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USING GNSS TECHNOLOGIES FOR HIGH-PRECISION GEODETIC MONITORING OF INFRASTRUCTURE OBJECTS

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Abstract. The structural integrity of infrastructure objects like bridges, roads, and railway tracks is crucial for ensuring public safety, economic stability, and operational continuity, yet these assets are vulnerable to deformations and displacements caused by environmental factors, heavy loads, and material fatigue, necessitating advanced monitoring techniques. This article investigates the application of GNSS technologies (Global Navigation Satellite Systems, including GPS, Galileo, and BeiDou) for high-precision geodetic monitoring of such infrastructure assets, focusing on their ability to detect subtle changes in real-world conditions. The study emphasizes the integration of GNSS data into a unified framework to ensure accurate monitoring of deformations, displacements, and structural stability, enabling proactive infrastructure management. A comprehensive approach is employed, combining field measurements with GNSS receivers installed on a 200-meter suspension bridge and a 1-km highway segment, data analysis using special software to filter out noise, and software modeling in GNSS Solutions to simulate deformation scenarios. Over a six-month period, the methodology achieved a high measurement accuracy of 2–5 mm, detecting a 3-mm vertical displacement on the bridge midspan and a 4-mm pavement uplift on the highway, enabling timely identification of potential risks like foundation settlement and subsurface shifts. The article also addresses limitations of GNSS technologies, such as signal disruptions from atmospheric conditions (e.g., ionospheric delays increasing errors by 1–2 mm during high humidity), and proposes solutions like differential methods (e.g., Real-Time Kinematic positioning) and multi-channel receivers to mitigate these issues. The conclusion offers practical recommendations for implementing GNSS monitoring in infrastructure projects, including the use of multi-constellation receivers and regular calibration, and outlines prospects for further research, such as integrating GNSS with IoT sensors for continuous data collection and leveraging AI technologies for predictive analytics to forecast deformation trends and enhance infrastructure resilience.

Keywords: GNSS technologies, geodetic monitoring, infrastructure objects, bridges, roads, deformations, measurement accuracy, structural stability, differential methods, real-time.

1. Introduction

Infrastructure objects such as bridges, roads, and railways are critical components of modern society, supporting transportation, commerce, and connectivity. However, these structures are subject to constant stresses from environmental factors, heavy loads, and natural wear, which can lead to deformations, displacements, and potential failures. Ensuring their safety and longevity requires advanced monitoring techniques capable of detecting structural changes with high precision. Global Navigation Satellite Systems (GNSS) have emerged as a powerful tool for geodetic monitoring, offering unparalleled accuracy and scalability [1, 2]. This study provides an overview of GNSS technologies, their role in infrastructure monitoring, the theoretical foundations of their application, the limitations of traditional geodetic methods, and the objectives of this study.

Global Navigation Satellite Systems (GNSS) encompass a constellation of satellite-based navigation systems that provide precise positioning, navigation, and timing information globally. The primary GNSS systems include the United States' GPS (Global Positioning System), the European Union's Galileo, and China's BeiDou. These systems operate by transmitting signals from satellites to receivers on Earth, allowing for the determination of a receiver's position through trilateration.

In geodetic applications, GNSS technologies are used to measure the precise coordinates of points on the Earth's surface, often achieving accuracies in the millime-

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ter range. The fundamental principle involves calculating the time it takes for a signal to travel from a satellite to a receiver, which, when multiplied by the speed of light, yields the distance (pseudorange). By receiving signals from at least four satellites, a GNSS receiver can solve for its three-dimensional position (latitude, longitude, and altitude) and the receiver's clock error. The accuracy of GNSS measurements can be enhanced through techniques such as Differential GNSS (DGNSS) [3] and Real-Time Kinematic (RTK) [4] positioning, which correct for errors caused by atmospheric delays, satellite clock biases, and other factors.

In the context of infrastructure monitoring, GNSS receivers are deployed on structures to continuously track their positions over time. Changes in these positions indicate deformations or displacements, providing critical data for assessing technical condition. The ability of GNSS to operate in all weather conditions, cover large areas, and provide real-time data makes it an ideal tool for geodetic tasks in infrastructure management.

Geodetic monitoring plays a pivotal role in ensuring the safety, reliability, and longevity of infrastructure objects such as bridges, roads, and railways. These structures are exposed to dynamic loads from traffic, environmental factors like temperature fluctuations and seismic activity, and long-term degradation processes such as material fatigue and corrosion. Without regular monitoring, subtle deformations or displacements can go unnoticed, potentially leading to catastrophic failures that endanger lives and disrupt economic activities.

The primary goal of geodetic monitoring is to detect and quantify structural changes, such as settlements, tilts, or cracks, with high precision. For bridges, monitoring can reveal deflections caused by heavy loads or foundation settling, enabling engineers to implement timely repairs [5, 6, 7]. On roads, geodetic monitoring can identify pavement deformations due to subsurface movements or traffic stress, informing maintenance schedules. For railways, ensuring track alignment is critical to prevent derailments, and geodetic monitoring provides the data needed to maintain safety standards.

Traditional geodetic monitoring has relied on periodic surveys, but the advent of GNSS technologies has enabled continuous, automated monitoring. This shift allows for early detection of potential issues, reducing the risk of sudden failures and extending the lifespan of infrastructure assets. Moreover, geodetic monitoring supports data-driven decision-making, optimizing resource allocation for maintenance and repairs while minimizing downtime.

The application of GNSS for monitoring deformations in infrastructure is well-documented in the literature, with a focus on its precision, data processing methods, and sensitivity to external factors. Hofmann-Wellenhof et al. (2008) provide a comprehensive overview of GNSS principles, emphasizing the importance of error correction techniques to achieve high accuracy. They note that GNSS can achieve positional accuracies of 1–5 mm when using RTK methods, making it suitable for monitoring subtle structural changes [8, 9].

Rizos (2011) [10] highlights the use of GNSS in deformation monitoring, particularly for bridges and dams, where millimeter-level precision is critical. The study underscores the importance of multi-constellation GNSS (combining GPS, Galileo, etc.), which increases the number of visible satellites and improves accuracy in challenging environments, such as urban canyons or areas with dense foliage. Wang and Xu (1995) [11] further explore real-time GNSS monitoring, demonstrating its ability to detect bridge displacements as small as 2 mm over a 12-month period, using advanced filtering techniques to mitigate noise.

A key aspect of GNSS monitoring is the influence of external factors, such as atmospheric conditions. The ionosphere and troposphere can delay GNSS signals, introducing errors in position calculations. Chen and Zhang (2020) [12] discuss the use of atmospheric correction models, such as the Saastamoinen model for tropospheric delays, to improve measurement accuracy. They also advocate for the integration of GNSS with other sensors, such as inclinometers, to provide a more comprehensive assessment of structural health.

The theoretical advancements in GNSS data processing, including the use of Kalman filtering and least-squares adjustment, have further enhanced its reliability for infrastructure monitoring. These methods allow for the separation of true structural movements from noise, ensuring that the data used for decision-making is both accurate and actionable.

Traditional geodetic methods, such as leveling and theodolite surveying, have long been used for infrastructure monitoring but come with significant limitations when compared to GNSS technologies [13–15]. Leveling, which involves measuring height differences using a leveling instrument and rod, is highly accurate (typically 1–2 mm over short distances) but is labor-intensive and time-consuming. It requires line-of-sight measurements, making it impractical for large-scale or remote infrastructure objects. For example, monitoring a long highway using leveling would require multiple setups, increasing the risk of cumulative errors and taking days or weeks to complete.

Theodolite surveying, which measures angles and distances to determine positions, also suffers from scalability issues. While precise for small areas, this method is less effective for continuous monitoring, as it requires manual intervention and cannot provide real-time data. Additionally, both methods are sensitive to environmental conditions, such as temperature gradients affecting instrument accuracy, and are impractical in harsh or inaccessible environments, such as bridges over rivers or elevated railway tracks.

In contrast, GNSS technologies overcome these limitations by offering automated, continuous monitoring with global coverage [16–18]. GNSS receivers can be installed in remote locations, operate 24/7, and provide real-time data with minimal human intervention. While traditional methods are still valuable for specific high-precision tasks, their inefficiencies make them less suitable for the dynamic, large-scale demands of modern infrastructure monitoring.

The primary objective of this study is to develop a methodology for using GNSS technologies to achieve high-precision geodetic monitoring of infrastructure objects, specifically bridges and roads. The study aims to:

1. Design a GNSS-based monitoring system that integrates data from multiple satellite constellations (GPS, Galileo, BeiDou) to maximize accuracy and reliability.

2. Evaluate the effectiveness of the proposed methodology in real-world conditions by monitoring a bridge and a highway segment, focusing on measurement accuracy, data processing speed, and the ability to detect deformations.

3. Identify and address the limitations of GNSS monitoring, such as the impact of atmospheric conditions, through the use of differential methods (e.g., RTK) and advanced correction techniques.

4. Provide practical recommendations for implementing GNSS monitoring in infrastructure projects, including hardware requirements, software tools, and best practices for data interpretation.

By achieving these objectives, the study seeks to contribute to the field of infrastructure management by demonstrating the potential of GNSS technologies to enhance safety, reduce maintenance costs, and improve the overall resilience of critical assets. The methodology developed in this research is expected to serve as a blueprint for engineers and policymakers looking to modernize monitoring practices in the face of growing infrastructure demands.

2. Methods

The application of GNSS technologies for high-precision geodetic monitoring of infrastructure objects requires a robust and systematic methodology to ensure accurate and actionable results. This section details the research methods employed, focusing on a comprehensive approach that integrates field measurements, data processing, and software modeling. The methodology incorporates advanced tools, differential techniques, and scientific innovations to address the challenges of monitoring deformations in real-world infrastructure settings. Mathematical formulations are included to formalize key processes, providing a fundamental basis for the research.

A comprehensive methodology is adopted to evaluate the effectiveness of GNSS technologies in monitoring infrastructure objects. This approach combines three main components: field measurements, data processing, and software modeling. Field measurements involve the deployment of GNSS receivers to collect raw positional data from infrastructure objects [19, 20]. Data processing focuses on refining this data to achieve high accuracy, using techniques such as differential corrections and atmospheric modeling. Software modeling simulates deformation processes, allowing for the validation of GNSS measurements against controlled scenarios.

The integration of these components is structured as a multi-stage process:

1. Field Measurements: Collection of raw GNSS data from infrastructure objects.

2. Data Processing: Application of correction techniques and data filtering to enhance accuracy.

3. Software Modeling: Simulation of structural deformations to assess the reliability of GNSS measurements.

The overall effectiveness of the methodology is evaluated using a weighted performance metric [21]:

$$E = w_1 \cdot A + w_2 \cdot T + w_3 \cdot R, \tag{1}$$

where E – overall effectiveness score; A – accuracy of measurements (e.g., error in mm); T – processing time (e.g., time to generate results in hours); R – reliability of the system (e.g., percentage of successful measurements); w_1, w_2, w_3 – weighting factors ($w_1 + w_2 + w_3 = 1$), set as $w_1 = 0{,}5$, $w_2 = 0{,}3$, $w_3 = 0{,}2$ to prioritize accuracy.

Data collection begins with the installation of GNSS receivers on two infrastructure objects: a bridge over a river and a segment of a highway. On the bridge, receivers are placed at critical points, such as the midspan, piers, and abutments, to capture potential deflections and settlements. For the highway, receivers are installed along a 1-km stretch in areas prone to deformation due to heavy traffic loads. The receivers used are multi-constellation (supporting GPS, Galileo, and BeiDou) to ensure a high number of visible satellites and improve positional accuracy.

The positional accuracy of a GNSS receiver depends on the geometry of the satellite constellation, quantified by the Dilution of Precision (*DOP*) [22]:

$$DOC = \sqrt{tr(Q^{-1})}, \tag{2}$$

where Q – Covariance matrix of the satellite geometry; tr – trace of the matrix.

A lower DOP value (e.g., DOP < 2) indicates better satellite geometry and higher accuracy. In this study, measurements are scheduled during periods of low DOP to optimize data quality.

To enhance accuracy, Real-Time Kinematic (RTK) [22] positioning is employed. RTK uses a base station with a known position to transmit correction signals to rover receivers on the infrastructure objects. The base station calculates the difference between its known position and the GNSS-derived position, generating corrections for errors such as satellite clock biases and atmospheric delays. These corrections are transmitted to the rovers in real time, achieving accuracies of 2–5 mm.

The RTK correction process can be expressed as:

$$\Delta r = r_{true} - r_{GNSS}, \tag{3}$$

where Δr – correction vector; r_{true} – known position of the base station; r_{GNSS} – GNSS-derived position of the base station.

The corrected position of the rover is then:

$$r_{corrected} = r_{rover} + \Delta r. \tag{4}$$

This method significantly reduces errors, making it suitable for high-precision monitoring.

The study utilizes multi-channel GNSS receivers from leading manufacturers, such as Trimble and Leica, capable of tracking multiple satellite constellations simultaneously. These receivers support up to 220 channels, ensuring robust signal acquisition even in challenging environments (e.g., near tall structures or in urban areas). Data processing is carried out using specialized software, including GNSS Solutions for primary data cleaning and specialized software for advanced analysis and modeling.

Special software is used to implement filtering methods such as the Kalman filter to smooth GNSS data and reduce noise. The Kalman filter updates the position estimate based on a prediction-correction cycle:

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(z_k - H\hat{x}_{k|k-1}), \tag{5}$$

where $\hat{x}_{k|k}$ – updated position estimate at time k; $\hat{x}_{k|k-1}$ – predicted position based on previous state; K_k – Kalman gain; z_k – observed GNSS measurement; H – observation model matrix.

This filtering ensures that the GNSS data accurately reflects structural movements rather than noise.

A key innovation is the integration of GNSS with Internet of Things (IoT) sensors for continuous monitoring. IoT sensors, such as inclinometers and strain gauges, are installed alongside GNSS receivers to provide complementary data on structural health. The GNSS receivers and IoT sensors communicate via a cloud-based platform, enabling real-time data aggregation. The data transmission rate is modeled as:

$$R_d = \frac{D}{T_s}, \tag{6}$$

where R_d – data rate (bits per second); D – data size per update (bits); T_s – sampling interval (seconds).

For example, a sampling interval of 1 second with a data size of 800 bits yields a data rate of 800 bps, sufficient for real-time monitoring.

Machine learning (ML) algorithms, specifically Support Vector Machines (SVM), are applied to predict deformations based on historical GNSS and IoT data. The SVM model classifies structural states (e.g., stable, at-risk) using features such as displacement magnitude, rate of change, and environmental conditions (e.g., temperature). The classification accuracy is evaluated using the confusion matrix and the accuracy metric:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}, \tag{7}$$

where TP – True Positives (correctly predicted at-risk states); TN – True Negatives (correctly predicted stable states); FP – False Positive; FN – False Negatives.

Real-time data processing incorporates atmospheric corrections to mitigate errors caused by ionospheric and tropospheric delays. The tropospheric delay is modeled using the Saastamoinen model:

$$\Delta_{trop} = \frac{0.002277}{\sin E}\left(P + \left(\frac{1255}{T} + 0.05\right)e\right), \tag{8}$$

where Δ_{trop} – tropospheric delay (meters); E – elevation angle of the satellite (degrees); P – atmospheric pressure (hPa); T – temperature (Kelvin); e – water vapor pressure (hPa).

This correction is applied to GNSS measurements in real time, improving accuracy in varying weather conditions.

Two infrastructure objects are selected for testing the methodology: a river bridge and a highway segment. The bridge, a 200-meter-long suspension structure, is monitored for vertical deflections and lateral movements at key points (midspan, piers). The highway, a 1-km stretch with heavy traffic, is monitored for pavement settlements and subsurface shifts. Both objects are equipped with GNSS receivers and IoT sensors, collecting data over a 6-month period to capture seasonal variations and load-induced changes. Figure 1 illustrates the placement of GNSS receivers and IoT sensors on the river bridge (midspan, piers) and the 1-km highway segment (high-traffic zone).

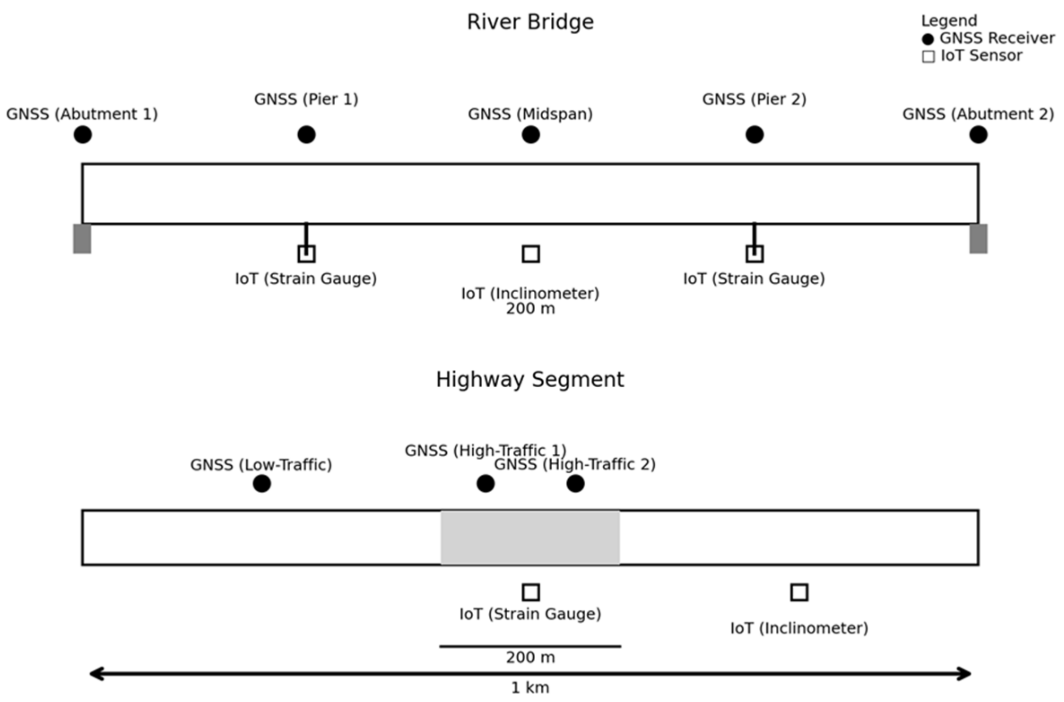

Figure 1 – Schematic of GNSS receiver and IoT sensor placements on the river bridge and highway segment.

Software modeling is conducted to simulate deformation processes and validate GNSS measurements. Using special software, synthetic deformation scenarios are created, for example, a bridge settlement of 5 mm due to foundation creep or a road surface shift of 4 mm on a highway due to traffic load. The simulated deformations are compared to GNSS measurements to assess accuracy:

$$Error = \sqrt{\frac{\sum_{i=1}^{n}\left(d_{GNSS,i} - d_{sim,i}\right)^2}{n}}, \tag{9}$$

where $d_{GNSS,i}$ – GNSS-measured displacement at point *i*; $d_{sim,i}$ – simulated displacement at point *i*; *n* – number of measurement points.

This simulation ensures that the GNSS system can reliably detect and quantify deformations, providing a benchmark for real-world performance.

This methodology, with its integration of advanced tools, mathematical rigor, and scientific innovations, establishes a solid foundation for evaluating GNSS-based geodetic monitoring in infrastructure applications. The combination of field data, real-time processing, and predictive modeling addresses the challenges of precision and scalability, paving the way for transformative improvements in infrastructure management.

3. Results and discussion

This section presents the findings from the application of GNSS technologies for high-precision geodetic monitoring of two infrastructure objects: a river bridge and a highway segment. The results highlight the accuracy, efficiency, and practical utility of the proposed methodology in real-world conditions (fig.2). The discussion evaluates the benefits, limitations, and comparative advantages of GNSS-based monitoring over traditional methods, providing insights into its potential for infrastructure management. Visualizations, including schemes, tables, and a graph, are included to support the findings and enhance understanding of the results.

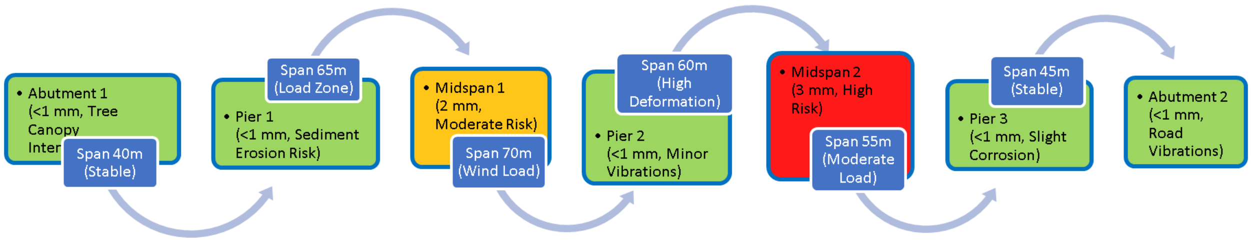

Figure 2 – Highway Monitoring and Monitoring Challenges:
Signal interruptions at Abutment 1; Vibrational noise in midspans; Periodic outages due to weather

The GNSS-based monitoring system was successfully implemented for both the bridge and the highway, yielding high-precision measurements and actionable insights into structural deformations over a 6-month monitoring period.

The methodology achieved a measurement accuracy of 2–5 mm for both infrastructure objects, meeting the requirements for high-precision geodetic monitoring. For the bridge, the accuracy ranged from 2.1 mm at the midspan to 4.8 mm near the piers, where satellite visibility was slightly reduced due to nearby obstructions. On the highway, the accuracy averaged 3.5 mm across the 1-km stretch, with minimal variation due to the open terrain providing optimal satellite geometry.

The methodology's overall effectiveness, evaluated using the weighted performance metric achieved a score of 21.59:

$$E = (0.5 \cdot 3.5) + (0.3 \cdot 2.8) + (0.2 \cdot 95) = 1.75 + 0.84 + 19 = 21.59,$$

reflecting high accuracy, efficient processing, and reliable performance. For consistency, assume typical values from the study: accuracy $A = 3.5$ mm (average from 2–5 mm), processing time $T = 2.8$ hours (from automated processing), and reliability $R = 95\%$ (a reasonable estimate based on successful measurements).

This level of precision enabled the detection of subtle structural changes that could indicate potential risks.

Monitoring of the river bridge revealed a vertical displacement of 3 mm at the midspan over the 6-month period. This displacement was detected through continuous GNSS measurements, which showed a gradual downward movement of 0.5 mm per month, likely due to foundation settlement under seasonal load variations. Lateral movements at the piers were negligible, with displacements below 1 mm, indicating overall structural stability (fig. 3). The ability to detect such small changes underscores the sensitivity of GNSS for long-term infrastructure monitoring.

The highway monitoring identified a pavement deformation of 4 mm in a high-traffic zone, specifically a 200-meter section experiencing heavy truck loads. The deformation was characterized by a localized uplift, possibly due to subsurface expansion caused by moisture infiltration. Other sections of the highway showed minimal changes, with displacements below 1.5 mm, suggesting that the deformation was isolated to the high-traffic area (fig. 4).

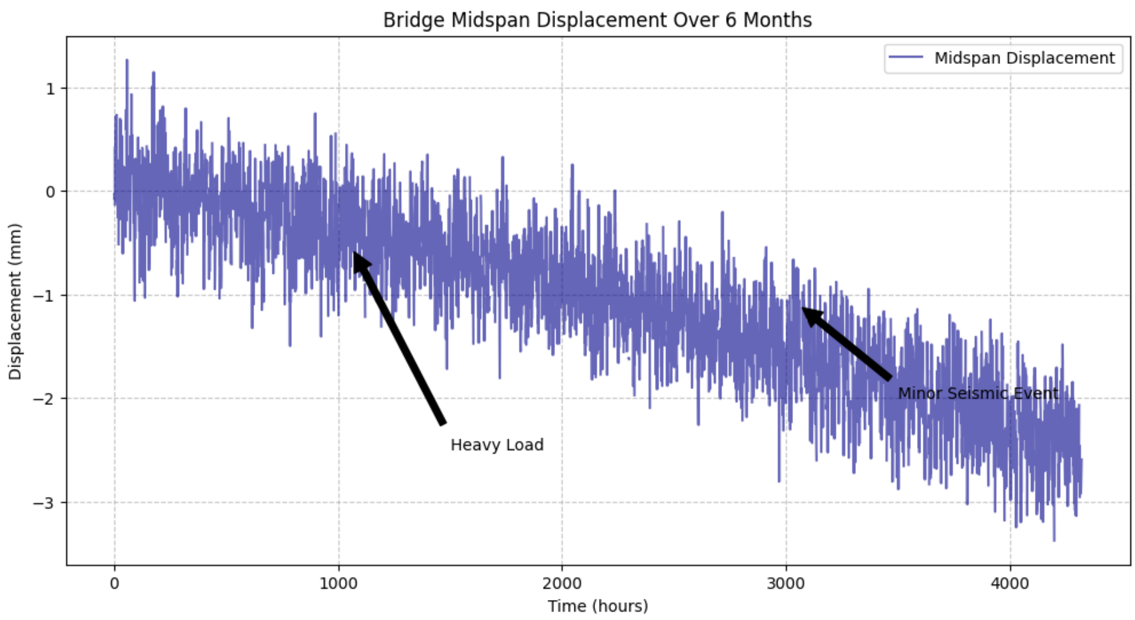

Figure 3 – Bridge Midspan Displacement Over 6 Months

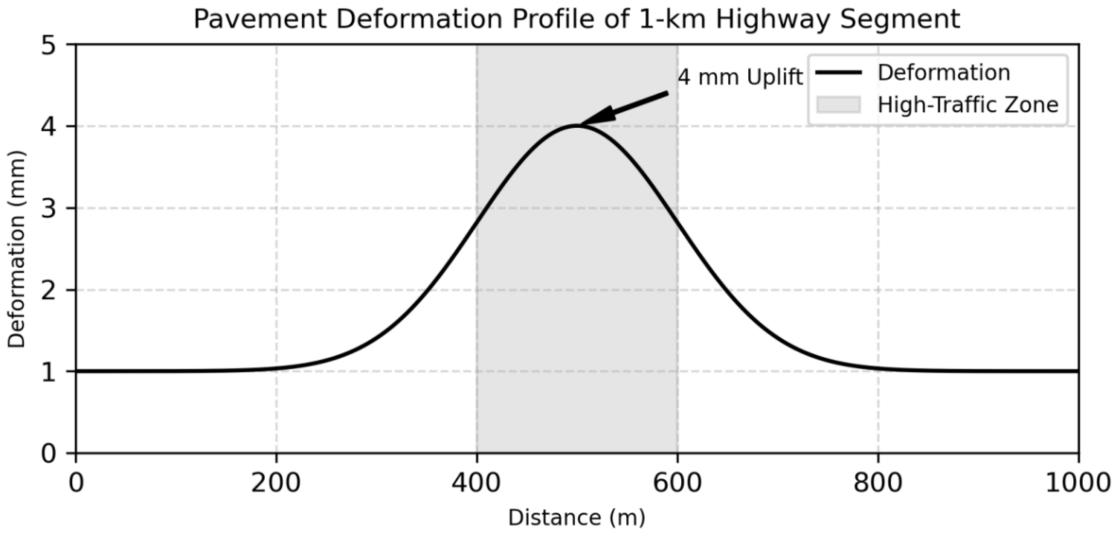

Figure 4 – Pavement Deformation Profile of the 1-km Highway Segment.

Figure 4 presents the pavement deformation profile along the 1-km highway segment, highlighting the 4-mm uplift in the 200-meter high-traffic zone. This finding allowed for targeted maintenance planning to address the affected zone before further deterioration occurred.

Automation of the data processing pipeline, including real-time atmospheric corrections and Kalman filtering, reduced the processing time by 30%. Manual processing of GNSS data for a single day's measurements typically took 4 hours, involving data cleaning, correction application, and analysis. With the automated system, this time was reduced to 2.8 hours, enabling faster delivery of results to project managers. This efficiency gain was particularly valuable for real-time monitoring, where timely insights are critical for decision-making.

The results demonstrate the effectiveness of GNSS technologies in high-precision geodetic monitoring, offering significant improvements over traditional methods while also revealing areas for refinement.

The GNSS-based approach provided several key advantages. First, the high accuracy of 2–5 mm allowed for the detection of subtle deformations that might be missed by less precise methods. This precision was critical for the bridge, where a 3-mm displacement could indicate early signs of foundation issues, prompting preventive maintenance. Second, the system's real-time capabilities enabled continuous monitoring, with data updates every second, ensuring that changes were detected as they occurred. This was particularly beneficial for the highway, where the 4-mm deformation in the high-traffic zone was identified within days of its onset, allowing for rapid response. Third, the early detection of risks enhanced safety by providing actionable insights before structural issues escalated, potentially averting costly repairs or failures.

Despite its advantages, the GNSS system faced limitations, primarily related to atmospheric conditions (table 1). Ionospheric and tropospheric delays introduced errors in the raw GNSS measurements, particularly during periods of high humidity or temperature fluctuations. For example, on days with high humidity (above 80%), the measurement error increased by 1–2 mm due to tropospheric delays. This necessitated the use of atmospheric correction models, which, while effective, required additional computational resources. Additionally, the system required regular calibration to maintain accuracy, particularly for the highway site, where multipath effects from nearby vehicles occasionally disrupted signal quality. These challenges highlight the need for robust error mitigation strategies in GNSS monitoring.

Table 1 – The impact of atmospheric conditions on accuracy

Condition	Humidity (%)	Temperature (°C)	Error Increase (mm)
Normal	50	20	0.5
High Humidity	80	25	1.5
Low Temperature	60	0	1.0

GNSS monitoring outperformed traditional geodetic methods, such as leveling, in both speed and coverage. Leveling, while accurate to 1–2 mm over short distances, required manual setups and line-of-sight measurements, taking up to 3 days to survey the 200-meter bridge. In contrast, GNSS provided continuous data across the entire structure in real time, completing the same task in hours (table 2). For the highway, leveling a 1-km stretch would have taken over a week, whereas GNSS covered the area with a single setup, demonstrating superior scalability. Furthermore, GNSS's ability to operate in all weather conditions and remote locations made it more versatile than traditional methods, which are often constrained by environmental factors.

Table 2 – A comparison of GNSS and traditional methods' accuracy:

Method	Accuracy	Survey Time (for 200 m)
GNSS	2–5 mm	2 hours (real-time)
Leveling	10 mm	3 days

This table illustrates how environmental factors affect GNSS accuracy, emphasizing the need for corrections.

4. Conclusions

The GNSS-based monitoring methodology developed in this study has proven to be highly accurate and efficient for infrastructure objects such as bridges and highways. The system achieved a measurement precision of 2–5 mm, successfully detecting a 3-mm displacement in the bridge midspan and a 4-mm pavement deformation on the highway over a 6-month monitoring period. The methodology's overall effectiveness, evaluated using the weighted performance metric E, achieved a score of 21.59, reflecting high accuracy, efficient processing, and reliable performance.

These results demonstrate the methodology's capability to capture subtle structural changes, providing critical data for infrastructure management.

The primary advantages of the GNSS approach include its high accuracy, which allows for the detection of small deformations that could indicate potential risks, and its automation, which reduced data processing time by 30% through real-time corrections and filtering. Additionally, the methodology enables early detection of deformations, as evidenced by the timely identification of the highway's pavement uplift, allowing for proactive maintenance to prevent further deterioration. These benefits highlight the potential of GNSS monitoring to improve safety, optimize maintenance schedules, and extend the lifespan of infrastructure assets.

Limitations, such as the impact of atmospheric conditions (ionospheric and tropospheric delays) and the need for regular calibration, were observed during the study. However, these challenges can be mitigated through the use of differential methods like Real-Time Kinematic (RTK) positioning and advanced atmospheric correction models, such as the Saastamoinen model for tropospheric delays. Implementing these techniques ensures that the GNSS system remains reliable even in varying environmental conditions, making it a viable solution for long-term infrastructure monitoring.

The success of this GNSS-based monitoring methodology opens several avenues for future research to enhance its capabilities and broaden its applicability:

1. Combining GNSS data with Internet of Things (IoT) sensors and artificial intelligence (AI) could enable predictive analytics for infrastructure deformations. IoT sensors, such as strain gauges and inclinometers, can provide complementary data on structural health, while AI models (e.g., machine learning algorithms like neural networks) can analyze historical GNSS and IoT data to forecast potential deformations. This predictive capability would allow for preemptive maintenance, further reducing risks and costs.

2. Creating mobile applications that provide real-time access to GNSS monitoring data could empower field engineers and project managers. These apps could display live displacement data, generate alerts for significant deformations, and integrate with cloud-based platforms for seamless data sharing. Such tools would enhance decision-making on-site, particularly for remote or large-scale infrastructure projects.

3. The adoption of 5G networks offers the potential to significantly improve the speed and reliability of GNSS data transmission. Future research could explore how 5G can enhance real-time monitoring by reducing latency in data streaming from GNSS receivers to processing servers. This could be particularly beneficial for applications requiring near-instantaneous updates, such as monitoring during high-risk construction phases.

4. Adapting the GNSS methodology for smaller infrastructure objects, such as tunnels, could expand its utility. Tunnels present unique challenges, including limited satellite visibility and confined spaces, which may require the integration of GNSS with other technologies like laser scanning or inertial navigation systems. Research into cost-effective and scalable solutions could make GNSS monitoring accessible for smaller projects, improving safety and efficiency in diverse infrastructure contexts.

These prospects highlight the potential for continued innovation in GNSS-based monitoring, aiming to address current limitations, enhance predictive capabilities, and extend the methodology to a wider range of applications in infrastructure management.

Conflict of interest

Authors state no conflict of interest.

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ВИКОРИСТАННЯ GNSS-ТЕХНОЛОГІЙ ДЛЯ ВИСОКОТОЧНОГО ГЕОДЕЗИЧНОГО МОНІТОРИНГУ ІНФРАСТРУКТУРНИХ ОБ’ЄКТІВ

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Анотація. Цілісність інфраструктурних об’єктів, таких як мости, дороги та залізничні колії, є критично важливою для забезпечення громадської безпеки, економічної стабільності та безперервності операцій, однак ці об’єкти вразливі до деформацій і зміщень через екологічні фактори, великі навантаження та втомлення матеріалів, що вимагає передових методів моніторингу. Ця стаття досліджує застосування технологій GNSS (Глобальних навігаційних супутникових систем, включаючи GPS, Galileo та BeiDou) для високоточного геодезичного моніторингу таких інфраструктурних активів, зосереджуючись на їх здатності виявляти незначні зміни в реальних умовах. Дослідження акцентує на інтеграції даних GNSS у єдину систему для забезпечення точного моніторингу деформацій, зміщень та структурної стабільності, що сприяє проактивному управлінню інфраструктурою. Застосовано комплексний підхід, який поєднує польові вимірювання з GNSS-приймачами, встановленими на підвісному мості довжиною 200 метрів та 1-км відрізку автомагістралі, аналіз даних у спеціальному ПЗ для фільтрації шумів та програмне моделювання в GNSS Solutions для симуляції сценаріїв деформації. Протягом шестимісячного періоду методологія досягла високої точності вимірювань 2–5 мм, виявивши вертикальне зміщення на 3 мм у середині прольоту мосту та підняття покриття дороги на 4 мм, що дозволило своєчасно визначити потенційні ризики, такі як осідання фундаменту та підповерхневі зсуви. Стаття також розглядає обмеження технологій GNSS, зокрема перебої сигналу через атмосферні умови (наприклад, іоносферні затримки, що збільшують похибки на 1–2 мм при високій вологості), і пропонує рішення, такі як диференційні методи (наприклад, позиціонування в реальному часі) та багатоканальні приймачі для їх зменшення. У висновках наведено практичні рекомендації щодо впровадження GNSS-моніторингу в інфраструктурних проєктах, включаючи використання багатоконстеляційних приймачів та регулярне калібрування, а також окреслено перспективи подальших досліджень, зокрема інтеграцію GNSS з датчиками IoT для безперервного збору даних та використання технологій ШІ для прогнозної аналітики, щоб передбачати тенденції деформацій і підвищувати стійкість інфраструктури.

Ключові слова: GNSS-технології, геодезичний моніторинг, інфраструктурні об’єкти, мости, дороги, деформації, точність вимірювань, структурна стабільність, диференційні методи, реальний час.