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Research Article

Monitoring the Ground Deformation Caused by Ankara M4 Subway Tunnel with SAR Images

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Abstract

Metro lines interconnect residential areas in different parts of the city, allowing people to travel faster, safer, and more comfortably. However, during the construction of tunnels, surrounding buildings and people may be negatively affected. The Keçiören-Kızılay M4 subway is a 16.5 km metro line in Ankara that extends from the city center Kızılay to the north of the city in Keçiören. Construction of the line began in 2002, and it was opened in 2017. The study conducted in the Dışkapı area, where the M4 metro line passes, shows that the tunnel excavation is situated in the alluvial soils of the Çubuk River between Km: 3+440.00 and Km: 3+580.00. This study utilizes two sets of Sentinel-1 data covering the years 2015-2016 and 2017-2022. The analysis between 2015-2016 represents the first observation, while the analysis between 2017-2022 represents the second observation. The Persistent Scatterer Interferometry (PSI) approach was employed for the analyses, and the Stanford Method for Persistent Scatterers (StaMPS) open source codes were utilized. The analyses were conducted from five different points determined within the study area. The results of the first observation show no deformation, whereas an average deformation of 10mm was observed in the second observation. According to literature and field studies, some structures in the area of interest experienced significant damage due to the tunnel opening, and soil and structural reinforcement works were carried out between 2015-2016. However, the results of the second observation in this study indicate that the deformation in the area is still ongoing, and the reinforcement works carried out may be insufficient, suggesting that the structures may still be at risk.

Keywords: Ground Deformation 1, Time Series Estimation 2, Subway 3, Ankara 4

Introduction

Persistent scattere strategies can be produced by using time series interferometry studies in the planning to be made by taking into account the ground deformations for the estimation of the useful life in the area where the Metro Railway routes are located. Thus, it suggests that longer-lasting plans can be created. The interferometry approach not only saves time using computers during the process, but also shows that with the estimation of the ground deformations, the major renovation costs that may occur when the project is implemented can be known at the beginning and precautions can be taken (Aslan et al., 2020). It is known that it can measure phase differences more precisely with Persistent Scatter Interferometry (PSI) (Tofani, et al., 2013). For example; Deformation analysis can be made from the differences between the two images just before and just after natural disasters such as earthquakes and floods. This means that healthier static planning can be done. From this point of view, it can be said that the cost of the project will mean that the costs of modification and improvement due to deformation can also be reduced. In the literature, it is seen that ground deformations and monitoring of the interferometry method are presented with two different approaches (Crosetto et. al., 2016). In the presented approaches, it is seen as an advantage that PSI can follow the changes that occur gradually over time (Eker, and Aydın, 2021). The disadvantage of the PSI method is that it requires a long time and a large number of images.In this article, it is aimed to determine the deformations in the ground around the tunnels of the rail systems network in An The development of rail systems was taken into account in the selection process of the image sets. Images from Sentinel-1 were chosen to capture the network of rail systems currently under development and construction in various regions. Both the 2015-2016 and 2017-2022 time periods were used for the analysis of this study and the comparison of the images.

The deformation characteristics of a metro tunnel were examined in this study using distributed optical fiber sensing technology. The study emphasized the significance of variations in the tunnel's structure by detecting varying rates of deformation across different sections (Du, et al., 2019). Using distributed optical fiber sensing technology, this research examined the deformation characteristics of a metro tunnel and revealed variations in deformation rates across different sections of the tunnel, indicating the significance of structural differences in these areas (Du, et al., 2019). The deformation characteristics of railway tracks were examined in this study using ground-based SAR interferometry. The study found that SAR interferometry offers superior resolution and accuracy in comparison to alternative techniques (Liu, et al., 2018). This study used the D-InSAR method to monitor the deformation of a metro line in Xiamen, China. The study focuses on developing a deformation model that takes into account environmental factors (Yan, et al, 2019). InSAR technology was utilized to monitor and detect deformation caused by various factors along a metro line located in Shenzhen, China. Additionally, an algorithm was developed to aid in the detection and analysis of deformation in the metro line (Li, et al, 2017).

Materials and Methods

Ankara is a city located in the central region of Turkey, generally known as the Central Anatolia region. The geology of Ankara is generally related to the underground structure of rocks and the displacement of sedimentary layers. In the center of Ankara, a ridge line extends northeast-southwest along the Central Anatolian fault zone, which is significantly higher than the surrounding plains and acts as a natural barrier (Yilmaz, 2006). This ridge line is composed of metamorphic rocks from the Paleozoic era. In addition to metamorphic rocks, Ankara also contains volcanic and magmatic rocks, such as the Elmadağ volcanic complex in the northwest, a result of volcanic activity dating back to the Miocene period, as well as common types of magmatic rocks such as granite, basalt, and andesite (Tuncer, 2001).

The Sentinel-1 satellite acquires synthetic aperture radar (SAR) images from both ascending and descending orbits. During the ascending orbit, the satellite moves in a north-south direction, while during the descending orbit, it moves in a south-north direction. The SAR images obtained from ascending and descending orbits provide different data for interferometric analysis, as they represent different perspectives of the same area. The differences between the ascending and descending images can be used to detect changes on the Earth's surface.

Fig. 1 Observation location of Aydınlıkevler region.

StaMPS/PSI is a remote sensing method that employs Synthetic Aperture Radar (SAR) images, obtained by either airborne or satellite platforms. The technique leverages the phase information of SAR images to identify persistent scatterers, which are typically human-made structures or stable natural features such as rocks or cliffs. These persistent scatterers serve as reference points to measure the deformations of the surrounding area over time. StaMPS/PSI can provide highly accurate measurements of surface deformation, with millimeter-level precision in some cases, making it a valuable tool for monitoring and forecasting natural hazards like earthquakes, landslides, and volcanic activity, as well as man-made structures such as buildings, bridges, and dams. The StaMPS/PSI technique entails a complicated data processing workflow that involves various steps, including image pre-processing, interferometric processing, and time-series analysis. Depending on the application, the processed data can be represented as deformation maps, displacement time series, or velocity maps. StaMPS/PSI finds applications in diverse fields like geohazards, geodesy, civil engineering, and environmental monitoring. For instance, the technique has been utilized to monitor the deformation of the Earth's crust in seismically active regions, to detect and monitor landslides in mountainous regions, and to monitor subsidence in urban areas due to the extraction of groundwater, construction of subway tunnels, or other factors.

The selected polygon in Figure 1 represents the observation area in the Aydınlıkevler region. The red line passing through the center of the polygon represents the metro route. Additionally, the PS points indicated at five different locations represent the selected locations for potential PSI candidates obtained through image and signal processing.

The ratio of the standard deviation to the mean amplitude value provides the threshold value for the dispersion. Selection of this value results in obtaining subsets. It is important to accurately determine the threshold value for the surfaces to be analyzed. This threshold value equation is,

$$D_a = \frac{\sigma_A}{\mu_A} \quad 1$$

It is expressed as σ_A for the standard deviation and μ_A for the mean amplitude (Hooper, A., & Zebker, H. A. (2007). After using amplitude relationships in PS values, the selection stage is reached for phase stability. Accurate PSI values are obtained using phase relationships. The phase correlation is used for this purpose,

$$\psi_{x,i} = w(\phi_{D,x,i} + \phi_{A,x,i} + \Delta\phi_{S,x,i} + \Delta\phi_{\theta,x,i} + \phi_{N,x,i}) \quad 2$$

It is defined as follows: $\phi_{D,x,i}$ is the angle-dependent component, $\phi_{A,x,i}$is the noise due to the atmosphere, $\Delta\phi_{S,x,i}$ *is* the noise due to the satellite orbit, $\Delta\phi_{\theta,x,i}$is the residual phase noise, and $\phi_{N,x,i}$is the noise due to thermal sources. The selection of PSI points is based on statistical criteria. After this operation, the scatterers are determined to be either persistent or non-persistent because sometimes the dominant scattered signals may not be persistent. The W operator is used to achieve accurate results. In this study, considering asphalt, concrete, and building structures for each selected area, a 0.38 average threshold value D_a was determined based on the reflection parameters of four different surfaces. Based on the literature review, it was deemed appropriate to use ascending datasets for this study. In studies conducted in the Northern Hemisphere, it was observed that the ascending direction of the satellite was less affected by equatorial acceleration when considering flight direction and scanning angle, thereby providing more coherent values. For this study, the first observation interval for Ankara was selected as 2015-2016, and a PSI analysis was conducted using 20 ascending Sentinel-1 images. The second observation interval was chosen to cover the years 2017-2022. Detailed information about the Sentinel 1A images is provided in Table 1.

For the first observation, a total of 20 ascending-oriented datasets were utilized, with the Sentinel 1A image acquired on August 19th, 2015 determinated as the master image. The observation period lasted from June 27th, 2015 to May 9th, 2016. In the second observation, a total of 68 ascending-oriented images were used. The master image was selected from the dataset acquired on August 16th, 2019, and the observation period lasted from June 27th, 2017 to January 15th, 2022.

Table 1 Dataset metadata for first and second observations

Observation	ImageNumber	TimePeriod	MasterImage
First	20(Ascend)	2015.01.27/ 2016.05.09	2015.08.19
Second	68(Ascend)	2017.06.27/ 2022.01.15	2019.08.16

Results

Observation results conducted at five different points between 2015-16 and 2020-2022 will be analyzed in accordance with the methodological approach discussed in previous sections. To obtain these analyses, two different Persistent Scatterer Interferometry (PSI) studies were conducted for the first and second periods of interest. Time series were obtained from the outputs of the PSI studies. The resulting graphs show the time series for the first period in the top panel and the time series for the second period in the bottom panel. Tunnel excavation with working area. Between Km: 3+440.00 and Km: 3+580.00, there are alluvial soils in the Çubuk Stream bed. In the first case, the groundwater depth is 4.5 m and the soils are silty sand, good grade sand, bad grade sand, silty gravel and fine gravel. The tunnel is 13.5 m deep and 5.90 m in diameter from the surface and was dug with a TBM(Sojoudi, H., Ulamis, K., & Kilic, R., 2021). During the excavation of the 2nd line in 2006, no serious damage was observed in the surrounding structures. Figure 2 represents the PSI analysis between 2015-2016 in the left image and the PSI analysis between 2017-2022 in the right image. The points marked as PS on the panels depict the regions where the time-series observations will be conducted. According Figure 3, five different points were determined for the time series analysis. The points are named PS1, PS2, PS3, PS4 and PS5. The location of the PS1 point of the Aydınlıkevler Zone is to the east of the deformation zone. This point is also located within the borders of Ankara University Faculty of Agriculture. There are no other settlements in the location. The first and second observations of the PS1 point are given in Figure 3.

Based on Figure 3, no significant deformation was observed at the PS1 point in Aydınlıkevler during the first observation period. However, a notable deformation of approximately 25 millimeters was detected during the second observation period (2017-2022), located on the border of the metro tunnel just east of the Kızılay-Keçiören line. Aydınlıkevler is situated at the PS2 point, west of the Keçiören-Kızılay metro line, and while it is not a heavily populated area, there are residential regions in the vicinity. Figure 5 illustrates the results for both observation periods at the PS2 point in Aydınlıkevler. In Figure 4, the top diagram depicts the data collected during the first observation at the PS2 point. The results indicated that there was no significant deformation in the vicinity of the PS1 point during the first observation period. However, during the second observation period, deformation of approximately 15 millimeters was observed, and the total displacement at the PS2 point was approximately 10 millimeters less than at the PS1 point. The PS3 point, located to the east of the Kızılay-Keçiören metro line in Aydınlıkevler, is located just east of the PS1 point and situated within the boundaries of the Ankara University Faculty of Agriculture campus. Figure 5 presents the time series analysis for both observations at the PS3 point

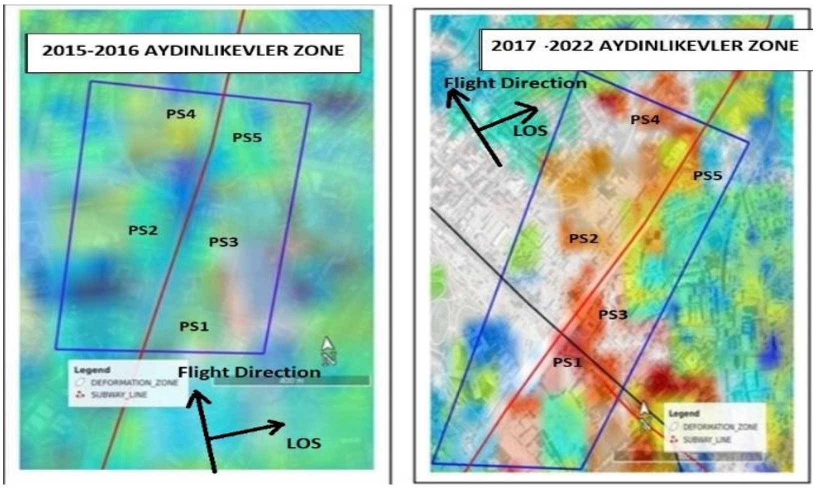

Fig. 2 PSI results for first and second observation.

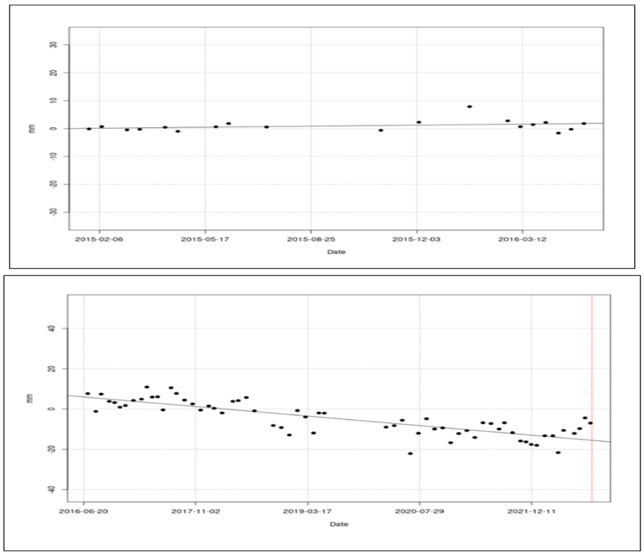

Fig 3.PS1 Values First (top) and second (bottom)

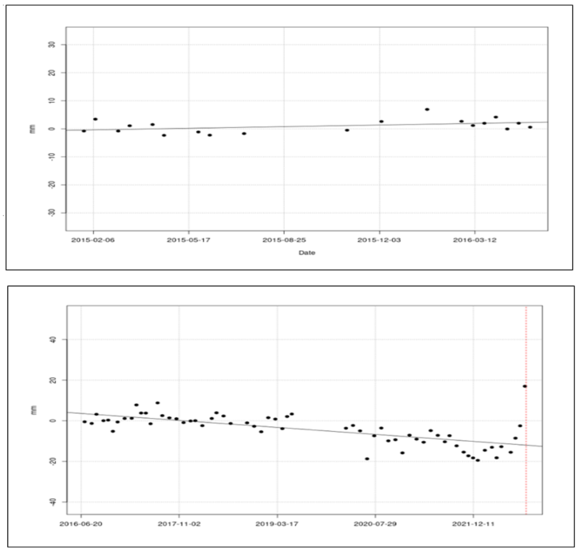

Fig 4. PS2 Values First (top) and second (bottom)

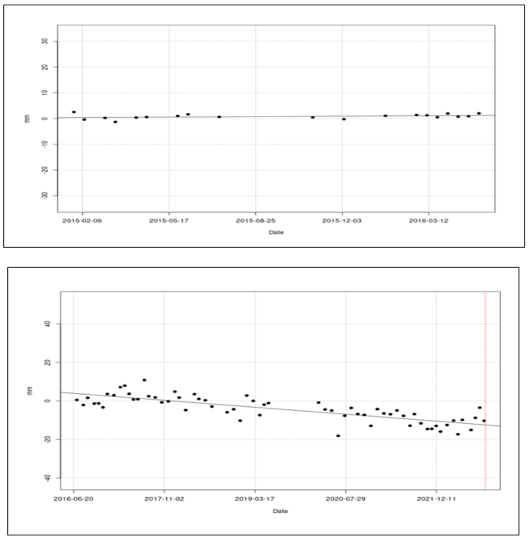

Fig 5. PS3 Values First (top) and second (bottom)

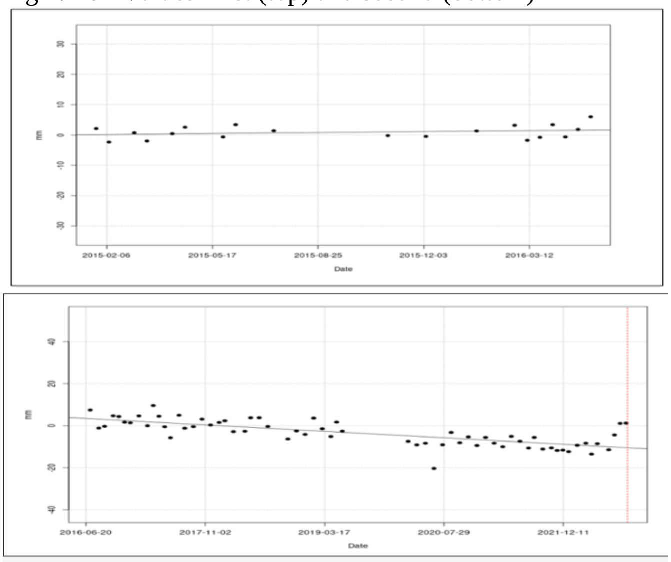

Fig6. PS4 values first (top) and second (bottom)

According to the first observation displayed in Figure 6, the PS3 point exhibited negligible displacement within the time series analysis between the years 2015-2016. The total displacement was observed to be almost zero at this location. In the subsequent observation period below, a notable displacement occurred. During this period, which covers the first quarter of 2017 and the last quarter of 2022, the time series analysis of the PS3 point showed a 20-millimeter difference. PS4, the fourth observation point within the Aydınlıkevler region, is situated in the northwest of the Kızılay-Keçiören M4 metro line, in an area near settlements. The time series analysis of this location is presented in detail in Figure 6 for both the first and second observations. The time series analysis presented in Figure 6 for the fourth observation point in the Aydınlıkevler area indicates that there was no significant displacement during the observation period of the first stage. However, in the second observation, a total LOS shift of 12 millimeters was observed, indicating the presence of deformation in the region. The PS5 point observation area is situated in the northeast of the Aydınlıkevler belt, close to the Kızılay-Keçiören metro line. Figure 7 presents the results of the two-stage observations carried out for the PS5 point, which provides valuable insights into the deformation behavior of the region.

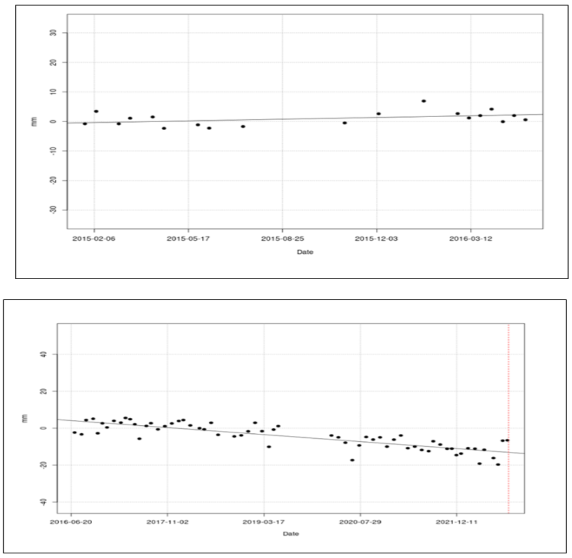

Fig.7 PS5 Values First (top) and second (bottom)

Fig.8. In-situ images taken from Aydınlıkevler (Sojoudi, 2015)

Figure 7 displays the time series analysis of the PS5 observation point in the Aydınlıkevler region, which is situated on the eastern boundary of the Kızılay-Keçiören metro line. The initial observation revealed no deformation with respect to time, whereas in the subsequent observation, a total LOS displacement of 15 millimeters was observed. Although the total displacement at PS5 is similar to PS4, it appears to be less than that of PS1, PS2, and PS3.

Discussion and Conclusion

Analyses of PSI and time series data were carried out for the M4 metro tunnels passing through the Aydınlıkevler region. A correlation was found between the in-situ observations and the PSI results. Based on these in-situ studies, it was observed that some buildings and grounds were damaged in areas where subsidence anomalies were present in the LOS direction..

The regional gravity areas (A) in Figure 8, the ground deformation caused by the tunnel can be seen in the area belonging to the Ankara University outer gate campus. In (B), cracks due to ground deformation are seen on the walls of a building belonging to the Faculty of Agriculture. (C) shows significant collapse in a part of the garden in the direction of the metro line. The findings obtained in this article study conducted in Ankara University Geology Department in 2015 revealed the effects of ground deformation caused by subway tunnels. It has been determined that the effect of this deformation supports the time series analyzes detected in the Aydınlıkevler zone.

As it can be understood from the whole study, it is possible to determine and predict the ground deformations before the construction is started by creating a data. This shows that it is possible to prevent it with the method and data generation method used in this study in order to reduce the costs of subsequent modifications.

This article study has shown that the ground structure and the structures built on this ground are directly affected by the subway tunnel works. In the first observation of the PSI studies, very little deformation is seen between the years 2015-2017. As stated in the in-situ research, strengthening studies were carried out on deformed buildings and floors. However, when the second observation is examined, deformation is observed in the same region in 2016-2022. This study clearly demonstrates that soil deformation can be detected with PSI. And it is effective in predicting possible damages and taking precautions. If the structures are examined regularly and the necessary precautions are not taken, it is highly likely that the buildings in the region will be damaged over time due to the tunnel work.

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