Evaluating Metro Construction Impacts on Urban Ground Stability Using Multi-Temporal Sentinel-1 InSAR

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Abstract

Large cities are complex areas containing densely populated areas along with their infrastructure. Surface movements can pose risks to the safety of structures, such as subway lines, in urban areas. Advanced multi-temporal Interferometric Synthetic Aperture Radar (InSAR) methods are used to obtain surface deformations, specifically those covering large areas. In this study, the new metro line under construction in the Koceeli Gebze region, adjacent to Istanbul, was analyzed with the multi-time InSAR method. In this context, PS/DS-based phase-linking approach is applied on Sentinel-1 that was acquired between 2019 and 2025. The displacement can reach up to about 13.5 mm/yr specifically where the maximum movement is obtained at the first station. Several time series indicated the evolution of the movement over the surface at the stations. The affected buildings were also examined surrounding of the first stations. The results provide information on monitoring the structural health of infrastructure under construction and also on the impact on surrounding structures. InSAR monitoring methods contribute to achieving the Sustainable Development Goals (SDG 9) and Sustainable Cities and Communities (SDG 11) by providing information about safe and sustainable building and settlement areas.

1. Introduction

Underground transportation networks constitute a significant part of the mobility in densely populated cities. They provide alternative solutions to urbanization-related problems such as traffic congestion, noise, and air pollution (Cui and Nelson, 2019). Structural health monitoring (SHM) systems have been developed to ensure the reliable and safe operation of these infrastructures. SHM systems are generally used to monitor the operational condition of structures, support uninterrupted functioning, and detect faults, deterioration, and damage (Bhalla et al., 2005). A variety of methods exist for monitoring structures, including wireless sensor networks, extensometers, GPS, terrestrial scanners, LiDAR, levelling, and inclinometers (Wang et al., 2024; Chen et al., 2025). In-situ measurements offer the advantage of providing real-time data; however, they can be economically restrictive (Macchiarulo et al., 2023).

Especially in construction processes where terrestrial measurements are either unavailable or impossible due to restrictions, Synthetic aperture radar interferometry (InSAR) stands out as the sole and most comprehensive deformation monitoring tool. Furthermore, activities such as the construction of underground transportation networks and tunnelling carry the potential to cause surface subsidence or structural deformations around the route. These surface movements can pose risks to existing infrastructure and buildings in the area. Continuous monitoring of the health of structures under construction is critical to detect and prevent potential movements in advance (Wang et al., 2024).

InSAR provides significant advantages due to its ability to cover large areas and its availability of long-term archival data. Das Adhikari et al. (2025) applied a conventional Differential InSAR (DInSAR) method to derive displacement measurements along railway lines in South Korea. However, DInSAR is limited by temporal decorrelation. To overcome these limitations, advanced techniques such as Persistent Scatterer InSAR (PS-InSAR) (Ferretti et al., 2001) and Small Baseline (SBAS) (Berardino et al.,2002) methods have been adopted. These advanced InSAR approaches are widely used to monitor various structures, including dams, bridges, tunnels, highways, and subway systems (Abdikan et al., 2025; Piter et al., 2024; Macchiarulo et al., 2023). However, the presence of surfaces exhibiting different reflection characteristics in urban areas has led to the development of more innovative approaches in deformation measurements. In this context, new algorithms have been developed that minimize phase noise caused by decorrelation by evaluating the statistical behavior of Permanent Scatterers (PS) and Distributed Scatterers (DS) together. Multi-time InSAR techniques such as FRInGE (Fattahi et al., 2019), ComSAR (Ho Tong Minh and Ngo, 2022), and Phase Linking stand out as highly effective tools for obtaining reliable deformation time series in areas with complex scatterer types (Guarnieri and Tebaldini, 2008; Mirzaee et al., 2023).

Monitoring of metro tunnel areas with InSAR is carried out using different satellite and multi-temporal InSAR methods. Garthwaite et al. (2026) used high-resolution COSMO-SkyMed data obtained over an eight-month period. Although the Sentinel-1 satellite provides limited pixels on infrastructure due to its resolution, its potential can be achieved on a local and regional scale in highway and railway structures (Piter et al., 2024). Halicioglu et al. (2021) determined the surface deformation caused by underground metro construction using Sentinel-1 and found a strong correlation with ground-measurement data.

Our paper presents surface displacement derived from multi-temporal InSAR analysis over a metro line. The study aims to detect surface movements associated with the construction of the metro line, which began in 2018 and is still ongoing. This study involved a comprehensive time-series analysis of nearly 7 years of Sentinel-1 data using advanced PS/DS-based phase-linking algorithms. The resulting long-term deformation dynamics contributed to the safety of the construction process and also provided a valuable data source for developing sustainable urban management and urbanization strategies.

2. Study Area

The study area is in the Gebze district of Kocaeli, located southeast of Istanbul, the eastern part of the Marmara Sea region, Türkiye (Figure 1). Gebze serves as a critical bridge between the megacity of Istanbul and Anatolia. This bridging role has made it one of the country's most important industrial and densely populated centers. Due to rapid urbanization, increasing population density, and heavy daily commutes, the existing surface transportation infrastructure is experiencing severe traffic congestion. To alleviate these problems, constructing a new underground mass transit system has become essential. The metro line is approximately 15,4 km long and includes 11 stations. It is designed to provide a sustainable, high-capacity and uninterrupted transportation network throughout the district.

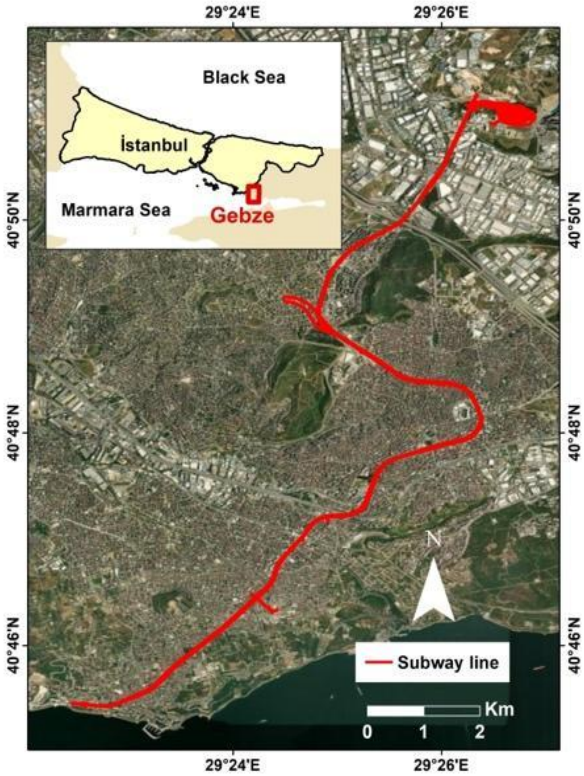

Figure 1. Study area

3. Methodology

Sentinel-1 SLC IW swath data were freely acquired from ESA and used to extract surface movements in the study area. The dataset includes descending-tracks acquisitions between January 2019 and October 2025 (Table 1). In total, 213 images of descending mode were processed.

The SAR data were processed using MiaplPy software, and 504 interferograms were generated from pairs with a 6-day temporal baseline (Figure 2). Phase Linking is a multi-temporal InSAR technique that minimizes decorrelation-induced phase noise by jointly exploiting information from Persistent Scatterers (PS) and Distributed Scatterers (DS). It fundamentally relies on the statistical behavior of pixels to form coherent neighbourhoods and estimate an optimized phase for each pixel (Guarnieri and Tebaldini, 2008).

Sensor	Sentinel-1
Acquisition mode	Descending
Image mode, Wavelength	IW C-band: ~5,6 cm
Polarization	VV
Period	Jan 2019 - Oct 2025
No. of Images	213
No. of Interferograms	504

Table 1. Specifications of SAR images.

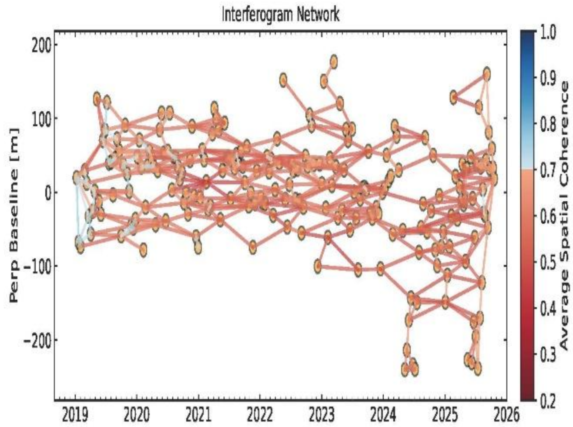

Figure 2. Interferogram network of the Sentinel-1 data.

Over the past decade, several implementations of the phase-linking approach have been developed, including FRInGE (Fattahi et al., 2019), the Python-based Miami Phase Linking software (MiaplPy) (Mirzaee et al., 2023), and TomoSAR within the Complex Synthetic Aperture Radar (ComSAR) framework (Ho Tong Minh & Ngo, 2022). Among these, MiaplPy is an advanced, open-source implementation of phase-linking algorithms that incorporates the classical PS/DS models as well as the recently introduced Combined Phase Linking (CPL) technique by Mirzaee et al. (2023). These extensions make MiaplPy an efficient tool for extracting reliable deformation time series in areas characterized by mixed scatterer types.

In this study, the phase-linking workflow was carried out using MiaplPy, implementing the standard PS/DS processing steps. First, Statistically Homogeneous Pixels (SHP) were identified using likelihood-based or distribution-based tests (Parizzi and Brcic, 2011), enabling the robust grouping of pixels exhibiting coherent scattering behavior. These SHP neighborhoods were then used to estimate local covariance matrices, which were processed through the CPL algorithm introduced in Mirzaee et al. (2023) to derive optimized wrapped-phase estimates across the interferogram stack. Additionally, PS were selected from full-resolution SLC amplitudes following the approach of Ferretti et al. (2001) to further stabilize the phase solution.

Subsequently, the interferograms were unwrapped by the Statistical-Cost Network-Flow Algorithm for Phase Unwrapping (SNAPHU) (Chen and Zebker, 2001), and the resulting unwrapped network was inverted to obtain the displacement time series and the mean deformation velocity. The general architecture of the PS/DS phase linking workflow is shown in Figure 3.

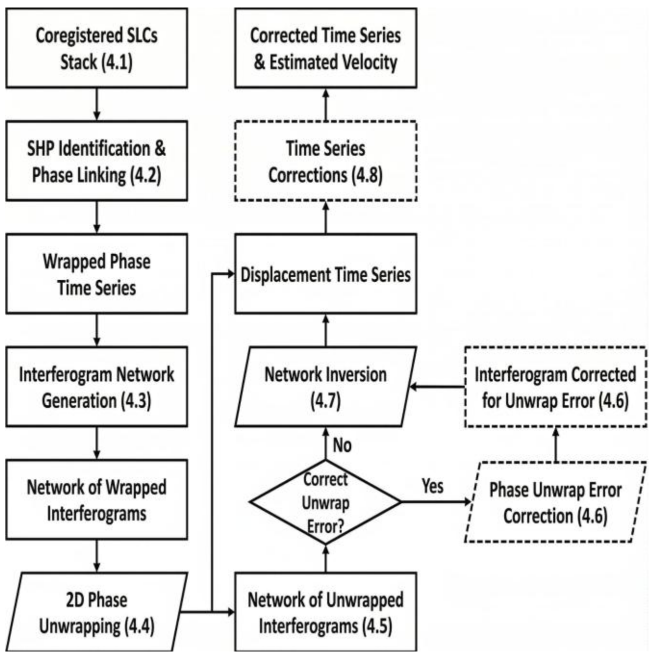

Figure 3. Flowchart of non-linear phase linking and time-series analysis steps.

4. Results and Discussions

A nearly seven-year time series indicates that displacement in the line-of-sight (LOS) direction ranges between -10 mm/year and 10 mm/year. The displacement velocity map clearly shows the deformation patterns along the metro line (Figure 4) including all stations. Surface movement is particularly pronounced near the first station located at south, close to the coastline. A detailed time series analysis was carried out for the subsection corresponding to the 1st station on the metro line (Figure 5) and shown in Figure 6. The results show that the area remained between 2019 and 2021. A sudden displacement occurred just before 2021 to mid-2022. In the following period, the deformation trend stabilized and remained steady until the end of 2025.

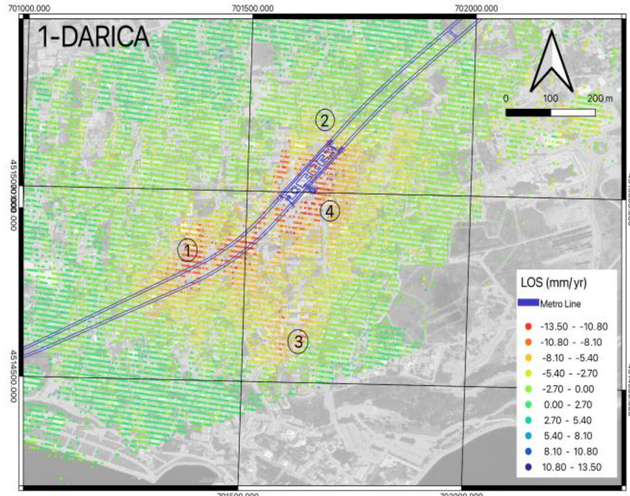

Figure 5. Darıca station of the metro line

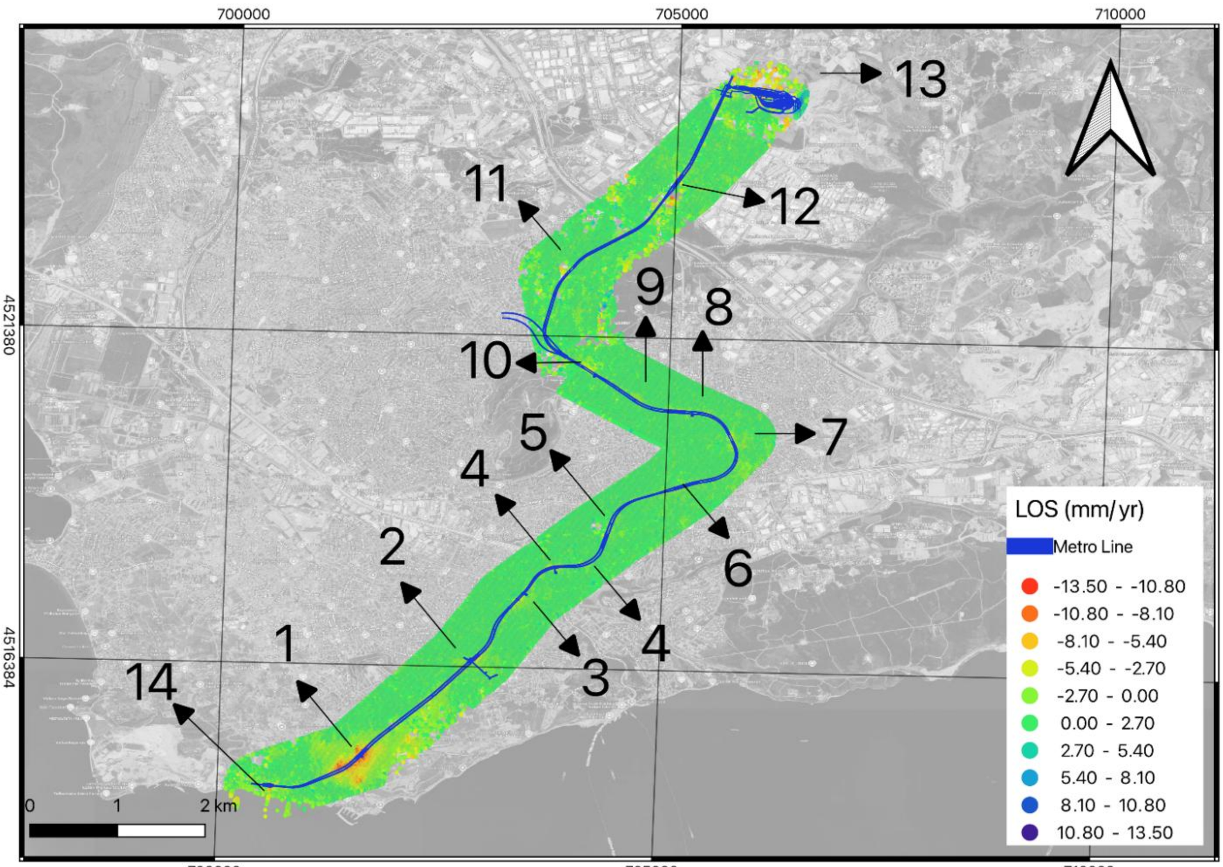

Figure 4. InSAR results of the metro line

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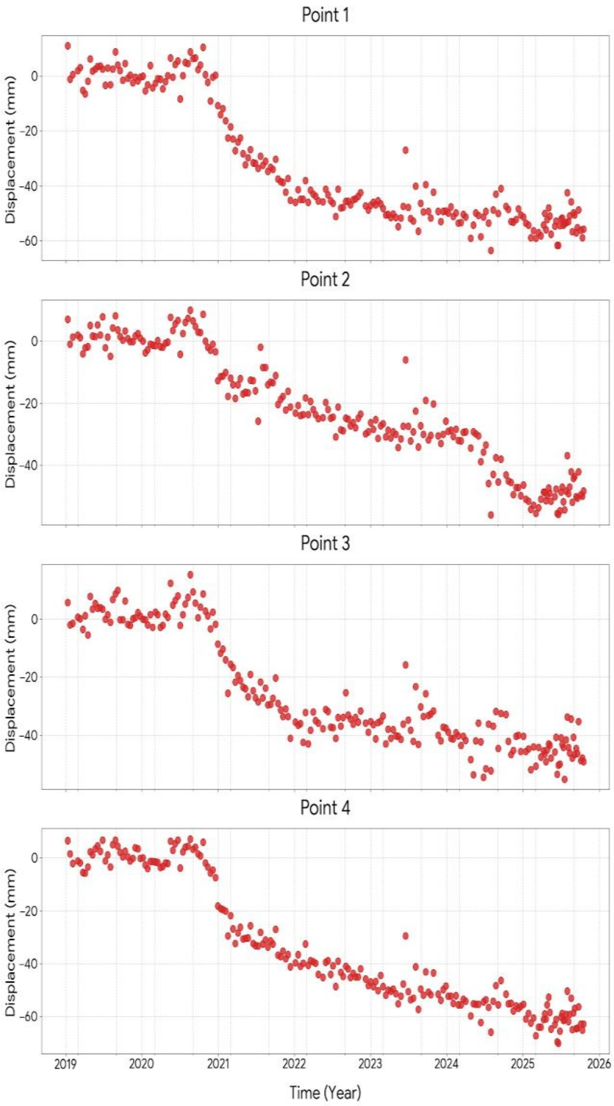

Figure 6. InSAR time series over the Darıca station

The first of these points showed a displacement of approximately 40 mm in the first year; then, in the following 4 years, it moved much more slowly, showing a displacement of approximately 20 mm (Figure 6, Point1). Looking at the time series for point number two, as with the first point, no movement is observed in the first year, and then a linear trend becomes evident until mid-2024 (Figure 6 Point2). After that, the movement continues at a slower pace. The stabilization seen in the first year is also observed at the other two points (Figure 6 Point3, 4). At all points, an accelerating movement occurs just before 2021, then transforms into a linear and slowing movement.

Surface motion is relatively lower at other stations compared to the first station (Figure 7). The time series for the Farabi station (Figure 7, Point1) shows a stable period before 2021, followed by a sharp drop just before 2021. It then shows a linear decrease until 2026. The subsequent stations, TCDD (Figure 7, Point2) and Fatih (Figure 7, Point3), were more stable before 2021, similar to Farabi, but experienced a sharp drop just before 2021. They show a more stable character compared to the other stations until 2026.

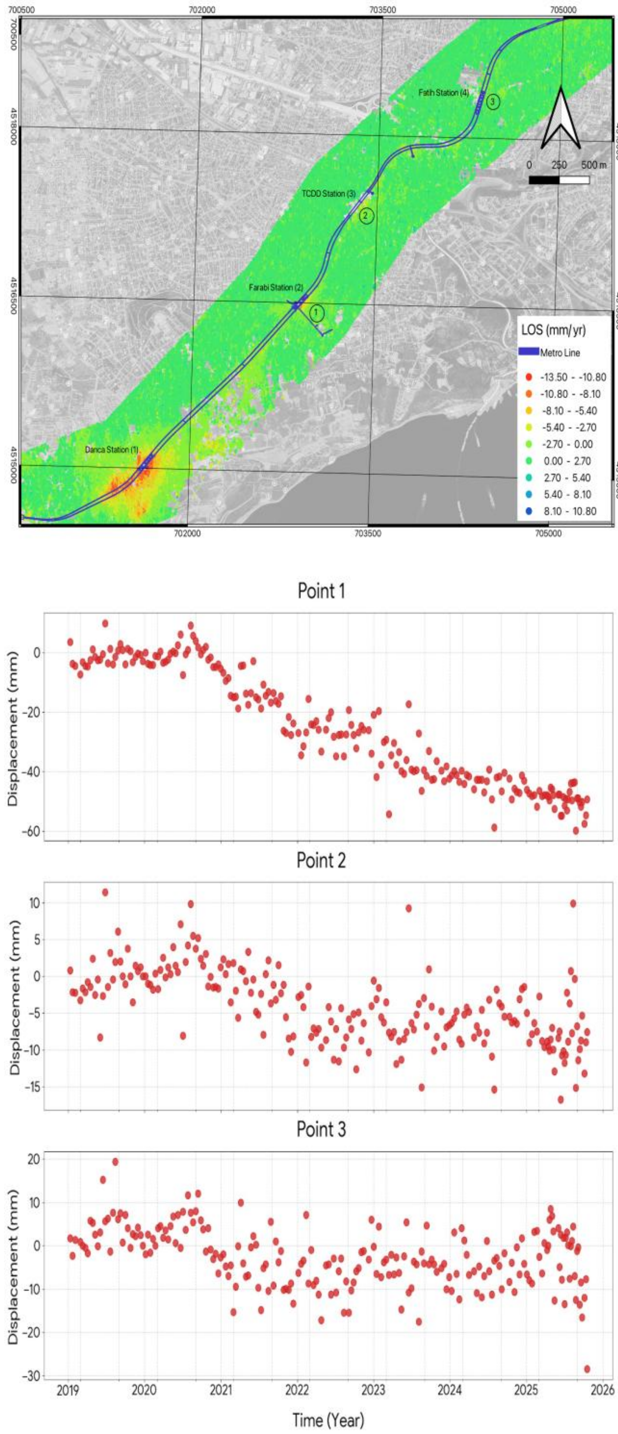

Figure 7. InSAR time series over the Farabi-TCDD-Fatih station

The analysis was carried out considering the displacements of buildings located around Darica station, where the most significant deformation occurred. 1936 buildings are located within the buffer zone and have been classified into 5 categories based on their surface movement values (Figure 8). While 1099 buildings experienced movement between 0 and 3 mm/yr, displacements varying between -3 and 0 mm/yr were observed on 665 buildings. 105 buildings are at risk between -3 and -6 mm/yr, and 57 buildings are at risk between -6 and -9 mm/yr. In the area closer to the station, where maximum movement occurs, the values vary between -9 and -12 mm/yr, affecting 10 buildings.

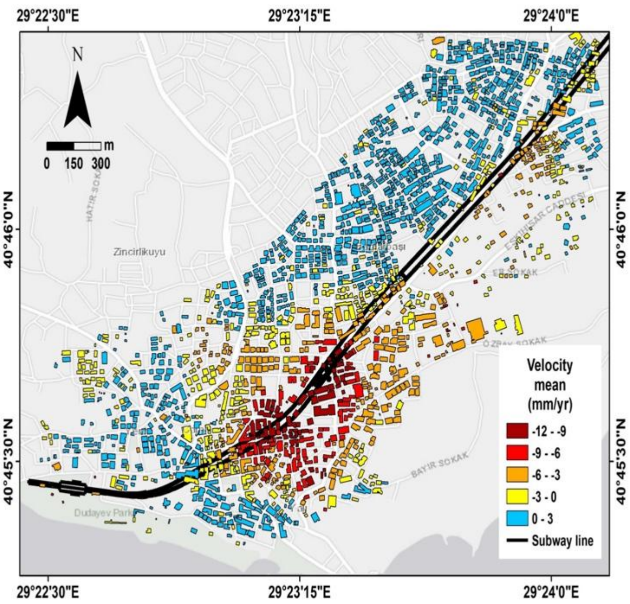

Figure 8. Buildings affected by metro construction

In this study, a single image set was used, and displacement values were obtained in the LOS direction. It provides information on one-direction results to quickly identify risky areas. In a study on metro construction in Istanbul's city center, LOS direction was measured, and a high correlation was observed with levelling data (Halicioglu et al., 2021).

However, horizontal, and vertical deformations can be obtained using data obtained in both descending and ascending directions. Garthwaite et al., (2026) obtained the surface movement using data obtained in both directions and compared it with the leveling values. Topography, land use, geology, and human-induced factors can all play a role in examining the factors affecting surface deformation, along with InSAR data. Chai et al. (2024) performed a surface deformation susceptibility analysis using the LightGBM method, incorporating InSAR motion obtained in the LOS direction along with factors that could influence the motion. Distance to the river was found to be the most influential factor, followed by distance to the road and the topographic witness index. Ancillary data, when combined with InSAR data, can better identify at-risk areas.

5. Conclusions

In this study, we applied the advanced multi-temporal InSAR techniques (PS/DS Phase Linking) to Sentinel-1 data to monitor displacement along a metro line under construction. The results reveal measurable movement along the alignment. Since no terrestrial measurements were available, no comparison was made with the InSAR results.

Time series analysis provides insights into the deformation dynamics that occur throughout the metro's development process. Monitoring the health of structures under construction provides crucial early-warning data to prevent potential movements in advance, thereby safeguarding both the new infrastructure and the existing surface buildings. In the next phase of the study, data-driven monitoring can be enhanced by incorporating additional information such as lithological, soil, geotechnical and, structural information. Long-term deformation monitoring frameworks, as demonstrated in this study, can inform the development of urbanization strategies for sustainable urban management in rapidly growing industrial cities. With Sentinel results, we can implement emergency plans not only in small areas such as metro lines but also across entire regions to prevent surface movement in surrounding buildings. Multi-temporal InSAR methods can be used to monitor urban areas, contributing to the goals of innovation and infrastructure (SDG 9) and sustainable cities and communities (SDG 11).

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