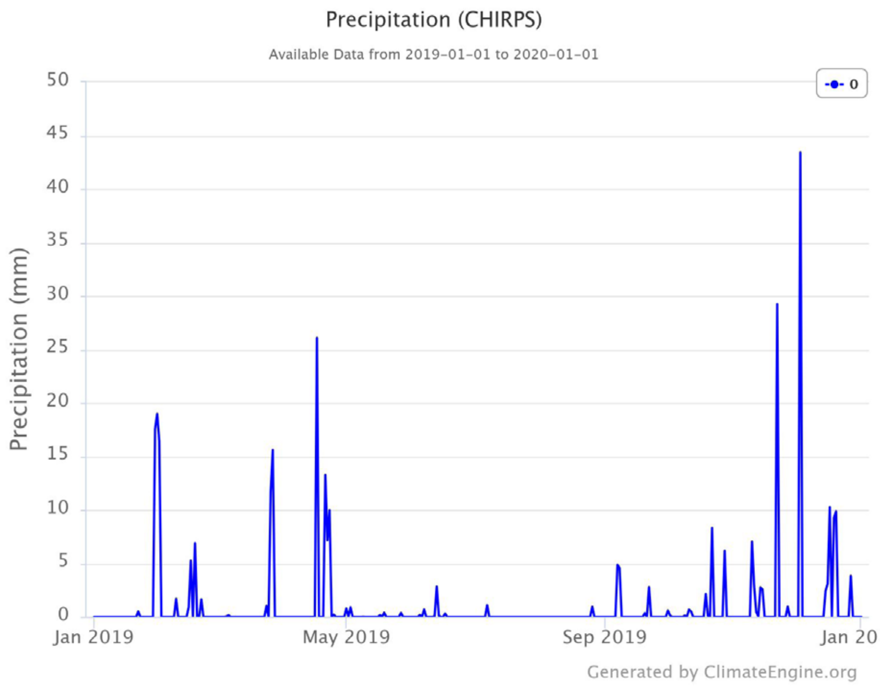

Fig. 4.- Daily Precipitation in El Jebha during 2019. See color figure in the online version.
Fig. 4.- Precipitación diaria en El Jebha durante 2019. Ver figura en color en la versión web.

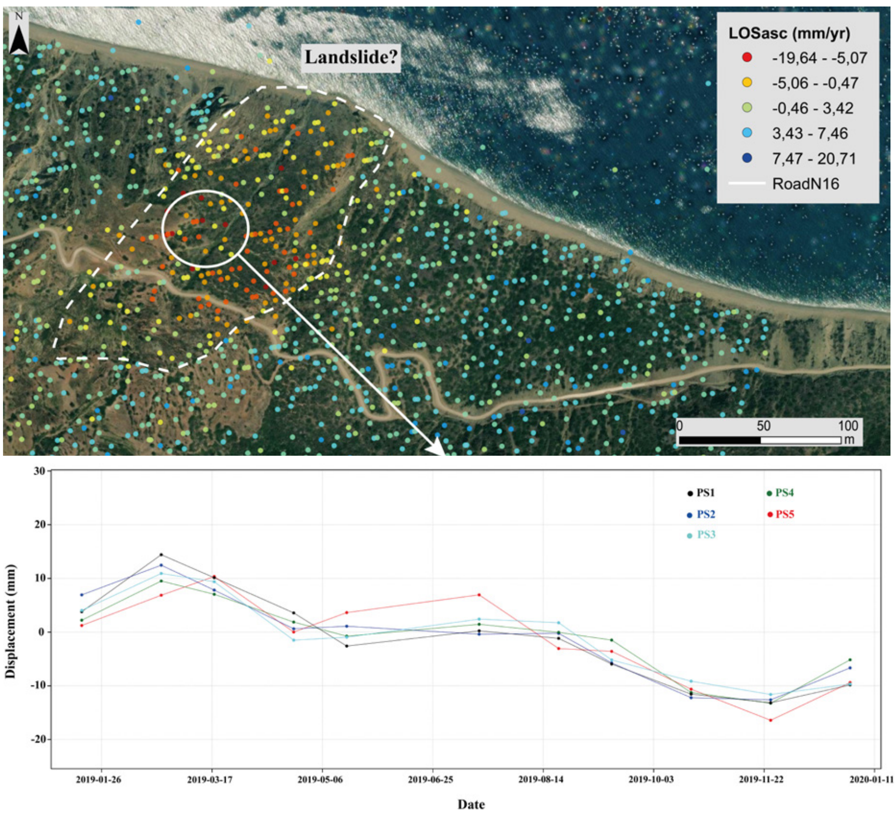

Fig. 5.- LOS time series with a cumulative displacement of −20mm of 5 PS, as illustrated in the flysch (Landslide) in Fig. 3. See color figure in the online version.
Fig. 5.- Serie temporal de la LOS con un desplazamiento acumulativo de −20 mm de 5 PS, como se ilustra en el flysch (deslizamiento) en la Fig. 3. Ver figura en color en la versión web.

units, further exacerbate erosional processes and slope destabilization during rainfall events.

In reference to Azizi et al. (2023), the reported subsidence rates in the El Jebha region varied from -14.28 cm to 2.21 cm in 2018, with significant displacements ranging from -6.06 cm to 5.97 cm in 2016, and extreme values recorded between -51.6 mm and 162 mm during 2017.

The November 2019 rainfall event was particularly noteworthy, coinciding with the highest recorded ground deformation in the descending mode, where subsidence reached -21.57 mm near El Jebha. This observation suggests that water infiltration through tectonic fractures plays a critical role in contributing to slope failures. In contrast, regions characterized by softer lithologies, such as the Predorsalian facies near Amtar, experienced minimal uplift, likely due to the presence of swelling clays or less compact sedimentary deposits.

The time series analysis presents the cumulative displacements of five Persistent Scatterers (PS) over the year 2019, illustrating a total displacement of approximately -20 mm. The graphs depict the line-of-sight (LOS) displacements recorded by the PS points, highlighting fluctuations that correspond with significant rainfall events. Peaks in the data indicate substantial subsidence, particularly following periods of heavy precipitation, which aligns with the temporal trends observed in the rainfall data for El Jebha. The graphical representation showcases how the displacements vary across different PS points, with some points exhibiting more pronounced subsidence than others. This information reinforces the correlation between precipitation and ground instability, emphasizing the importance of monitoring these changes to assess landslide risk effectively in the region (fig.5)

Conclusions

This study highlights the critical impact of rainfall on ground displacement patterns in the El Jebha-Amtar corridor, analyzed through Persistent Scatterer Interferometry (PSInSAR) over 2019. Significant subsidence and uplift were observed, particularly in response to heavy precipitation events in November and December, with displacement values reaching up to -21.57 mm. The findings underscore how saturated fractured rock formations in tectonically stressed regions, such as the Ghomarides and Upper Sebtides units, can significantly exacerbate landslide activity.

The integration of PSInSAR data with daily precipitation records reveals a clear relationship between rainfall and slope stability, emphasizing the need for continuous monitoring and early warning systems in this landslide-prone area. Future research should focus on long-term monitoring strategies and predictive modeling that incorporates geological and climatic factors. By addressing these aspects, this study contributes to improved risk management and informs infrastructure planning to mitigate the impacts of ground instability on local communities.

Contribution of the authors

Rida Haddane: Data acquisition, figure editing, fieldwork, surveys, data analysis, manuscript writing.

Afaf Amine and Mohamed Saadi: Fieldwork, surveys, revision of the manuscript, supervision, and coordination.

Morad Taher: manuscript revision of the manuscript, realization and interpretation of Daily Precipitation

Mohamed El Amrani: Design, manuscript writing, drafting the manuscript, realization.

Soukaina Mouljebouj: Design and conceptualization, manuscript writing, drafting the manuscript.

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