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InSAR TECHNOLOGY FOR RISK MANAGEMENT AND NATURAL DISASTER IMPACT ASSESSMENT IN BUCHAREST

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Abstract

The study analyzes the use of InSAR technology and validated data for risk management and natural disaster impact assessment, focusing on the subsidence in Bucharest, associated with underground works and activities, and earthquakes. The TerraSAR-X and TanDEM-X satellites provide crucial information for rapid mapping, spatial analysis, and thematic mapping, supporting effective responses to earthquakes, floods, and other hazards. The analysis identifies ground changes based on radar data using techniques such as Persistent Scatterers (PS) and Small Baseline Subset (SBAS). The study integrates decision analysis into the ILWIS software, using the multi-criteria method (SMCE) to assess vulnerabilities along the M5 Metro Line. The methodology involves structuring problems, evaluating alternatives, and prioritizing solutions, demonstrating the applicability of innovative tools in reducing urban risks. The results highlight the importance of advanced technologies in risk prevention and management, providing recommendations for reducing the impact of subsidence and improving urban planning. There is a clear need for integrated, rapid, and accurate approaches to respond to the more frequent and complex challenges in contemporary society based on validated data and modern technologies.

Key words: *remote sensing, interferometry, subsidence, risk management, urban planning.*

INTRODUCTION

With rapid population growth and urban expansion, urban risk management has become a global priority (Oprea et al., 2015; Sabău et al., 2023; Sanda et al., 2023). Bucharest, a city with an intense pace of development, faces major challenges related to subsidence, seismic vulnerability, and the impact of anthropogenic activities on soil and buildings. Previous studies have shown that Bucharest is one of the most vulnerable cities to earthquakes, with a historical rate of 2-3 major earthquakes per century (Armaș et al., 2017). Research conducted after the earthquake from 1977 highlighted the influence of the surface geological layer on seismic movements, and the damage reported to tall buildings is closely related to the subsurface sedimentology and the seismic amplification effects due to the Vrancea earthquakes (Radulian et al., 2007). More recently, to improve the understanding of seismic risks, a 3D geological model of the city was developed, based on hundreds of boreholes made for the metro and a digital terrain model (DEM), using GIS kriging interpolation, thus highlighting the Quaternary layers and the influence of hydrogeology on seismic micro-zonation (Bala et al., 2023).

The first decision-making analyses on urban vulnerability were conducted for the Historic Center of Bucharest by Gheorghe and Armaș (2015), identifying buildings that can serve as shelters in case of disaster.

In addition to seismic risk, subsidence is an aggravating factor of urban vulnerability and is caused by both natural phenomena and anthropogenic activities (Huang et al., 2016). New constructions, including taller buildings, deep foundations, expansion of the metro network, and aboveground transportation infrastructure, can have a significant impact on soil stability (Poncos et al., 2014). In this context, monitoring land surface deformations is one of the most reliable methods for assessing and managing geological hazards.

In Bucharest, using Sentinel-1 data and the PSI technique, a map of vertical displacements was produced for the period 2014-2018, identifying several subsidence areas, one of which contains a thick layer of debris from urban constructions, analyzed in detail in correlation with the local geological model and the urban hydrogeological system (Radutu et al., 2020).

Also, a combined *in situ* monitoring and remote sensing study investigated the effects of metro tunneling and groundwater pumping, demonstrating that interferometric remote sensing is a viable alternative to *in situ* measurements (Boukhemacha et al., 2021).

Long-term monitoring of urban subsidence and its correlation with metro infrastructure development and local hydrogeological characteristics are essential for risk prevention and optimization of urban planning (Bala et al., 2023). International studies have shown that subsidence is more pronounced in cities with intense economic activity and extensive urban infrastructure (Wang et al., 2024). Cities such as Mexico City and Istanbul have implemented effective risk reduction strategies, demonstrating that adopting proactive measures can significantly contribute to the protection of infrastructure and population (Glod-Lendvai, 2019). In this context, Bucharest must adapt its monitoring and prevention strategies to face the challenges related to subsidence and seismic risk in a continuously expanding urban environment.

The present study explores the use of InSAR (Interferometric Synthetic Aperture Radar) technology for monitoring and assessing urban subsidence, providing a solid scientific basis for the reliable management of urban planning and associated risk reduction.

MATERIALS AND METHODS

Subsidence monitoring was carried out using advanced Persistent Scatterers (PS) and Small Baseline Subset (SBAS) techniques, applied to a set of 24 TRS-X (downslope) and 27 TRS-X (upslope) scenes, covering the period 2011-2014. Analysis of radar data provided by the TerraSAR-X and TanDEM-X satellites provided a detailed picture of ground changes, and their correlation with field measurements allowed the identification of areas with the highest risk of instability.

An essential component of the study was the application of the Spatial Multi-Criteria Evaluation (SMCE) method in the ILWIS software, to classify vulnerable areas based on critical factors, such as geological composition, infrastructure density, and the impact of anthropogenic activities.

By using InSAR technology and advanced analysis methods, the study provides a detailed perspective on soil dynamics, contributing to a better understanding of geotechnical risks and the substantiation of decisions regarding sustainable urban development. The vulnerability of buildings was analyzed through an analytical method based on the correlation of information about buildings, obtained from the Digital Terrain Model (DTM) and the Digital Surface Model (DSM). In parallel, the vulnerability of the population was determined through the analytical method.

The validation of the results was achieved by correlating radar images provided by the TerraSAR-X and TanDEM-X satellites with field measurements. This integrated approach provided a detailed perspective on the evolution of subsidence and the risks associated with it, contributing to a better understanding of the phenomenon and the substantiation of decisions regarding urban infrastructure.

The decision-making analysis carried out for the M5 Metro line from Drumul Taberei was carried out using the multicriteria method, using a spatial decision-making assistance system through the SMCE (Spatial Multicriteria Evaluation) module of the ILWIS software. The study aimed to identify the most vulnerable sectors along the M5 Metro Line, considering the impact of subsidence caused by underground works, in the seismic context specific to the city of Bucharest.

The analyzed area includes a 400-meter-wide corridor, located along the M5 metro line (Figure 1). The route starts from the Dâmbovița meadow and crosses the Drumul Taberei neighborhood to the west, passing through a complex urban environment, with different types of constructions and varied geotechnical conditions.

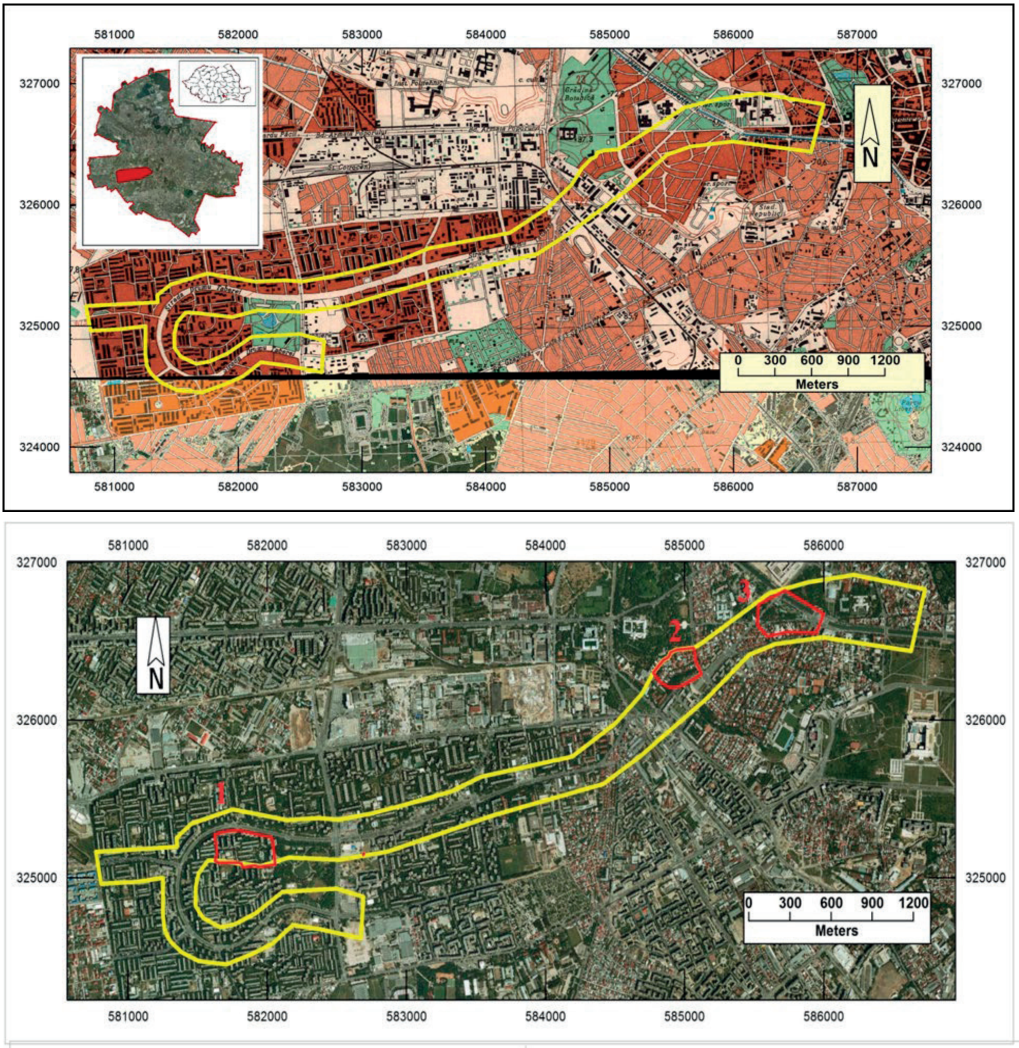


Figure 1. Study area in Bucharest, Romania

The incident at Eroilor station raised essential questions regarding the safety of buildings located above the metro tunnels.

The main concerns focused on their vulnerability in the event of an earthquake and on the influence that underground works may have on the stability of the buildings. Also, the trends of vertical movements captured by satellite interferometry were studied, to determine to what extent these phenomena are the result of anthropogenic interventions.

The analysis followed a clear methodology, structured in several stages. In the first phase, the problem was defined and organized by developing a decision tree using the ILWIS-SMCE module. In the next stage, relevant InSAR points were selected for the assessment of subsidence, using the PS (Persistent Scatterer) and SBAS (Small Baseline Subset) techniques (Figure 2). The obtained data were statistically analyzed to determine the speed of land movement over one year, highlighting the areas with the highest subsidence (Figure 3).

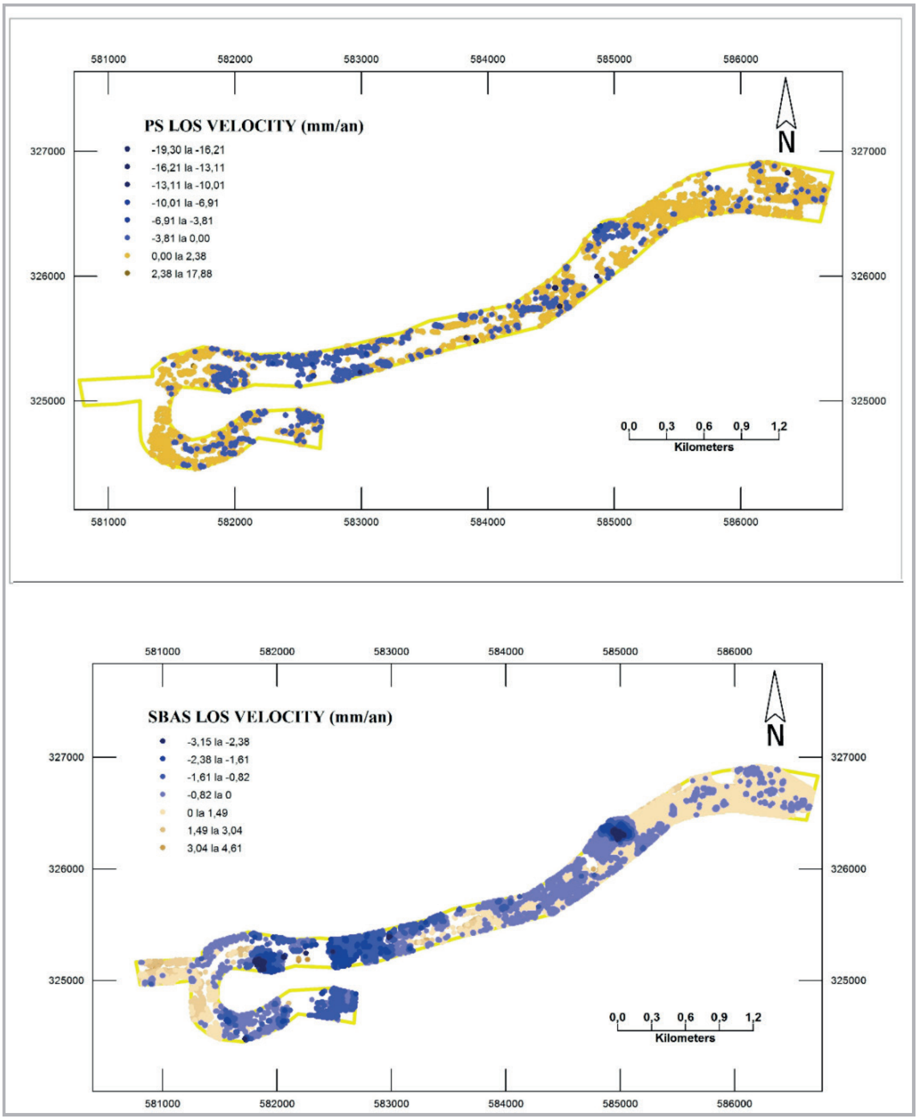


Figure 2. Deformation rates in the M5 metro line area

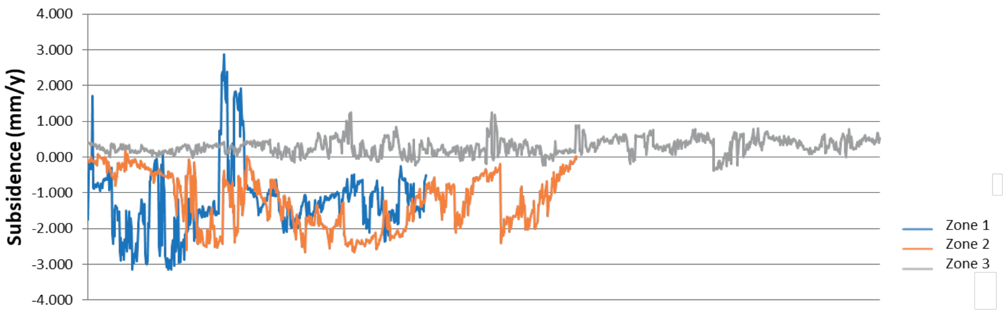
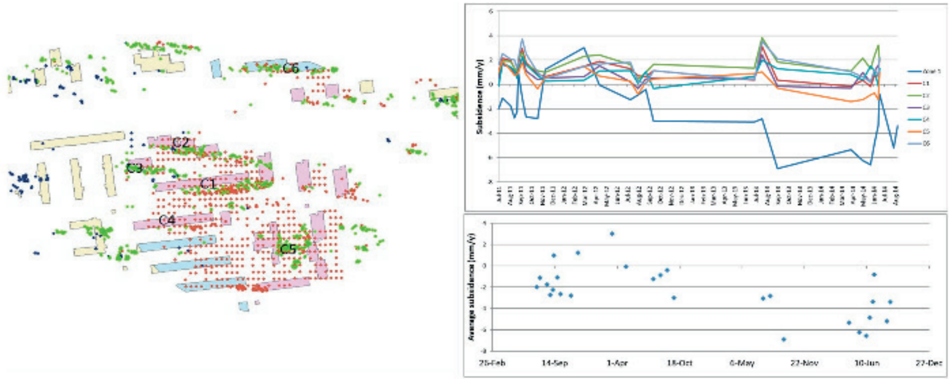


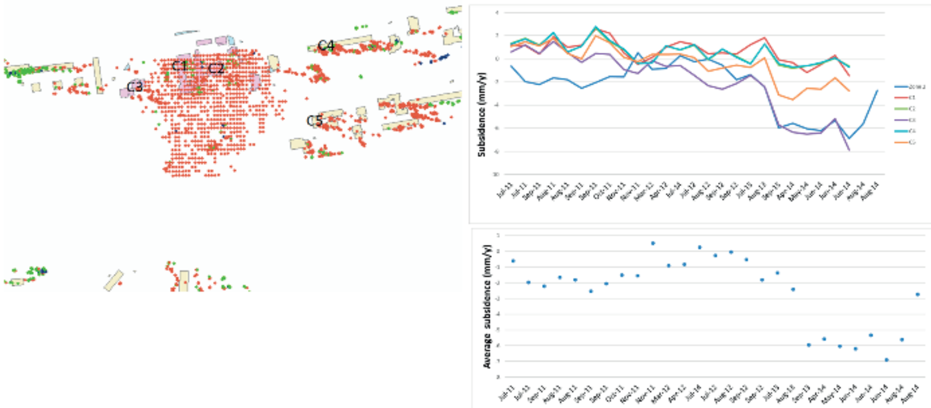
Figure 3. Vertical displacements from SBAS points in time

RESULTS AND DISCUSSIONS

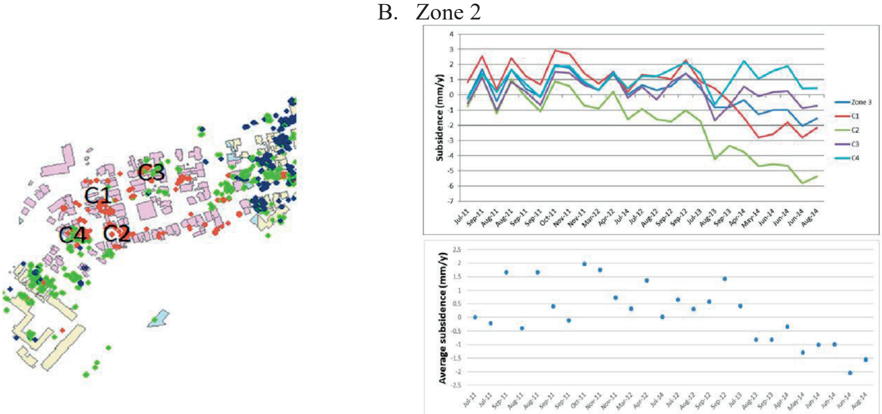
The results showed that the most pronounced subsidence was found in two main areas, located in sectors where infrastructure works were carried out between 2011 and 2020. The Eroilor area was also identified as the most affected, given the major incident that occurred during the execution of the metro line (Figure 4).



A. Zone 1



B. Zone 2



C. Zone 3

Figure 4. Estimation of subsidence at the level of buildings in all three zones between 2011 and 2014

To understand the impact of these phenomena on buildings, the InSAR analysis was extended to buildings in the most affected areas. The results indicated that, in general, most buildings are stable, and the observed subsidence movements did not exceed the critical threshold of 25 mm mentioned in the specialized literature. The highest values were recorded in the Eroilor area, where settlements reached a peak of 21 mm during the incident.

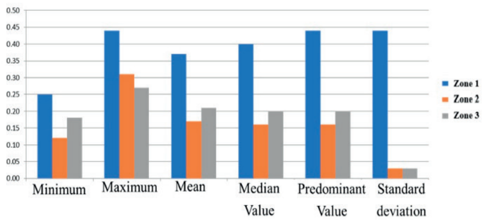
The study highlighted significant differences between the construction typologies in the three analyzed areas. The buildings in the first area are reinforced concrete structures, with a high height regime, built between 1977 and 1985 according to the construction norms of that period. In contrast, most buildings in areas two and three are masonry constructions, with rigid or flexible ceilings, built before the earthquakes of 1977 and even 1940, which makes them more vulnerable to seismic risks and subsidence phenomena.

For a correct assessment of vulnerability, the data were subjected to a normalization process. The interval procedure was used to highlight and differentiate even the smallest variations in the datasets. Regarding the seismic vulnerability of buildings, the maximum procedure was applied, thus avoiding any intervention that could alter the initial distribution of the data. Also, the distance from the RATB stations was considered an important factor, being evaluated in inverse proportion to the vulnerability of the area, with short distances being perceived as an advantage.

To rank the risk factors and calculate the specific scores, the SMCE module of ILWIS was used. After selecting the indicators, normalizing them, and defining the weights, the analysis led to the generation of vulnerability maps.

The final results indicated a variable vulnerability index depending on the area analyzed. The lowest values of this index, i.e., 0.12, were recorded in zone two, while zone one presented the highest level of vulnerability, with a maximum index of 0.44. The detailed analysis of each indicator and sub-objective confirmed that zone one is the most vulnerable of the entire investigated sector (Figure 5). By applying a rigorous multi-criteria assessment method, this decision-making analysis allowed the identification of the sectors with the highest degree of vulnerability and provided a solid basis for making informed decisions regarding the necessary protection and consolidation measures along the M5 Metro Line.

The results of the study showed that the vulnerability index varied between 0.12 and 0.44, with the highest values being recorded in the area delimited by Drumul Taberei (north), Târgu Neamț Street (east), Pașcani Alley (south), and Cetății Street (west). In this region, the analysis indicated a higher predisposition to soil instability and possible negative effects on buildings.



Zone	Minimum	Maximum	Mean	Median Value	Predominant Value	Standard deviation
Zone 1	0.25	0.44	0.37	0.40	0.44	0.44
Zone 2	0.12	0..31	0.17	0.16	0.16	0.03
Zone 3	0.18	0.27	0.21	0.20	0.20	0.03

Figure 5. Statistical analysis for the three studied areas

A consistent uplift pattern was identified in the interfluve area between the Dâmbovița and Colentina rivers, suggesting an active process of land deformation. In addition, subsidence phenomena were evident in the northwestern and southeastern outskirts of Bucharest, highlighting the need for prevention and intervention measures to reduce the risks associated with these areas.

CONCLUSIONS

The analysis of urban vulnerability and subsidence in Bucharest highlighted the need to implement advanced risk monitoring and management strategies. The use of modern technologies, such as InSAR, together with advanced analytical methods, provides a solid basis for informed decision-making, contributing to the protection of infrastructure and population against natural and anthropogenic hazards.

The application of these methods allows for an efficient management of urban risks, demonstrating that validated data can be used to reduce the impact of subsidence, optimize urban planning, and prevent disasters. By integrating advanced technologies, such as InSAR and multi-criteria analysis, it is possible to identify and classify vulnerable areas, providing support for evidence-based urban policies.

These conclusions confirm that an integrated approach, based on long-term state-of-the-art monitoring technologies, is an essential tool in securing the urban environment and adapting the city to geodynamic risks. Implementing proactive strategies can significantly contribute to reducing infrastructure vulnerability and creating a safer and more sustainable urban environment.

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