PREDICTION OF LONG-TERM SENTINEL-1 INSAR TIME SERIES ANALYSIS

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ABSTRACT:

This paper presents an initial analysis of predicting time series derived from long-term interferometric Synthetic Aperture Radar (InSAR) data. Time series analysis provides insights into the temporal evolution, variation, and dynamic nature of events. In this study, we focus on the Istanbul region, which is the most populous city in Turkey and spans both Europe and Asia. While the area is prone to seismic risks caused by active tectonic faults, it is also susceptible to other risks due to various phenomena. Therefore, this study investigates landslides triggered by geological structure and human-induced activities, particularly in Tepekent, a landslide-prone area in the town of Buyukcekmece located on the European side. We utilized the StaMPS persistent scatterer InSAR (PSI) method to detect slow movements over time. A total of 157 archive Copernicus Sentinel-1 data, acquired over the region between June 2017 and August 2022, were processed, primarily observing human structures with a maximum displacement amount of approximately 1 cm/year. About 500 persistent scatterer points were identified in the region, and the time series was formed by taking the average of these points. The Long Short-Term Memory (LSTM) neural network method was used to estimate motion. We trained the model with data from the first three years of the time series and used the data from the remaining two years for estimation, while the accuracy analysis was performed with the 5-year time series data. The RMSE values for the training and test data were determined to be 0.725 mm/year and 0.656 mm/year, respectively. Additionally, we estimated the time series for the period from August 2022 to August 2024. The observation and prediction results could be beneficial in developing efficient mitigation risk actions and sustainable urban management strategies.

1. INTRODUCTION

Geohazards represent one of the major concerns in many countries being also exacerbated by the climate changes. Among countries, Turkey is one of the most vulnerable to earthquakes, landslides, fires and floods (Tatar, 2020). Particularly, Istanbul which is the most crowded city of Turkey and Europe is threatened by the North Anatolian Fault that passes through the Marmara Sea representing a relevant source of risk for the city (Ergintav et al., 2011). Meanwhile, there are also small-scale local movements affecting many people and infrastructures of the city. Previously, several studies based on using multi-temporal Interferometric Synthetic Aperture Radar (SAR) techniques, showed the long-term surface displacements triggered by both man-made activities and natural events. Persistent Scatterer Interferometry (PSI) and Small Baseline (SB) techniques have been extensively employed in previous studies to analyse long-term displacement, particularly in large regions and urbanized areas (Ferretti et al., 2001; Berardino et al., 2002; Hooper et al., 2012; Calò et al., 2015; Aslan et al., 2018; Bayik et al., 2021).

Calò et al. (2015) presented one of the first studies over the old peninsula of Istanbul using high resolution TerraSAR-X data. The authors applied SB approach and identify local subsidence areas along the Golden Horn (Halic) where filling and recreation areas are located. The one and half year period of data results indicated displacements up to 4 cm at underground subway stations. The geological data showed that most of the subsidence occurred in the Quaternary layers. Aslan et al. (2018) showed 25 years of movements occurring in Istanbul city using ERS, ENVISAT and Sentinel-1 data processed through PSI method. The authors presented the localized movements on recreational areas, coastal zones, river valley and sliding regions in Istanbul city center. Halicioglu et al. (2021) reported the surface displacements of metro constructions in the Asian side of Istanbul by using Sentinel-1 and PSI approach for the period of 2015 and 2018, and in situ levelling measurements. Yagmur et al. (2022) monitored the site of the

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new Istanbul Airport. The authors applied both SB of LiCSAR approach and STAMPS of PSI approach, and showed the slow-developing surface displacement of runway between for the period 2018 and 2021 using Sentinel-1 data.

The analysis of landslide area nearby the case study was carried out by Bayik et al. (2021) using five years (2015-2020) of Sentinel-1 data. The authors investigated the landslide phenomena at the east of Lake Buyukcekmece, over residential areas. They also highlighted the contribution of L-band over C-band data. Previous studies, focused on mapping surface displacements and determining the mean velocity, provided the current situation of the deformation in the area. However, its prediction for future years can play an essential role to prevent/mitigate the associated risks. Recent studies showed the potential of prediction models for InSAR time series. In particular, Long Short-Term Memory (LSTM) neural network method that use time dependency of archived data, is exploited to provide accurate prediction results (Bao et al., 2022). The method has been applied for displacement prediction of the airport in Shanghai (Bao et al., 2022), in Beijing (Chen et al., 2021), of the land subsidence in Iran (Radman et al., 2021) and in the urban area of Wuhan (Ding et al., 2021) using InSAR time-series data.

In this study, the LSTM approach is applied for the prediction of time series related to a landslide-induced deformation. In the analysis, Sentinel-1 data were used, and PSI method was applied to retrieve the slow movements associated with landslides near Buyukcekmece Lake in western Istanbul (Figure 1). The study is aimed at predicting time series of the displacements, to understand the behaviour of the trend and, possibly, the total displacement value.

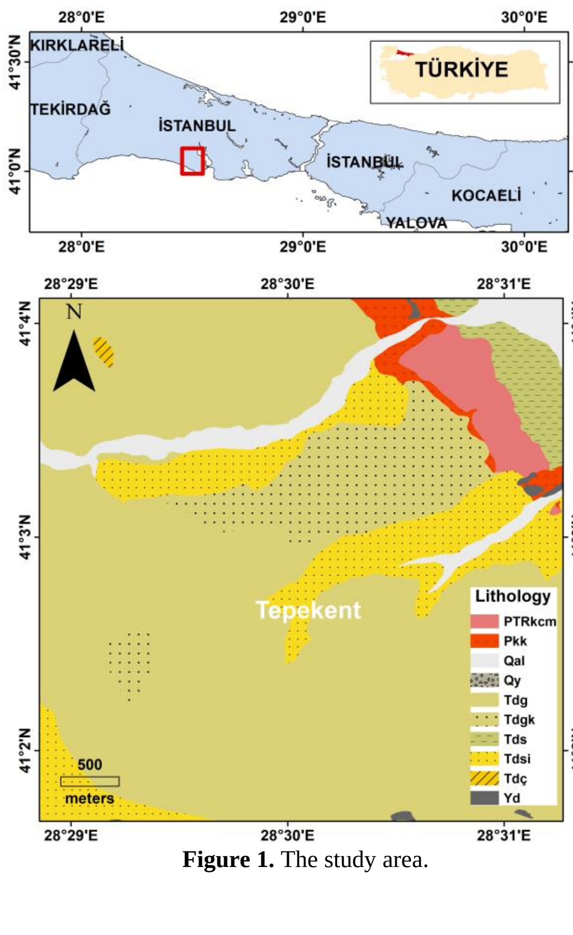

Figure 1. The study area.

2. DATA AND METHOD

2.1 The study Area

The study area is located in the European side of Istanbul, a megacity wherein more than 15 million inhabitants live (Figure 1). In particular, the region under investigation is located in the Buyukcekmece district, prone to two main types of hazards: earthquakes and slow-moving active landslides, threatening thousands of residents. Lake Buyukcekmece is located at the northeast of the study area where a long landslide history exists (Duman et al., 2006). Southern part is bordered with the Marmara Sea.

A large part of the region consists of lithological units such as Oligocene (Tdg, Tdgk, Tds), Miocene (Tdc, Tdsi) (Figure 1). Among the units, Tdsi is composed of ash brown, thick bedded, coarse-grained sandstone-conglomerate, Tdd and Tdgk are greenish, dark gray, purple, mottled, claystone-shale; interbedded with sandstone and claystone, interbedded with thin lignite structures. The rest are alluvium (Qal), artificial filing (Yd), phyllite, garnet schist, graphite schist, calcschist (PTRkcm), and Kızılağaç metagranite formation (Pkk) (Seyyar et al, 2020).

2.2 Sentinel-1 Data Analysis

In order to analyse the landslide kinematics, 157 Copernicus Sentinel-1A data taken along descending orbit between June 2017 and August 2022, were acquired through NASA Alaska Satellite Facility (ASF), as shown in Table 1. The Single Look Complex (SLC) images were pre-processed with SNAP 9.0, and StaMPS (4.1 beta) approach of PSI was utilized for the analysis of deformation time series and mean velocity. Among the images, 03.02.2020 dated one was selected as primary, and 156 interferograms were generated using SNAP software. (SNAP 2022). The Toolbox for Reducing Atmospheric InSAR Noise (TRAIN) was used to reduce the atmospheric effects (Bekaert et al., 2015). The PSI approach identifies persistent scatterers based on their amplitude dispersion and interferometric phase correlated in space. We considered an amplitude dispersion D_A value of 0.4 to eliminate non-PS candidate pixels. The DA is calculated as;

$$D_A = \frac{\sigma_A}{\mu_A} \tag{1}$$

where, σ_A = standard deviation
μ_A = mean of amplitude

Specifications	Description
Sensor	Sentinel-1A
Wavelength	C-band
Orbit	Descending
Acquisitions	06.06.2017-29.08.2022
Image size	157
Pixel spacing	14 m (Rg:4 Az:1)
Polarization	VV

Table 1. Specifications of the Sentinel-1 data used for the study

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2.3 The Long Short-Term Memory

To predict time series monitored by InSAR, we exploited the the Long Short-Term Memory (LSTM) approach, which offers advantages, particularly for historical datasets and nonlinear time series. A feedback mechanism has been added to the code of the Recurrent Neural Network (RNN), which is one of the feedforward networks structures, by making additions (Hochreiter and Schmidhuber, 1997). In this way, LSTM can access the input and output information realized in the previous steps when they needed to. The general structure of LSTM comprises layers of forget gate, update gate, Tanh, and output gate layers (Bao et al. 2022). In our study, we utilized the LSTM model developed with the keras package (Url-1), and the analyses were performed using the open-source R programming language (Url-2). As per the code, data normalization is mandatory, and for this purpose, the recipes package was used in the code. Here, the square root is taken while normalizing. The code selected Batch size= 1, Time steps=1, epochs =100. We employed Root Mean Square Error (RMSE) (eq. 2) and %RMSE (eq.3) to assess the accuracy of the test data and determine the accuracy rate, respectively.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i^{act} - y_i^{cal})} \quad (2)$$

$$\%RMSE = \sqrt{100 * \frac{1}{n}\sum_{i=1}^{n}(y_i^{act} - y_i^{cal})} \quad (3)$$

where n= the number of samples
y_i^{act} = is the 2-year LOS value
y_i^{act} = is the 2-year estimated LOS value

3. RESULTS AND DISCUSSION

The temporal and geometrical baselines of the 156 interferograms created based on a single image are depicted in Figure 2. The maximum temporal baseline spans approximately 3 years and the temporal baseline is less than 200 m. The findings of PSI analysis revealed that displacement velocity along the Line of Sight (LOS) ranged between -10 to 2 mm/year with a standard deviation of less than 0.5 mm/year, as shown in Figure 3.

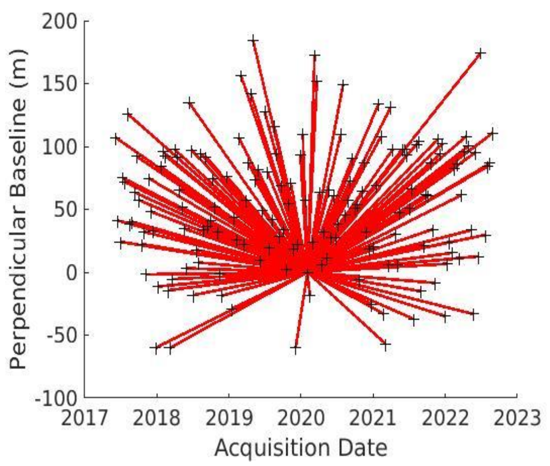

Figure 2. The baselines of the computed interferograms.

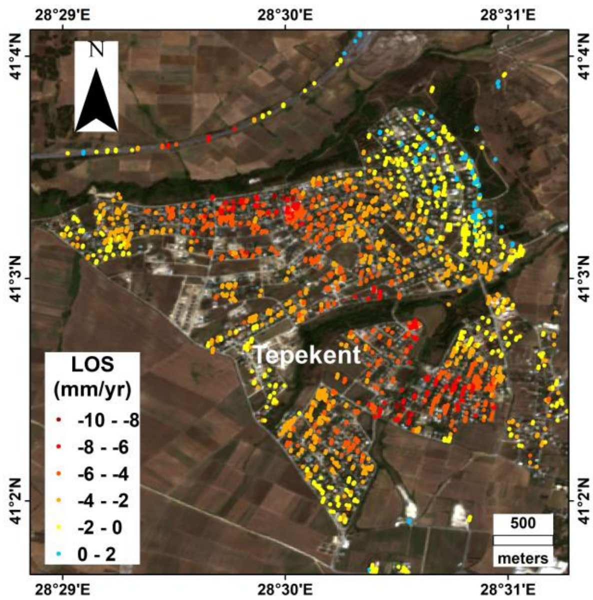

Figure 3. PSI deformation velocity map.

The majority of high movement and PS points were located over the coarse-grained sandstone-conglomerate, claystone, and sandstone structures. PS measure points were predominantly identified on building structures, and along the road line situated in the northern region. As anticipated, no PS points were detected in the agricultural areas surrounding the Tepekent region. Notably, PSs with higher displacements were primarily identified in the valley situated in the central part of the study area. To demonstrate the relationship between the spatial distribution of moving points and the topography, two perpendicular profiles were analysed (Figure 4 and 5). In the A-B profile extending from the north to the southeast, the deformation value increases and decreases in parallel with the increase and decrease in the topography. In the C-D profile, extending from west to east, the movement increased as the elevation decreased. After reaching the minimum at the valley floor, the movement decreased with the height towards the east (Figure 5).

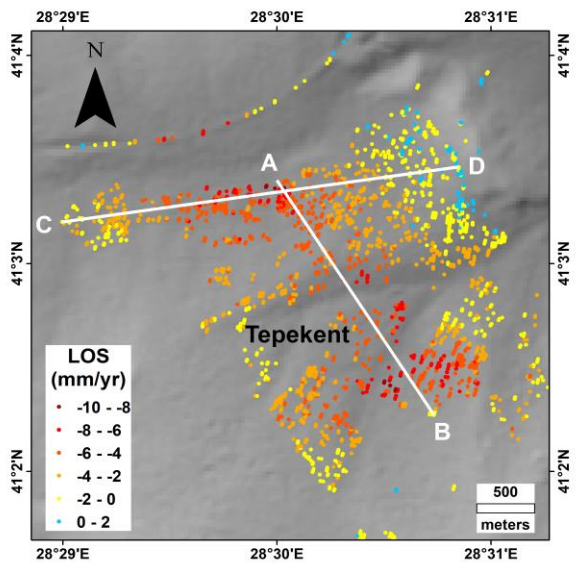

Figure 4. Profiles along the topography and PSI velocity map.

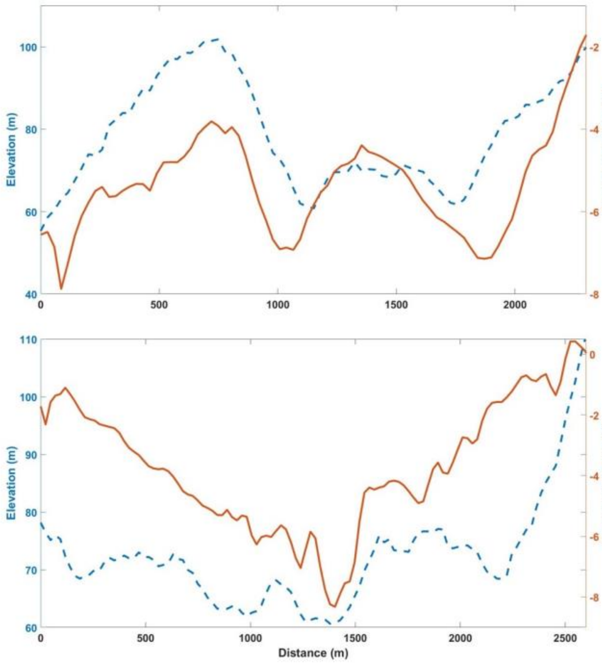

Figure 5. Profile of PSI displacements vs. profile of elevation

A mean time series was constructed by using an average of 513 points in time series analysis. The first three years of the time series (91 images), spanning from June 2017 to August 2020, were used to train the displacement model and predict the last two years (60 images) from August 2020 to August 2022. The predicted values were then compared with the monitored time series, and their accuracy was evaluated using the correlation coefficient (R), Root Mean Square Error (RMSE), and RMSE% evaluation indices. The R values for the train and test data were 0.988 and 0.986, respectively (Table 2). The RMSE values were 0.725 mm/year and 0.656 mm/year for the train and test data, respectively. Although the predicted time series exhibited a velocity for the test data, its RMSE% (8.766 mm/year) was approximately half that of the train data (15.749 mm/year). The results indicate a high level of agreement between the monitored and the predicted time series (Figure 6). Furthermore, a prediction for the next two years of the time series, from August 2022 to August 2024, was also performed (Figure 6).

	LSTM results	
	Train	**Test**
R	0.988	0.986
R^2	0.973	0.973
RMSE (mm/year)	0.725	0.656
%RMSE	15.749	8.766

Table 2. Results of the LSTM method

In a previous study, Chen et al., (2021) compared prediction models for ENVISAT time series data, including LSTM, Multi-Layer Perceptron (MLP) and Recurrent Neural Network (RNN) models. They analysed displacement at Beijing Capital International Airport using images from 2005 to 2010 and found that the cyclic prediction model of LSTM produced the best results, with RMSE of 4.60 mm.

Ding et al. (2021) used Multi-temporal InSAR approach on Sentinel-1 data acquired between 2018 and 2020 to study urban surface subsidence in Wuhan city. They analyzed time series data from eight points and found varying behaviours in the data with RMSE values ranging from 1.89 mm to 3.48 mm.

Bao et al. (2022) conducted an analysis of surface deformation at Shanghai Pudong International Airport using StaMPS PSI technique and Sentinel-1 data. They used data from 2016 to 2021 and applied the LSTM method to predict the time series. The researchers reported that they experimentally combined and determined the parameters for the model. The results showed an RMSE of less than 3.52 mm for the test data.

Radman et al. (2021) conducted research on the environment of Lake Urmia, Iran, using the SB approach to determine surface subsidence, with time series of Sentinel-1 data acquired between 2014 and 2019. In the study, LSTM, multi-layer perceptron (MLP) and convolutional neural network (CNN) methods were compared. In addition to vertical deformation derived from SB analysis, ancillary data such as precipitation, NDVI and groundwater data were included as inputs to the models. Overall, LSTM provided the lowest RMS of 8.1 mm, but CNN showed the lowest RMSE of 8.7 mm in testing results. Among all methods, CNN was considered to be the best approach for the estimation.

Previous studies have examined surface subsidence in various locations, including airports, cities, and natural areas. Two studies comparing different methods have shown that LSTM method provided the best results in one, while CNN was superior in the other. Both PSI and SB methods have been utilized for time series analysis. Considering the studies mentioned above, an RMSE of less than 9 mm was achieved. It should be noted that the differences in how the models are trained can impact their accuracy.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

Due to intense human activities and its geological structure, Istanbul is vulnerable to several anthropogenic and natural hazards. In this study, we focus on investigating landslides that affect some neighbourhoods of the megacity. The time series prediction of InSAR - derived results is investigated through the application of the LSTM method. The approach has shown its potential with RMSE values lower than 1 mm. This proves LSTM method is a promising method for predicting landslide deformation time series, thereby contributing to geo-hazards related risk prevention and reduction.

In the analysis, only the mean of the PS points was used. As further research direction, the study will be extended to time-series of each point to predict spatial distribution of the landslide effects. Furthermore, the time series will be refined by eliminating the observed seasonal effects. Additionally, data obtained with long terrestrial measurements will be incorporated to determine whether the estimation results are more reliable.

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Figure 6. Time series of monitored and predicted displacements. The vertical axes show the LOS displacement velocity (mm/year).

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