

Satellite-Enhanced Structural Digital Twin for Bridge Health Monitoring

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ABSTRACT

This paper investigates the feasibility of integrating satellite data into structural health monitoring (SHM) systems for transport infrastructure subjected to extreme loads. By combining InSAR satellite data, structural digital twin simulations, and advanced post-processing techniques, the study evaluates the potential of spaceborne remote sensing to provide insights into structural displacement and overall health conditions. A real-world pilot was conducted on the Kalix Bridge in Sweden using Sentinel-1-derived InSAR time series from the European Ground Motion Service (EGMS). The analysis demonstrated consistent uplift trends and highlighted the critical role of coherence-based filtering in extracting reliable displacement data. The results offer a foundation for future research in satellite-based SHM and underscore the importance of integrating geospatial and structural data for infrastructure resilience.

INTRODUCTION

The intensification of climate-induced hazards poses significant risks to the integrity of aging transport infrastructure. Structural Health Monitoring (SHM) is an essential tool for risk-informed asset management, yet conventional sensor-based approaches often fall short in coverage, scalability, and cost-effectiveness. Satellite-based Earth Observation, particularly Interferometric Synthetic Aperture Radar (InSAR), offers a compelling complement to traditional SHM methods due to its non-contact, wide-area, and time-resolved displacement measurement capabilities.

Despite the growing adoption of SHM systems, challenges persist in delivering cost-effective, long-term monitoring solutions for geographically remote or hard-to-access structures. InSAR data offers a globally consistent and temporally rich source of information, yet its integration into SHM workflows remains limited. Understanding how to effectively process, interpret, and validate satellite-derived displacement data in the context of structural behavior is key to advancing SHM.

This study focuses on integrating satellite InSAR data into the structural digital twin workflow for bridge health monitoring. The Kalix Bridge in northern Sweden served as the testbed for validating satellite-derived displacements.

KALIX BRIDGE

Overview

The Kalix Bridge, constructed in 1956 and located over the Kalix River in Sweden, is a post-tensioned concrete box girder bridge. It spans five sections, with the longest span measuring approximately 94 meters; see Figure 1. The bridge's symmetrical geometry includes a hinge at the midpoint to accommodate thermal expansion and contraction. The deck width is approximately 13 meters at the top slab and narrows to 7.5 meters at the bottom slab. Wall thickness is 45 cm, while the bottom slab varies from 20 cm to 50 cm to optimize performance under varying loads.



Figure 1. The Kalix bridge [1].

Existing Monitoring Systems and Data Availability

The Kalix Bridge was equipped with a comprehensive SHM system comprising contact-based sensors that provide real-time data on structural parameters such as strain, displacement, and acceleration [1]. The sensor network included strain gauges installed at critical points to measure structural strain, accelerometers to monitor the bridge's dynamic response to traffic, and LVDTs to measure component displacements and reveal structural deformations; see Figure 2.

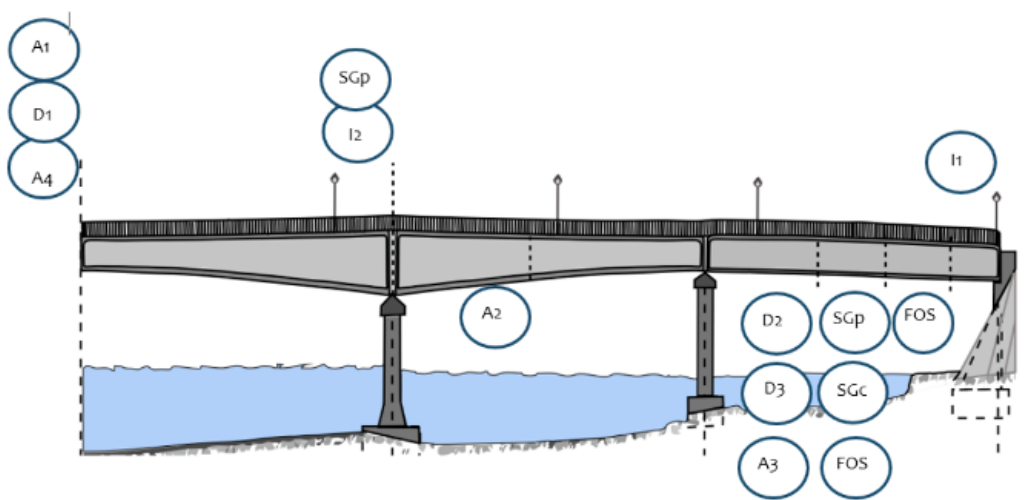


Figure 2. Sensor distribution on Kalix Bridge [1].

METHODOLOGY

InSAR Data Source and Preprocessing – The study used European Ground Motion Service (EGMS) Level-2B data based on Sentinel-1 radar acquisitions during 2019–2023 [2]. A total of 146 Persistent Scatterer (PS) points were identified within the area of interest around the Kalix Bridge; see Figure 3. Data were categorized by acquisition geometry (ascending/descending) and swath. Each PS point included a Line-of-Sight (LoS) displacement time series, geographic coordinates, and coherence indicators. Vertical displacement components were isolated via reprojection using the LoS vector.

Segment-Based Analysis – The bridge was divided longitudinally into seven zones: five spans and two abutments; see Figure 4. Location-averaged displacement trends were computed for each segment. Six intersecting swaths were filtered using a temporal coherence threshold of 0.65. Data were averaged per segment and swath, then aggregated across swaths.

Time-Averaged and Spatial Displacement Analysis – To assess spatial displacement, time-averaged displacements across the observation period were projected along the bridge axis, originating from the western abutment. The displacement field was plotted against longitudinal coordinates to detect non-uniform deformation.



Figure 3. Map of 146 points in the Area of Interest on/around Kalix bridge as displayed on EGMS [2].

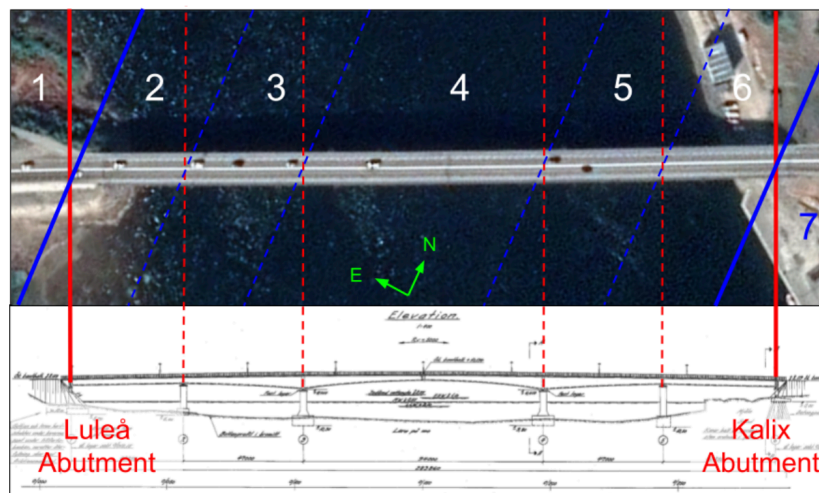


Figure 4. Annotated illustration of data splitting segments as well as a reference drawing of Kalix bridge.

RESULTS

Impact of Coherence Threshold – Following initial data processing, several anomalous displacement points were identified, reducing the interpretability of the results. To mitigate this, temporal coherence—a measure of signal consistency across multiple satellite passes—was employed as a filtering criterion; see Figure 5. Coherence values range from 0 (random noise) to 1 (highly stable signal). A threshold of 0.65 was adopted based on established practices in InSAR literature [3,4]. Higher thresholds, such as 0.70, excessively reduced point density, while lower thresholds (e.g., 0.60) retained unreliable outliers. Thus, 0.65 provided an effective balance between data quality and coverage; Figure 6. Although statistical outlier removal was considered, coherence filtering proved sufficiently robust, and no additional statistical methods were applied. The coherence distribution of persistent scatterer points is summarized in the following table.

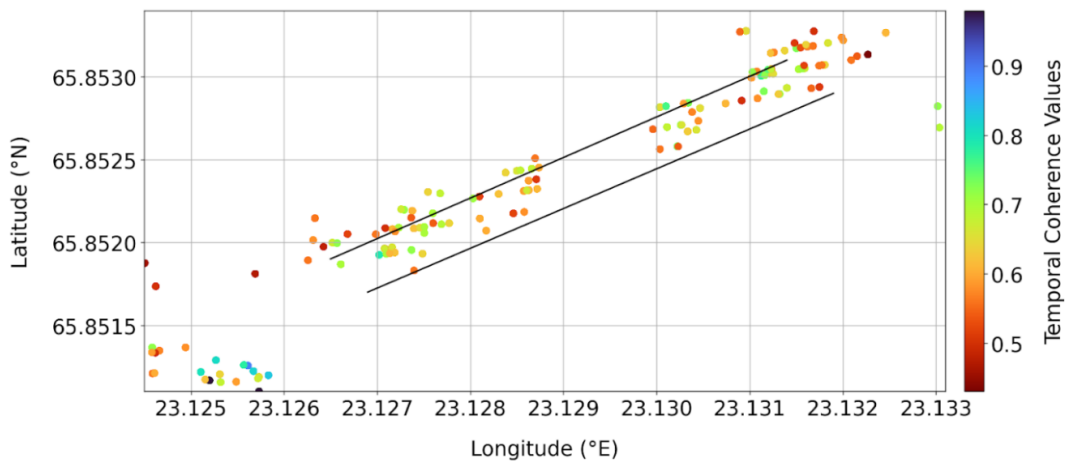


Figure 5. Coherence Values of Permanent Scatters on Kalix Bridge (2019-2023).

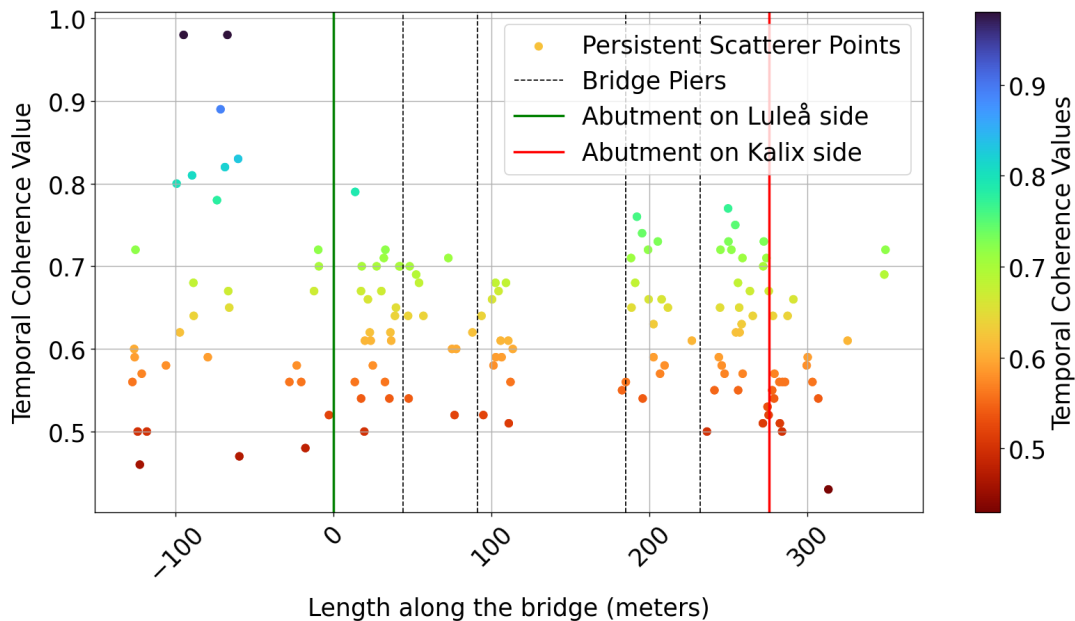


Figure 6. Persistent Scatterer Temporal Coherence Values versus Projected Length (2019-2023).

Location-Averaged Displacement Over Time – Figure 7 reveals a clear upward displacement trend across the bridge, indicating gradual vertical uplift during the observation period. The relatively uniform distribution of displacement values suggests consistent behavior across most bridge segments. However, segment 7 (the eastern abutment) exhibited significantly lower displacement magnitudes compared to the bridge spans. In contrast, segment 1 (the western abutment) showed displacement values comparable to those observed in segments 2–6, despite being located off the bridge deck. These results are based on data filtered using the critical coherence threshold of 0.65, as described above, and constitute a key outcome of the analysis. The unfiltered data presented in Figure 8 highlights the importance of coherence filtering.

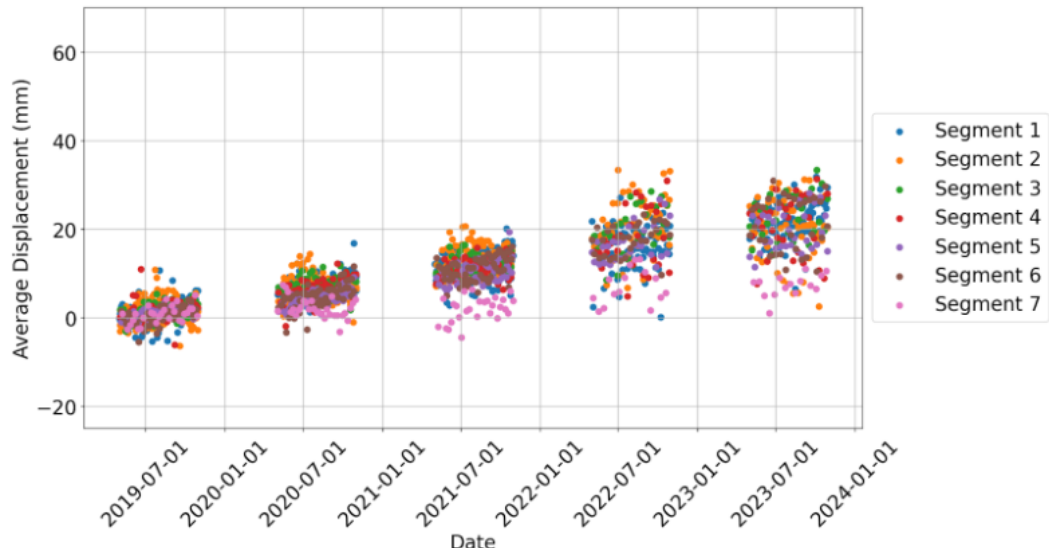


Figure 7. Location-averaged Displacement versus Time Across All Segments – Data Filtered to Include Only Points from Coherence > 0.65.

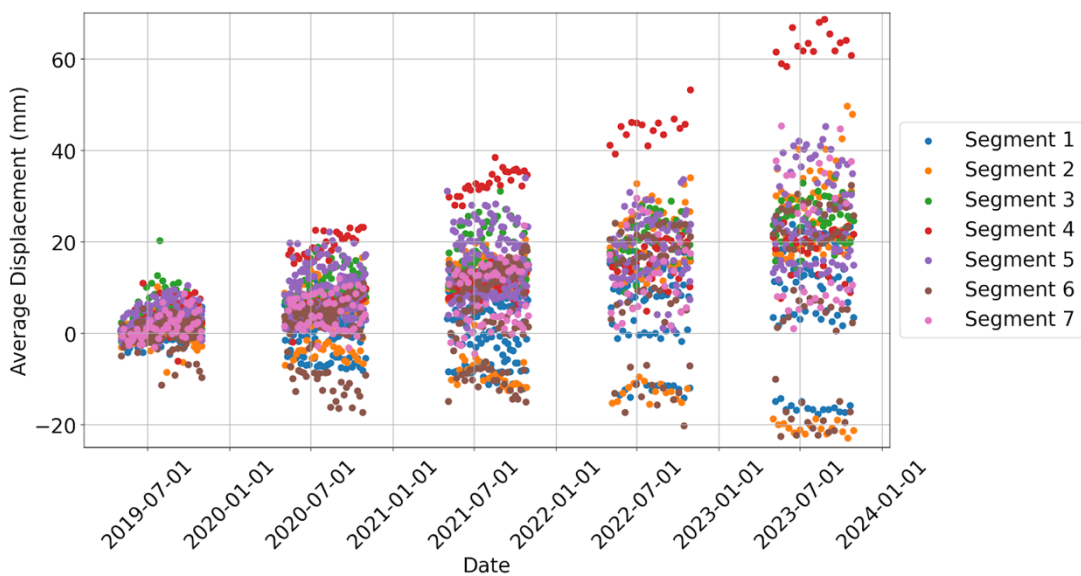


Figure 8. Location-averaged Displacement versus Time Across All Segments – Data Unfiltered By Coherence.

Time-Averaged Displacement vs. Projected Length – Figure 9 presents the time-averaged displacement along the bridge length. The data indicate minor but consistent uplift across the bridge and adjacent abutments. Notably, there is an uneven spatial distribution of valid points, with a lack of persistent scatterers at mid-span and a limited number of points exceeding the 0.65 coherence threshold. Despite these limitations, the displacement values across the available points remain relatively uniform, suggesting stable structural behavior during the observation period.

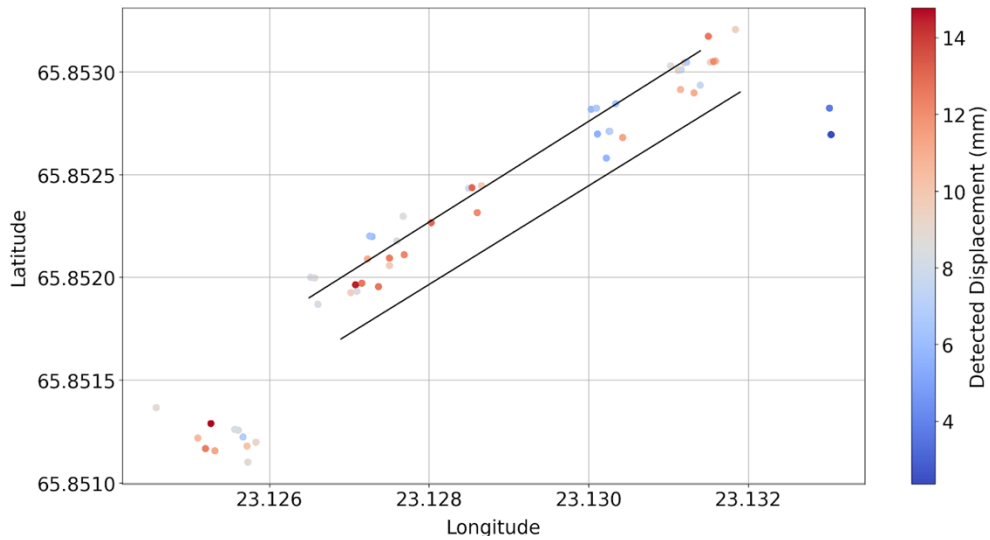


Figure 9. Time-averaged Displacement versus Location – Data Filtered to Include Only Points from Coherence > 0.65.

Projection of displacements along the bridge axis confirmed a uniform uplift trend with minimal spatial variability; see Figure 10. No significant deformation was detected, and the complete bridge replacement during the observation period was not identifiable in the InSAR data, likely due to resolution limitations.

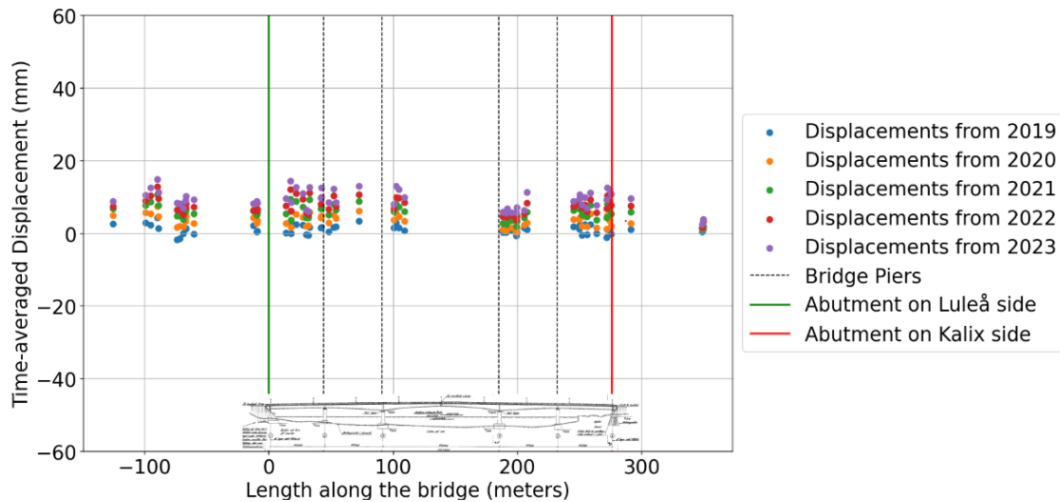


Figure 10. Time-averaged Displacement versus Projected Length – Data Filtered to Include Only Points from Coherence > 0.65.

DISCUSSION

The analysis indicates that the Kalix Bridge did not exhibit the expected deformation pattern typically associated with long-span structures, where mid-span deflection would be observed due to flexural response. Instead, a relatively uniform upward displacement was detected across the spans and abutments. This atypical uplift is likely attributed to regional post-glacial rebound, consistent with known tectonic uplift in the Gulf of Bothnia region. The magnitude and trend of displacement observed support this geophysical interpretation.

Notably, the InSAR data failed to capture the bridge replacement that occurred between September 2021 and December 2022. While a slight change in displacement variance was observed post-2022, the transition was not explicitly reflected. This limitation is likely due to the ~10 m spatial resolution of Sentinel-1 SAR data, which may have averaged both the old and new bridge structures within the same resolution cell. The minimal spatial separation between equivalent positions on the two bridges supports this hypothesis.

Temporal coherence was a critical factor in ensuring data reliability. Although 146 Persistent Scatterer (PS) points were initially available, only 30–50% exhibited coherence above the 0.65 threshold. Points with low coherence introduced significant noise, while some swaths consistently exhibited lower coherence in specific segments, reducing intra-swath consistency. Improving PS density and coherence, and understanding the causes of coherence degradation, are essential for refining InSAR-based SHM.

The comparison between raw EGMS displacement outputs and post-processed results underscores the importance of careful interpretation. While EGMS visualizations suggested excessive uplift—up to 60 mm—the processed results indicated a more moderate, spatially consistent trend. This discrepancy highlights the risk of misinterpretation without rigorous filtering and contextual understanding. Post-processing and structural insight, such as that applied here, are necessary to inform actionable decisions.

To enhance accuracy and reliability, future work should explore integration of ground-truth data from contact-based sensors, adoption of higher-resolution SAR datasets, and cross-validation using third-party InSAR providers. Such steps would support more confident assessments of structural behavior in bridge monitoring applications.

CONCLUSION

This study demonstrated the utility and limitations of using post-processed InSAR data to assess structural behavior, with the Kalix Bridge serving as a representative case. By analyzing EGMS Level-2B products derived from Sentinel-1 acquisitions between 2019 and 2023, two complementary analyses—location-averaged displacement over time and time-averaged displacement over location—were performed to characterize bridge displacement trends.

Results indicated a slow, uniform uplift consistent with regional tectonic activity, with minimal variation across spans. Segment 7, corresponding to the eastern abutment, exhibited slightly lower displacement. Coherence filtering was found to be essential for

ensuring data integrity; a threshold of 0.65 provided an effective balance between reliability and point density. Despite the bridge's reconstruction in 2021–2022, this structural change was not distinctly captured, likely due to the spatial resolution limits of Sentinel-1.

To advance InSAR-based SHM, future efforts should prioritize integration with on-site sensing systems, enabling cross-validation and enhanced interpretation of structural dynamics. Disentangling tectonic uplift from localized structural effects will be critical. Additionally, identifying coherence loss mechanisms and evaluating commercial InSAR providers with improved resolution and point density could enhance reliability.

Overall, effective use of satellite-based SHM requires rigorous post-processing and an understanding of structural context. While the current findings underscore the potential of InSAR data for monitoring displacement trends, further refinement of processing workflows and hybrid monitoring approaches is needed to ensure actionable insights for infrastructure resilience.

REFERENCES

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