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Transformasi Digital Teknik Sipil: Sintesis Penginderaan Jauh, GIS, dan BIM dalam Pengambilan Keputusan

Digital Transformation in Civil Engineering: A Synthesis of Remote Sensing, GIS and BIM for Enhanced Decision-Making

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Abstrak: Perkembangan teknologi digital saat ini membawa perubahan besar dalam cara kerja dunia teknik sipil, terutama dalam hal pengambilan keputusan berbasis data. Artikel ini mengulas bagaimana penginderaan jauh, Sistem Informasi Geografis (SIG), dan Building Information Modeling (BIM) dapat bekerja sama untuk mempermudah pengelolaan proyek infrastruktur. Selama ini, data sering kali terpisah-pisah, sehingga sulit untuk melihat gambaran besar dari sebuah proyek. Artikel ini mencoba mengisi celah tersebut dengan mengeksplorasi cara menggabungkan data dari berbagai sensor ke dalam satu sistem kerja yang terintegrasi. Kami membandingkan beberapa teknologi, seperti satelit InSAR untuk melihat pergeseran tanah di area yang luas, hingga penggunaan drone (UAV) LiDAR untuk memodelkan bangunan. Selain itu, artikel ini juga membahas kecerdasan buatan (AI) dalam mempercepat pengolahan data mentah menjadi informasi yang siap digunakan oleh para insinyur. Penulis juga menekankan bahwa teknologi ini memiliki batasan, sehingga data lapangan tetap diperlukan sebagai pembanding. Kesimpulannya, efisiensi di masa depan bukan lagi tentang penggunaan media yang canggih, melainkan tentang bagaimana menghubungkan penginderaan jauh, SIG, dan BIM agar manajemen infrastruktur menjadi lebih cepat, lebih akurat, dan lebih terencana.

Keywords: *AI, BIM, GIS, Infrastructure*

Abstract: *The rapid evolution of digital technologies is fundamentally reshaping the landscape of civil engineering, shifting the industry toward data-driven paradigms. This study provides a critical-thinking synthesis of how remote sensing, Geographic Information System (GIS), and Building Information Modeling (BIM) converge to facilitate enhanced decision-making throughout the infrastructure lifecycle. While traditional methods often suffer from data fragmentation and localized perspectives, this review identifies a significant research gap in the seamless integration of multi-scale spatial data into automated engineering workflows. Through an application-driven framework, this paper evaluates the comparative performance of various sensing platforms, ranging from InSAR-based satellite monitoring for regional deformation to UAV-borne LiDAR for high-precision as-built modeling. Furthermore, it examines the pivotal role of Artificial Intelligence (AI) in bridging the gap between raw data acquisition and actionable intelligence. By critically discussing technical limitations, such as data uncertainty and the “black-box” nature of automated processing, the study highlights the need for a hybrid approach that combines the efficiency of remote sensing with rigorous ground-truthing. The findings underscore that the future of civil engineering lies not in standalone technologies, but in a unified digital ecosystem where GIS serves as the spatial backbone and BIM as the micro-scale digital twin, together enabling more resilient and proactive infrastructure management.*

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1. INTRODUCTION

Civil engineering projects are fundamentally dependent on the acquisition of high-fidelity, accurate, and timely data regarding a variety of environmental and physical parameters, including terrain conditions, subsurface characteristics, fluctuating environmental factors, and long-term infrastructure performance (Sestras et al., 2025)(Hrůza et al., 2018). The successful execution of these projects often hinges on anticipating geotechnical risks and environmental constraints before construction begins, as unforeseen site conditions are a primary driver of budget overruns. Historically, the industry has relied heavily on traditional field-based surveys and manual geotechnical investigations, which, while providing highly reliable site-specific data, are frequently characterized as being extremely time-consuming, prohibitively costly, and fundamentally spatially limited (Kaffa et al., 2021). These conventional methods typically produce “point-based” datasets that require significant interpolation, potentially overlooking critical geological anomalies or structural defects located between survey points, As modern infrastructure systems become increasingly complex and geographically extensive-spanning hundreds of kilometers in the case of linear assets like railways, highways, and pipelines, there is a critical and growing demand for innovative technologies that can provide comprehensive, continuous spatial coverage with minimal operational disruption to the surrounding environment or existing traffic flow (Vries, 2021).

In response to these logistical and economic challenges, remote sensing has emerged as a transformative discipline, referring specifically to the acquisition of detailed information about Earth’s surface and man-made structures without requiring direct physical contact, typically through the use of sophisticated sensors mounted on satellites, manned aircraft, or Unmanned Aerial Vehicles (UAVs) (Shanmugapriya et al., 2019). Remote sensing is essential in construction management by providing valuable information and insight throughout the project cycle (Almohsen, 2024). Over the past two decades, this technology has moved from a specialized research niche to a widespread, accepted standard in civil engineering practice, a transition fueled by rapid improvements in spatial resolution, temporal revisit frequency, and the general accessibility of raw data products. Unlike early iterations of the technology, which were primarily used for visual mapping and simple site visualization, modern remote sensing applications now extend deeply into rigorous quantitative analysis and automated decision support (Borah et al., 2024). Civil engineering application also integrated with several sensors, forging a trajectory toward intelligent and sustainable civil infrastructure, augmenting functionality across all aspects (Kantsepolsky & Aviv, 2024). This evolution enables engineers to perform complex tasks, such as measuring millimeter-scale structural deformations from space using radar interferometry, generating centimeter-level 3D digital twins via drone-based photogrammetry, and monitoring construction progress across vast sites in real time using high-frequency temporal datasets.

Accuracy remains a key issue for civil engineers. Rusgiyarto et al (2025) used a Digital Elevation Model (DEM) to estimate the most efficient route for the toll road and found that the DEM SRTM accuracy of 30 m was not sufficient to be the basemap for the toll road planning (Rusgiyarto, Kaffa, Hadi, Iqbal, & Putra, 2025)(Preety et al., 2022). The lack of high-resolution and up-to-date Digital Elevation Models (DEMs) remains a critical bottleneck in modern civil engineering applications, particularly during the preliminary design and hydrologic modeling phases (Bounab & Kharim, 2022). Hamunzala et al (2024) also used DEM for assessing bridges in Cambodia and found that this data is sufficient, as DEM only has a spatial resolution of 30m, which is unable to detect bridges with a length under 30 m (Hamunzala et al., 2024). In another study, Hruza et al (2018) found that close-range photogrammetry and geodetic measurement are sufficient for the monitoring of the asphalt wearing course of the forest road (Hrůza et al., 2018). Gegliardi et al (2023) found that satellite remote sensing techniques such as the multi-temporal interferometric Synthetic Aperture Radar (MT-InSAR) method are effective in monitoring ground displacement of transport infrastructure (roads, railways, and airfields) with a much higher temporal frequency of investigation and the capability to cover wider areas (Gagliardi et al., 2023). Feng et al (2023) did ‘building change detection’ (BCD) using a remote sensing method and found that it was a useful method (Feng et al., 2023). Most of them have good accuracy but are expensive to acquire.

Thus, the literature review provides a brief, systematic examination of the multifaceted role that remote sensing currently plays in the civil engineering industry, summarizing its major application areas, diverse sensor technologies, complex analytical approaches, and evolving integration frameworks. By synthesizing existing knowledge, the review explores how data from optical, radar, and laser sensors are processed and subsequently fused with other digital environments, such as Geographic Information Systems (GIS), Building Information Modeling (BIM), and Artificial Intelligence (AI), to enhance project outcomes and structural longevity. Beyond providing a current snapshot of the state of the art, the review also identifies critical research gaps, such as the ongoing need for more robust data validation protocols and standardized processing workflows across diverse engineering environments. Furthermore, it highlights emerging trends, particularly the integration of artificial intelligence and deep learning for automated defect detection, that are poised to define the next generation of civil engineering practice and shape future developments in the field.

2. METHOD

The literature review was conducted using journal articles published between 2008 and 2026. Major academic databases, including Google Scholar, ScienceDirect, SpringerLink, IEEE Xplore, and MDPI, were used to retrieve relevant studies. Search keywords included applications of remote sensing in the civil engineering field, Building Information Modeling (BIM), civil engineering sensors, and remote sensing-based civil engineering planning. We collected about 80 journals, most published within the last five years. We also considered the journals published before 2016 (the last 10 years), as some references, especially those discussing the core definition of remote sensing tools, are more than 10 years old. The article's year of publication and distribution are shown in the graph below,

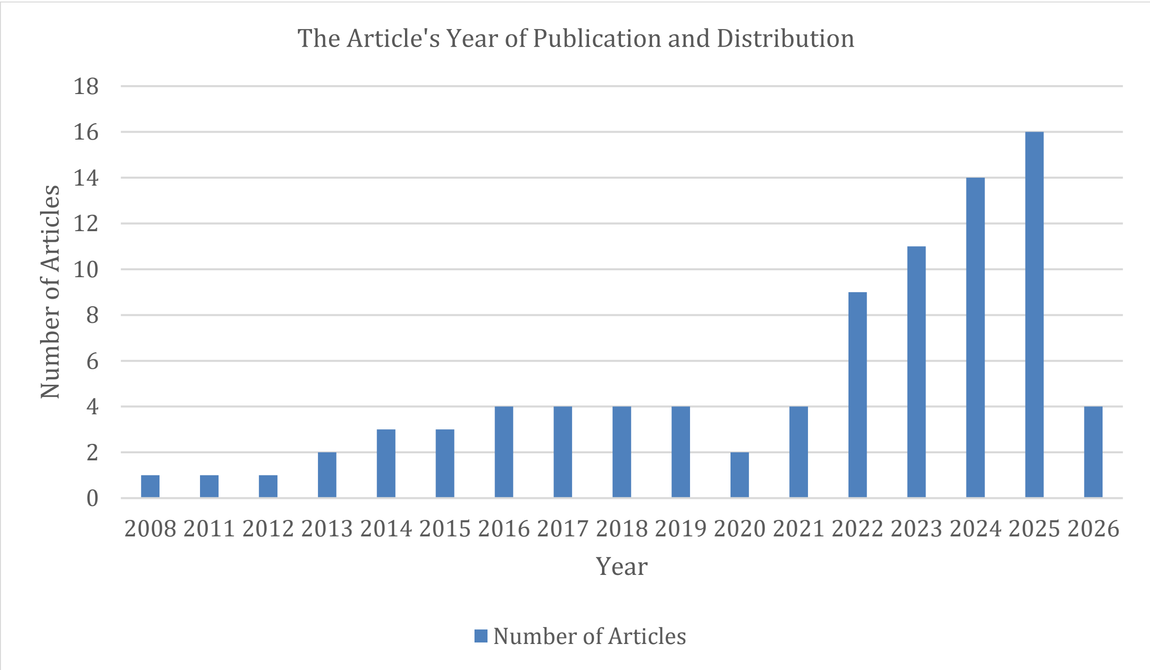

Figure 1. The Article's Year of Publication and Distribution

Articles were selected based on relevance to civil engineering applications, clarity of methodology, and contribution to technological or methodological advancement. The selected literature was categorized thematically to facilitate synthesis and comparative analysis. We found out that at least eighty-seven references discussed the application of remote sensing in the civil engineering field with the topic distribution as follows

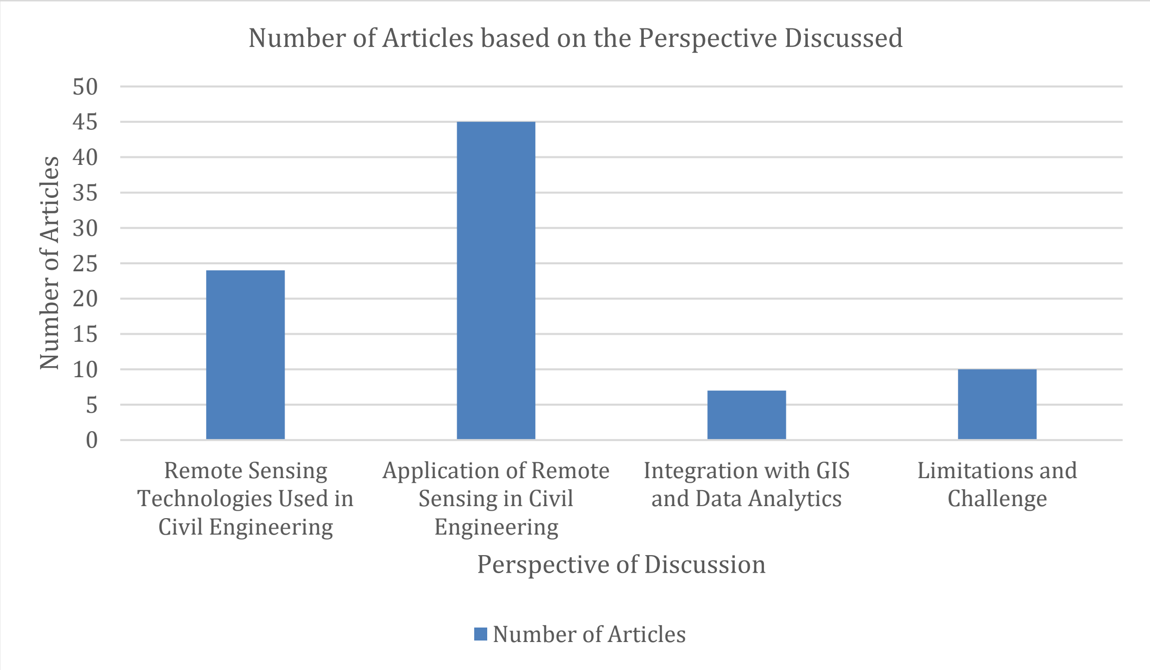

Figure 2. Number of Articles based on the Perspective Discussed

Most of the selected articles discussed the application of remote sensing in the civil engineering field, and the second-most-discussed article was about the remote sensing technologies used in civil engineering. This happens because, in the second part, we found many articles discussing more specific fields that vary in every aspect of their applications.

3. DISCUSSION

This literature review discussed the topic from four perspectives: remote sensing technologies used in civil engineering, the application of remote sensing in civil engineering, integration with GIS and data analytics, and limitations and challenges.

3.1 Remote Sensing Technologies Used in Civil Engineering

We defined three remote sensing tools commonly used by civil engineers: satellite-based remote sensing, UAV-based remote sensing, and LiDAR and active sensors. We found at least eight references for each category to support and demonstrate the use of a specific tool in the civil engineering field.

3.1.1 Satellite-Based Remote Sensing

Satellite remote sensing has redefined the scale at which civil engineering projects are managed, offering unparalleled spatial coverage and vast, long-term temporal datasets that are essential for regional-scale infrastructure planning and feasibility studies. By providing a macro-view of the Earth's surface, these platforms allow engineers to conduct comprehensive land use mapping and monitor the pace of urban expansion with high accuracy, while also facilitating environmental impact assessment that accounts for regional drainage (Kaffa et al., 2023) and habitat changes (Zlinszky et al., 2015). While optical satellite imagery relies on reflected solar radiation to distinguish surface features, it is often limited by atmospheric conditions such as cloud cover and poor lighting. In contrast, radar-based systems, specifically Synthetic Aperture Radar (SAR), represent a significant advancement because they utilize active microwave sensors that emit their own energy pulses. This active sensing capability ensures consistent data acquisition under all-weather conditions, including heavy rain and complete darkness, which is vital for the continuous monitoring of high-risk engineering assets where data gaps could lead to catastrophic failures (Y. Wang et al., 2020).

The application of Interferometric SAR (InSAR) techniques has further revolutionized the precision of remote monitoring, enabling the detection of subtle ground deformations with millimeter-scale accuracy (Gong et al., 2016). By processing the phase difference between multiple radar acquisitions taken from the same orbital position at different times, InSAR can map surface displacement associated with high-impact engineering activities such as tunneling, large-scale mining operations, and intensive groundwater extraction (Bianchini et al., 2019). These radar-based measurements are particularly critical for safeguarding large infrastructure projects, such as dams and high-rise developments, during their construction and operational phases. Unlike traditional ground-based monitoring systems, such as total stations or leveling pins, which provide discrete point-based data and are often physically inaccessible in rugged or hazardous terrain, InSAR provides a continuous displacement map across the entire project area. This comprehensive “area-based” surveillance allows engineers to identify localized settlement trends and early warning signs of structural instability that would otherwise remain undetected by localized sensors.

Despite these capabilities, satellite-based monitoring is constrained by several fundamental boundaries that necessitate a cautious approach in engineering applications. A primary limitation is the trade-off between spatial coverage and temporal resolution (Almohsen, 2024). While satellites can monitor entire cities, the “revisit time” or frequency of data acquisition may not be sufficient for projects requiring real-time oversight, such as active excavation or rapid slope failure events. Furthermore, satellite sensors, both optical and radar, primarily capture near-surface characteristics, leaving a significant data void regarding subsurface geotechnical properties and internal structural integrity. The phenomena of “shadowing” and “layover” also pose significant challenges in urban canyons and steep mountainous terrain, where vertical structures or topography can obstruct radar signals, resulting in distorted or missing data in critical zones (W. Zhao et al., 2026). Additionally, while InSAR offers millimeter-scale precision, its accuracy depends heavily on the presence of coherent reflectors and atmospheric stability (Ding et al., 2008). These limitations underscore the fact that satellite remote sensing cannot serve as a total replacement for traditional methods; rather, it must be integrated with ground-truthing and in-situ sensors to ensure the legal and technical validity of the data within a professional engineering framework.

3.1.2 UAV-Based Remote Sensing

Unmanned Aerial Vehicles (UAVs) have become increasingly adopted in civil engineering applications due to their operational flexibility, ability to capture ultra-high spatial resolution data, and relatively low deployment costs compared to traditional aerial surveys (Wijayanti et al., 2023). Through UAV-based photogrammetry, detailed digital elevation models (DEMs), high-quality orthophotos, and dense three-dimensional point clouds can be generated with centimeter-level accuracy, which are essential for construction planning, earthwork volume calculation, progress monitoring, and the inspection of structural and infrastructure components such as roads, bridges, and embankments (Outay et al., 2025). The rapid data acquisition capability of UAVs also enables frequent updates of site conditions, supporting dynamic decision-making during construction phases.

Compared to satellite-based remote sensing, UAV platforms provide significantly higher spatial resolution and greater control over flight timing, altitude, and sensor configuration, allowing engineers to tailor data collection to specific project requirements. This flexibility is especially beneficial for site-specific investigations, where detailed surface characteristics and localized changes must be captured accurately, as well as for short-term monitoring tasks, including deformation detection and post-disaster assessment (Wijayanti et al., 2023). Consequently, UAV-based remote sensing has emerged as a highly effective complement to conventional surveying techniques and satellite observations in modern civil engineering practices.

Despite these advantages, integrating UAVs into engineering workflows is constrained by several critical limitations. Operationally, UAVs are highly sensitive to environmental factors, such as high wind speeds, precipitation, and poor lightning conditions, which can severely degrade data quality or prevent deployment altogether, creating significant reliability issues for time-sensitive projects (Mohsan et al., 2022). Technically, while UAVs offer centimeter-level precision, this accuracy is not inherent; it depends on the rigorous implementation of Ground Control Points (GCPs) and high-quality GNSS-PPK/RTK systems (Štroner et al., 2021)(K. Zhang et al., 2022). Without such measures, internal model distortions can lead to catastrophic errors in earthwork calculation and structural assessment. Furthermore, UAVs face the “big data” bottleneck, where the massive volume of high-resolution imagery and dense point clouds requires substantial computational power and specialized expertise for processing, often resulting in delays in generating actionable insights (Fan & Cao, 2026). Lastly, strict aviation regulations and “no-fly zones” in urban or sensitive industrial areas often limit their geographical applicability (Lozano Tafur et al., 2025). These factors necessitate a hybrid approach, ensuring that UAV data is always validated against traditional geodetic benchmarks to maintain the high safety standards in civil engineering.

3.1.3 LiDAR and Active Sensors

Light Detection and Ranging (LiDAR) systems provide highly accurate three-dimensional representations of terrain surfaces and built structures by emitting laser pulses and measuring the time of their return, generating dense spatial point clouds (Killinger, 2014). Both airborne and terrestrial LiDAR platforms have been widely used in civil engineering for high-precision topographic mapping, slope stability assessment, and continuous monitoring of infrastructure deformation, including embankments, bridges, and retaining structures. The ability of LiDAR to capture fine-scale elevation variations enables engineers to identify subtle surface changes that may indicate early-stage geotechnical instability (Khan, 2024) or structural deterioration (Kaartinen et al., 2022), thereby supporting proactive maintenance and risk mitigation strategies.

LiDAR data are particularly advantageous in densely vegetated landscapes and complex urban environments (Caynes et al., 2016), where conventional photogrammetric techniques often struggle due to occlusions and limited ground visibility. The ability of laser pulses to partially penetrate vegetation enables more accurate extraction of the ground surface, improving terrain modeling in forested or mountainous regions. In urban settings, high-density LiDAR point clouds facilitated detailed mapping of buildings, road networks, and infrastructure components, making the technology highly valuable for urban planning, construction monitoring, and resilience assessment (Zou et al., 2025). Consequently, LiDAR has become an essential remote sensing tool for capturing complex surface conditions in modern civil engineering projects.

Despite its superior precision, LiDAR deployment in civil engineering is constrained by significant economic and computational constraints. The high cost of equipment and specialized sensor integration remain major barriers to smaller-scale projects, often making it less cost-effective than photogrammetry for simple topographic tasks (Liang et al., 2023). Technically, while LiDAR is celebrated for its ability to “see through” vegetation, this penetration is only partial; in extremely dense tropical canopies or multi-layered undergrowth, the number of pulses reaching the ground may be insufficient to generate a reliable Digital Terrain Model (DTM), leading to potential errors in hydraulic or geostatistical modeling (Fradette et al., 2019). Furthermore, the sheer density of LiDAR point clouds, often containing billions of points, poses a ‘data management crisis’ that requires high-performance computing (HPC) infrastructure and sophisticated filtering algorithms to remove non-ground noise, such as vehicles or temporary structures (S. Zhang et al., 2025). This complexity necessitates highly skilled personnel to ensure that the final engineering deliverables are free from processing artifacts. Consequently, LiDAR should be viewed as a high-fidelity specialty tool that requires careful strategic planning to justify its operational overhead.

3.2. Applications of Remote Sensing in Civil Engineering

We found at least 45 articles discussing the application of remote sensing in civil engineering. All the articles collected were published in the last 10 years to ensure the reference novelty. We categorized the application of civil engineering into 5 most favorable fields: site investigation and land preparation; geotechnical and subsurface assessment; infrastructure monitoring and maintenance; hydrology and water research; and disaster risk management. The reference distribution was then modeled in the graph below

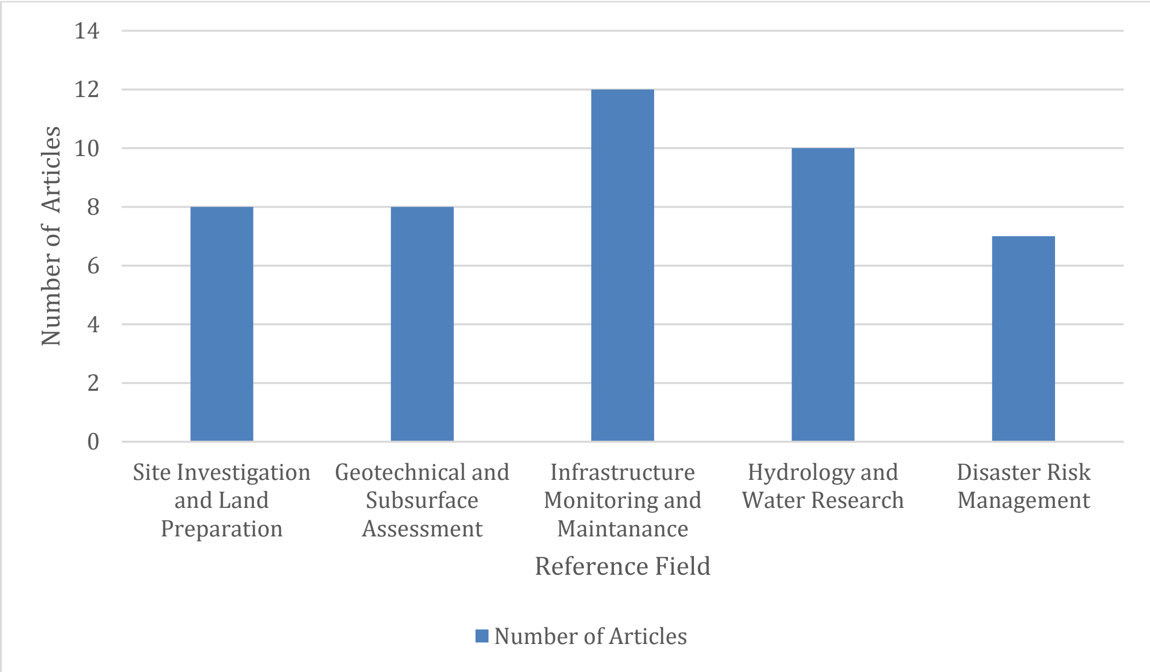

Figure 3. Reference Distribution for Remote Sensing Application in the Civil Engineering Field

We found that most references discussed the application of remote sensing in infrastructure monitoring and maintenance, followed by hydrology and water research. It shows that most civil engineers use remote sensing for infrastructure monitoring and maintenance, including the application of Building Information Modeling (BIM) and similar tools, which can support engineers in comprehensive decision-making. Hydrology and water research was the second most favorable because remote sensing could model water distribution over large areas, such as paddy fields. Disaster risk management was the least favorable topic for a civil engineer, as it may be relevant to other fields of engineering, such as geotechnical or geomatics engineering.

3.2.1 Site Investigation and Land Preparation

Remote sensing plays a crucial role in preliminary site assessment by providing spatially continuous information on terrain characteristics such as topography, surface roughness, drainage networks, and land cover conditions (Kaffa et al., 2023) (Kaffa et al., 2024). These surface parameters are fundamental for understanding site morphology and hydrological behavior, which directly influence soil stability, erosion potential, and construction feasibility. High-resolution digital elevation models (DEMs) generated from LiDAR surveys or UAV-based photogrammetry enable detailed slope analysis, watershed delineation, and the early detection of potential geohazards such as landslide-prone zones and areas susceptible to surface runoff accumulation, allowing engineers to prioritize field investigations more efficiently (Schlögel et al., 2017).

In addition to contemporary surface characterization, satellite remote sensing has been widely used to analyze historical land-use and land-cover changes that may affect subsurface conditions and long-term site performance (Tian et al., 2014). Temporal imagery provides insight into previous agricultural activities, urban expansion, deforestation, or waterlogging, all of which can alter soil compaction, moisture content, and bearing capacity (Nakhili et al., 2024). By integrating historical satellite data with current terrain models, civil engineers can better evaluate construction suitability, anticipate geotechnical challenges, and develop more informed site preparation strategies prior to detailed geotechnical testing and design.

Despite its utility, remote sensing in site assessment is constrained by its inability to directly provide data on subsurface geotechnical properties (Orfanos et al., 2025). While surface morphology can hint at underlying conditions, sensors cannot measure soil stratification, shear strength, or groundwater table depth, which are primary drivers of foundation design (Delaney et al., 2025). Consequently, a “surface only” assessment risks overlooking deep-seated geological anomalies or contaminated soil layers that are not visible from above. Furthermore, the lack of standardized protocols for integrating remote sensing-derived data into traditional geotechnical reports often leads to a “data trust gap” between geologists and design engineers (Khalilidermani et al., 2025). Therefore, remote sensing should be framed as a high-level reconnaissance tool meant to optimize, rather than replace, physical site investigation. Its primary value lies in its ability to pinpoint high-risk areas, thereby reducing the number of required boreholes while ensuring those drilled are placed in the most critical locations.

3.2.2 Geotechnical and Subsurface Assessment

Although remote sensing technologies cannot directly replace conventional in situ geotechnical testing methods such as borehole sampling, standard penetration tests, or cone penetration tests, they provide valuable complementary information by revealing the surface expression of subsurface conditions. Surface deformation monitoring techniques, particularly Interferometric Synthetic Aperture Radar (InSAR), enable the detection of subtle ground settlement and vertical displacement over large areas with high temporal resolution (H. Wang et al., 2022). Such deformation patterns are often associated with weak or compressible soil layers, groundwater withdrawal, or underground construction activities, enabling engineers to identify potential geotechnical risk zones prior to detailed field investigations (Radutu et al., 2017).

In addition to deformation analysis, thermal and multispectral remote sensing imagery have been increasingly explored for characterizing soil moisture distribution and surface heterogeneity (Periasamy & Shanmugam, 2017), which are closely linked to subsurface material properties. Variations in surface temperature and spectral reflectance can indicate differences in moisture content, compaction, and material composition, all of which influence bearing capacity and ground stability. These insights are particularly valuable for foundation design and earthworks planning, as they support the identification of problematic soil zones and help optimize the placement of ground investigation points (Hassan-esfahani et al., 2015).

However, the transition from remote sensing observations to geotechnical design parameters remains bounded by significant interpretive uncertainties (Ramirez et al., 2020). While surface thermal and spectral signatures can suggest moisture variations, they are highly sensitive to surface conditions such as vegetation density, atmospheric humidity, and recent weather events, which can mask the true characteristics of the underlying soil (D. Zhang & Zhou, 2016). Without rigorous calibration against physical samples, remote sensing-derived moisture maps remain qualitative and cannot be used for precise calculations of pore water pressure or effective stress in slope stability analysis (Yao et al., 2025). Furthermore, the correlation between surface deformation and subsurface soil compressibility is often non-linear and site-specific, requiring complex constitutive modeling to be geotechnically meaningful. These limitations highlight a critical boundary: remote sensing serves as an advanced predictive indicator that must be systematically validated by in situ testing (Pause et al., 2016). In the context of engineering liability, remote sensing data should be utilized to refine the conceptual site model, ensuring that traditional geotechnical resources are focused on the most heterogeneous and high-risk soil units identified during the digital reconnaissance (Ijaz et al., 2025).

3.2.3 Infrastructure Monitoring and Maintenance

The application of remote sensing has become an indispensable framework for the continuous monitoring of the structural health and operational performance of critical civil infrastructure, including extensive road networks (Rusgiyarto, Kaffa, Hadi, Iqbal, & Lutfian, 2025), complex bridge systems (Casas et al., 2024), large-scale dams, and vulnerable geotechnical embankments (Scaioni et al., 2018). The integration of Unmanned Aerial Vehicles (UAVs) into standard inspection protocols has specifically revolutionized the ability to conduct rapid, high-resolution assessments of structural defects, such as fatigue cracks, spalling, and surface deterioration. These aerial platforms provide a significant logistical advantage by enabling the close-range acquisition of visual and thermal data without the need for costly traffic closures or the total suspension of facility operations, which are often required during traditional manual inspections (Tan et al., 2022). By generating precise 3D reconstructions and Ortho mosaics, UAV-based inspections facilitate a detailed digital audit of an asset's external condition, enabling engineers to identify localized distress signals that might be missed during periodic ground-based walk-throughs.

Complementing these site-specific aerial surveys, the use of multi-year time-series satellite data enables comprehensive, long-term monitoring of infrastructure deformation across vast, often inaccessible geographical areas. By leveraging dense archives of satellite imagery and radar data, engineers can track subtle geomechanical shifts and settlement patterns over several years, providing a vital historical baseline of structural behavior essential for robust maintenance planning (Suh et al., 2024). This longitudinal perspective is a cornerstone of modern early warning systems, as it enables the identification of accelerating deformation rates or anomalous displacement trends that may signal impending instability in large assets such as dams or high embankments (Marchamalo-Sacristán et al., 2023). Such data-driven insights facilitate a transition from reactive, "break-and-fix" repair strategies to proactive, predictive asset management, ensuring that maintenance interventions are strategically timed to extend the service life of the infrastructure and minimize the risk of catastrophic failure (X. Chen et al., 2026).

However, the efficacy of remote sensing in structural health monitoring is constrained by its inability to directly assess internal structural integrity (Yang et al., 2024). While UAVs and satellites excel at capturing surface expression of distress, such as exterior cracking or settlement, they cannot penetrate concrete or soil to evaluate reinforcement corrosion, internal voids, or changes in pore water pressure within an embankment (Pan et al., 2024). This creates a 'diagnostic boundary' in which remote sensing data must be interpreted as a proxy rather than a direct measure of structural capacity. Furthermore, the transition toward proactive asset management is often hindered by the 'latency boundary'; the time required to process massive datasets from UAV flights or satellite passes can delay the issuance of early warnings during rapid-onset failure events (Meng et al., 2025). Additionally, the lack of a standardized 'damage threshold' for remote sensing-derived measurements remains a challenge, as a millimeter-scale shift detected by InSAR may not always correlate to a loss of structural safety without context from calibrated structural models (Guzman-Acevedo et al., 2023). Therefore, for critical assets such as dams and bridges, remote sensing must serve as a complementary layer within a broader sensor fusion framework, integrated with internal piezometers, strain gauges, and finite element modeling to ensure a comprehensive and legally defensible safety assessment (Sivasuriyan et al., 2026)(Ghahremani et al., 2022).

3.2.4 Hydrology and Water Resources Engineering

The integration of remote sensing into water-related civil engineering projects has fundamentally transformed the management of hydrological systems by providing a continuous spatial perspective that traditional point-based gauges cannot achieve. This technology is extensively utilized to estimate regional rainfall patterns by analyzing cloud properties and atmospheric moisture through satellite-derived precipitation products (Dashti et al., 2023). Such data is critical for monitoring surface water extent and assessing flood hazards in real-time, particularly in ungauged basins where ground data is sparse or non-existent (Huang, 2018) (Al-omari et al., 2024). Furthermore, remote sensing is instrumental in evaluating complex watershed characteristics, such as drainage density, slope, and land-use patterns, which are derived from high-resolution Digital Elevation Models (Shaikh & Birajdar, 2015). By combining these datasets, engineers can generate sophisticated flood risk assessments and optimize reservoir management strategies, enabling more precise predictions of inflows and outflows during extreme weather events. The ability to visualize and quantify water movement across vast landscapes ensures that hydraulic structures are designed with a comprehensive understanding of the environmental variables that influence their long-term safety and efficiency.

Beyond inland hydrology, remote sensing provides a robust framework for monitoring the dynamic interactions between water bodies and coastal or riverine environments. This includes the quantitative monitoring of sediment transport, where multispectral sensors analyze changes in water reflectance to estimate turbidity levels and sediment plumes that could impact the operational capacity of dams and irrigation canals (Espinoza et al., 2013). Along coastal zones, the technology is essential for tracking shoreline changes over decadal scales, allowing engineers to calculate rates of erosion or accretion and identify vulnerable stretches of land (Tsiakos & Chalkias, 2023). This longitudinal data is particularly valuable for evaluating the stability and performance of coastal infrastructure, such as breakwaters, jetties, and sea walls, which are subject to constant wave action and rising sea levels (Yong et al., 2018). By utilizing high-resolution imagery and radar data, civil engineers can detect subtle shifts in these protective structures and implement timely maintenance before structural integrity is compromised. This transition from periodic manual surveys to continuous remote monitoring ensures a more resilient approach to managing water resources and protecting vital infrastructure from the erosive forces of nature.

Despite these advancements, the application of remote sensing in hydrology is bound by significant uncertainties in data precision and volumetric estimation (Benli et al., 2025). While satellite-based precipitation products offer wide coverage, they often struggle with ‘bias errors’ and may miss localized, high-intensity convective rainfall events that are critical for urban drainage design. Furthermore, remote sensing primarily observes ‘surface expression’ of water; it cannot directly measure water depth or bathymetry in turbid or deep river systems without specialized green-laser LiDAR (J. Zhao et al., 2017). This creates a volumetric boundary where engineers must still rely on cross-sectional field measurements to convert surface extent into actual discharge volumes. Additionally, multispectral sediment monitoring is highly sensitive to variations in mineral composition and biological factors such as chlorophyll, which can lead to misinterpretations of turbidity if not rigorously calibrated against physical water samples (Zeng & Binding, 2019). These limitations underscore that, in hydraulic engineering, remote sensing should be viewed as a tool for spatial scaling, providing context and extent for water movement, while precise hydraulic modeling still requires integrating high-fidelity ground-based gauges and bathymetric surveys to ensure the structural safety of water-retaining assets.

3.2.5 Disaster Risk Management

The role of remote sensing in disaster management has evolved into a cornerstone of modern civil engineering, providing an essential framework for the three critical stages of disaster preparedness, response, and recovery. The primary technical strength of this technology lies in its use of “change detection” workflows, in which high-resolution pre-event baseline imagery is systematically compared with post-event imagery to facilitate rapid, objective damage assessments. In the immediate aftermath of catastrophic events such as regional flooding (Munawar et al., 2022), or sudden landslides (Scaioni et al., 2014). These comparative datasets allow engineering teams to pinpoint the exact extent of structural failures and terrain instability that might be hazardous or inaccessible via ground surveys. By using a multi-sensor approach that combines optical imagery for visual confirmation with radar sensors that can penetrate cloud cover, authorities can maintain a continuous flow of intelligence during the most volatile stages of a disaster, ensuring that emergency response efforts are directed to the most vulnerable locations with unprecedented speed and precision.

Beyond the immediate crisis response, remote sensing provides the quantitative evidence base required for long-term recovery and the rehabilitation of critical infrastructure following high-magnitude earthquakes (Dong & Shan, 2013), and various coastal hazards (Eckert et al., 2012). In seismic zones, satellite and aerial platforms enable the identification of large-scale structural deformations and the blockage of vital transportation corridors, which is crucial for orchestrating large-scale rescue and clearing operations. In coastal regions, the technology maps the long-term impacts of storm surges and erosion on sea walls and jetties, providing the data needed to design more resilient protective structures for the future. These wide-area monitoring capabilities support high-level decision-making by providing a holistic view of the disaster’s impact at the regional level, rather than relying on fragmented local reports. This transition from manual site inspections to digital, remote sensing-driven assessment ensures that infrastructure rehabilitation is grounded in comprehensive spatial data, ultimately enhancing the resilience of the built environment against future environmental threats.

However, the efficacy of remote sensing in disaster management is strictly bound by the time-criticality gap and the limitations of automated interpretation (Paolanti et al., 2024). While satellite constellations offer vast coverage, the interval between a disaster event and the next available orbital pass can create a data blackout during the first few golden hours of emergency response. Furthermore, while change detection algorithms can identify surface-level rubble or flooding, they often struggle with false positives caused by shadows, seasonal vegetation changes, or temporary debris, leading to misallocated rescue resources (Jiang et al., 2025). There is also significant damage to the boundary. Remote sensing indicates that a structure has been impacted, but cannot assess whether the remaining load-bearing elements are safe for re-entry or whether a bridge deck has suffered internal shear failure (Casas et al., 2024). These constraints underscore that in disaster contexts, remote sensing should not be viewed as a standalone solution for safety certification. Instead, it must be integrated with rapid on-ground structural triage and real-time UAV deployments to verify satellite-derived findings, ensuring that the engineering response is both spatially comprehensive and structurally validated.

3.3. Integration with GIS and Data Analytics

The integration of remote sensing data with Geographic Information Systems (GIS) has fundamentally enhanced the capacity for sophisticated spatial analysis and multidimensional visualization within modern civil engineering frameworks. GIS served as the central analytical environment, where raw imagery and sensor data were transformed into actionable engineering intelligence by overlaying diverse datasets in a unified coordinate system. These platforms enable seamless integration of high-resolution remote sensing outputs with critical ground-based information, including geotechnical borehole logs, complex hydrological models, and socio-economic demographic data (Goodchild, 2011). This synthesis is particularly vital for supporting multi-criteria decision analysis (MCDA), a process where multiple environmental, technical, and economic variables are weighted and compared to optimize site selection for large-scale infrastructure, such as dams and reservoirs, or to determine the most cost-effective and least-impactful routes for new highway and rail corridors (Kaffa et al., 2021). By centralizing these disparate data types, GIS-based platforms provide a holistic “spatial twin” of the project environment, enabling engineers and stakeholders to visualize potential environmental impacts and structural interactions in high-fidelity 3D space, far exceeding the capabilities of traditional 2D paper-based blueprints.

Building upon this integrated spatial framework, recent academic and industrial studies have increasingly incorporated advanced machine learning and artificial intelligence (AI) techniques to manage and interpret the massive volume of “Big Data” generated by modern remote sensing sensors (Y. Chen et al., 2023). These automated approaches are revolutionizing standard workflows for feature extraction, damage detection, and complex pattern recognition, which were previously dependent on labor-intensive, subjective manual interpretation. AI-driven algorithms, such as convolutional neural networks (CNNs), can now automatically identify building footprints, sprawling road networks, and specific land-use changes from high-resolution aerial and satellite imagery with unprecedented speed and consistency (Li et al., 2024). In the specific context of structural health monitoring, these techniques enable the automated recognition of structural anomalies – such as concrete spalling on bridge piers or subtle pavement distress patterns- by training deep learning models on vast libraries of standardized defect images (Yang et al., 2024). This shift toward computational automation not only significantly improves the efficiency of large-scale infrastructure audits but also enhances the objective accuracy of the results by eliminating human fatigue and the inconsistencies of manual visual inspections. As these AI frameworks become more sophisticated, they are expected to usher in a new era of real-time predictive analytics, enabling civil engineers to detect pattern shifts that signal the early stages of structural failure long before they become visible to the naked eye.

However, the transition toward a fully automated digital twin environment is constrained by significant challenges in data interoperability and the inherent black-box nature of AI. While GIS provides a powerful platform for data synthesis, the lack of standardized data formats between remote sensing providers and engineering software often leads to integration silos, where critical spatial information is lost or distorted during translation. Furthermore, although AI-driven automation significantly reduces human labor, deep learning models remain highly dependent on the quality and diversity of the training datasets (Fotovvatikhah et al., 2025). A model trained on standardized bridge defects may fail to recognize unique structural anomalies in different climatic or material contexts, leading to algorithmic bias or missed detection. This creates a critical boundary where AI cannot yet function as an autonomous decision maker in civil engineering (Sun et al., 2023). Instead, these computational tools must be framed as augmented intelligence that requires expert engineering oversight to validate automated findings. The ultimate goal is not to replace the engineer's judgment, but to provide a synthesized, GIS-based analytical framework that allows for more informed, objective, and feasible professional decisions.

3.4. Limitations and Challenges

Despite the transformative advantages of these technologies, remote sensing in civil engineering continues to face several fundamental limitations that require careful methodological consideration. These constraints often begin with data availability, where the acquisition of high-quality imagery may be hindered by orbital revisit cycles or restrictive commercial licensing. Furthermore, atmospheric effects, such as scattering and signal absorption by water vapor and aerosols, can significantly degrade the quality of optical and radar signals, introducing radiometric noise into the final engineering datasets. Beyond these environmental factors, sensor-specific limitations such as the "shadowing" effect in SAR data caused by steep terrain or "layover" in urban canyons can obscure critical infrastructure features. Perhaps most significantly for civil engineers, the technology is characterized by an indirect nature of subsurface interpretation. Unlike physical excavation or borehole drilling, remote sensing primarily captures surface or near-surface characteristics, requiring engineers to infer underlying soil layers, geological bedding, and groundwater conditions solely from surface indicators.

This transition to higher-resolution data acquisition, while beneficial for engineering precision, introduces secondary challenges related to specialized expertise and the consumption of significant computational resources. Processing dense LiDAR point clouds or multi-temporal InSAR datasets requires high-performance computing (HPC) environments and advanced software architectures that are not always accessible to every engineering firm (Ghaedi et al., 2021). Furthermore, the ultimate reliability and legal defensibility of remote sensing-based analysis depend heavily on rigorous validation through ground-based measurements. This "ground-truthing" process, which involves comparing digital sensor outputs with physical data from total stations, piezometers, or high-precision GNSS sensors, remains an essential component of the professional engineering workflow (Kaffa et al., 2024). This inherent reliance underscores the importance of integrated, hybrid approaches, where remote sensing does not replace traditional surveying but rather serves as a powerful enhancement. By fusing the broad spatial coverage of remote sensors with the high-fidelity, localized accuracy of ground-based measurements, civil engineers can create a more resilient and validated data framework for the design, construction, and long-term monitoring of the built environment. To better illustrate the trade-offs between spatial coverage, accuracy, engineering applicability, and operational constraints, **Table 1** provides a comparative summary of the principal remote sensing technologies currently employed in civil engineering practice.

Table 1. The Technology Application and Boundaries

Technology	Spatial Coverage	Typical Accuracy	Primary Engineering Application	Key Technical/ Operational Boundary
Satellite (InSAR)	Regional/Global	Milimeter (Deformation)	Subsidence monitoring, regional planning, and dam stability	Limited by satellite revisit times, signal decorrelation in high vegetation areas
UAV (Photogrammetry)	Site-specific	Centimeter (X, Y, and Z)	Earthwork volume, progress photos, and bridge surface inspection.	Highly dependent on Ground Control Points (GCPs); sensitive to wind/weather.
LiDAR (Airborne/TLS)	Local/Corridor	Sub centimeter	DTM generation in forested areas; high fidelity as-built BIM	High equipment cost; massive data processing/computational overhead
Multispectral/ Thermal	Regional/Local	N/A (Spectral)	Soil moisture mapping, identifying subsurface drainage leaks	High sensitivity to atmospheric interference; requires rigorous physical calibration.

4. CONCLUSION

This integration of remote sensing technologies into civil engineering has evolved from a supplementary surveying tool into an indispensable framework for data-driven decision-making. This synthesis confirms that while platforms such as InSAR, UAVs, and LiDAR offer unprecedented spatial coverage and precision, their effectiveness is fundamentally constrained by operational constraints, including signal decorrelation and atmospheric interference, as well as high computational overhead and the need for rigorous ground truthing. Therefore, these technologies should be viewed as high-level reconnaissance and monitoring tools that optimize, rather than replace, traditional in situ geotechnical and structural investigations.

The primary contribution of this study highlights that the future of the industry lies in the seamless convergence of multi-scale data. By leveraging GIS as a spatial backbone to integrate macro-scale satellite imagery with micro-scale BIM digital twins, engineers can eliminate information silos that have traditionally hindered project efficiency. Furthermore, the emergence of AI and machine learning offers a pathway to address the big data bottleneck, provided these tools are framed as augmented intelligence under expert engineering oversight to ensure safety and professional liability. Ultimately, a successful digital transformation in civil engineering requires a hybrid approach: leveraging the speed and scale of remote sensing while maintaining the technical rigor of conventional engineering practices to build a more resilient, proactive infrastructure ecosystem.

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