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# Post-Earthquake Damage Mapping via Remote Sensing: Lessons from the 2023 Türkiye Disaster

***Abstract*—This review addresses the urgent need for scalable, accurate, and reproducible remote sensing solutions following the February 2023 Türkiye earthquakes. It synthesizes the contributions of five peer-reviewed studies published in the IEEE JSTARS Special Issue on post-earthquake damage and risk assessment. These studies cover areas such as damage classification with deep learning, fusion of multisource remote sensing data, creation of benchmark datasets, detailed damage mapping, and analysis of geophysical signals using outgoing longwave radiation. The article summarizes the methodological approaches and the practical relevance of the reviewed studies for detecting, evaluating, and quantifying damage, and outlines key challenges, including model generalization, class ambiguity, and data integration. It also discusses emerging trends, including explainable artificial intelligence, multimodal data fusion, and open-data platforms. This synthesis provides a foundation for building robust, interpretable, and real-time disaster response systems and aims to guide future research in earthquake-related Earth observation and rapid damage assessment.**

***Index Terms*—Post-earthquake assessment, Türkiye earthquakes, deep learning, remote sensing, damage classification, dataset benchmark, disaster response, Earth observation.**

## I. Introduction

FEBRUARY 6, 2023, marked one of the most devastating seismic events in Türkiye's recent history, when two powerful earthquakes with magnitudes of 7.8 and 7.4 struck the southeastern region near the city of Kahramanmaraş. The first quake occurred at 4:17 a.m. local time, followed approximately nine hours later by a second major earthquake at 1:24 p.m. The sequential nature of these events, both originating from known but underestimated fault segments within the East Anatolian Fault Zone, heightened the severity and complexity of their impact. These catastrophic events caused widespread destruction across eleven Turkish provinces—Adana, Adıyaman, Diyarbakır, Elazığ, Gaziantep, Hatay, Kahramanmaraş, Kilis, Malatya, Osmaniye, and Şanlıurfa—as well as parts of northern Syria. Many multi-story residential buildings and apartment complexes collapsed, especially in densely populated areas such as Hatay, Kahramanmaraş, and Adıyaman. Critical infrastructure, including hospitals, airports, and utilities, was rendered inoperative, and major disruptions occurred in transportation and communication networks. With over 50,000 confirmed deaths and millions displaced, the 2023 earthquakes are among the deadliest and most significant seismic disasters in the region's recent history.

In the immediate aftermath, the need for rapid, accurate, and scalable damage assessments became crucial—not only for guiding search and rescue operations but also for optimizing emergency resource allocation, coordinating humanitarian aid, and planning effective post-disaster recovery. However, the vast area of the disaster zone, along with challenging weather conditions and access issues, greatly limited traditional ground-based survey methods. This issue highlighted the essential role of remote sensing technologies, especially satellite-based observations, in providing timely and large-scale damage intelligence across affected urban and rural areas.

Remote sensing technologies, mainly satellite imagery from optical and synthetic aperture radar (SAR) sensors, as well as aerial platforms such as drones, played a key role in supporting these efforts [1]. Thanks to national and international space agencies, a wide range of remote sensing data — collected before and after the earthquakes — was made publicly available. This variety of data, with different spatial resolutions, viewing angles, and sensor types, created a unique opportunity for the scientific community to develop and test methods for damage and risk assessment at scale.

In response to this devastating event, the IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS) launched a special issue titled *Damage/Risk Assessment for the 2023 Turkey Earthquakes Using Remote Sensing*. The call for papers desired innovative research on cross-modal change detection, data fusion, and the rapid assessment of building damage using remote sensing data, paving the way for replicable frameworks applicable in future disaster response and inspiring the development of more resilient, data-driven risk management strategies. The special issue also promoted the use of additional data sources, such as *in-situ* and crowdsourced data, and stressed the importance of sharing data openly to support accurate and rapid damage assessment. To facilitate rapid access to relevant data in line with the goals of this call, Istanbul Technical University – Research and Application Center for Satellite Communications and Remote Sensing (ITU-CSCRS) made its extensive collection of satellite images and ground reference data available to support large-scale, reproducible earthquake damage analysis. The distribution of these open-access remote sensing datasets is shown in Fig. 1 and they can also be accessed online [1][2]. To further support research and collaboration in this critical area, and to encourage contributions from those directly impacted, IEEE JSTARS waived open access publication fees for authors affiliated with institutions in the disaster-affected region.

This closing article provides a focused overview of the research contributions featured in the special issue, with particular emphasis on methodological innovations, remote sensing techniques, and practical tools designed for damage and risk assessment following the 2023 Türkiye earthquakes. Building

[1] https://codeocean.com/capsule/8064452/tree/v1
[2] https://codeocean.com/capsule/9061546/tree/v1

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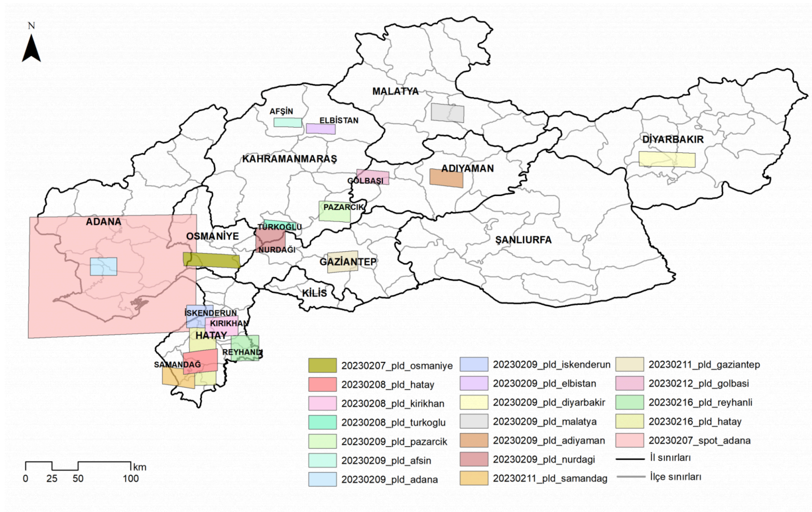


Fig. 1. Post-earthquake observation sites in southeastern Türkiye following the February 6, 2023, earthquakes. The map displays the geographic coverage of publicly available remote sensing data across various provinces and districts, including Adana, Hatay, Gaziantep, Kahramanmaraş, Osmaniye, and Diyarbakır. Colored polygons show acquisition zones corresponding to different dates and image sources, as indicated in the legend. District and provincial boundaries are overlaid for reference.

on the goals of the original call, the article synthesizes the key findings of the accepted papers, highlighting their scientific importance and potential for operational use. Instead of exploring peripheral topics, this review concentrates solely on the peer-reviewed studies published in this issue, providing insights that may guide future academic research and real-world decision-making in earthquake risk mitigation and emergency response planning.

## II. Overview of Contributions

Following a thorough peer-review process in line with the JSTARS editorial policy, five articles were accepted for publication in this special issue. The accepted contributions represent diverse yet complementary approaches to post-earthquake assessment, each demonstrating methodological rigor, clear relevance, and effective use of remote sensing data. These works span a range of topics, including deep learning-based classification, multi-sensor fusion, benchmark dataset development, 3D-aware damage grading, and geophysical signal analysis.

A key requirement in post-disaster response is the ability to quickly and reliably assess building-level damage over large geographic areas. Addressing this need, Wuguna et al. [2] evaluated several deep learning (DL) models for building damage mapping in realistic emergency response scenarios where ground-truth data is unavailable. The authors systematically trained and tested various Convolutional Neural Network (CNN)- and transformer-based architectures—particularly Swin Transformer—using the xBD disaster dataset, a large-scale dataset of building footprints containing satellite imagery with associated four damage levels: *no damage, minor damage, major damage, and destroyed*. They also assessed different loss functions, including cross-entropy, focal, and a combined CE-Focal loss. The best-performing model (Swin Transformer with CE-Focal loss) was then applied to two unseen disaster events—the 2011 Tohoku tsunami and the 2023 Türkiye earthquake—to simulate rapid damage assessment in real-world settings. Results show that the model effectively identified *no damage* and destroyed buildings, but often confused the intermediate categories *minor* and *major*. Using both pre- and post-disaster images enhanced the model's ability to distinguish damage levels and was recommended when available. Nonetheless, relying only on post-event images still produced reasonable results in situations with limited data. Compared to the xView2 baseline, the transformer-based model achieved more stable, consistent results across satellite and aerial images, highlighting its robustness and suitability for rapid damage assessment.

Complementing this focus on automation, the Earthquake Engineering Field Investigation Team (EEFIT) [3] conducted an investigation after the February 2023 Türkiye–Syria earthquakes to support field teams by identifying diverse damage areas using satellite data, including SAR, optical imagery, and AI-derived maps, and validating these findings through ground surveys. By combining multiple datasets and applying zonal statistics, the team prioritized key locations for field assessments and identified significant inconsistencies across damage products, particularly at moderate damage levels. While binary classifications such as "collapsed" versus "standing" performed more reliably, the challenge of accurately detecting intermediate damage remained. The study emphasized the need to harmonize data sources, enhance spatial alignment, and combine remote sensing with on-site validation to improve disaster response efforts.

Recognizing the lack of standardized resources for training and evaluating artificial intelligence (AI)-based damage assessment models, Ekkazan and Karsligil [4] introduced TE23D, a curated benchmark dataset focused on post-earthquake building damage in Türkiye following the February 2023 earthquakes. It included 1183 image patches and 2080 damage polygons, annotated using a binary segmentation strategy that marked only damaged areas, given the indistinct nature of rubble and collapsed structures. The study compared TE23D with existing datasets, highlighting its earthquake-specific focus and enhanced spatial detail achieved through polygonal annotations rather than image-level classification or bounding boxes. For benchmarking, seven segmentation models—including BEiT, Mask R-CNN, U-Net++, and SegFormer—were trained on TE23D, with SegFormer-B5 achieving the best results, a pixel accuracy of 92.49%, and a mean Intersection over Union (mIoU) of 74.45%. The dataset aimed to facilitate rapid, accurate automated damage detection for emergency response and to provide a scalable framework for future disaster assessments.

For large-scale assessment of building damage using satellite-based height information, Hong et al [5] presented a rapid, detailed, and automated method for large-scale building collapse assessment using high-resolution stereo satellite imagery (HRSSI), focusing on Kahramanmaraş, Turkey. The proposed approach dealt with several challenges, such as limited ground control points (GCPs), lengthy 3D reconstruction processes, and dense urban environments, by integrating GF-7 stereo imagery with ICESat-2 laser altimetry data to achieve vertical accuracy within 1 meter. A fast 3D reconstruction pipeline was developed, improving the efficiency of Digital Surface Model (DSM) generation by more than 8 times through ORB-based feature matching and GPU-accelerated dense matching. Registered Microsoft building footprints were rasterized and aligned with DSMs via affine transformations to enable precise height change detection. Building collapse classification was then performed using connected-component analysis and elevation thresholds, with collapsed floors estimated by analyzing differences in the DSMs. Applied to an 800 $km^2$ area in Kahramanmaraş, this method processed $48,092$ buildings and produced floor-level damage maps within one hour. Validation using Google Street View for 361 buildings yielded floor-level accuracy of 93.27%. The results revealed 2,709 collapsed buildings and estimated a total collapsed volume of 5 million $m^3$, providing essential information, supported by geospatial data-derived insights, for emergency response, reconstruction, and humanitarian aid logistics.

Lastly, Cui et al [6] examined the ability of FengYun-3E (FY-3E) satellite's outgoing longwave radiation (OLR) data to detect pre-earthquake thermal anomalies using the ATSCTF (Additive Tectonic Stress from Celestial Tide-Generating Force) algorithm in relation to the 2023 Türkiye double earthquakes. The results indicated that the quartile-based thresholding method effectively identified abnormal changes in OLR values that coincide with seismic activity, especially during the critical pre-seismic phase. Strong agreement was observed between ascending and descending satellite data and previous NOAA-based results. The study further noted that tidal stress alone cannot trigger earthquakes without existing tectonic stress nearing a critical level. It highlighted the advantages of FY-3E's medium-resolution spectral imager low-light sensor — such as high resolution, dynamic range, and accuracy — for future seismic monitoring. Additionally, it mentioned limitations of the ATSCTF method and the quartile thresholding approach that need further exploration.

## III. Challenges and Limitations

Despite recent advances in AI-based remote sensing for disaster assessment, several challenges persist across different studies. Below, we summarize the key limitations reported in this special issue:

- **Generalization to Out-of-Distribution Data**: DL models often suffer from significant performance degradation when applied to regions or events outside the distribution of their training data (namely, out-of-distribution, OOD) due to domain shifts, geographic variability, differences in sensor type (e.g., aerial vs. satellite), and inconsistencies in class label definitions between training and test datasets.
- **Ambiguity in Intermediate Damage Classes**: Classes like "Moderate" and "Heavy" damage are visually subtle and often confused, especially in top-down or oblique imagery. This is compounded by annotation subjectivity and class imbalance in the training data [7].
- **Limitations of Optical Imagery**: Roof-level or nadir-view satellite images cannot capture *façade* damage or internal structural failures. These limitations restrict the reliability of remote-only assessments unless complemented by ground truth or oblique views [8].
- **Data Latency and Tasking Delays**: In emergency scenarios, delays in acquiring and disseminating satellite imagery—especially from commercial providers—limit the effectiveness of rapid assessments.
- **Cloud Cover and Atmospheric Obstruction**: Persistent cloud cover degrades the usability of optical imagery, often requiring the use of alternative data sources, such as SAR.
- **Multi-source Data Integration Difficulties**: Integrating data from drones, satellites, and ground surveys introduces alignment challenges, inconsistent spatial resolutions and spectral bands, as well as labeling mismatches, all of which hinder unified model training and validation [9].
- **Uncertainty and Noise in Ground Truth Labels**: Labels derived from field inspections are subject to regional inconsistencies and human error, introducing noise that affects both model training and evaluation [10].
- **Spatial Bias in Training Data**: Models trained on spatially clustered data may not generalize well to new regions due to overfitting to local patterns.
- **Uncertainty in Anomaly Threshold Determination**: While the quartile-based method offers a more objective approach than empirical thresholds, it remains sensitive to outliers, may not reliably capture anomaly distributions in skewed datasets, and can overlook finer variations—posing a critical challenge for robust and consistent detection of pre-seismic OLR anomalies.

Among these, the most critical challenge is the poor generalization of models to unseen geographic regions or disasters.

This limitation directly undermines the operational utility of AI-based methods during real-world emergencies where annotated training data is unavailable immediately. Improving domain adaptation, dataset diversity, and robustness to sensor and context variability remains essential for scalable and trustworthy deployment.

## IV. Opportunities and Future Directions

Building on the challenges identified in the current research, several promising opportunities and directions for further study can enhance AI-based damage and disaster assessment workflows:

- **Domain Adaptation and Generalization Techniques**: To overcome performance issues with OOD data, future efforts should investigate domain adaptation, domain generalization, and meta-learning strategies that enable models to transfer knowledge across various geographic areas, sensor types, and disaster scenarios.
- **Multimodal and Multisource Data Fusion** Combining optical imagery with SAR, LiDAR (light detection and ranging), DSMs (Digital Surface Model), drone data, and even thermal or atmospheric signals (e.g., OLR) can compensate for the limitations of single-modality systems. Such fused data enhances the robustness and stability of algorithms while providing complementary benefits from different modalities.
- **Improved Ground Truth and Standardized Labeling Protocols** Developing more reliable and consistent datasets via standardized annotation guidelines, expert validation, and consensus labeling can reduce subjectivity and improve consistency, particularly regarding mid-level damage classes. Leveraging authoritative post-disaster inspection records offers an important avenue for strengthening these efforts.
- **Addressing Class Imbalance and Rare Event Detection** Future models should adopt advanced class-balancing methods such as focal loss variants, class-weighted training, synthetic oversampling (e.g., GANs), and uncertainty-aware learning to better identify underrepresented yet critical classes like “Destructed” or “Heavy” damage.
- **Scalable and Real-Time Deployment Pipelines** To advance operational-ready model deployment, the remote sensing and disaster-response research community would benefit from focused efforts to develop scalable inference pipelines capable of near-real-time operation, integrate with data streams (e.g., Copernicus, Planet, ICEYE), and deliver actionable outputs for emergency responders.
- **OLR-Based Early Warning Research**
While still in the exploratory phase, detecting pre-seismic OLR anomalies presents a new avenue in short-term earthquake forecasting. Combining these atmospheric signals with geodetic, seismic, or geochemical indicators may enhance reliability. Further research is required to understand causal mechanisms and reduce false alarms.
- **Open-Access Platforms and Collaborative Mapping**
Creating open-access geospatial data portals and AI benchmarking platforms can encourage collaboration, reproducibility, and large-scale validation efforts among research institutions and operational agencies.

Overall, future research should focus on developing AI systems that are not only accurate but also resilient across diverse conditions, intuitive for human users, and interoperable across platforms and organizations. As disasters increasingly test the boundaries of existing technologies, there is a growing need for end-to-end solutions that can integrate heterogeneous data sources, operate reliably in real-world settings, and support transparent, accountable decision-making. Bridging the gap between innovation and practical deployment demands a comprehensive approach—one that blends technical advancement with domain expertise and effective coordination between automated systems and human actors on the ground.

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