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Structural evaluation of urban bridges in Amsterdam through InSAR-based displacement data

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Abstract. Thousands of bridges worldwide face growing risks due to aging materials, increased traffic loads, and climate change-induced weather extremes. Managing these assets is financially demanding, and requires prioritisation strategies for interventions. Consequently, innovative approaches are urgently required to evaluate the structural conditions of these bridges continuously and regularly. Recent advancements in space-borne Interferometric Synthetic Aperture Radar (InSAR) technology offer cost-effective remote monitoring capabilities, ensuring extensive coverage and high spatial resolution. Multi Temporal (MT) InSAR techniques enable the reconstruction of millimetre-scale deformation measurements for a large number of assets, opening opportunities for long-term regional-scale monitoring of bridge deformations. However, a major challenge in utilising MT-InSAR-based displacement data operationally is that MT-InSAR analysis reconstructs only the projection of displacements along the satellite Line of Sight (LOS) direction. Due to the typical availability of only two satellite viewing geometries, in most cases the three-dimensional displacement field cannot be fully reconstructed. Consequently, without accounting for the anticipated motion of a given structure and its alignment with respect to the satellite flight path, the actual asset movement is likely to be underestimated, leading to erroneous interpretation. In this paper, we propose a method using the bridge typologies and their associated likely failure mechanisms to derive assumptions regarding expected displacement directions. Then, the information on bridge alignments with respect to the satellite flight direction is used to assess the MT-InSAR sensitivity to the expected displacement directions and define ad-hoc damage indicators. We tested the proposed method on urban bridges in Amsterdam, the Netherlands, using deformation measurements derived from TerraSAR-X data spanning 2016 to 2020. Findings have potential to enhance current procedures for the structural evaluation of bridges.

Keywords: infrastructure, MT-InSAR, remote sensing, structural monitoring, damage indicators

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Introduction

In many countries worldwide, the intensity of bridge usage has evolved significantly over time, surpassing original design expectations. These bridges were not initially designed to accommodate modern traffic loads, leading to concerns regarding their structural capacity and resilience in the face of escalating demands, material degradation, and changing environmental conditions [1, 2]. As economies expand and reliance on these transportation links increases, the cost of replacement or refurbishment escalates, emphasising the urgent need for innovative approaches to effectively evaluate thousands of bridges [3].

Unlike traditional sensor-based monitoring, Interferometric Synthetic Aperture Radar (InSAR) satellites [4, 5] operate remotely, enabling simultaneous observation of multiple assets over extensive regions at a relative low cost. This remote sensing capability reduces the need for on-site sensors, making it suitable for monitoring inaccessible or hazardous areas. Moreover, InSAR offers the advantage of all-weather and day-and-night acquisitions, as well as retrospective monitoring capabilities. In particular, Multi Temporal (MT)-InSAR techniques [6, 7] can be used to retrieve high-resolution displacement data with precision up to the millimetre scale [8]. Over extended periods, MT-InSAR can offer continuous monitoring without the need for physical interventions or human presence, facilitating long-term detection of changes in structures.

Over the last two decades, advancements in algorithms and data quality have led to an increasing use of MT-InSAR data for infrastructure monitoring [9]. In the specific context of bridges, recent studies have investigated the suitability of MT-InSAR for evaluating bridge conditions, showing its potential in detecting anomalous deformations for early warning [9-11] and identifying pre-failure precursors [12-15]. Other studies assessed its effectiveness in conjunction with terrestrial monitoring methods [16] and numerical modelling [17], aiming to improve interpretation of deformation and structural assessment of bridges.

However, although previous studies highlighted the potential of MT-InSAR for structural health monitoring of individual assets, for operational implementation a major challenge is given by the fact that MT-InSAR analysis reconstructs only the projection of displacements along the satellite Line of Sight (LOS) direction [18, 19]. This limitation becomes particularly pronounced in regional-scale applications, where numerous assets of various types are distributed across a wide geographic region. Without considering the anticipated motion of each structure and its alignment with the satellite flight path there is a risk of underestimating the actual asset movement, leading to potentially erroneous interpretations.

In this study, we introduce an approach that uses bridge typologies and their corresponding potential failure modes to establish assumptions concerning anticipated displacement directions. Subsequently, we retrieve bridge orientations relative to the satellite flight path to evaluate the MT-InSAR sensitivity to these anticipated displacement directions and formulate customised indicators for detecting potential damage. The proposed approach is implemented on 505 bridges in Amsterdam, using displacement time-series derived from TerraSAR-X imagery collected from descending geometry between 2016 and 2020.

The Amsterdam case study

The city of Amsterdam, renowned for its dense network of canals, includes approximately 1,800 bridges, many of which are built on wooden foundation piles and have been in service up to 400 years. These bridges, constructed from various materials including wood, concrete, masonry, and steel, represent unique cultural and historical values. The city's local soil structure, predominantly consisting of highly compressible clay and peat deposits, contributes to persistent ground subsidence [20], impacting the stability of buildings and infrastructure, including bridges.

In response to the deteriorating condition of the city's bridges, the Amsterdam municipality launched the Bridges and Quay Walls program (PBK) in 2018. This program focuses on the restoration of 820 bridges and over 200 km of quay walls. It involves investigations, monitoring, renovation, strengthening, and life-extension to ensure the safety and preservation of these assets. This initiative is particularly urgent given Amsterdam's UNESCO World Heritage status, emphasising the importance of safeguarding its unique architectural and historical heritage.

Methodology

1. Data

1.1 MT-InSAR data

The MT-InSAR dataset used in this study consists of Permanent Scatterer (PS) points [7] and their respective displacement time-series derived from 3-m-resolution TerraSAR-X imagery captured over Amsterdam from descending geometry between 2016 and 2020. Data processing was conducted by SkyGeo using their proprietary PyAntares algorithm, using a MT-InSAR approach based on the method proposed by Van Leijen, 2014 [21]. The MT-InSAR data, shown in Figure 1, was provided in vertical projection, obtained by dividing the LOS measurements Δr by the cosine of the radar incidence angle θ: $\Delta r_v = \Delta r / cos\theta$.

Fig. 1. Velocity map derived from vertically projected MT-InSAR data, as viewed in the SkyGeo dashboard. The map originates from TerraSAR-X descending imagery captured over Amsterdam from 2016 to 2020.

1.2 Bridge data

The bridge data used in this study consists of bridge geometries derived from the Basic Register Large-Scale Topography (BGT) map and a bridge database shared by the Amsterdam (AMS) municipality. The BGT is a digital topographic map of the Netherlands including different objects such as buildings, roads, waterways, green spaces, and railway lines, which can be imported into any Geographic Information System (GIS). The municipality database contains detailed information for each bridge asset managed by the AMS municipality, such as bridge name, ID, type (e.g., movable or fixed), designated usage (e.g., pedestrian, cyclist, motorised traffic), construction year, and construction material. Additionally, a Bridge Failure Mechanism Report [22] was supplied, offering information on the likelihood of failure mechanisms for Amsterdam bridges based on their typology.

2. Workflow

The methodology adopted for evaluating bridges using MT-InSAR data can be summarised in the following steps:

1. **Preparation of a regional GIS bridge database:** Initially, we extracted bridge deck geometries from the GIS catalogue, i.e., the BGT map, covering the study area. To accommodate potential geolocation errors of PS points and capture regions corresponding to bridge abutments, which were not represented in the catalogue, a 6-m-wide buffer was created around each bridge polygon. These buffer geometries were then enriched with the information contained in the AMS municipality dataset to create a comprehensive bridge database.
2. **Identification of bridge typologies and likely failure mechanisms:** For fixed bridges, we used the information provided in the Bridge Failure Mechanism Report [22] to classify the Amsterdam bridges into different typologies, including bridges on wooden pile foundations with no intermediate supports, bridges on wooden pile foundations with several intermediate supports, bridges on concrete or steel pile foundations with no intermediate supports, bridges on concrete or steel pile foundations with several intermediate supports, and those of unknown typology. Movable bridges were not analysed in this study due to their inherent complexity, which requires a separate assessment. Figure 2 shows the distribution of bridge typologies across central Amsterdam. Based on the respective typology, we assigned likely failure mechanisms to each structure. Figure 3 provides an overview of the failure mechanisms that can be expected in Amsterdam and for which there is enough time between the initial signals or damage patterns and the occurrence of actual failure, allowing for detection with MT-InSAR. We then used bridge typologies and their associated likely failure mechanisms to make assumptions regarding expected displacement directions.

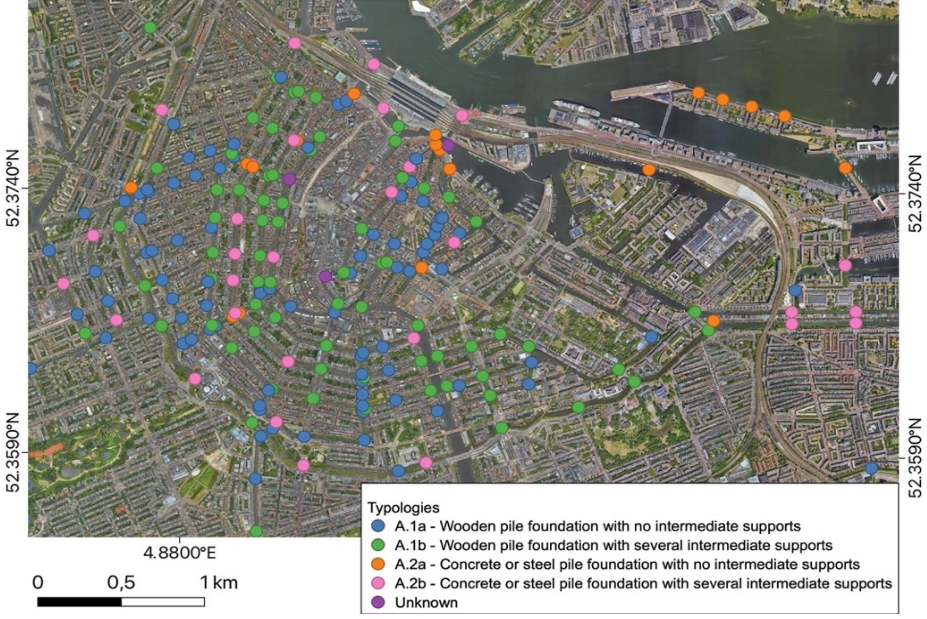


Fig. 2. Bridge typologies in Amsterdam as classified in this study.

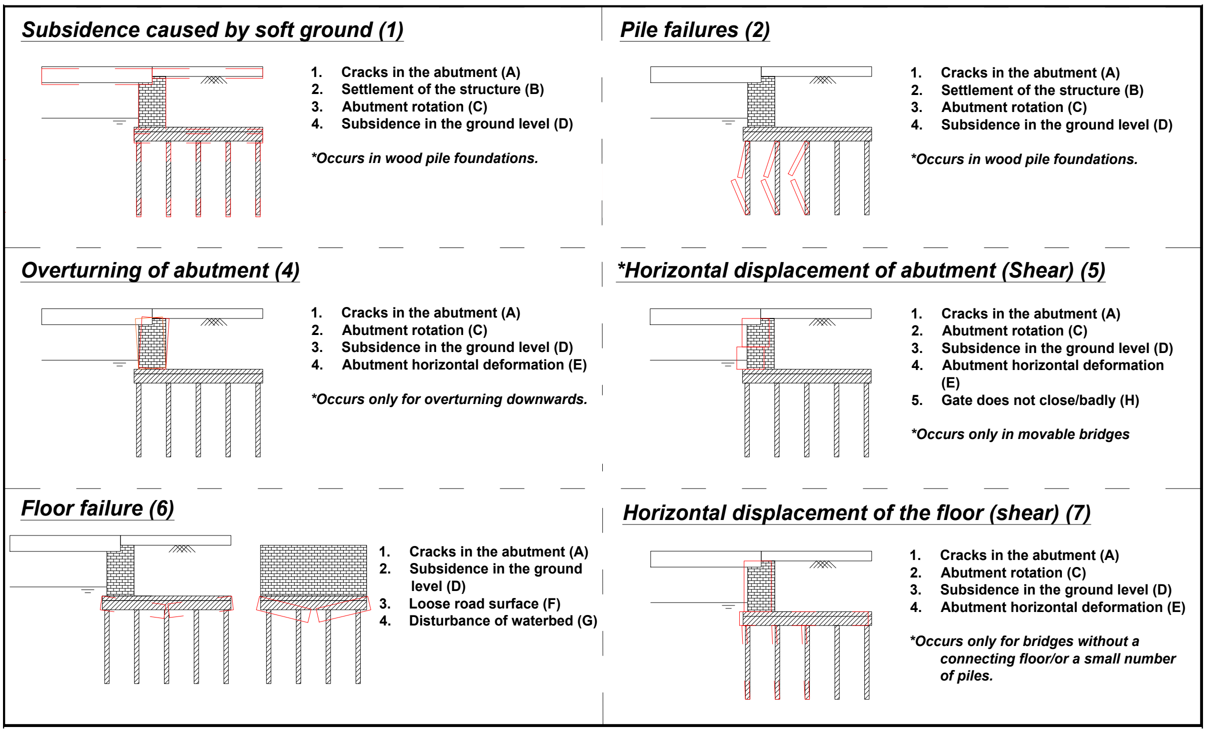


Fig. 3. Bridge failure mechanisms that can occur in Amsterdam and can be detected by MT-InSAR (after Damen and van der Peet, 2023 [22]).

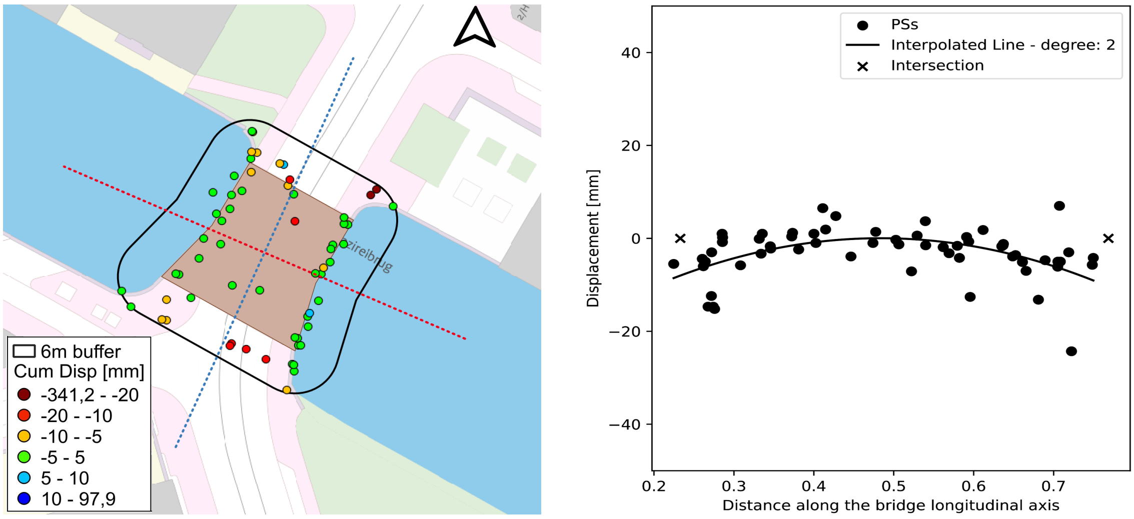
3. **Establishment of a bridge local reference system:** Subsequently, we used bridge geometries to establish a local reference system on each asset, defining longitudinal and transversal axes. This local reference system is useful to assess the satellite sensitivity to the expected asset motion and for interpretation of projected MT-InSAR displacements.
4. **Integration of GIS bridge database and MT-InSAR data:** Following the preparation of the GIS bridge database in step 1, we integrated the enriched bridge polygons with the MT-InSAR data. This integration involved assigning PSs to the corresponding bridge assets. We filtered PSs in the x-y plane using the buffer polygons and in the z direction based on a height threshold, with PSs below 5 m in height being selected.
5. **Estimation of bridge alignments relative to the satellite flight path:** To interpret MT-InSAR measurements captured in 1-D LOS configuration within the context of 3D structural deformations and considering the satellite movement along orbits nearly parallel to the North-South (N-S) direction, it is necessary to make assumptions regarding the anticipated asset movement [15, 19] taking into account the alignment of the bridge with the satellite flight path [18]. For Amsterdam bridges, assuming zero displacement along the transversal axis is reasonable, as transversal deformations in bridges typically result from external factors such as landslides and flood events. Under this assumption, two primary scenarios were identified based on the orientation of the bridge longitudinal axis relative to the N-S direction. For bridges with a longitudinal axis orthogonal to the N-S direction, the satellite captures a combination of longitudinal and vertical displacements. Conversely, for bridges with a longitudinal axis nearly parallel to the N-S direction, measurements exhibit low sensitivity to longitudinal displacements. For each asset, we used the orientation of the bridge longitudinal axis to quantify the asset alignment with respect to the N-S direction. Based on these alignments, bridges were categorised into two categories: parallel or orthogonal to the N-S direction.
6. **Assessment of MT-InSAR data sensitivity and projection based on bridge alignments:** For bridges aligned parallel to the N-S direction, measurements exhibit low sensitivity to longitudinal displacements, making MT-InSAR alone inadequate for detecting damage scenarios associated with abnormal longitudinal deformations.

Consequently, complementary monitoring data is required to fully understand the health of the asset when damage scenarios anticipated by horizontal movements are a concern. Under the assumption of zero transversal displacements (step 5) for bridges parallel to the N-S direction, it is reasonable to assume that all measurements along the satellite LOS represent a projection of the asset vertical movement. Thus, for these cases we used vertically projected MT-InSAR data from a single acquisition geometry to estimate the vertical displacement of each asset. Conversely, for bridges orthogonal to the N-S direction, two distinct acquisition geometries are needed to retrieve longitudinal and vertical displacements. If data from both ascending and descending geometries are available, decomposition methods such as the one described in Farneti et al. 2023 [15] can be applied. In this study, only bridges parallel to the N-S direction will be further analysed.

7. **Estimation of MT-InSAR-based damage indicators:** Given the identified bridge typologies and expected failure mechanisms in Amsterdam (step 2), the angular distortion between abutments and the deflection-to-span ratio were identified as relevant indicators for detecting damage scenarios associated with vertical movements, particularly settlement-prone conditions. To determine these parameters, PSs were interpolated along the longitudinal axis of each asset categorised as parallel to the N-S direction using a quadratic polynomial function. This interpolation allowed for retrieval of the vertical displacement profile of the asset. Subsequently, the angular distortion and deflection ratio of this function were calculated over the length of the bridge.

3. Results

Figure 4 shows an Amsterdam bridge categorised as parallel to the N-S direction. The distribution of projected vertical displacements of PS points detected on the asset indicates settlements near the bridge abutments. The PSs detected on the asset were projected along the bridge longitudinal axis and interpolated through a second-order polynomial function to reconstruct the vertical displacement profile of the asset (Figure 4b).



(a) (b)

Fig. 4. MT-InSAR data in vertical projection for a bridge in Amsterdam: (a) a plan view of the bridge, with blue and red dashed lines indicating the bridge longitudinal and transversal axes, respectively, and PSs located on the asset; (b) bridge displacement profile with data fitting of PS vertical displacements achieved through a second order polynomial.

We used the vertical displacement profile of each asset, derived from the fitting curve shown in Figure 4b, to quantify the angular distortion between abutments. This was computed as the difference in vertical displacements at the end of the fitted profile, divided by the length of the deck. To correlate the angular distortions values between abutments with potential damage, three value ranges were defined. Across all analysed bridges, angular distortion values remained below 0.005, with only six assets showing values between 0.003 and 0.005. Figure 5 shows the distribution of angular distortions between abutments for a subset of bridges categorised as parallel to the N-S direction situated within a central Amsterdam region.

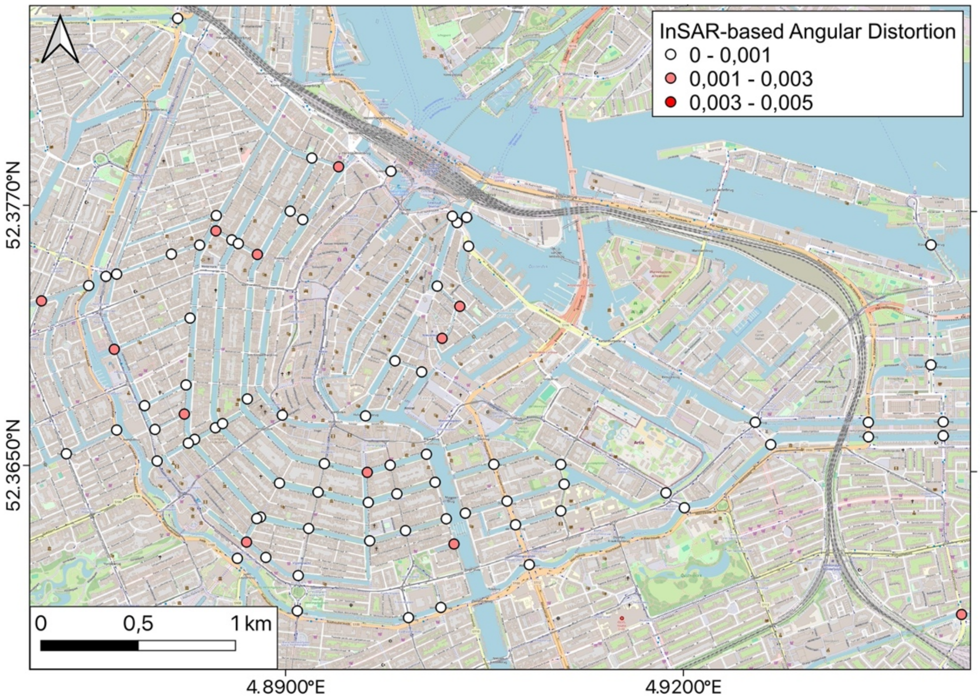


Fig. 5. MT-InSAR-based angular distortions between abutments for bridges in central Amsterdam.

4. Conclusions

We developed a method for the regional-scale evaluation of bridges using MT-InSAR displacement data. By integrating GIS bridge databases with MT-InSAR datasets and considering bridge typologies and orientations relative to the satellite flight path, the study establishes a framework for assessing bridge conditions on a regional scale, particularly in damage scenarios involving vertical movements. This study was conducted within a test area in Amsterdam, using displacement data obtained from a MT-InSAR analysis of TerraSAR-X images spanning from 2016 to 2020. Overall, the study contributes to the use of MT-InSAR data for bridge monitoring, underscoring the importance of integrating advanced monitoring techniques into infrastructure management practices.

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