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InSAR as a Component of Geotechnical Monitoring During Subway Construction in Prague

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ABSTRACT: A new subway line is under construction in Prague, Czechia. The drilling and construction potentially affect the structural health of buildings and infrastructure in the zone of influence. As part of geotechnical monitoring for the Metro Line D construction, subsidence is monitored through 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 standard monitoring stages 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 tailored enhancements to the InSAR methodology, including advanced time series segmentation considering statistically significant differences in displacement velocities or noise levels. Validation confirms strong agreement between displacement trends measured through InSAR and conventional geotechnical methods.

KEY WORDS: InSAR; Subway; Subsidence; Structural health.

1 INTRODUCTION

1.1 MT-InSAR as a tool to monitor tunnel drilling impacts in an urban environment

Urban tunnelling projects, particularly those involving mechanised excavation methods such as Tunnel Boring Machines (TBMs), are known to induce subsidence ground deformations that can compromise the structural integrity of buildings and infrastructures above the tunnel alignment. Monitoring and assessing these effects is crucial for mitigating risk in densely built environments. Interferometric Synthetic Aperture Radar (InSAR), particularly advanced multi-temporal techniques (MT-InSAR), has emerged as a reliable and cost-effective method for monitoring such deformations with millimetric precision over extensive spatial and temporal scales.

Recent studies have demonstrated the efficacy of InSAR in tracking surface displacements due to tunnelling activities in various urban contexts. For example, [1] utilised InSAR to monitor tunnel-induced ground movements and demonstrated its value in complementing conventional geotechnical instrumentation during tunnelling operations in Turin, Italy. Similarly, [2] applied InSAR to assess accumulated settlement related to highway tunnel construction in Genoa, Italy. The [3] showcased a novel integration of MT-InSAR and the relative stiffness method to assess structural damage during the London Crossrail project, highlighting the role of soil-structure interaction in deformation modelling. These approaches allow for better estimation of tensile strains and more accurate prediction of damage potential compared to greenfield assumptions.

The [4] emphasised the integration of InSAR in all phases of tunnelling—from planning to post-construction monitoring—noting its advantage in detecting both anticipated and unexpected deformations across large urban sectors. Meanwhile, [5] applied retrospective PSI analysis in East London during the Lee Tunnel construction, revealing previously undetected geotechnical anomalies and advocating for InSAR's role in early risk identification.

Beyond deformation detection, translating InSAR-derived ground displacement data into actionable insights for building vulnerability assessment is gaining traction. Damage level on buildings and infrastructure caused by subsidence depends on the asset's position in the subsidence bowl, displacement direction and magnitude [6]. The [7] and [8] successfully derived empirical fragility curves by correlating InSAR-derived displacements with in-situ damage surveys, enabling probabilistic assessments of structural risk across extensive building inventories. These methods have proven especially pertinent in older urban centres, where subsidence impacts are compounded by complex underground networks and historical constructions, such as in Madrid [9] and Pistoia [6].

1.2 MT-InSAR supporting geotechnical monitoring during subway construction in Prague

In this context, the present study describes the operational use of MT-InSAR as a component supporting complex geotechnical monitoring during the construction of the Prague D line subway. Spatially dense and temporally resolved deformation data from MT-InSAR complement traditional operational monitoring techniques, providing additional

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insights about the extent and chronology of tunnelling-related hazards.

A new subway line is under construction in Prague, Czechia, traversing from the city's peripheral regions to its central districts through geologically complex and challenging conditions. The influence of subway construction potentially affects the structural health of buildings and infrastructure in the zone of influence, which is being monitored by standard geotechnical and geodetic techniques, including precise levelling. A network of more than 900 static measurement points has been established in the zone of influence between planned stations Pankrac and Olbrachtova by the client. Measurements identify deformation trajectories reaching or exceeding pre-established hazard warning levels to allow early and timely mitigation during construction.

InSAR complements the monitoring in two ways:

- Stage 0: Provision of passportization status documenting the level of (in)stability within and beyond the zone of influence before the construction started as of April 2022.
- Stage 1-8: Regular monitoring during construction with variable monitoring interval lengths (6 – 12 months) and satellite data acquisition frequency (11 – 33 days). The InSAR monitoring set-up has been designed to be efficient and cover periods with the highest expected deformation rates and measurement frequencies.

As of the end of 2024, the fifth monitoring stage has been completed, with stages 6-8 planned for 2025-2026 (refer to Figure 1). The overall size of the core area of interest (AOI) along the zone of influence is approximately 0.5 km^2. InSAR monitoring covers the area of the AOI extended by a 0.5 km wide buffer.

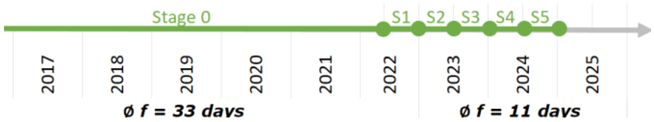

Figure 1: Passportization (Stage 0) and subsequent monitoring stages (up to Stage 5). The average frequency of TSX imagery acquisition is indicated below the graph. From 2025 on, additional stages follow up after Stage 5.

2 SATELLITE DATA

TerraSAR-X data (X-band, wavelength 3.08 cm) in StripMap mode (spatial resolution 3x3 m) are being used for InSAR monitoring. The images cover the monitoring period 2016-2024, and their total number is 129.

As a supplementary dataset, freely available Sentinel-1 (C-band, wavelength 5.6 cm) data were processed for the same area of interest from three tracks (ascending 146 (looking from West) and descending 22 and 95 (looking from East)). The look angle is flatter than that of TerraSAR-X and, therefore, more sensitive to the horizontal (East-West) displacements. Sentinel-1 images were processed from 2015 to the end of 2024, amounting to 430-450 images per track. An overview of satellite datasets is listed in Table 1.

Digital terrain models (DTMs) and digital surface models (DSMs) obtained from open data sources [10] were used to estimate the location of each PS point (ground, facade, roof, etc.) and to determine its height above ground.

Table 1. Baseline and supplementary satellite datasets.

Satellite/mode / track	Images used	Inc angle [deg]	Spatial resolution [m]
TerraSAR-X / SM / D2	129	22	3x3
Sentinel-1 / IW /D95	441	32	20x5
Sentinel-1 / IW / D22	436	44	20x5
Sentinel-1 / IW / A146	429	39	20x5

3 METHODOLOGY

3.1 MT-InSAR analysis

The InSAR processing was performed using the persistent scatterers algorithm (PS-InSAR) in the SARproZ(c) software, which is tailored for infrastructure monitoring. For Sentinel-1, all pixels within the area of interest were processed to reach the highest possible point density. In contrast, for TerraSAR-X, point selection was based on local amplitude maxima to streamline the processing timeline. A reference point was selected in another stable part of the city to avoid being influenced by the construction works.

Subsequently, proprietary post-processing techniques have been employed to enhance results from the standard PS-InSAR algorithm. In particular, the detection of temporally coherent targets and time series segmentation has been used to retain a higher density of candidate PS measurement points.

The time series of each PS point was segmented into intervals with constant velocity and noise, and abrupt movements were excluded within a single segment. The segmentation method is data-driven, based on statistical tests to compare principal values for subsequent segments (such as velocity and noise). The segmentation enables us to more accurately estimate the quality of the time series for PS points experiencing highly non-linear displacement. In conventional InSAR workflows, the estimated reliability expressed by coherence "averaged" over the whole monitoring period is low for these points, resulting in their discarding in the candidate selection phase. For each segment, displacement noise was estimated, and if it was too high, that segment was considered unreliable. However, if a point is reliable for at least part of the monitoring period, it can be interpreted for that period. The tolerable noise level was calculated based on statistical simulations, considering ambiguous fundamentals of InSAR, and depends on the SAR wavelength and the length of a segment. Generally, the allowed noise level is around 2.8 mm for TSX for long segments, and slightly lower for shorter segments. This is particularly important in areas with ongoing construction work, where a point may become unreliable for shorter periods and then regain reliability. These periods may repeat frequently. The

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segmentation is performed for each PS point individually; therefore, the segments vary between points.

With special attention, the displacement velocity in the last reliable segment (i.e. the most recent displacement velocity) is estimated, together with its standard deviation, at the end of each monitoring stage.

3.2 Estimation of horizontal component

The TSX dataset, featuring a steep incidence angle in the area of interest, is particularly suitable for detecting displacements with a dominant vertical component. In addition, due to suspicions of displacements with strong horizontal components in certain zones of the drilling influence zone, the Sentinel-1 dataset has been employed. Measurements from opposite ascending and descending orbits feature flatter incidence angles and are more sensitive to horizontal displacements in the East-West direction. Standard decomposition using a custom grid size was implemented to convert displacement rates from the LOS (radar line-of-sight) to vertical and horizontal deformation components. Sentinel-1 measurements at the end of Stage 3 and Stage 5 from their most recent reliable displacement rates (in mm/year) were used. This option turned out to be less noisy compared to processing options utilising stage-wise or cumulative displacements (in mm).

3.3 Estimation of buildings affected by geotechnical hazard

Geotechnical hazards and the structural health of buildings can be assessed using PS-InSAR results through various methodologies. For the pilot demonstration of technology utility for the D line subway in Prague, we focused on testing existing approaches, their customisation, and developing a new one.

The [11] combined PS-InSAR with damage surveys to develop empirical building fragility curves. The approach focuses on monitoring settlement-induced damage through parameters summarily ranked as SRI (Subsidence-Related Intensity), such as differential settlement and relative rotation (deflection ratio), calculated from a cloud of PS points for building polygonal footprints or their immediate vicinity. Ancillary metrics (length, width, buffer) are computed from the polygonal geometry. SRI proxies the potential damage risk for different classes of building construction materials.

The [9] employ PS-InSAR to monitor deformation in urban environments, particularly in historical city centres, where underground activities may induce ground subsidence. Their method applies novel classification indices, including deformation velocity, dispersion, and acceleration indices, as a proxy for assessing the structural health of buildings.

To complement the above methodologies for specific types of buildings in dense residential urban stock (tall and with a small footprint area), we developed an additional index to indicate the potential tilt of the building. It is based on the correlation between the estimated height of a PS point (above ground) and the estimated displacement velocity. Figure 2 displays the simple model of the situation.

Supposing the correlation exceeds the threshold and the difference between the highest and lowest PS points in the footprint exceeds the set value, then the rate between the displacement velocity and height is estimated and converted to tilt angle, assuming that the differential displacements are horizontal (East-West direction). In our case, the tunnel's orientation is ideal for InSAR, as the expected East-West displacements are most sensitive to this technique.

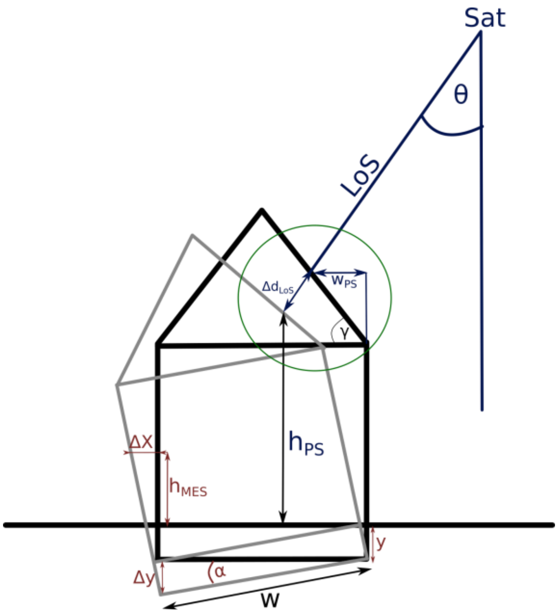

Figure 2: Illustration of the relation between the measured line-of-sight displacement and height for a tilted building.

To estimate the tilt angle, the least squares method accounting for errors in both x and y axes (i.e., height and displacement velocity) was used [12], as both values were estimated from the original InSAR data. Practically, the stochastic model is not precise as it does not consider the relation between the estimated height and displacement velocity. This is because the relationship is not straightforward, as the height is calculated from all the SAR data, while the displacement velocity is not. Moreover, outliers were excluded from the adjustment. Finally, the tilt angle was confirmed only if it was higher than its standard deviation; the tilt angles are overall smaller than, e.g., 2.5 times the standard deviation.

The correlation method can only be used for X-band data. Sentinel-1 data have a high standard deviation in height, which leads to a too-high standard deviation of the estimated tilt angle.

3.4 Cross-validation

Total displacements measured converted to vertical direction were compared with geodetically measured settlements for a set of buildings in the zone of influence.

4 RESULTS

At the end of each monitoring stage, results with a standardised structure and formatting are delivered to the construction monitoring committee. These include maps of ground displacements in LOS from the baseline TSX dataset complemented by additional metrics derived by analysis of segmented deformation time series (refer to Figure 3):

- Displacement rates – average, last reliable velocity (mm/yr)
- Stage-wise and cumulative displacement (mm)
- Acceleration
- Classification of displacement trend typology
- Classification of reflecting target type

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In total, more than 4,000 temporally coherent PS measurement points are being detected for each monitoring stage in the core AOI from the TerraSAR-X dataset, and over 22,000 measurement points for the extended AOI.

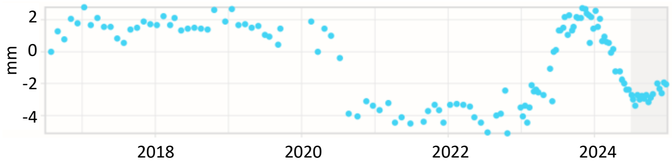

Figure 3. Example of PS points' displacement time series from a building affected by repeated drilling-induced settlements and injecting-induced uplifts in the meantime.

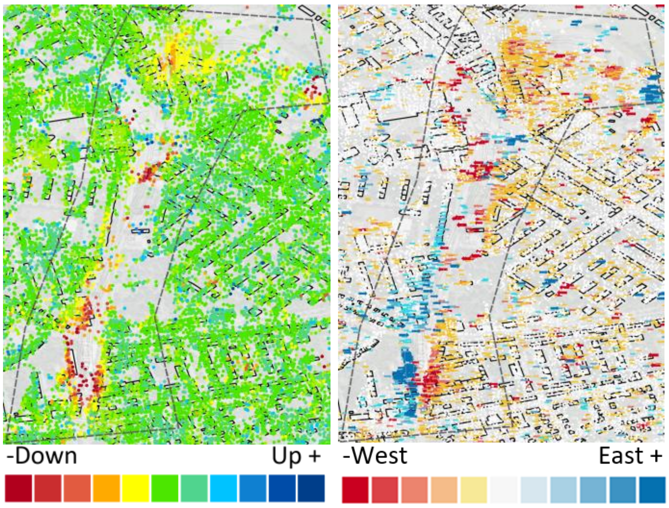

Figure 4. Ground displacement velocity (from at least a 1-year-long reliable time-series segment) in the core AOI from the Sentinel-1 dataset decomposed from LOS to (a) vertical and (b) East-West direction, which is roughly perpendicular to the subway drilling axis (please note: displacement velocity magnitude could not be disclosed).

Validation revealed discrepancies between InSAR displacements from TSX converted to vertical direction and geodetic measurements by levelling. These discrepancies in measured settlements amounted up to 3-4 mm over a comparable measurement period for a line of tall buildings at the east side of the settlement zone, while being negligible in other areas. After a thorough analysis, we can attribute these discrepancies to the influence of horizontal displacements – the buildings are slightly leaning away from the satellite in LOS. These displacements increase the displacement magnitude in the LOS and subsequently in the vertical direction, if projected without considering the horizontal component. Furthermore, the horizontal component estimated from InSAR for tall multi-storey buildings is higher than the magnitude measured trigonometrically at the buildings' foot or first storey level. As a result of tilting, the horizontal displacement is more pronounced at the rooftop level, where most of the PS measurements are located, than at the ground.

After realising the occurrence of horizontal displacements (accompanied by building tilting), the ground displacements map from the TSX has been complemented by MT-InSAR analysis of the Sentinel-1 dataset, followed by decomposition of LOS velocities into vertical and horizontal displacement components for selected monitoring stages. These results (refer to Figure 4) confirm the existence of horizontal displacements and show the extent and heterogeneity of the phenomena.

The methodology of [8] was found helpful in detecting differential settlements for larger buildings as an indicator of potential damage risk. Buildings need to have enough PS points detected within the building footprint. Furthermore, the distance between PS points with minimum and maximum deformations, which is used to calculate the deflection angle, needs to be sufficiently long. The method is applicable to buildings regardless of their height; however, the deflection angle is estimated more reliably for buildings elongated parallel to the settlement sloping gradient vector.

Similarly, [9] provides a means for more complex assessment by considering aggregated displacement velocities complemented with their acceleration and spatial dispersion within a building polygon. This is an indicative proxy metric for building tilting regardless of height; however, buildings must have enough PS points within the footprint.

The correlation-based tilting indicator supplemented the above techniques by pointing to tilts of high buildings with relatively small footprints, which are common in the residential urban fabric.

5 CONCLUSIONS

During its operational execution, InSAR proved to provide highly valuable and complementary insights into the spatial and temporal context of settlement phenomena during Prague's Metro D line construction.

The most pronounced advantages and benefits of InSAR identified by its practical and operational application are listed below:

- High density of measurements that allows more precise delineation of the zone of influence.
- Delineation of the real extent of the zone of influence. Assessment of specific drilling-induced trend patterns in measurement time series and their spatial distribution reveals that this extent is larger in some areas compared to the projected zone of influence.
- Delineation of additional settlement zones within and beyond the core AOI. The geotechnical and hydrogeological interpretation indicates their association with groundwater withdrawal in the aquifers.
- Differentiation between drilling-induced settlement and subsidence caused by other drivers. This may turn instrumental for assessment and passportization of damages and as evidence in potential legal disputes.

Furthermore, results showcase that:

- The use of the temporally coherent targets variant of the PSI algorithm is instrumental in maintaining a high density of measurements during different monitoring stages.
- TSX data are indispensable to obtaining the highest measurement density, allowing detailed settlements and uplift impact assessment at the level of individual buildings.
- TSX measurements from single track suffer from biased displacement rate magnitude in LOS when buildings tilt

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in a direction parallel to LOS. The bias is propagated in a vertical direction after simple reprojection.

- The monitoring should be complemented by InSAR measurements from ascending and descending paths of Sentinel-1 and their decomposition to map the extent of the horizontal deformation field.
- Appropriate geotechnical methodologies and metrics need to be selected, customised, and combined to indicate risk and tilting for a broader spectrum of different building sizes and heights. The reflective position of the PS measurement point (on the roof, facade, or from the ground) needs to be estimated and considered.

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DISCLAIMER

Detailed results and scales of vertical or horizontal displacement velocities could not be disclosed due to their sensitive nature.

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