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Review Article

Remote Sensing in the Transport Industry: A Review of Satellite Applications for Resilient Infrastructure

Annabel Morkporkpor Ami Dompey[1], Abdul-Mugis Yussif[1], Tarek Zayed[1]

[1]The Department of Building and Real Estate, The Hong Kong Polytechnic University

Correspondence: bella-ami.dompey@connect.polyu.hk

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Abstract

While the presence of various transport infrastructures is essential for completing everyday tasks, their maintenance remains a challenge. Remote sensing techniques, such as satellites, have emerged as non-destructive and efficient methods, capable of managing this challenge by providing predictive maintenance options, large-scale inspections, and cost-effective solutions. There has been growing interest in this regard, and recent studies have highlighted the potential of satellites as an early warning and complementary tool for condition assessment, thereby underscoring the need to track trends in usage, identify gaps, and explore opportunities for further research. The aim of this study is to provide a comprehensive review of satellite applications for assessing transport infrastructure. Following the PRISMA guidelines, this study conducts keyword co-occurrence analysis and content analysis of selected relevant papers. The results showcase an interest in utilising satellite imagery for early decision-making in maintaining the safety and resilience of transport infrastructures. Furthermore, the use of Synthetic Aperture Radar (SAR) satellites, particularly Sentinel-1 and Cosmo-SkyMed, was found to be more profound for transport assessment than optical satellites. The primary application of satellite imagery was associated with structural health monitoring and change detection, with some studies advocating for the integration of satellite data with ground-based techniques to yield holistic assessments. Performing economic analyses, developing regulatory standards, and sustainability metrics were highlighted as gaps. These findings reinforce the potential of satellite data in enhancing maintenance strategies and pave the way for future research to explore the usage of satellite imagery for comprehensive and resilient transport infrastructure monitoring.

Keywords: Condition assessment; Remote sensing; Resilient infrastructure; Satellite; Transport infrastructure

Highlights

- Satellite remote sensing supports resilient and economical transport assessments
- SAR satellites outperform optical satellites in monitoring transport networks
- Satellite insights map future directions for sustainable and resilient transport assessment

1 Introduction

The built environment encompasses all physical structures and systems made by human beings to support their daily activities of living, working, and recreation (Portella, 2014). Within this built environment, civil infrastructure systems comprising buildings, transport infrastructure, and other systems play crucial roles in ensuring the seamless operation and progress of society. To achieve optimal functionality, these civil infrastructural elements are usually designed and constructed to be durable (Lebaku et al., 2024). However, in modern times, having resilient infrastructure is not only tied to durability but also to adaptability and sustainability. These ties have therefore transformed the outlook of research in the built environment and necessitated investigations into innovative ways of developing and maintaining various civil infrastructure.

Transport infrastructure stands out amongst the civil infrastructure as a crucial system in need of continuous monitoring and maintenance due to deteriorations that affect its safety and serviceability (Ponzo et al., 2021). Insights from various infrastructure management agencies and research have shown that early detection and maintenance practices are a guarantee for improved transport resilience (Lebaku et al., 2024; Ponzo et al., 2021). Hence, efforts are being made to improve condition assessment methods by transitioning from manual field inspections to non-destructive techniques. These non-destructive techniques are available in two forms: vibration-based methods and remote sensing methods (Lebaku et al., 2024; Guo et al., 2022). Vibration-based methods utilise accelerometers and global positioning systems (GPS) for data collection, whereas remote sensing-based methods utilise sensors mounted on unmanned aerial vehicles (UAVs), satellites, aeroplanes, and survey vehicles for data collection (Guo et al., 2022). Evidently, the recent advancements in satellite technology and image processing techniques, coupled with the demand for large-scale monitoring, have amplified the potential of using satellites for infrastructure condition assessment (Lebaku et al., 2024; D'Aranno et al., 2021). Taking advantage of this technological reform and advancement, this study reviews the applications of satellite for transport infrastructure assessment.

Previous studies have demonstrated significant interest in remote sensing for transport infrastructure assessment. However, a gap remains in the practical application of these sensing technologies (Benedetto et al., 2022). This gap has led to several literature analyses on the subject matter, but none have specifically targeted the applications of satellites alone. For instance, Quqa et al. (2025), Rakoczy et al. (2024), and Casas et al. (2024) reviewed the applications of remote sensing technologies for bridges only, without considering other types of transport infrastructure. Koohmishi et al. (2024), Benedetto et al. (2022), and Tosti et al. (2021) also explored the latest developments in remote sensing. However, the study focused on the integration potential of ground-penetrating radar (GPR) and interferometric synthetic aperture radar (InSAR). Additionally, Gagliardi et al. (2023) provided a comprehensive review of satellite applications and non-destructive testing methods for transport infrastructure assessment. However, their scope of satellite applications was limited to only multi-temporal InSAR. To resolve this, this study synthesises insights from multiple studies to answer two main questions. (1) What are the satellite technologies and the associated data processing techniques used by the transportation industry? (2) What are the main applications of satellite imagery for transport infrastructure assessment?

2 Methodology

A mixed-methodology approach combining scientometric and systematic analyses was employed in this study. The ability to gain detailed insights into existing literature surrounding the subject matter and identify potential areas for further research was the guiding principle in adopting this methodology. To ensure transparency of the process and complete comprehension among the scholarly community, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which include database identification, keyword selection, establishment of inclusion and exclusion criteria, and snowballing, were adhered to (Page et al., 2021).

Two databases, Scopus and Web of Science, were selected for this study. This selection was made due to the global recognition of these databases for their vast bibliometric coverage and compatibility with scientific mapping tools (Gusenbauer, 2024). Once the databases were selected, Boolean search terms were formed. These search terms were guided by the research questions and included terms such as "satellite", "condition assessment," and "transport infrastructure," as well as their alternatives. The various lengths and spellings of the search terms were accounted for using truncated symbols and joined together using operators such as "AND" and "OR" to help refine the search results. Further improvements to the search results were achieved by establishing inclusion and exclusion criteria. Due to the scope and nature of the study area, the inclusion criteria were set to comprise all peer-reviewed journal articles and conference papers. Case studies and experimental studies utilising satellite imagery for any transport infrastructure were also included. Non-English papers, records without full-text availability, and publications unrelated to engineering comprised the exclusion criteria for this study.

Following the establishment of the inclusion and exclusion criteria, the PRISMA guidelines were adhered to in selecting suitable papers for the review (See Figure 1). This operation yielded a total of 149 papers for the study. The selected papers were then analysed using scientometric and systematic methods. The scientometric analysis, which visually presents academic knowledge and contributions, and is limited in this study to keyword co-occurrence, was undertaken using VoSviewer. This application was selected due to its friendly interface, large network display, and specialised text-mining functionalities (van Eck & Waltman, 2014). For the systematic analysis, the contents of the selected papers were assessed in line with the research questions. They were divided into two main parts: satellite types and processing techniques, as well as the applications of satellite imagery for assessing transport infrastructure. The systematic analysis aimed to evaluate the current literature, identify gaps, and propose further studies.

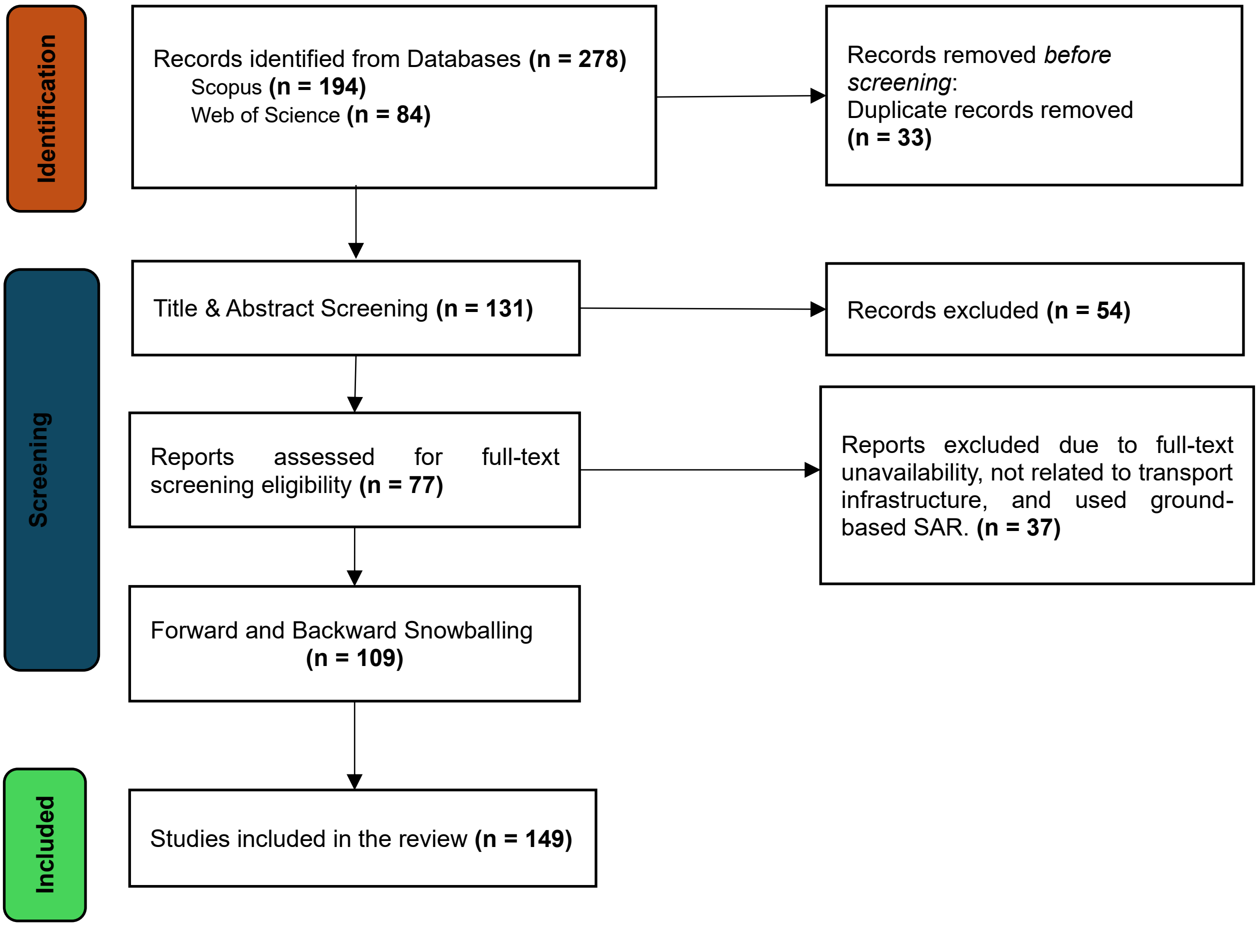


Figure 1. PRSIMA diagram for screening and paper selection

Source: Authors' Construct

3 Scientometric Analysis (Keyword Co-occurrence)

Keywords represent the basic content of research articles and define the specific areas covered within a particular field (van Eck & Waltman, 2014). This review utilised a co-occurrence analysis of keywords, employing "all keywords" as the unit of analysis and "full counting" as the method of measurement. A minimum occurrence threshold of 5 was applied, resulting in the extraction of 46 keywords from a total of 1246. To refine the dataset, synonymous terms such as "satellite," "satellite data," and "satellite imagery," as well as "structural monitoring" and "structural health monitoring," were merged. Additionally, unrelated terms, such as "case studies," "Shanghai," and "China," were excluded. Ultimately, the analysis identified 42 significant items distributed across 3 clusters.

The findings illustrated in Figure 2 reveal that the keywords "interferometric synthetic aperture radar (InSAR)," "synthetic aperture radar (SAR)," and "structural health monitoring (SHM)" are the most frequently used. This outcome highlights the growing emphasis among researchers on utilising InSAR for SHM. The first cluster (green) consists of 18 items representing scholarly interests in the application of satellite and radar methods for SHM, particularly for bridges. It further highlights the interest of the scholarly community and industry professionals in seeking proactive strategies and real-time alerts for minimising failure or collapse of various transport infrastructure and utilising satellite imagery for informing prompt engineering interventions.

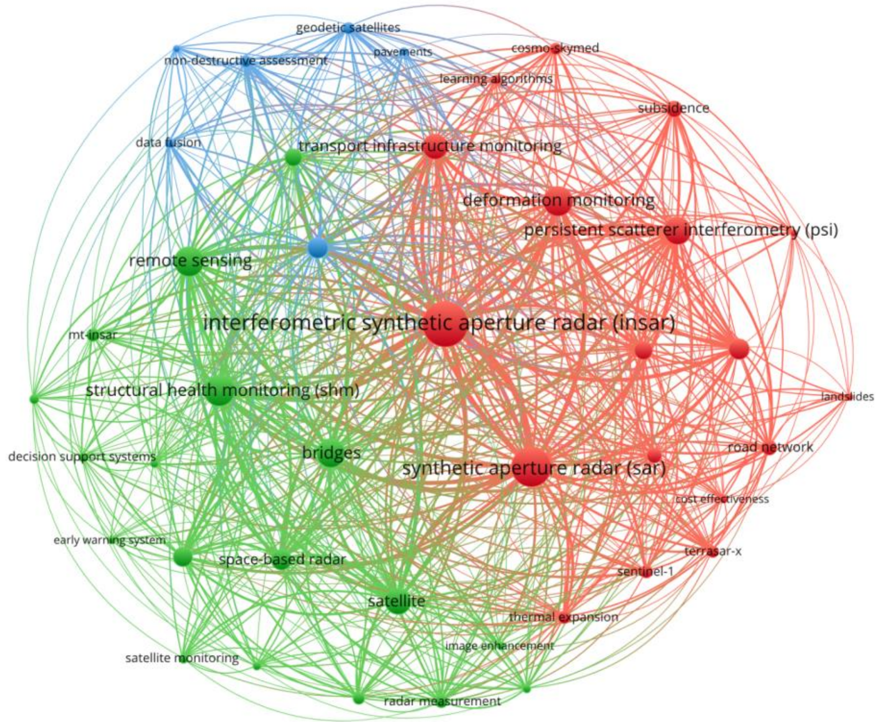


Figure 2. Network Visualisation of Keywords

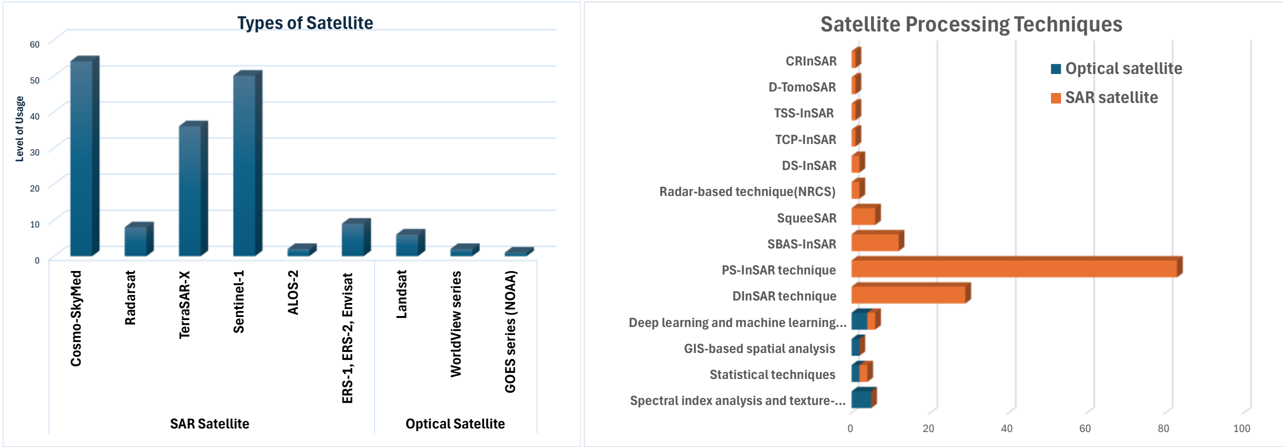
Source: Authors' Construct

The second cluster (red) also comprised 18 items, underscoring the use of InSAR and SAR for deformation monitoring in various transport infrastructure. In this cluster, the presence of satellite types such as "Sentinel-1," "Cosmo-SkyMed," "Envisat," and "Terrasar-X" highlights the dominant usage of these satellite constellations for data collection. Furthermore, the appearance of keywords such as "road networks" and "railway" suggests the use of these remote sensing methods for large-scale infrastructure monitoring. The third cluster comprises only six items related to the use of multiple methods for non-destructive assessment of various transport infrastructure. Terms such as "geodetic satellites," "data fusion," and "GPR" indicate the need for integration to make a holistic assessment of the condition of the transport infrastructure. Additionally, it highlights the emerging trend in research towards the integration of satellite-based approaches with ground measurements for macro and micro inspection and assessment. Overall, the results of this analysis indicate a trajectory of research moving towards cost-effective and data-driven methods to maintain the safety and resilience of transport infrastructure.

4 Results and Discussion of Systematic Analysis

4.1 Types of Satellites and Processing Techniques

The demand for radar assessments has led to the emergence of several satellite missions. Based on the analysis of the literature, the satellite technologies used in the transport industry were identified and grouped into two main categories: optical Earth observation satellites and SAR satellite missions (See Figure 3a). Under these two categories, the optical earth observation satellites were primarily limited to the use of Landsat, with minor usage of other optical missions such as Worldview and the GEOS series. Six primary SAR satellites were identified, with Cosmo-SkyMed and Sentinel-1 recording the highest usage rates. This observation confirms the details of the second cluster (red) in the quantitative analyses, where these satellites were flagged in the keywords.



(a) (b)

Figure 3. Overview of Satellite Classifications: (a) Types of Satellite Missions (b) Types of Processing Techniques

Source: Authors' Construct

Optical satellites produce images capturing the visible portions of sunlight (Kim et al., 2024). They exist as hyperspectral, panchromatic, and multispectral images, consisting of single to multiple bands (Bashar et al., 2022). On the other hand, SAR images are produced by means of radar pulses that measure reflected waves from surfaces such as the ground or ocean. Unlike optical satellites, which depend on sunlight for accurate readings, SAR satellites can produce images at night and in adverse weather conditions (Kim et al., 2024; Selvakumaran et al., 2021). Due to this limitation, it is evident that for transport infrastructure monitoring, which requires continuous evaluation, SAR satellites are the best-suited and most adopted. These SAR satellites, however, operate in different bandwidths and *are subject to access restrictions*. The TerraSAR-X satellites from the German Aerospace Centre and the Italian Cosmo-SkyMed operate on the X-band, whilst the Advanced Land Observing Satellite (ALOS) from the Japan Aerospace Exploration Agency (JAXA) operates on the L-band. The Sentinel-1 satellite from the European Space Agency (ESA) operates on the C-band, with ERS-1/2, ENVISAT, and RADARSAT-1 being the first production of C-band data (Stawinoga et al., 2021; Meyer et al., 2020).

In processing images obtained from various satellite constellations, several researchers have explored different image processing techniques. From the selected papers, optical satellite images were predominantly found to be processed using spectral index analysis, GIS-based analysis, and machine learning or deep learning techniques, whilst SAR images were primarily processed using InSAR techniques. A summary of satellite processing techniques is shown in Figure 3b. Depending on the purpose and application of SAR imagery, various forms of InSAR techniques have been adopted. These techniques can assess large coverage networks, provide remote and high-density measurements (Kim et al., 2024; Selvakumaran et al., 2021). This study analysed the major InSAR techniques and their differences, providing a summary in Table 1. Among the earliest methods developed, Differential InSAR (DInSAR) remains the foundation for broad geophysical assessments and regional surveys (Stawinoga et al., 2021). Nevertheless, its limitations in precision and vulnerability to atmospheric noise led to the advancement of Time series InSAR (TS-InSAR) or Multi-temporal InSAR (MT-InSAR) approaches aimed at achieving higher accuracy in infrastructure monitoring (Xing et al., 2018).

Permanent or persistent scatterer InSAR (PS-InSAR) is the most widely used MT-InSAR technique, and its reliance on stable reflectors makes it an ideal choice for monitoring various transport networks. From the reviewed literature, some studies showed advancements to this technique by adopting an InSAR imaging mode known as Terrain Observation with Progressive Scans SAR (TOPSAR) (Schlögl et al., 2022), whilst others opted for the Stanford Method for PS-InSAR (STAMPS), which provides better performance in urban environments (Yaşar & Eronat, 2023; Vadivel et al., 2020). Other emerging MT-InSAR techniques surfaced in the analysis, including Small Baseline Subset (SBAS), for analysing distributed targets, SqueeSAR, Distributed scatterer (DS-InSAR), and temporal coherence-based models like Temporal Coherent Point InSAR (TCP-InSAR) and Temporary Scatterers Stacking InSAR (TSS-InSAR), which offer solutions for low coherence regions and complex terrains. Corner reflector InSAR and Differential SAR Tomography extend these capabilities, providing novel approaches for artificial reflector analysis and three-dimensional deformation modelling, respectively (Markogiannaki et al., 2022; Gagliardi et al., 2020; Xing et al., 2018).

Table I. Comparison of InSAR Processing Techniques

Type of technique	Category of InSAR technique	Scatterer type	Sensitivity to atmospheric noise	Level of precision	Source
Differential InSAR (DInSAR)	InSAR processing technique	Natural terrain features	Highly sensitive	Low precision	(Giordano et al., 2022; Infante et al., 2019; Miele et al., 2023; Sousa & Bastos, 2013)
Persistent or Permanent Scatterer InSAR (PS-InSAR)	Scatterer-based MT-InSAR technique	Persistent scatterer (PS)/ stable reflectors	Less sensitive	High precision	(Cusson & Stewart, 2024; Gagliardi et al., 2020; Koudogbo et al., 2018; Vaccari et al., 2018; Qin et al., 2017)
Small Baseline Subsets (SBAS-InSAR)	Scatterer-based MT-InSAR technique	Distributed scatterers (DS)	Moderately sensitive	Moderately precise as it trades some precision for coverage and flexibility	(Stawinoga et al., 2021; Karimzadeh & Matsuoka, 2020; Zhu et al., 2019; Selvakumaran et al., 2018)
SqueeSAR	Advanced MT-InSAR technique	Persistent and distributed scatterers	Less sensitive	High precision, but slightly lower when compared to PS-InSAR	(Henrion et al., 2024; Sartorelli et al., 2021; Hoppe et al., 2019; Koudogbo et al., 2018; Vaccari et al., 2018; Barla et al., 2016)
Distributed Scatterer InSAR (DS-InSAR)	Scatterer-based MT-InSAR technique	Weak distributed scatterers	Moderately sensitive	Low precision	(Zhou et al., 2025; Koudogbo et al., 2018)
Corner Reflector InSAR (CRInSAR)	Scatterer-based MT-InSAR technique	Artificial scatterers (corner reflectors)	Less sensitive	High precision	(Xing et al., 2018)
Temporary Scatterers Stacking InSAR (TSS-InSAR)	Scatterer-based MT-InSAR technique	Temporary scatterers (varies from PS/DS or TCP)	Less sensitive	High precision but not reliable for long-term	(Dai et al., 2018)
Temporal Coherent Point InSAR (TCP-InSAR)	Scatterer-based MT-InSAR technique	Temporal coherent points (TCP)	Less sensitive	Moderately precise, as it balances coherence and coverage	(Zhang et al., 2018)
Differential SAR Tomography (D-TomoSAR)	Advanced MT-InSAR technique	Persistent scatterers	Less sensitive	Varied levels due to height differences	(Markogiannaki et al., 2022)

Source: Authors' Construct

4.2 Applications of Satellite Imagery for Transport Infrastructure Assessment

The application of satellite imagery for monitoring and surveillance of transport infrastructure has become increasingly popular among civil engineers and researchers. Notably, they have been used in monitoring highways (Tessema et al., 2024; D'Aranno et al., 2021), airport runways (Gagliardi, Ciampoli, et al., 2021), railways (Shami et al., 2022), and bridges (Pięk & Pawłuszek-Filipiak, 2025; Qin et al., 2019). In rare cases, they have also been used for subway tunnels (Perissin et al., 2012).

With these infrastructure applications, studies have demonstrated the use of satellite techniques to produce datasets that require minimal preprocessing for determining displacement levels, deformations, and unevenness on pavements, compared to methods such as crack meters and inclinometers (Shami et al., 2022; Gagliardi et al., 2021). Utilising the PS-InSAR technique, Gagliardi et al. (2021) devised a method that converts the vertical and horizontal velocity components of satellite imagery acquisition geometries to calculate the actual ground deformation and ultimately determine the deformation pattern of an airport runway. Similarly, Tessema et al. (2024) assessed network-level road deformation using a blend of Sentinel-1 and TerraSAR-X data. Despite the precision and ease of velocity determination of PS-InSAR, only the data points from TerraSAR-X showed clear and detailed deformation patterns at strategic areas due to its higher resolution compared to Sentinel-1. Identifying bridge deformations using satellite imagery was the focus of most studies. However, the complex nature of bridges poses some challenges, especially in interpreting deformation maps from scans. To tackle these challenges, Qin et al. (2019) developed a coherence-driven point targeting approach based on DInSAR to analyse 3D deformation and visualise bridges. The developed algorithm, combined with the DInSAR technique, enabled the identification of symmetrical and asymmetrical deformations on bridges, making the outcome suitable for practical bridge structural health monitoring.

The deformations of bridges and other transportation infrastructure are monitored continuously for specific timeframes to observe their structural changes using satellite techniques, such as DInSAR (Pięk & Pawłuszek-Filipiak, 2025; Qin et al., 2019), PS-InSAR (Cusson & Stewart, 2024), and DS-InSAR (Zhou et al., 2025). Time series predictive monitoring techniques are often the most successful for these observations, given the need to continuously observe the structure's responses to load. However, other studies have adopted numerical modelling, especially for infrastructural thermal deformations (Ponzo et al., 2024). However, numerical methods are computationally resource-intensive, resulting from extensive parameter optimisations, thereby requiring significant capital investments.

To better understand the cause-and-effect relationship between transport infrastructure and its environment, as well as providing holistic monitoring results, some scholars have turned towards multi-assessment approaches. For instance, D'Aranno et al. (2021) investigated the slope displacement and stability of a viaduct on sedimentary plains by combining temperature sensors, an inertial measurement unit (IMU), and the SBAS-InSAR to measure the causes of viaduct deformation and the relationship with the embankment. Bianchini Ciampoli et al. (2020) also explored the potential for integrating data from GPR with InSAR techniques for assessing linear transport infrastructure. Additionally, Ibrahim et al. (2024) investigated the impact of subsidence on roads by validating satellite results with ground-based techniques, including UAVs and smartphones.

Satellite technologies spur the creation of digital twin systems for the structural monitoring of transport infrastructure (Ponzo et al., 2024). The satellite data provide continuous information on changes due to the infrastructure's reaction to loads, while predictive analyses are conducted using machine learning mechanisms. The digital twin enables real-time monitoring and assessment, relying on the sustained and reliable high-quality data provision. Simulating future structural scenarios is also possible when digital twin systems are combined with temporal satellite data and deformation patterns to inform maintenance schedules and prevent hazards. Computer vision and image processing techniques are also fundamental for detecting, visualising, and estimating the extent of deformations using the imagery (Yussif et al., 2025). Furthermore, some studies employed satellite images to conduct risk assessments and classifications along transport networks (Miano et al., 2024; Suárez-Fernández et al., 2024).

The transportation industry has demonstrated extensive applications of satellite technologies for SHM, change and damage detection, risk assessment, and predictive analysis. However, most of these applications remain in the experimental stages, thus requiring more studies to conduct real-time case studies and assessments. Liaising the outcome of Figure 2 with the content analysis, it was observed that most studies predominantly utilized satellites for structural health monitoring in bridges. This observation opens up additional areas for further research on underexplored transport networks, including roads and railways.

4.3 Opportunities for Future Research

The outcome of this analysis has revealed significant progress in developing processing methodologies for transport infrastructure assessments, yet several critical challenges remain. Most of these techniques are utilised in the absence of hazard assessment frameworks, which, when integrated, could enable holistic condition evaluation and enhance infrastructure resilience. Research work should focus on developing multidisciplinary models that fuse satellite-derived information with diverse hazard indicators, such as risk assessment metrics, human behavioural indicators, and climate-induced stressors. This integration could support more effective resilience-building strategies and long-term sustainability planning for transport systems. Furthermore, the reviewed literature showed an emerging interest in leveraging deep learning and machine learning techniques to mitigate atmospheric noise in satellite observations. However, most of these atmospheric correction models remain regionally tailored and fail to account for localised weather variability. Future research should build upon current trends and explore the potential of quantum-enhanced processing and IoT sensor-based integration to improve the accuracy and applicability of satellite-derived assessments.

With the emergence of many processing methodologies, future research into workforce training and development is also essential. Studies could explore workers' adaptability to using satellite imagery and training media to achieve higher comprehension and usability rates. Examining the application of satellites through the lens of sustainability, the review reveals a gap in current practices. Exploring *its* potential to detect large surface defects, encroachment activities around transport routes, and material degradation is yet to be considered. Moreover, studies investigating its economic benefits, environmental impacts, and social value in comparison with other existing ground-based techniques remain limited. Future research is needed to bridge these gaps. Additionally, with structural health monitoring being a primary application of satellite imagery, future research could focus on developing deformation ratings that can be integrated with existing condition ratings to assess the overall condition of transport infrastructure.

5 Conclusion

Recently, urbanisation and population growth have led to increasing climatic issues, and the need for more resilient infrastructure has become paramount. The transport infrastructure is not exempt. From exploring sustainable materials, smart assessments, and innovative construction methods, researchers, in collaboration with industry professionals in the civil and construction industry, have discovered the use of satellite remote sensing technologies as a remedy for keeping transport networks durable, adaptable, and sustainable. The extent to which these technologies are applied is the focus of this review study. Although limited in scope and depth of analysis, this review has synthesised the current applications of satellites by the transport industry and paved the way for further research in exploring the following areas towards a resilient transport industry. (1) develop automated early warning detection systems, (2) improve current methodologies and data processing techniques, (3) explore alternative uses of optical satellites by the transport industry, (4) create and update regulatory standards and sustainability metrics.

To supplement the efforts of researchers in developing a resilient transportation industry, transportation departments and civil engineering firms should document the costs of their traditional and ground-based technological inspections to establish a baseline for cost metrics and facilitate cost-benefit assessments. Additionally, agencies that adopt satellite monitoring as a continuous and early warning system could be incentivised to promote its widespread adoption. There should be a constant effort to make satellite data more affordable and easily accessible. Continuous professional training sessions and workshops should be organised for inspectors to enhance their skill set and specialisation in processing satellite imagery, subject to the findings of researchers. Pilot programs, funded by the government, could be made available to accelerate the development, testing, and adoption of satellite standards.

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No data available

Conflicts of Interest
The authors declare no conflict of interest

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