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Risk Assessment of Cultural Heritage Buildings using InSAR Monitoring

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Cultural heritage assets represent core aspects of history, tradition, culture, emotions and values of a society. Due to their unique nature, they require preservation approaches that respect their identity while addressing challenges such as the occurrence of natural disasters, urbanization, and socio-economic changes. In particular, ground deformations can compromise the structural integrity of cultural heritage buildings. This study proposes a framework to integrate the ground displacement values derived from Interferometric Synthetic Aperture Radar (InSAR) into a finite element model of a cultural heritage building, enabling a quantitative link between ground motion and structural response which has been largely overlooked in previous studies. The approach is demonstrated through application to the Riga Central Market (RCM) in Latvia. InSAR analyses were performed for the period 2016 to 2025 using a combination of Small Baseline Subset (SBAS) and Persistent Scatterer Interferometry (PSI) techniques to capture both stable and distributed reflectors. The resulting displacement data were incorporated into a finite element model of the RCM building as prescribed deformations. The results indicate significant ground movement in the RCM building, particularly subsidence in the north-eastern periphery and uplift in the south-eastern corners, consistent with the recorded history of ground movement in Riga related to construction processes and tectonic movements. The proposed framework demonstrates the potential of integrating InSAR-derived ground displacement data with finite element analysis to support early warnings of settlement-induced cracks in heritage buildings. This approach could be further developed to form the basis of a digital twin for continuous monitoring and predictive maintenance of the RCM.

Keywords: InSAR, Finite Element Model, Ground Displacement, Structural Analysis, Risk Assessment, Small Baseline Subset, Persistent Scatterer Interferometry, Crack Widths, Damage States.

1. Introduction

Cultural Heritage represents the core aspects of history, tradition, culture, emotions and values, manifesting in forms like monuments, natural features or architectural spaces. It operates as a valuable means in politics, culture, education and business, empowering individuals to share perspectives and express identity (Nilson and Thorell 2018). Despite their importance, they are increasingly threatened by several natural and man-made hazards. These disasters have repeatedly caused severe damage to cultural heritage properties. Recent examples of such natural disasters are the 2019 Floods in Venice, 2015 Nepal Earthquake, 2024 Landslides near Machu Picchu and the 2024 Fire in Notre Dame Cathedral, France (Li 2024). These escalating risks underscore the urgent need for performing risk assessments to support robust decision-making for selecting mitigation measures and adaptation strategies tailored to the unique vulnerabilities of cultural heritage assets.

The preservation of cultural heritage structures has emerged as a significant issue in areas prone to ground movement. The main hazards causing ground movements are geological phenomena, anthropogenic activities or both (Lin et al. 2025; Haghshenas Haghighi and Motagh 2024). Consequently, these factors can give rise to substantial ground movements in areas of cultural heritage, jeopardising their preservation. Moreover, the vulnerability of cultural heritage buildings to ground movements has been evidenced in several cases such as the Colosseum, the Palatine Hill, and the Baths of Caracalla in Rome (Cigna et al. 2014) , Mecca in Saudi Arabia (Elhag et al. 2025), the Valle dei Templi in Italy, and Ahmedabad in India (Dumka et al. 2022). These examples highlight the importance of continuous assessment of the effects of ground movements on cultural heritage structures.

To continuously monitor these effects, a time series covering ground movements at regular intervals is indispensable. These ground movements can be determined using various methods such as differential levelling, GNSS Levelling, Airborne LiDAR and Photogrammetry. However, a continuous time series of ground movements can be best quantified using Interferometric Synthetic Aperture Radar (InSAR) (Owczarz 2020). Hence, a model integrating a continuous InSAR time series into a Finite Element Model (FEM) would facilitate a real-time risk assessment of structures subjected to ground movements.

Research on the assessment of ground displacement effects on structures has emerged over the years. Different approaches have been employed such as modelling the whole soil as a 3-dimensional mesh, adding subsidence and uplift as loads and modelling the soil as an interface, have been developed for monitoring methods other than InSAR. For instance, (Yiu et al. (2017) developed a FEM for simulating building damage caused by a tunnel construction. Another common practice to simulate soil structure interaction is based on assuming the soil as a collection of independent springs with a value of stiffness (modulus of subgrade reaction) associated with them (Burd et al. 2022). However, these models require precise geotechnical data, are computationally expensive and are very complicated in nature. Also, models involving Winkler's Spring assumption undermine the fact that soil is a non-linear, non-elastic and continuous in nature (Madhav et al. 1971). The most effective approach in integrating InSAR with FEM was performed by (Dabiri et al. 2025) in which ground movements were modelled using prescribed deformations. This method eliminates the requirement of an extensive geotechnical investigation prior to modelling. However, the results of the FEM were not integrated into a risk-based framework to support decisions on intervention strategies. Therefore, this study proposes a framework for integrating ground deformation values obtained through a combination of Small Baseline Subset (SBAS) and Persistent Scatterer (PS) Interferometry into a FEM of the Riga Central Market (RCM). The results of this analysis are subsequently mapped into five damage states to provide a comprehensive idea of the vulnerabilities of this cultural heritage structure.

2. Study Area: Historic Centre of Riga and Riga Central Market

Located on the banks of the Daugava River, Riga was established as a strategic port city in the Baltic by the Teutonic Invaders in 1201. Due to its strategic proximity to the Baltic Sea, a meeting point between East and West Europe, it quickly became a prominent member of the Hanseatic League, driving a surge in exports and economic activity. As a result, the city's Daugavmala Market became a prominent Market for commerce in the region (Grava 1993).

From 1572 to 1922, the Daugavmala Market was the foremost commercial hub in the city. However, as it was positioned on the riverbank, poor hygiene led to its closure in 1922, paving the way for the creation of the Central Market in Riga (Rīgas Centrāltirgus in Latvian). The RCM is the largest marketplace in the entirety of Europe (Fig. 1), with a total area of 72,300 m^2 and more than 3,000 stalls. It is an example of how an obsolete military infrastructure can be used for public use, as the trusses used in the construction of this market were basically made by repurposing the ones present in the Vianode Airbase, a German Airbase located 150 kilometres south of Riga (Bennett 2019).

Fig. 1. Dairy Pavilion of the Riga Central Market (Māris Strazdiņš 2024)

Each pavilion hall is 20.5 meters high and 35 meters wide, with a basement built under the entire hangar area. The basement slab, supported by the foundation structure and a grid of masonry columns, is a cast reinforced concrete slab on steel beams. The load-bearing walls of the market pavilions were built of reinforced concrete and masonry (Bennett 2019).

Since Riga lies within a tectonic zone between the Olaine-Incukalns and Bergi faults, it has a documented history of ground movements. The most prominent recent event occurred on 22 November 2010, when seismic tremors were felt across the region. These tremors resulted in structural damages in several buildings, including damage to load-bearing columns, large wall cracking (Fig. 2), and noticeable tilting (Ņikuļins 2019). Moreover, a recent structural inspection report of the RCM revealed the presence of visible cracks in the North and South faces, raising concerns regarding its serviceability (as shown in Fig. 3) (Māris Strazdiņš 2024).

Fig. 2. Cracks in the North Face of the Dairy Pavilion (Māris Strazdiņš 2024)

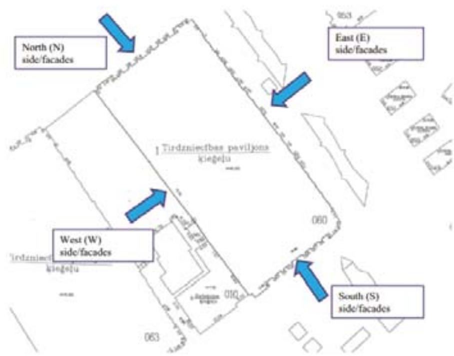

Fig. 3. Site plan of the Dairy Pavilion showing the north, east, south, and west facades (Māris Strazdiņš 2024)

3. Methodology

The methodology of this study is structured into four main steps as illustrated in Fig. 4. There are two preliminary steps: (1) Model preparation and (2) conversion of ground deformation data. The results of these two steps serve as inputs to the (3) structural assessment using InSAR deformation. Afterwards, the results of the structural assessment are used for (4) the risk assessment and the proposal of mitigation strategies.

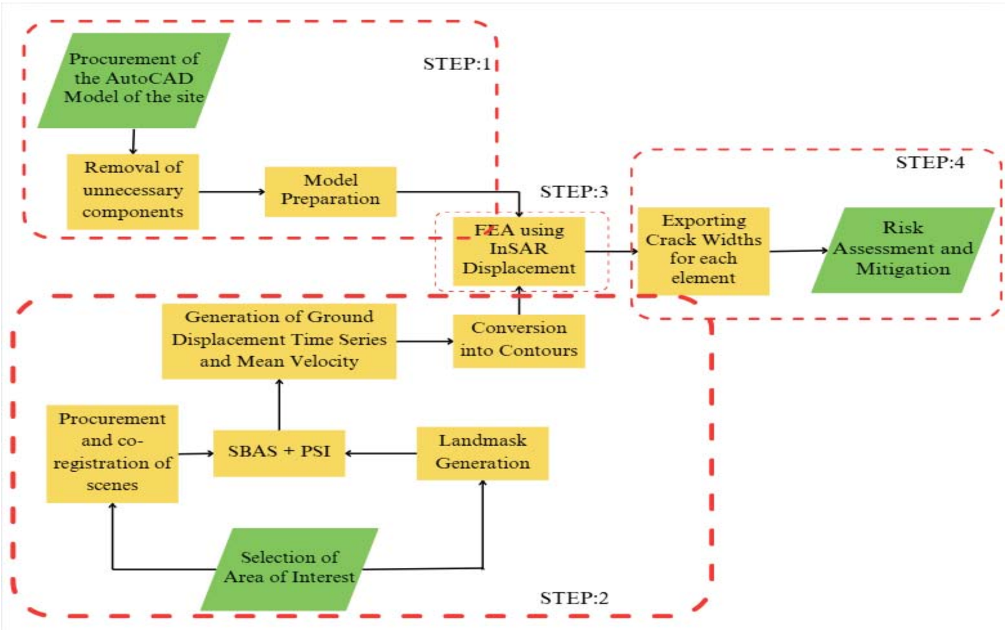

Fig. 4. Overall flowchart of the proposed methodology

3.1. ***Numerical modelling***

The model preparation includes the procurement of an AutoCAD 3D model provided by the consulting team and performing the necessary cleaning to retain only the structural components required for analysis.

The resulting structural model was then imported into DIANA v10.9 software (DIANA FEA BV.2025). Material properties like the Young's modulus, tensile strength, yield stress, Poisson ratio and material grades were defined based on the structural drawings and the design codes of the period. Depending on the shape and size of different components, the mesh size and shape were also defined.

To ensure dimension accuracy, the north and south faces were redrawn in DIANA 10.9. A mesh size of less than one-third of the smallest structural element dimension was considered. The structure also comprised a system of longitudinal and transverse trusses, which were simplified into equivalent loads and rigid links. Finally, the dead loads, live load and the ground displacements were applied to model (as shown in Fig.5).

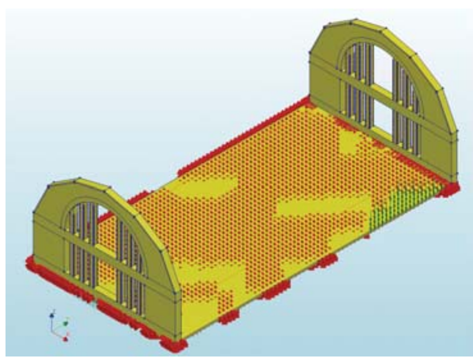

Fig. 5. Simplified FEM of the RCM Dairy Pavilion

3.2. ***InSAR***

In order to generate a ground displacement time series using SBAS and PS-InSAR, the PyGMTSAR library of python was used. Initially, the PyGMTSAR environment was configured by installing the core modules, such as S1 for Sentinel 1 data handling and stack for interferometric stacking. Relevant libraries for data visualisation, high-performance data structures, parallel computing, and essential data manipulation libraries were also imported to facilitate the efficient processing of large geospatial datasets.

Subsequently, the Area of Interest (AOI) was demarcated using Well-Known Text (WKT) format. To establish a baseline, control points such as the known subsidence point and the mostly stable point were identified using the European Ground Motion Service (EGMS) data for the Riga region. Moreover, Sentinel 1 bursts of VV Polarisation, C Band, and IW beam mode were used from 2016 to 2025 as the primary datasets. These bursts were aligned and reframed according to the AOI. Given that the AOI includes a water body, namely the Daugava river, a land mask was superimposed on the reframed scenes in order to mask out unreliable data. Successively, images were paired based on a temporal baseline for SBAS and Persistent Scatterers were computed using the inbuilt PS function. To minimize atmospheric noise, multilooking was performed on all the pairs keeping the PS as weights. Subsequently, phase unwrapping was performed to phase values between -π and π. Using this unwrapped phase, the unwrapped phase difference was computed and used to calculate the Line of Sight (LOS) displacement. Thereafter, the mean velocity was determined by linearly interpolating the LOS displacement values. A sufficiently large area of interest containing the RCM was selected, and the scenes were procured and co-registered. A land mask was generated, masking off the water bodies that are not suitable for InSAR analysis, as they reflect the backscatter away from the satellite and therefore contribute to noise. After these steps, SBAS and PSI were performed to obtain a time series of the ground deformation. Ultimately, contours of ground displacements were generated for the area encompassing the RCM.

3.3. *Non-linear static analysis*

The ground displacement contours were added into the FEM as prescribed deformations, applied to a mesh of points. Moreover, to simulate the effects of differential settlements, ground displacement values under a certain range were set to zero, and translation along the z-direction was restricted at those locations. This range of ground displacements, for which the points are considered static, varied for each period and depended on the minimum and maximum values of ground displacements for the corresponding time frame. A static non-linear analysis was performed considering physical nonlinearity. A single load step was used. The equilibrium iterations were solved using the Newton-Raphson method, with a maximum of 100 iterations and convergence criteria defined for displacement and force. As output, global Green-Lagrange crack widths were calculated.

3.4. *Risk Assessment*

Table 7.1N of Eurocode 2 (EN 1992-1-1:2004) (CEN 2004) specifies allowable crack widths in the range of 0.1mm to 0.4mm, depending on the exposure class of concrete. In general, larger crack widths are allowed for structures exposed to less severe environmental conditions. These ranges of allowable crack widths can be used as damage states thresholds, to link the physical condition of the buildings to structural serviceability performance. Moreover, the crack widths when used as damage states can be used to interpret the numerical results in terms of their practical implications. Therefore, in this study, the values of crack widths generated for the North and South faces of the RCM were extracted from the FEM, and then the percentage of elements falling within different ranges of crack widths was categorised into the corresponding damage states, as presented in Table 1. Elements within the DS1 represent the lowest serviceability risk, which increases up to DS5, corresponding to the maximum risk.

Table 1. Crack widths for each damage state based on Eurocode 2 (CEN 2004)

Damage States	Crack Widths (mm)
DS1	<0.1
DS2	0.1-0.2
DS3	0.2-0.3
DS4	0.3-0.4
DS5	>0.4

4. Results

4.1. *InSAR*

The PS InSAR and SBAS analyses were both successful in capturing the ground deformation values for the AOI (Fig.6). Across the entire AOI, PS InSAR captured the ground deformation for

783013 points, whereas SBAS did it for 200646 points. This is because the AOI chosen for this study is highly urbanised and contains a high concentration of infrastructure that can act as Persistent Scatterers. Upon removal of all the points that lie outside the RCM, a total of 64 measurement points for PS InSAR and 16 measurement points for SBAS remained. Based on the analysis, ground deformation patterns generated by PS InSAR show a maximum mean uplift rate of 14.1 mm/year and a maximum mean subsidence rate of -7.2 mm/year over a period of 9 years (from 2016 to 2025).

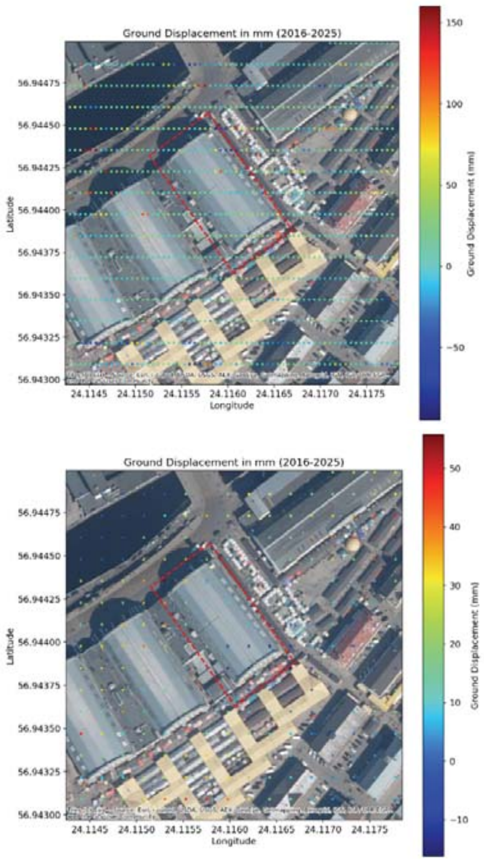

Fig. 6. (a) Ground Displacement values generated by PSI (b) Ground Displacement values generated by SBAS

Using the combined results of the ground displacement and mean velocity data obtained from PS InSAR and SBAS, contour plots for the RCM were generated for different time intervals. As shown in Fig. 7a, for the period 2016-2025, high values of subsidence can be observed at the basement walls adjacent to the north-eastern corners of the building, reaching approximately 100 mm Noticeable subsidence is also present in localized areas along the periphery of the eastern and western walls. Elevated values of uplift can be observed near the centre of the plot (Fig.7b), exceeding 100mm. Significant uplift is also visible around the south-eastern corner of the building. Furthermore, moderate uplift can be observed in some areas near the centre of the north wall, south wall, and in the periphery of the western wall of the basement, with uplift values approaching 50 mm.

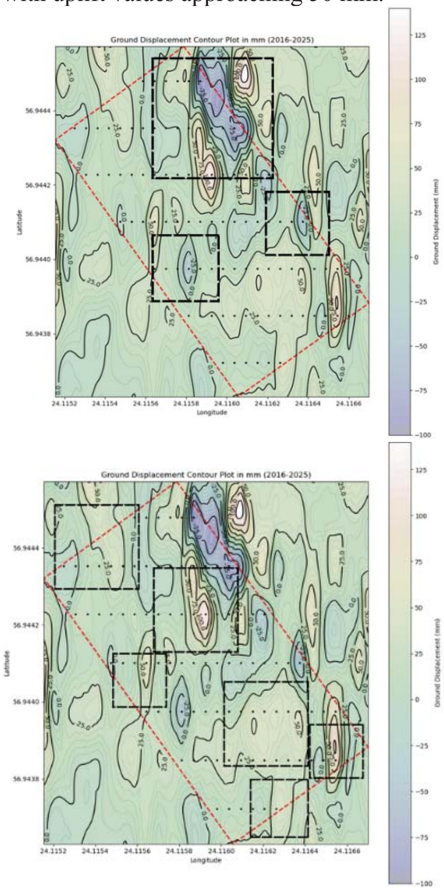

Fig. 7. Ground Displacement contour plots (a) Regions of subsidence (b) Regions of uplift

4.2. *FEM*

Crack widths were obtained for the RCM through the FEM based on the ground displacement contours generated for the 2016-2025 period. The crack width patterns are consistent with the photographic evidence of existing cracks. Cracks are expected to form in the north and south faces, particularly at the locations where the masonry and inner lintel connect. A considerable difference can be observed in the cracked elements on the north and south faces (see Fig.8). The south face exhibits a significantly higher number of cracked elements as compared to the north face. This can be attributed to the higher uplift value of approximately 75 mm, observed at the south-eastern corner of the building, as shown in Fig.8. In contrast, on the north face, the maximum uplift of about 25mm is observed only near the centre of the northern edge, as shown in Fig.8. This explains the presence of localised cracks concentrated near the centre of the northern edge.

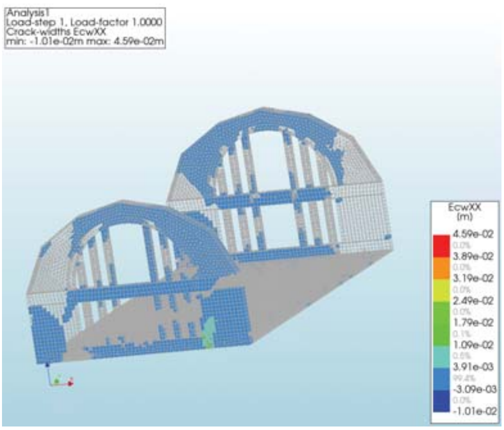

Fig. 8. Crack width results of the FEA

4.3. *Risk Assessment*

The distribution of elements across the different damage states shows that DS1 has the largest share of elements, followed by DS5, DS2, DS3 and DS4 (see Fig. 9). The presence of 18.13% of elements in DS5 is a matter of concern, as this damage state corresponds to the highest serviceability risk and indicates the presence of locations where cracking may affect durability and functional performance. These zones may require detailed inspection, monitoring, or localized intervention to prevent further deterioration. However, most of the elements fall within the lower damage states, which represent minor or acceptable crack widths under serviceability criteria. This indicates that, at the global level, the structure remains within acceptable serviceability limits, and the overall serviceability risk can be considered low.

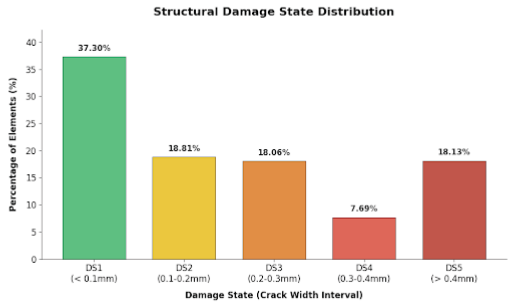

Fig. 9. Distribution of elements across damage states

5. Conclusion

This study presented a framework for integrating ground displacement data obtained from InSAR to finite element analysis for the early detection of structural vulnerabilities. The approach was applied to the Dairy Pavilion of the Riga Central Market, a cultural heritage structure located in an area affected by ground movements. Through the processing of SAR images using PSI and SBAS, ground displacement values were generated for the period 2016 to 2025. These ground displacement values were then combined to obtain spatially continuous displacement contours. Subsequently, these ground displacements were integrated into a finite element model of the RCM as prescribed deformations using a mesh of points underneath the foundation. The structural response was evaluated through nonlinear analysis, and the resulting crack widths were mapped into damage states based on serviceability criteria. The results indicated that most structural elements remained within the lower damage states, corresponding to acceptable crack widths, and therefore the overall serviceability risk during the analysed period can be considered low, although localized areas exhibited higher vulnerability suggesting the need for preventive maintenance strategies. Additionally, the findings indicate that integrating SBAS and PSI to derive ground displacements is highly precise because of their complementary nature. The main limitations of this study relate to the lack of actual material properties and the deterministic approach for the structural analysis. Future work should focus on extending the framework toward probabilistic analyses to better represent the uncertainties in the materials, ground displacements and the structural response.

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