InSAR time-series analysis of surface motions caused by the 2023 Kahramanmaraş earthquake in Hatay, Türkiye

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Abstract

Earthquakes are among the most devastating natural events. Interferometric Synthetic Aperture Radar (InSAR) methods are used to obtain fault parameters from co-seismic earthquakes, particularly those covering large areas. This study presents initial analyses to see the effects of the 2023 Kahramanmaraş earthquake that occurred along the East Anatolian Fault Zone of Türkiye. The study area covers the Hatay region. The analysis of different structures and earthquake-triggered landslides was conducted to investigate their impact. The small baseline method was applied to Sentinel-1 data taken in both the ascending and descending directions. The images cover the years 2019 and 2024, including the earthquake. The results vary between -20 cm/year and 25 cm/year. The earthquake co-seismic effect is visible in the time series obtained in both directions, and structural movement was observed leading up to and following the earthquake. This allows structures caused by an earthquake to be monitored afterward. Furthermore, events such as landslides and landslides that may be triggered by an earthquake can be monitored.

1. Introduction

Türkiye is one of the most seismically active regions in the world and has experienced several major earthquakes over the past three decades. These include the 2020 Izmir (Mw 7.0) and Elazig (Mw 6.8) earthquakes, the 2011 Van (Mw 7.1), the 1999 İzmit (Mw 7.6), and the 1999 Düzce (Mw 7.2) earthquakes (Gorum et al., 2023). The next major earthquake occurred on February 6, 2023, along the left-lateral in the East Anatolian Fault Zone.

The devastating Kahramanmaras earthquake sequence occurred on February 6, 2023. Two main events, Mw 7.8 and Mw 7.5, occurred 9 hours apart, affected 11 cities in Türkiye, caused more than fifty thousand deaths, about a hundred thousand injuries, and displaced about three million people. This was the strongest historical earthquake doublet of magnitudes above 7.5 ever recorded in this region, and the consequences were catastrophic. The earthquake doublet triggered more than 7,000 landslides (Gorum et al., 2023 and Gorum et al., 2025). One of the affected regions is the Hatay district. The study area covers a wide area starting from İskenderun Bay in the south of Türkiye and extending to the north of Osmaniye and Adana (Figure 1). This area is located close to the western end of the East Anatolian Fault Zone (EAFZ) and is in one of the critical seismic zones of Türkiye. It is also located on an active tectonic boundary where the Arabian plate collides with the Anatolian plate because of its northward movement. Therefore, it has strong ground motion dynamics shaped by past and present earthquakes.

After the earthquake, many studies investigated deformation analysis and fault properties using various methods. Optical data have been used for deformation analysis. Provost et al. (2024) used Sentinel-2 data and an offset method, which is based on sub-pixel image correlation to identify the fault offset of the co-seismic event. However, cloud-free data might not always be acquired. SAR data provides advantages in situations where atmospheric conditions are not suitable.

The Interferometric Synthetic Aperture Radar (InSAR) method has been widely used for earthquake, landslide (Bayik et al., 2023), and other natural and anthropogenic surface deformation monitoring. Multitemporal InSAR methods, generally divided into Persistent Scatterer InSAR (PSI) and Small Baseline (SB), are used in different studies. PSI is more prominent for urban objects such as buildings, structures, and bridges, while SB methods are preferred in rural areas where PS points may be scarce.

Kobayashi et al (2024) studied low-resolution ScanSAR data of ALOS-2 and InSAR pairs to determine the rupture properties of the fault along the EAFZ. Mikhailov et al. (2023) used co-seismic pairs of Sentinel-1 data and the offset method to identify the rupture surface model.

In addition to SAR data, optical data were also considered, and data fusion methods were used. An et al. (2023) combined Sentinel-1 and ALOS-2 SAR and optical Sentinel-2 datasets to determine 3D deformation along the EAFZ. The offset methods applied to both optical and SAR data showed that the dominant deformation occurred horizontally in the east–west direction.

In the Iskenderun city center, especially in the coastal area, soil liquefaction after the earthquake was evaluated. It is noted that A high number of buildings showed low foundation performance because of soil liquefaction (Baser et al., 2023; Öztürk et al., 2024. Cetin et al. (2025) evaluated the liquefaction occurring in Hatay Airport and its surroundings.

This paper presents an initial time-series analysis of surface displacement using long-term InSAR analysis over the Hatay

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district, located southeast of Türkiye near the borders of Syria. For the analysis, we used Sentinel-1 data for the six years that cover co-seismic activity. The study aims to examine the behavior of surface movements over a long period and analyze the movements that started before the earthquake and the movements that continued after the earthquake.

2. Methodology

The study area includes low-altitude coastal plains starting from İskenderun Bay and a slightly rugged terrain structure in the inner parts. The ground structure consists of young alluvial units in the coastal areas and older sedimentary rocks in the inner parts. These various structural features cause the response of the area to earthquake effects to be variable at the local scale. According to the Köppen-Geiger climate classification (Peel et al., 2007), the study area has a Hot-summer Mediterranean climate.

Figure 1. Study area

3. Methodology

In this study, long-term and temporal analysis of surface deformations was performed using the Miami InSAR Time Series in Python (MintPy) software (Yunjun et al., 2019). Prior to MintPy, in order to determine the interferometric pairs to be used, Sentinel-1A data of Single Look Complex Interferometric Wide Swath images covering the study area were obtained from the Alaska Satellite Facility (ASF) Vertex portal. The dataset covers image acquisition of ascending and descending tracks between January 2019 and October 2024. In total, 171 images of descending mode were processed.

Sentinel data, both transmitted and recorded vertically (VV), were used to obtain displacement in the study area (Table 1). Image pair selection was based on time and vertical baseline criteria to minimize atmospheric effects and phase noise. The geometric baselines between ascending and descending image pairs are generally short, exceeding 200 m in only a few pairs. For the identified pairs, the relevant burst data were processed using InSAR Scientific Computing Environment (ISCE) software (Fattahi et al., 2017). During interferogram generation, coregistration, flattening, and topographic phase removal processes appropriate to the data geometry were applied (Rosen et al., 2012).

Sensor	Sentinel-1	
Acquisition mode	Ascending	Descending
Image mode	IW	
Wavelength	C-band: ~5,6 cm	
Polarization	VV	
Period	20190101-20240814	20190114-20241014
No. of Images	169	171
No. of Interferograms	168	170

Table 1. Specifications of SAR images.

The resulting interferograms were subjected to time series analysis using the MintPy software. In this phase, ISCE2 outputs were first converted into a processable format by MintPy. The input dataset included interferograms, correlation maps, masking files, and digital elevation model (DEM) information. Before starting the time series analysis, a reference pixel with high coherence and away from topographic influences was selected, and low-coherence regions were excluded from the analysis using masking. The coherence threshold value of 0.5 was selected for the processes.

Correction modules within MintPy were used to reduce the impact of errors caused by atmospheric delays. For the atmospheric correction, the Python-based Atmospheric Phase Screen Estimation (PyAPS) approach, which uses ERA5 data distributed through the Copernicus Climate Data Store, was implemented (Jolivet et al., 2011). This allows the data to be free of atmospheric and orbital effects, highlighting true deformation signals.

Time series analysis was performed using the small baseline approach (SBAS), and all interferograms were inverted using this method (Anjasmara et al., 2020; Berardino et al., 2002). This process yielded time-dependent satellite-relative displacement values for each pixel. Displacement rate maps were generated in mm/yr. Finally, the resulting deformation products were used to assess geological and anthropogenic processes. This demonstrates the applicability of Sentinel-1 data within time series analysis with MintPy and provides highly accurate results in deformation monitoring studies.

According to the results obtained by the six-year time series analysis, the displacement varies between approximately -20 cm/year and 25 cm/year. The results were obtained in the line-of-sight (LOS) direction. The time series analysis shows the dynamics of the developing displacements and coseismic movement in the long term.

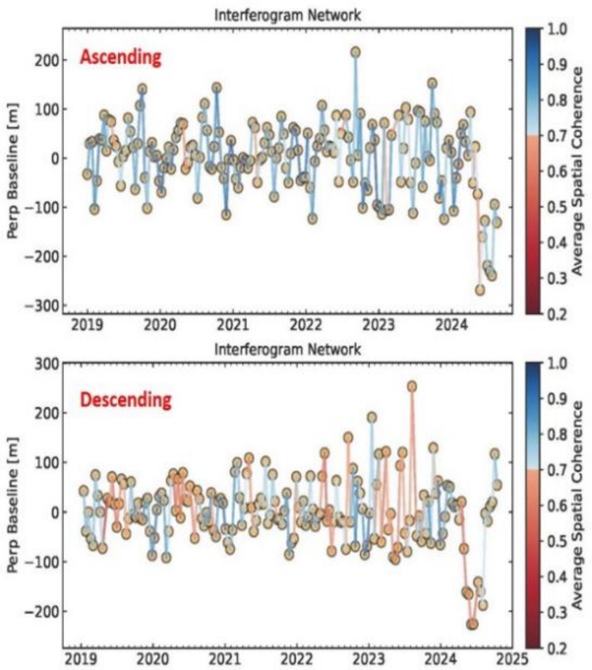

Figure 2. Interferogram network of the Sentinel-1 data

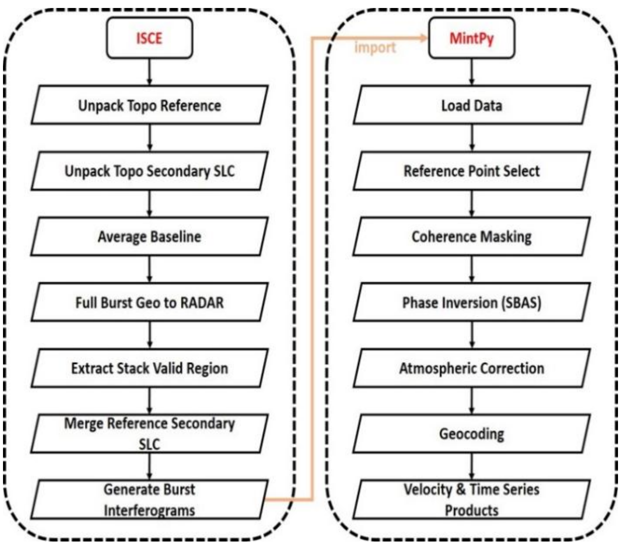

Figure 3. Flowchart of the InSAR processes

4. Results

While more positive values appear in the ascending image, negative values come to the fore in the descending image. Most of the movement obtained was observed in the city center of Iskenderun and over the human-made structures, such as ports and coastal areas. A time-series indicated the displacement over the tension cracks (Figure 5a, 6a) (Öztürk et al., 2024). Several movements are observed in the north and northeast of the Iskenderun city center. A slowly developing landslide is determined, and the time series shows that the movement is still active (Figure 5b, 6b). The coseismic effect is obtained over the agricultural fields located north of the Kirikhan district center (Figure 5c, 6c). It is noticed that after the earthquake, the surface maintained its stability. The time series taken at Hatay International Airport also indicated that the movement started before the earthquake and continued after it (Figure 5d, 6d).

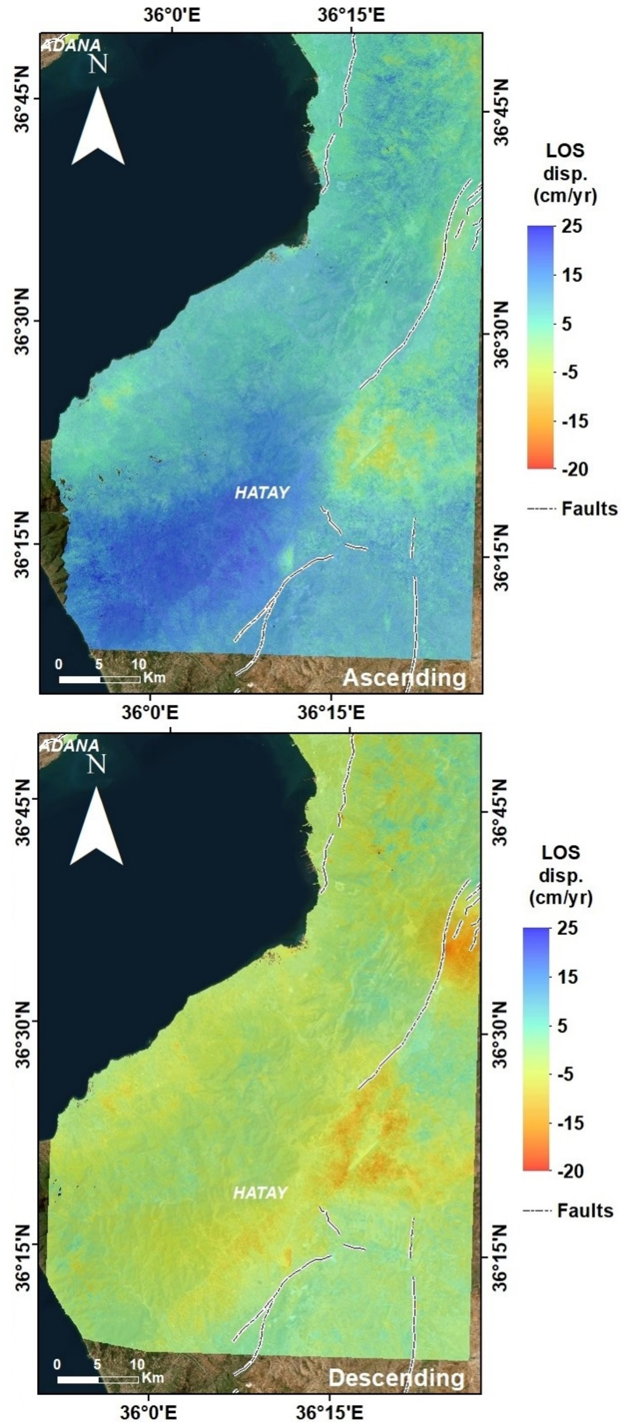

Figure 4. Displacement maps derived from InSAR ascending (up) and descending (down) orbits.

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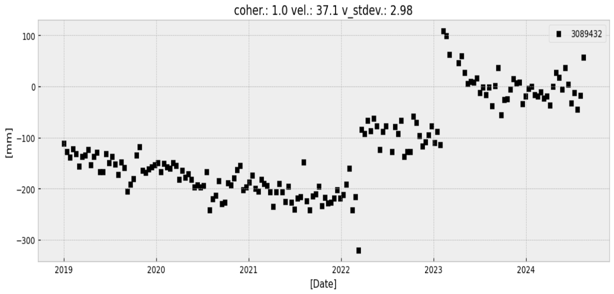
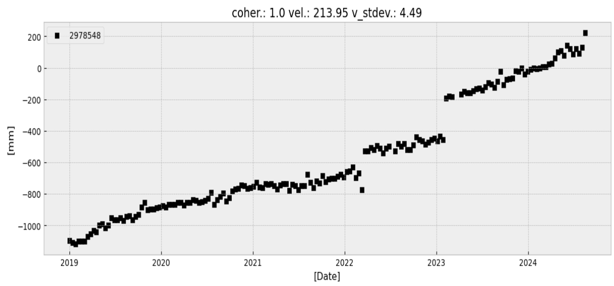
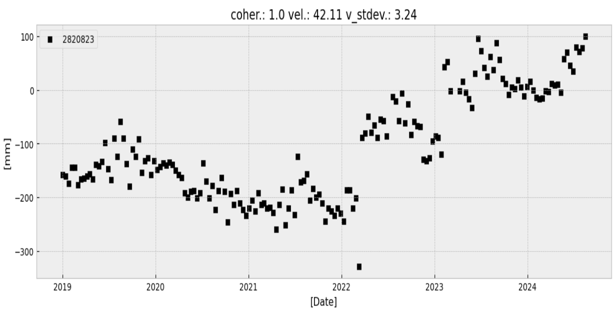


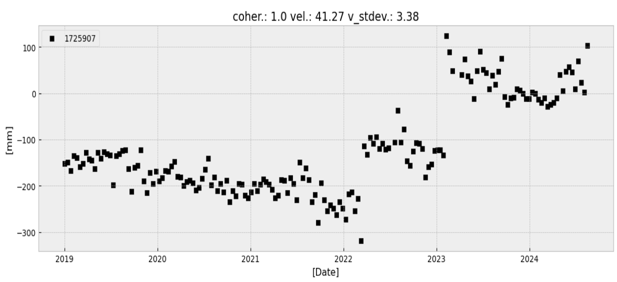
a) Iskenderun port



b) A landslide

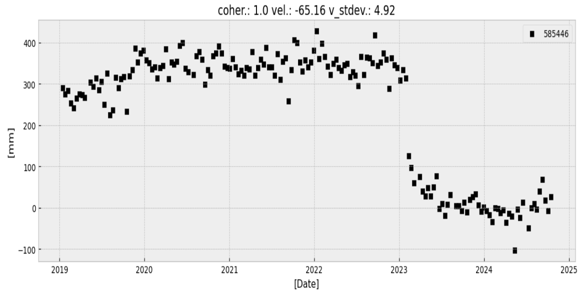


c) An agricultural field

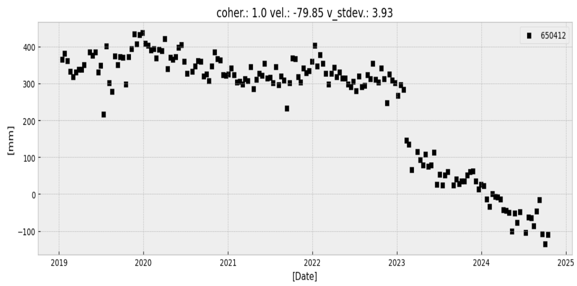


d) Hatay International Airport

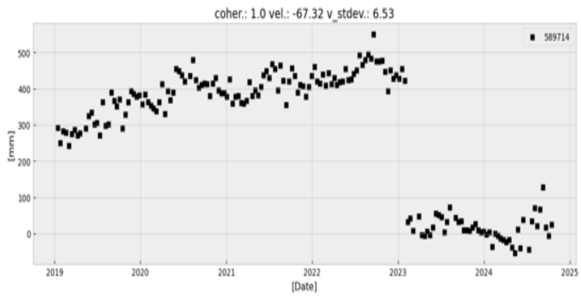
Figure 5. Ascending orbit Sentinel-1 time-series of different locations



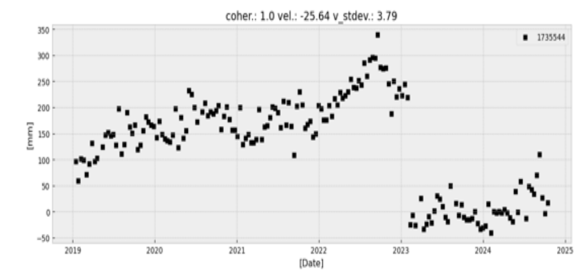
a) Iskenderun port



b) A landslide



c) An agricultural field



d) Hatay International Airport

Figure 6. Descending orbit Sentinel-1 time-series of different locations

5. Discussions and Conclusions

In this study, we analyzed long-term displacement over the Hatay region of Turkiye, where heavily affected by the earthquake on February 6, 2023. Studies on the estimation of surface rupture and fault parameters have been carried out in the region using different data and methods.

This is the first study that has been conducted for this region using the InSAR time series. Previous studies showed the soil liquefaction areas where surface displacement is determined by this study (Taftsoglou et al., 2023).

In order to analyze the impact of the earthquake on time series, archive Sentinel-1 data were used, including the

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time after the earthquake, and velocity vectors were obtained. Images obtained from both descending and ascending directions were used in the analysis. The earthquake's impact is visible in both orbit time series. However, this is more pronounced in the descending results. In areas such as settlement, ports, airports, highways, and other infrastructure areas that were inactive until the moment of the earthquake. In a landslide area, ascending results show that movement has begun and continues after the earthquake. While the descending results show a smaller movement, post-earthquake acceleration is detected.

The majority of landslides mapped in the study area after the event were rockfalls. In contrast, more than 300 lateral spreads were mapped along the Asi River (Çetinkaya and Görüm, 2024). However, the number of slide types was lower in the southern part, which was affected by the earthquake. The pre-earthquake deformations observed, which generally correspond to liquefaction, must have been primarily influenced by the high groundwater level and its fluxes during the pre-seismic period in this area. Time series indicate movements with different dynamics in the region. Deformation results indicate that in certain areas, ground deformations were initiated prior to the earthquakes and continued after the incident. Local movements are also observed in the region, except for the city centers, and it is revealed that these areas should also be examined. Slow-moving mass movements, in particular, should be considered high-risk areas because they can impact settlements and infrastructures for an extended period; thus, precautions should be taken by examining the deformation dynamics of the region.

As a further study, the LOS values can be converted to vertical and horizontal movement. The prediction approaches can benefit from risk reduction activities and sustainable urban management strategies. Monitoring the time series provides important information for future urbanization and infrastructure works planned for the region.

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