InSAR AS AN OPERATIONAL COMPONENT OF GEOTECHNICAL MONITORING: PRACTICAL APPLICATION FOR SUBWAY LINE D CONSTRUCTION IN PRAGUE

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ABSTRACT: A new subway line is under construction in Prague, Czechia. Drilling and construction can potentially impact the structural health of buildings and infrastructure within the zone of influence. As part of geotechnical monitoring for the Metro Line D construction, surface and building displacements are monitored using conventional methods and satellite interferometry (InSAR). Measurements from TerraSAR-X/PAZ are analysed using a customised PS-InSAR algorithm to capture evolving deformation patterns during construction. In addition, several add-on methods have been developed to provide targeted trend analysis and geotechnically relevant metrics. The retrospective "passportization stage" has been followed by seven standard monitoring stages, each with adaptive stage duration and frequency of satellite acquisitions. The nonlinear characteristics of displacement trends present challenges for InSAR. Particularly in X-band data, phase unwrapping errors compromise spatial interpretation, elevate noise levels, and diminish the reliability of results. Issues are addressed by tailoring the InSAR methodology, including advanced time series segmentation considering statistically significant differences in displacement velocities or noise levels. Multi-directional measurements from Sentinel-1 satellites complement the geotechnical impact assessment of baseline interferometric results by providing horizontal deformation field displacements. Validation confirms strong agreement between displacement trends measured through InSAR and conventional geotechnical methods.

1. INTRODUCTION

The construction of new underground transport lines in densely populated urban environments represents one of the most complex geotechnical challenges. In the case of the Prague Metro Line D construction, specifically the section I.Dla between Pankrác and Olbrachtova stations, the situation is complicated not only by complex geological conditions but also by the presence of dense surface structures and existing infrastructure. Therefore, standard geotechnical monitoring (GTM), based on terrestrial geodetic methods (levelling, trigonometry), is supplemented by satellite radar interferometry (InSAR) technology.

Multi-temporal InSAR (MT-InSAR) is utilized as a key complementary technology in this project. This method allows the measurement of surface and object deformations with millimetric precision without the need for physical access to the monitored buildings. The integration of InSAR into routine geotechnical supervision has been successfully documented in several major projects, such as in Turin (Barla et al., 2016) or London (Milillo et al., 2018), where data served to assess structural damage and refine soil interaction models. A significant benefit is the early identification of risks through retrospective analyses, which enable the detection of previously undetected geotechnical anomalies (Scoular et al., 2020). Beyond displacement measurement itself, data are used for building vulnerability assessment, which depends on the asset's position in the subsidence bowl (Saeidi et al., 2009).

This paper focuses on the operationalization of this technology within the ongoing construction in Prague as an integrated part of a complex GTM. Attention is paid to the transition from retrospective evaluation (passportization) to active monitoring implemented in adaptive stages. The use of InSAR for the detection of geotechnical risks, such as building tilts and horizontal displacements, is highlighted through the combination of different satellite systems and advanced processing algorithms.

2. SATELLITE DATA AND METHODOLOGY

2.1 SATELLITE DATASETS

A combination of commercial and freely available radar data was chosen for the monitoring of Metro Line D. The primary source is imagery from the TerraSAR-X/PAZ satellite system (X-band, wavelength 31 mm). These images in StripMap mode provide a high spatial resolution of 3x3 m, which is critical for identifying measurement points—Persistent Scatterers (PS)—on individual urban features such as roofs, facades, or cornices.

Additionally, data from Sentinel-1 satellites (C-band, wavelength 56 mm) are used. Although they have lower resolution (20x5 m), their benefit lies in the availability of measurements from opposite orbits (ascending and descending). Furthermore, the larger incidence angle of these satellites increases sensitivity to horizontal displacements in the east-west direction, which is necessary for a comprehensive analysis of the deformation field.

Table 1: Basic parameters of the satellite systems used

Satellite system	Resolution [m]	Wavelength [mm]	Typical interval [days]
TerraSAR-X / PAZ	3 x 3	31 (X-band)	11 – 33
Sentinel-1	20 x 5	56 (C-band)	6 – 12

2.2 PS-INSAR PROCESSING AND TIME SERIES SEGMENTATION

Processing was carried out using the PS-InSAR algorithm, which evaluates signal phase differences for points with high reflection stability over time. The standard procedure was modified by introducing advanced time series segmentation. Since tunnel drilling induces non-linear movements (sudden settlements followed by stabilization or uplifts due to grouting), a constant velocity model over time is not sufficient.

Each time series was divided into segments within which constant velocity and noise levels were statistically tested. This approach allows the elimination of phase unwrapping errors, which are a common problem in the X-band with large displacement gradients. For each segment, the current velocity is estimated, which is the primary focus during the interpretation of geotechnical risks. Results were referenced to a stable part of the city outside the construction zone.

Within the processing framework, various algorithm configurations were tested to generate optimal PS point density: ranging from standard (thousands of points per km^2) to densified (over 10,000 points per km^2). The use of an adapted PS-InSAR algorithm variant, which allows for the detection of so-called temporally (temporarily) coherent scatterers, maintains high point density across monitoring stages in environments with frequent surface changes (e.g., due to construction works).

2.3 DERIVATION OF GEOTECHNICAL HAZARDS

To estimate geotechnical risk, metrics based on differential settlement and stress states were tested and implemented. Building vulnerability assessment (Peduto et al., 2021) utilizes parameters such as differential settlement and relative rotation (deflection ratio), calculated from the PS point cloud within building footprints. For taller objects, a tilt index was designed based on the correlation between the estimated PS point height and its displacement velocity. The complex approach integrates InSAR data with geotechnical information on drilling progress, allowing the determination of hazard scores relevant to engineering practice (Saeidi et al., 2009; Ezquerro et al., 2020).

3. MONITORING OPERATIONALIZATION

3.1 STAGE 0: DRI PASSPORTIZATION

In 2022, a retrospective analysis of archival data from 2016 to April 2022 was performed. This stage, referred to as passportization, served to document the baseline stability of the area. It was found that some areas and objects in the area of interest showed settlements beforehand, which were attributed to their consolidation or exploratory drilling performed in 2020. Establishing a "zero state" is necessary for an objective assessment of the drilling influence and for resolving potential disputes regarding the causes of structural damage.

3.2 ADAPTIVE MONITORING STAGES

Active monitoring is carried out in consecutive stages (7 stages completed as of May 1, 2026). The stage duration and the frequency of satellite imagery acquisition are adjusted adaptively according to the drilling progress and the expected intensity of surface influence.

- **Intensive monitoring:** During periods with the highest drilling rates, the measurement frequency is set to 11 days.
- **Standard supervision:** In calmer phases, the frequency is reduced to 22 or 33 days for cost optimization.

The arrangement of the individual phases is shown in the timeline in Figure 1. The total monitored area includes the core zone of influence (AOI) of approximately 0.5 km^2 and the wider surroundings with a 0.5 km buffer zone. Inter-stage deliveries include interferometric and geotechnical interpretations performed in cooperation with the complex GTM provider.

Figure 1: Timeline of DRI monitoring stages and radar measurement frequency during construction.

4. RESULTS AND GEOTECHNICAL RISK DETECTION

4.1 VERTICAL DEFORMATION FIELD (TERRASAR-X/PAZ)

At the end of each monitoring stage, displacement rate maps in the line-of-sight (LoS) from the TerraSAR-X/PAZ system are evaluated. These results document the spatial extent and dynamics of subsidence bowls induced by the excavation of main line tunnels. Results show that sudden increases in settlement velocities occur in areas above the tunnel face, which gradually subside after the excavation passes. Furthermore, the analysis of Stage 0 revealed areas of local instability related to earlier excavation of shafts and adits (Figure 2).

Figure 2: LoS velocity maps from TSX/PAZ for Stage 0 and monitoring stages 1-5 documenting the evolution of vertical deformations.

High point density is crucial for the reliable detection of differential settlement within building footprints and the subsequent derivation of geotechnical risks. An example of point distribution on a specific building is shown in Figure 3.

Figure 3: Visualization of PS points on building 11.B15 in the densified processing variant from TSX/PAZ for detailed differential settlement analysis.

4.2 BUILDING TILT ANALYSIS

A significant risk during drilling in urban areas is differential settlement, which can lead to building tilts. A special indicator based on the correlation between the height of the InSAR point on the object and its displacement velocity was developed to detect this phenomenon. For buildings exposed to tilt, a statistically significant difference is evident between displacements measured at the base of the object and at its roof or upper floors.

This effect was particularly observed in several multi-storey buildings on Na Strži Street. Due to the acquisition geometry from TerraSAR-X, which has a steep look angle, the tilt of the building away from the satellite manifests as an apparent increase in vertical settlement, and vice versa when tilting toward the satellite. This finding was key to the correct interpretation of the data, as a purely geometric conversion of the measured LoS velocity to the vertical direction led to an overestimation of actual settlement by several millimeters.

4.3 HORIZONTAL DEFORMATION FIELD

Supplementary processing of Sentinel-1 data allowed the decomposition of the displacement vector into vertical and horizontal (East-West) components. The horizontal deformation field was analyzed at the end of selected stages. The results confirmed that objects located at the edges of the settlement bowl are exposed to horizontal movements (Figure 4) and that the extent of zones exposed to horizontal movements changes over time (between stages).

Figure 4: Selected maps of horizontal displacement rates for stages 3, 5 and 6 derived by decomposition of Sentinel-1 measurements.

4.4 GEOTECHNICAL RISK SCORE

Based on the measured data, an aggregated geotechnical risk score was calculated for each building in the AOI. This score considers:

- Differential settlement.
- Current displacement velocity at the end of the stage.
- Displacement acceleration between time series segments.

These metrics are integrated into map outputs in the InSARviz online application, which serves for interactive work with DRI results from individual monitoring stages.

5. VALIDATION

5.1 COMPARISON WITH PRECISE LEVELLING

Validation of InSAR measurements with geodetic methods was performed continuously. A comparison of InSAR-derived settlements with precise levelling data showed agreement in trends, but with local discrepancies. For buildings on the eastern side of the influence zone on Na Strži Street, discrepancies reached up to 3–4 mm/year in the vertical plane. Analysis confirmed that these discrepancies are caused by horizontal displacements and building tilts, which the InSAR method detects at roof levels, while levelling marks are installed at the base of the buildings.

5.2 COMPARISON WITH 3D TRIGONOMETRY

Quantitative agreement was also confirmed by comparison with trigonometric measurements. An example is building 13.B32, where InSAR time series closely follow the trend of geodetically measured movements (see Figure 5). Differences in absolute values are explained by the different height positions of the measurement points. InSAR points on the upper part of the facade and roof show more pronounced horizontal movements (tilts) than points at the first-floor level, where trigonometric marks are located.

Figure 5: Displacement time series from TSX/PAZ and 3D trigonometry converted to LoS direction; from S-1 and 3D trigonometry in x,y,z directions for building 13.B32.

6. DISCUSSION AND CONCLUSIONS

The implementation of MT-InSAR during the Metro D construction confirmed that this technology is a full-fledged complementary measurement tool with unique properties. A comprehensive evaluation of the stages performed so far has led to the formulation of several key benefits:

- **Synopticity and spatial coverage:** Unlike point-based geodetic measurements, InSAR provides a comprehensive picture of deformations and allows their real delineation across extensive areas. It was demonstrated that the method is capable of detecting settlement bowls even outside the primary zone of projected influence. These settlements often relate to changes in hydrogeological conditions due to excavations and construction works and can manifest at a considerable distance from the drilling site.

- **Retrospection and passportization:** The ability to "go back in time" and evaluate archival data from 2016 allowed for an objective retrospective determination of the area's zero state. This passportization is crucial for distinguishing construction impacts from previous deformation processes and can provide valuable insights into area stability before conventional passportization during the design phase of a tunnel structure.
- **Measurement density and detail:** Utilizing high-resolution TerraSAR-X data and measurement precision allows for tracking the reactions of individual buildings and detecting local anomalies within footprints that standard base-level measurements might miss.
- **Economic efficiency and scalability:** The method does not replace but supplements conventional measurement methods. The possibility of adaptive acquisition frequency adjustment depending on drilling progress, measurement density, and synopticity can help streamline cost management within complex GTM while maintaining the ability to capture dynamic trends. DRI monitoring of peripheral areas of the designated influence zone or beyond can indicate the need for precise conventional methods only if significant movements or accelerations are detected.
- **Detection of horizontal components:** Combining different orbits and decomposing the displacement vector provides complex information on object behavior, including tilts and horizontal tensions at the edges of settlement bowls.

The integration of InSAR into geotechnical monitoring contributes to a better understanding of the interaction between drilling and the overburden in urban environments by expanding the spatial and temporal context. Its deployment within the Metro D GTM proved that the method is suitable for routine use in demanding underground construction projects and is recommended for routine implementation in further stages of Prague's transport infrastructure development.

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