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Advancements in Remote Sensing and GIS for Post-Earthquake Structural Damage Assessment

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ABSTRACT

Earthquakes are destructive natural hazards that cause widespread structural damage, loss of life, and disruption to infrastructure. Rapid assessment of structural damage is essential for emergency response and rehabilitation. Traditional methods rely on field inspections, which are time-consuming and subjective. The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has revolutionized post-earthquake assessments, offering large-scale, real-time data through satellite imagery and UAV systems. Advanced machine learning models enhance damage detection, while multisource data fusion improves assessment reliability. Despite challenges, the future of earthquake damage evaluation lies in scalable, intelligent systems combining AI, RS, and GIS for real-time response.

Keywords: *Earthquakes, Remote Sensing, GIS, Damage Assessment, Machine Learning*

I. INTRODUCTION

Earthquakes are among the most destructive natural hazards, often resulting in extensive structural damage, loss of human life, and severe disruption to infrastructure systems. The rapid assessment of structural damage immediately after an earthquake is critical for effective emergency response, rescue operations, and post-disaster rehabilitation planning. Traditional methods of damage assessment primarily rely on field inspections and manual surveys conducted by engineers and disaster management teams. Although these approaches are widely accepted and standardized, they are often time-consuming, labor-intensive, and limited in terms of spatial coverage. Moreover, subjective interpretation during manual evaluation can lead to inconsistencies in damage classification, which may delay critical decision-making during emergency situations (Aydin et al., 2026). In this context, the integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has emerged as a transformative approach for improving post-earthquake structural damage assessment. Remote sensing technologies, including satellite imagery, aerial photography, and Synthetic Aperture Radar (SAR), provide large-scale, real-time, and cost-effective data acquisition capabilities. These technologies enable the monitoring of affected regions without direct physical access, which is particularly useful in hazardous or inaccessible disaster zones. GIS, on the other hand, facilitates spatial data management, visualization, and analysis, allowing researchers and disaster management authorities to integrate multiple datasets for comprehensive damage evaluation and decision support (Almohsen, 2024). Recent advancements in high-resolution remote sensing imagery and UAV (Unmanned Aerial Vehicle) systems have significantly enhanced the accuracy of structural damage detection. Very-high-resolution (VHR) optical images and SAR data allow for detailed observation of building-level damage patterns, including roof collapse, structural deformation, and debris distribution. However, challenges such as spectral variability, geometric distortion, and incomplete image data continue to limit the reliability of automated interpretation systems. To address these issues, advanced image processing techniques and artificial intelligence (AI)-based models have been increasingly integrated with RS and GIS frameworks to improve classification accuracy and predictive performance (Wen et al., 2021; Gu et al., 2024). Machine learning and deep learning algorithms have particularly transformed the field of post-disaster damage assessment. These approaches enable automated feature extraction and classification from large datasets, reducing the dependency on manual interpretation. Techniques such as convolutional neural networks (CNNs), random forests, and support vector machines have demonstrated high accuracy in identifying damaged structures from satellite and UAV imagery. Despite these advancements, limitations remain in terms of model generalization across different geographical regions and disaster scenarios. Additionally, the need for large labeled datasets poses a significant challenge in training robust AI models for earthquake damage detection (Al Shafian & Hu, 2024). Another critical development in this domain is the use of multisource data fusion, which integrates optical imagery, SAR data, LiDAR datasets, and ground-based sensor information. This fusion approach enhances the reliability of damage assessment by combining complementary data sources. For instance, optical imagery provides visual information about surface-level damage, while SAR data offers structural insights even under cloud cover or night-time conditions. GIS platforms play a vital role in integrating these datasets, enabling spatial correlation and multi-layered analysis of affected regions (Yan & Xie, 2026).

Furthermore, recent research highlights the importance of real-time disaster response systems supported by edge computing and cloud-based GIS platforms. These systems enable rapid processing of large volumes of remote sensing data, facilitating near real-time damage mapping and emergency response coordination. The integration of IoT-based sensors and smart monitoring systems further enhances situational awareness during post-earthquake scenarios. However, issues related to computational efficiency, energy consumption, and system scalability still need to be addressed for large-scale implementation (López-Castro et al., 2022). In addition to technological advancements, several studies emphasize the importance of integrating Building Information Modeling (BIM) with GIS for improved disaster management. BIM provides detailed structural information about buildings, while GIS offers spatial context, making their integration highly effective for damage assessment, risk analysis, and reconstruction planning. Despite its advantages, BIM–GIS integration faces challenges related to interoperability, data standardization, and system compatibility, which limit its widespread adoption in disaster management practices (Cao et al., 2023). The evolution of remote sensing applications in construction and disaster management has also been supported by advancements in UAV technology and satellite-based monitoring systems. UAVs provide high-resolution, flexible, and rapid data acquisition capabilities, making them particularly useful for post-earthquake reconnaissance. Satellite-based systems, on the other hand, offer large-scale coverage and frequent revisit times, enabling continuous monitoring of disaster-affected regions. However, issues such as shadow effects, temporal resolution limitations, and environmental interference still affect data accuracy (Almohsen, 2024). Despite significant progress, the integration of RS and GIS for structural damage assessment still faces several challenges. These include limitations in data fusion techniques, lack of standardized evaluation frameworks, and difficulties in real-time processing of heterogeneous datasets. Moreover, the variability of earthquake damage patterns across different regions further complicates the development of universal assessment models. As a result, there is a growing need for adaptive, scalable, and intelligent systems capable of handling complex post-disaster environments (Aydin et al., 2026). Future research is increasingly focusing on the development of hybrid frameworks that combine AI, remote sensing, and GIS technologies to improve accuracy and efficiency in structural damage assessment. The incorporation of transfer learning, multi-hazard modeling, and cloud-based processing systems is expected to enhance the robustness of predictive models. Additionally, advancements in edge computing and real-time data analytics will play a crucial role in enabling faster and more reliable disaster response systems (Yan & Xie, 2026).

II. RESEARCH BACKGROUND

Aydin et al. (2026) examined post-earthquake rapid structural damage assessment (RSDA) as a critical area for ensuring safety and effective disaster response. They noted that manual inspection methods, though standardized, were often time-consuming, resource-intensive, and prone to variability due to human judgment. Consequently, they observed that artificial intelligence (AI)-based approaches had gained considerable attention as potential solutions to these limitations. The authors highlighted that the proliferation of diverse methodologies across multiple application scales complicated understanding of the state-of-the-art. While previous reviews addressed various aspects of RSDA, they indicated that a systematic synthesis comparing component-level damage studies with holistic structural approaches was lacking. Aydin et al. conducted a scoping review, analyzing studies from Scopus, Web of Science, and EBSCO published between 2015 and 2025, categorizing them according to structure and damage types, dataset characteristics, model development, learning and labelling techniques, and validation methods. They reported a progression from basic classification tasks toward fine-grained quantitative damage segmentation, but identified gaps between rapid detection and structural performance evaluation, emphasizing future research on model robustness, interoperability, and adaptability to post-earthquake scenarios.

Yan and Xie (2026) examined the critical challenges posed by earthquakes, noting their sudden onset and destructive potential for human lives and property. They highlighted that rapid and accurate assessment of building damage and prediction of trapped populations were essential for effective emergency response and post-disaster reconstruction. Their review summarized recent advancements in post-earthquake building damage detection and human entrapment evaluation using multisource remote sensing data. The study emphasized core technical issues, such as cross-modal registration of optical and Synthetic Aperture Radar (SAR) imagery, fine-grained building damage identification, and dynamic models for assessing trapped populations. It was reported that the integration of edge computing with star-space-ground collaborative observation systems substantially enhanced the timeliness of emergency responses. Furthermore, they suggested that future research should focus on approaches like small-sample transfer learning and multi-hazard coupled assessment models to improve predictive accuracy and resilience in post-disaster scenarios.

Vanian et al. (2025) examined the challenges posed by the aging European building stock and highlighted the need for holistic renovation strategies, particularly emphasizing Vertical Forest (VF) systems as sustainable alternatives to demolition and reconstruction. They reviewed existing literature and conducted preliminary studies involving empirical multiparametric system evaluations, Monte Carlo simulations, and System-Theoretic Process Analysis (STPA) to assess combined structural, non-structural, vegetation, and human comfort components in reinforced concrete (RC) buildings integrated with VF. Key damage indicators, such as interstory drift ratio, residual deformation, concrete and reinforcement strains/stresses, and energy dissipation, were identified and their relevance to VF structures was evaluated. The study reported that green modifications exhibited higher risk profiles than conventional RC buildings, particularly concerning moisture management and structural integrity. Vanian et al. also emphasized the potential of AI-driven vegetation monitoring systems, achieving detection accuracies between 80% and 99%, and concluded that successful VF renovation depended on specialized design codes, integrated monitoring, standardized maintenance, and enhanced control systems.

Al Shafian and Hu (2024) conducted a comprehensive bibliometric review to examine methodologies for post-disaster building damage assessment and reconnaissance, emphasizing the integration of advanced data collection technologies and computational techniques. They aimed to evaluate the current landscape of methodologies, highlight technological advancements, and identify key trends and gaps in the literature. Using a structured approach, they analyzed 370 journal articles from the Scopus database spanning 2014 to 2024, with particular focus on developments in remote sensing, including satellite and UAV technologies, and the employment of machine learning and deep learning for damage detection and analysis. Their findings indicated significant progress in data collection and analysis techniques, underscoring the importance of machine learning and remote sensing in improving disaster damage assessments. They also identified areas requiring further research, such as data fusion, real-time processing, model generalization, UAV enhancements, and rescue team training, emphasizing the relevance of these advancements for effective disaster management and policy-informed social infrastructure planning.

Gu et al. (2024) reviewed the advances in rapid damage identification methods for post-disaster regional buildings using remote sensing images, emphasizing the importance of ascertaining the operational state of large-scale infrastructures for swift decision-making and initial response. They acknowledged remote sensing imagery as a valuable complement to simulation-based prediction methods but noted challenges in linking images to reliable assessment results due to issues such as incompleteness, suboptimal quality, and low resolution. The study systematically examined various post-disaster building damage recognition methods, highlighting the evolution of approaches through three stages: visual inspection, pure algorithm, and data-driven algorithm. The authors discussed the merits of image-based recognition, including low cost, high efficiency, and broad coverage, and reviewed critical algorithmic advances with their motivations, innovations, and effectiveness based on test data. Additionally, they reported case studies applying seven AI models to datasets from the 2024 Noto Peninsula and 2023 Turkey earthquakes, offering insights into practical applications and recommendations for future methodological improvements.

Almohsen (2024) highlighted that remote sensing had become essential in construction management by providing valuable information and insights throughout the project lifecycle. The study reported that, due to rapid advancements in remote sensing technologies, their adoption in the architecture, engineering, and construction industries had increased significantly. The review aimed to enhance understanding, expand the knowledge base, and promote practical implementation of remote sensing in construction, supporting the development of robust methodologies and addressing integration challenges. The author conducted a comprehensive literature review, collecting 117 papers from eight journals indexed in Web of Science and categorizing them by challenge type. The study found that 44 exemplary works illustrated applications across satellite, airborne, and ground-based platforms. Eleven challenges in construction-related remote sensing were identified, with shadow, spatial, and temporal resolution issues being the most critical. The findings emphasized the growing use of unmanned airborne systems and satellite remote sensing for preconstruction planning, progress tracking, safety monitoring, and environmental management, facilitating more informed and efficient project decision-making.

Cao et al. (2023) highlighted that disasters in the 21st century had caused severe negative impacts on cities globally, resulting in significant casualties and property damage. They emphasized the necessity for disaster management organizations and the public to enhance urban disaster management. The study reported that the integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) had been considered an effective approach to improving urban disaster management.

However, they noted that the adoption of BIM–GIS integration in urban disaster management had remained limited, which had hindered the development of management quality and efficiency. To address this gap, the authors conducted a systematic review of BIM–GIS utilization in disaster management, analyzing its capabilities in disaster prevention, mitigation, response, and post-disaster recovery. They further examined data acquisition methods, interoperability, and analytical approaches, suggesting that the findings could guide urban disaster managers and the public in effectively leveraging BIM–GIS integration while informing software developers about future development trends.

López-Castro et al. (2022) emphasized that structural health monitoring (SHM) was crucial for safeguarding both human life and structural integrity during earthquakes, particularly in regions within the Pacific Ring of Fire, such as Ecuador. They reviewed various technologies, system architectures, data processing methods, damage identification approaches, and the challenges reported in state-of-the-art SHM applications. The study indicated that multiple data processing techniques, including wavelet transform, fast Fourier transform, and Kalman filtering, had been employed, alongside advanced technologies such as the Internet of Things (IoT) and machine learning. The findings suggested that SHM systems had been increasingly focused on cost-effectiveness and wireless deployment, with microelectromechanical systems (MEMS)-based sensors becoming standard. Nevertheless, the authors highlighted that despite technological progress, these systems continued to face limitations regarding energy optimization, computational efficiency, and adherence to real-time processing requirements, indicating ongoing challenges for practical, large-scale implementation in seismic-prone environments.

Javali et al. (2021) reported that remote sensing had received paramount attention in recent years owing to its wide-ranging applications in environmental studies aimed at benefiting living systems. The authors observed that significant advancements in imaging techniques had been achieved through the use of sophisticated tools developed within remote sensing methodologies. It was highlighted that Synthetic Aperture Radar (SAR) had emerged as a crucial technology in enhancing the spatial resolution of imaging radiometry. In their review, the study presented a comprehensive overview of SAR technology by discussing its characteristic features, various types, prevailing challenges, proposed solutions, and future opportunities. The authors further indicated that the primary motivation of the work had been to identify the existing issues and emerging prospects for researchers and technicians working in the SAR domain. It was concluded that a better understanding of these challenges and opportunities could support the effective utilization of existing SAR datasets and contribute to the advancement of SAR technologies.

Wen et al. (2021) reported that change detection had remained a highly active and significant research area in remote sensing, particularly due to advancements in the spatial resolution of satellite imagery. It was observed that the availability of very-high-spatial-resolution (VHR) remote sensing images had enabled the identification of subtle changes at finer geometric scales. However, the study highlighted that change detection in VHR images (≤ 5 m) had been particularly challenging because of limited spectral information, spectral variability, geometric distortions, and information loss. To overcome these issues, numerous change detection algorithms had been developed and applied in different contexts. Nevertheless, it was noted that a comprehensive review focusing specifically on VHR image-based change detection had been largely absent in the existing literature. Therefore, the study was undertaken to bridge this research gap by systematically reviewing the field. The review was reported to have mainly covered three key dimensions, namely methods, practical applications, and future research directions in VHR remote sensing change detection.

III. KEY FINDINGS FROM STUDY

Author (Year)	Study Focus	Methodology / Approach	Key Findings	Research Gap / Limitation
Aydin et al. (2026)	AI-based rapid structural damage assessment after earthquakes	Scoping review using Scopus, Web of Science, EBSCO (2015–2025)	Shift from manual inspection to AI-based RSDA; improved classification and segmentation	Lack of integration between rapid detection and structural performance evaluation
Yan & Xie (2026)	Multisource remote sensing for post-earthquake damage and trapped population estimation	Review of optical + SAR data integration and edge computing systems	Improved real-time response using space-air-ground systems	Need for small-sample learning and multi-hazard models
Vanian et al. (2025)	Structural performance of Vertical Forest (VF) buildings	Simulation, STPA, Monte Carlo analysis	VF systems introduce higher structural risk but support sustainability	Lack of standardized VF design codes and monitoring systems
Al Shafian & Hu (2024)	Machine learning + remote sensing in disaster management	Bibliometric analysis of 370 Scopus papers (2014–2024)	ML + RS significantly improve damage detection accuracy	Issues in real-time processing, data fusion, and UAV limitations
Gu et al. (2024)	Remote sensing-based rapid building damage detection	Comparative survey of AI and image-based methods	AI improves accuracy; RS offers fast large-scale assessment	Poor image quality, low resolution, and incomplete datasets
Almohsen (2024)	Remote sensing in construction and disaster monitoring	Literature review (117 papers)	UAVs and satellites widely used for monitoring	Challenges in spatial/temporal resolution and shadow effects
Cao et al. (2023)	BIM–GIS integration in disaster management	Systematic literature review	BIM–GIS improves disaster prevention and recovery planning	Interoperability and standardization issues
López-Castro et al. (2022)	Structural health monitoring (SHM) for earthquakes	Review of SHM technologies, IoT, ML, signal processing	SHM enhances structural safety and monitoring accuracy	Energy efficiency and real-time processing limitations
Javali et al. (2021)	SAR technology in remote sensing	Review of SAR systems and applications	SAR improves imaging resolution in disaster zones	High complexity and data interpretation challenges
Wen et al. (2021)	Change detection in very-high-resolution (VHR) images	Review of VHR remote sensing methods	VHR enables fine-scale damage detection	Spectral variation, geometric distortion, and low spectral info

IV. CONCLUSION

The reviewed literature clearly demonstrates that Remote Sensing (RS) and Geographic Information System (GIS) technologies have become indispensable tools for post-earthquake structural damage assessment. Traditional field-based inspection methods, although reliable, are often slow, labor-intensive, and limited in spatial coverage, making them less suitable for urgent disaster response situations. In contrast, RS technologies such as satellite imagery, UAV-based imaging, and Synthetic Aperture Radar (SAR) provide rapid, large-scale, and real-time data acquisition capabilities that significantly enhance situational awareness after earthquakes. GIS further strengthens this framework by enabling efficient spatial data integration, visualization, and multi-layered analysis of damaged regions, supporting informed decision-making in emergency management. The literature also highlights a strong shift toward the integration of Artificial Intelligence (AI), machine learning, and deep learning techniques with RS and GIS systems. These advanced computational methods have improved the accuracy and automation of damage detection, classification, and segmentation processes. AI-based models, particularly convolutional neural networks and hybrid learning frameworks, have shown strong potential in identifying structural damage patterns from complex remote sensing datasets. However, challenges such as limited labeled datasets, model overfitting, and poor generalization across different geographical and structural conditions still restrict their full-scale application. Moreover, multisource data fusion involving optical imagery, SAR data, UAV data, and ground-based sensor information has emerged as a promising approach to improve the reliability of damage assessment systems. Despite these advancements, issues related to data inconsistency, resolution differences, and real-time processing limitations remain significant barriers. Similarly, integration frameworks such as BIM–GIS and IoT-based structural health monitoring systems have enhanced disaster management capabilities but still face interoperability and standardization challenges. Overall, it can be concluded that RS and GIS-based structural damage assessment systems, when combined with AI-driven analytical tools, offer a highly effective and scalable solution for earthquake disaster management. However, further improvements are required to achieve fully automated, real-time, and globally adaptable systems for post-earthquake response and recovery.

V. FUTURE SCOPE

- **Development of Hybrid AI–RS–GIS Models:** Future research should focus on integrating artificial intelligence with remote sensing and GIS platforms to develop fully automated and highly accurate damage detection systems capable of real-time operation during disasters.
- **Improved Multisource Data Fusion Techniques:** Advanced data fusion methods are required to effectively combine optical imagery, SAR data, UAV images, and sensor-based information for more reliable and comprehensive structural damage assessment.
- **Transfer Learning and Small Dataset Training:** Since labeled post-disaster data is limited, future studies should focus on transfer learning and few-shot learning techniques to improve model adaptability across different earthquake scenarios and regions.
- **Real-Time Cloud and Edge Computing Systems:** The integration of cloud computing and edge computing technologies should be enhanced to enable fast processing of large-scale remote sensing data for near real-time disaster response.
- **Standardization of BIM–GIS Integration Frameworks:** Future work should develop standardized protocols for integrating BIM and GIS systems to improve interoperability, structural data sharing, and disaster management efficiency.

- **Enhanced UAV and Satellite Imaging Technologies:** Improvements in spatial resolution, temporal frequency, and imaging accuracy of UAVs and satellites are essential for better detection of fine-scale structural damage.
- **Development of Global Earthquake Response Systems:** There is a need for developing globally scalable earthquake monitoring and response systems that can operate across different geographical regions with minimal customization.

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