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VULNERABILITY ASSESSMENT AND SEISMIC RISK ANALYSIS OF BUILDINGS IN IRAQ: INSIGHTS FROM BUILDING SURVEYS AND DAMAGE SCENARIOS

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Abstract

Seismic risk analysis of building stocks in earthquake-prone regions builds the entry for any kind of mitigation measures, especially in the case of fast urbanization in developing countries. Iraq, one of such countries, lies in the northern portion of the Arabian plate, bounded in the North-East by the Bitli-Zagros fold and Thrust belt, where the convergent tectonic boundary between the Eurasia and Arabian plates generates intense earthquake activity. In addition, there are no or only very few accurate studies that map out or provide statistics on the number of buildings in Iraq.

This study presents a detailed vulnerability assessment and seismic risk analysis of buildings in Iraq, based on data collected from 4,724 structures through random urbanization methods. Extensive field surveys were conducted to capture key building characteristics, and this data has been digitized to support future research in earthquake engineering, urban planning, and disaster risk management. Each building was classified by vulnerability class and building type using the European Macroseismic Scale (EMS-98) and the Global Earthquake Model (GEM) building taxonomy. These taxonomies enabled a detailed categorization of buildings, helping to assess their expected seismic performance. The validated dataset can be used to develop seismic damage models and conduct risk and loss analyses for the region. Preliminary results from the survey show that 45% of the buildings assessed in Iraq can be classified as non-engineered, primarily constructed using brick masonry and concrete blocks.

Reports of damages in the surveyed buildings were collected from past earthquakes mainly damage reports from the 2017 Iran-Iraq border earthquake with magnitude 7.3, providing valuable insights into the potential impacts of future seismic events. The collection of this data highlights the vulnerabilities of different building types and estimates the economic and human losses that could result from significant earthquakes in Iraq, as well as preparation for future damage scenarios and risk assessment studies. The findings emphasize the importance of targeted interventions, such as retrofitting and emergency preparedness, to reduce seismic risks. In addition to offering insights into potential damage patterns, the digitized data serves as a critical resource for future studies. It supports regional seismic hazard mapping, the improvement of building codes, and the enhancement of emergency response planning. By making this data available, the study promotes collaboration and future research efforts aimed at improving seismic resilience in Iraq and similar regions.

Keywords: Earthquake Response, Vulnerability Assessment, EMS-98, Seismic Risk.

1. Introduction

Seismic risk analysis is an essential component in developing effective mitigation strategies for earthquake-prone regions, particularly in rapidly urbanizing countries like Iraq. Iraq is located at the northern margin of the Arabian Plate, bordered by the tectonically active Bitlis-Zagros Fold and Thrust Belt, where the convergence of the Eurasian and Arabian plates generates intense seismic activity [1,

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2]. This complex tectonic setting subjects Iraq to significant seismic hazards, particularly in its northern regions, where the population density and urban expansion are also high [3]. Recently, the increase in earthquake activity in this region has been observed, with the most recent damaging event being the November 12, 2017, Iran-Iraq border earthquake with a magnitude of 7.3 which caused several damages killing 9 people and injuring 55. Despite the evident risks, comprehensive seismic risk assessments and detailed data on Iraq's building stock remain limited, which are crucial for understanding and mitigating earthquake impacts. Understanding and mitigating these risks is increasingly important as Iraq undergoes rapid urbanization, leading to the expansion of urban settlements and infrastructure development [4]. The unregulated nature of many of these developments results in a substantial increase in non-engineered buildings, which are particularly vulnerable to seismic events [5, 6]. Assessing and mitigating these risks is therefore critical not only for infrastructure protection but also for minimizing the economic and human impact of future seismic events.

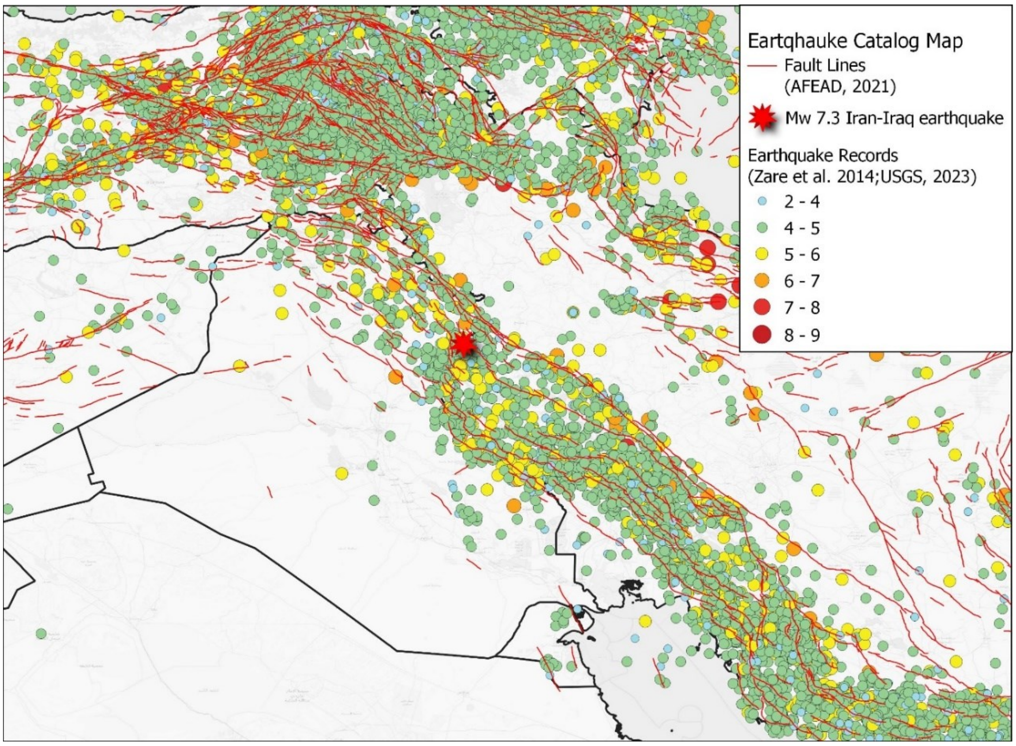

Figure 1. Earthquake catalog between years (0-2020), Zare et al., 2014 [7]; USGS Earthquake Catalog [8]

Despite the pressing need for accurate seismic risk assessments in Iraq, the country currently lacks detailed, comprehensive studies that map the vulnerability of its building stock. Existing research highlights the general geological and seismic characteristics of Iraq but falls short in providing specific, comprehensive data on building inventories and their structural performance during earthquakes [3, 9]. This gap is significant because reliable data on building vulnerability is a fundamental prerequisite for developing effective mitigation strategies, such as retrofitting measures and updating construction codes [4]. The absence of comprehensive and a systematic vulnerability assessment leaves planners and policymakers with limited information, which reduces their ability to adequately prepare for or respond to seismic events.

While regional seismic hazard models such as the Earthquake Model of the Middle East (EMME) have been developed [10, 11], these models often lack the localized data necessary to refine risk estimates for Iraq's unique geological and structural conditions. Previous research has demonstrated the value of integrating local geological conditions and detailed building typologies into seismic risk models to improve accuracy [9, 12]. Addressing these gaps, the present study aims to conduct a detailed vulnerability assessment of buildings in Iraq using data collected from 4,724 structures through field

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surveys. These surveys utilize international standards such as the European Macroseismic Scale (EMS-98) and the Global Earthquake Model (GEM) taxonomy to classify buildings according to their structural characteristics and vulnerability [13–15].

The primary objective of this study is to provide a robust and systematically digitized dataset that supports the development of seismic risk models tailored specifically to Iraq's building stock. By digitizing and categorizing the building data systematically, the research aims to create realistic damage scenarios using past earthquake shake maps to predict potential impacts and economic and human losses. This data-driven and evidence-based approach will inform targeted interventions such as retrofitting programs and emergency preparedness strategies, ultimately enhancing Iraq's resilience to seismic events. Additionally, the study's findings will contribute to improving regional seismic hazard mapping, updating and strengthening building codes, and supporting future disaster risk management efforts in Iraq.

2. Study Area

The city of Sulaimani is a rapidly growing urban center in Iraq, with an estimated population of 823,199 and an annual growth rate of 2.8% [16]. This population increase has led to significant urban development and the planning of new construction projects within the city. While no precise studies currently provide statistics on the total number of buildings in the city, the Microsoft Planetary Computer [17] has identified 86,000 buildings nationwide using high-resolution satellite imagery and deep neural networks (DNNs) to detect building pixels in aerial images. However, the DNN model used for this analysis is trained on datasets derived from international housing imagery, which limits its accuracy in identifying the full scope of buildings in Sulaimani. It is estimated that the actual number of buildings in the city could be a few times higher than the figure provided by Microsoft. This discrepancy highlights the need for localized studies and the development of customized models that reflect Iraq's specific construction types.

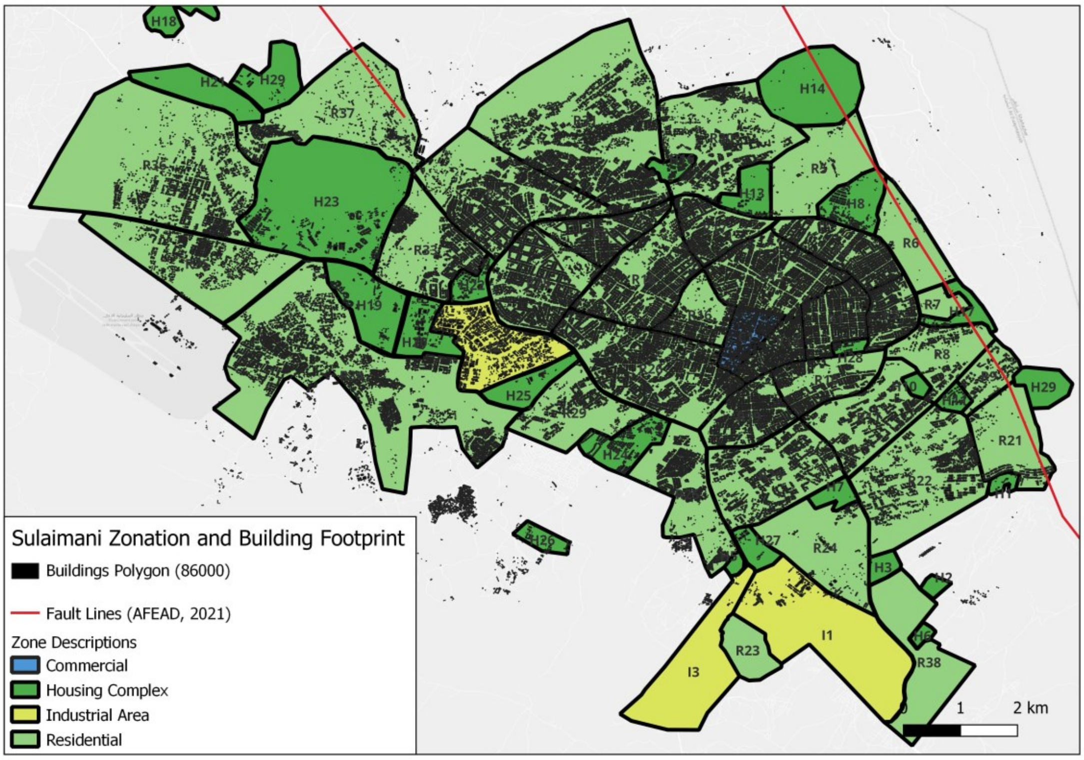

Figure 2. Urban zonation of the study area including building footprints

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The development of Sulaimani has occurred in distinct phases, influenced by different construction styles over time. In recent years, the government has issued permits to several construction companies for the development of housing complexes at multiple stages and locations throughout the city. These projects primarily consist of high-rise residential complexes and standardized structural buildings, typically ranging from one to three stories. These houses are often identical in design, planned, and constructed under the supervision of engineers. However, alongside these planned developments, residential areas have also emerged through the distribution and sale of land to individual homeowners. Many of these houses were constructed by the homeowners themselves, based on varying plans and permits. While government regulations require structural plans for building permits, some houses have been built without full compliance with engineering guidelines, resulting in a high percentage of non-engineered structures. These deviations, including unapproved modifications, make it difficult to ensure that buildings meet safety standards. The survey conducted in this study revealed that 55% of the buildings in Sulaimani are non-engineered, highlighting a major structural risk in the event of an earthquake.

Furthermore, while Sulaimani has only one identified commercial area, commercial buildings are often integrated into residential neighborhoods. The city also contains three primary industrial zones, further contributing to its diverse urban landscape. The locations of these zones are demonstrated in Figure 2, which provides a visual representation of their distribution across the city. The zonation of the city is well-described; however, the building types and their attributes in Sulaimani remain largely undocumented. Previous studies conducted in Erbil [6] have successfully collected building attributes to identify vulnerabilities and classify building types, which offers a valuable basis for this study. Since construction practices across the country share significant similarities, these findings can inform the framework developed for Sulaimani.

In addition to the built environment, subsoil conditions play a crucial role in determining ground motion amplification and directly affect building vulnerability during earthquakes. Studies on site response investigation in Sulaimani [9] have classified the city's subsoil primarily as Class C and Class D, according to Eurocode 8 [18]. Class C soils consist of dense or stiff deposits, while Class D soils represent soft deposits that are more prone to ground motion amplification. In certain areas, particularly those dominated by Class D soils, the presence of soft sediments poses a significant risk, as amplified shaking can increase structural damage during earthquakes. This effect is particularly concerning in the southern parts of the city, where deeper sediment layers further intensify seismic hazards.

Understanding these site-specific soil conditions is essential for seismic risk assessments and can support urban planners and engineers in making informed decisions about building regulations, retrofitting strategies, and land-use planning. By integrating subsoil data with structural assessments, targeted seismic mitigation measures can be developed to enhance earthquake resilience across Sulaimani.

3. Methodology

In order to give a systematic and comprehensive classification of building taxonomies in Sulaimani, this study introduces a modular framework for seismic vulnerability assessment. The framework is designed to work at varying levels of data availability, making it particularly suitable for developing countries where detailed structural inventories may be limited. Unlike traditional classification methods, which often apply fixed or rigid vulnerability classifications, this modular approach allows for incremental refinement of vulnerability classes (VCs) as more structural details become available. The framework integrates structural attributes, soil characteristics, seismic intensity data, and empirical observations, ensuring a more comprehensive and data-driven seismic risk assessment. Through standardization of the assessment process, this framework ensures that buildings are evaluated using globally recognized criteria, which aligns with the European Macroseismic Scale-98 (EMS-98) providing a consistent and reliable understanding of seismic performance across different building types.

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The modular framework is designed specifically to align with the EMS-98 system, offering flexibility and adaptability in classifying building vulnerabilities. Unlike a fixed classification system, this approach operates at varying levels of detail, ensuring that assessments can be performed even with limited data while allowing for progressive refinement depending on the availability of different details.

The framework introduces multiple levels (Level 1, Level 2, and Level 3), which incorporates increasing levels of structural and vulnerability detail, as outlined below:

- Level 1 (Basic Structural Type): In this level the fundamental building parameter material type, is used for an initial vulnerability classification based on EMS-98. This level provides a baseline assessment when only minimal data is available.
- Level 2 (Structural Modifiers & Configuration): Incorporates additional structural and architectural details, these attributes refine the initial classification by incorporating key performance factors that influence seismic response.
- Level 3 (Advanced Seismic & Geotechnical Refinements): Provides a highly detailed classification by integrating seismic code compliance, soil-structure interactions, liquefaction susceptibility, and empirical earthquake impact data, enabling accurate risk assessment.

Table 1: A modular framework for building vulnerability classification, allowing for progressive refinement based on data availability ranging from Level 1 to Level 3.

Level	Category	Attributes
Level 1	Basic Structural Attributes	Material type
	Building Location	Geographic coordinates (latitude, longitude)
Level 2	General Building Information	Construction/retrofit date, building height category, building age, primary use/occupancy
	Structural Configuration	Structural system type, material technology, system ductility
	Geometric & Structural Irregularities	Plan irregularity, vertical irregularity, soft story indicators
	Roof System	Roof Cover, Roof Development, Parapet height
	Foundation & Soil Interaction	Foundation type, foundation-soil interaction, liquefaction susceptibility
	Building Condition & Safety	Retrofitting status, structural integrity (good/poor)
	Non-Structural Components	facade materials, parapet & overhang stability
	Fire & Post-Earthquake Hazards	Fire risk level (post-earthquake hazard), pounding risk between adjacent buildings
Level 3	Seismic & Geotechnical Performance	Seismic code compliance, peak ground motion, site-specific soil classification
	Empirical Data & Damage History	Reported earthquake intensity, observed structural & non-structural damage during past earthquakes
	Heritage & Societal Factors	Cultural or Historical Significance, Proximity to Critical Infrastructure (Hospitals, Lifelines)
	Economic & Recovery Indicators	Ownership Type (Owned vs. Rented), Insurance Coverage, Expected Recovery Time

The attributes associated with each level are outlined in Table 1, showing the progression from fundamental attributes at Level 1 to increasingly detailed characteristics at Level 3. Level 1 gives a basic vulnerability class based on the material type of the building, this could account for a mean vulnerability class of the building giving a preliminary assessment. Level 2 introduces structural modifiers and configuration details, including building height, primary use, irregularities, roof system

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characteristics, foundation type, and non-structural components, refining the initial classification by incorporating key structural and architectural factors that influence seismic response. Level 3 further expands the classification by integrating seismic code compliance, peak ground acceleration (PGA), soil-structure interactions, liquefaction susceptibility, and empirical earthquake impact data, enabling a highly detailed risk assessment. This scalable, modular structure ensures that the EMS-98 classification can be effectively applied in both limited and extensively available data environments, allowing for incremental refinement as more comprehensive data becomes available. By accommodating varying levels of detail, the framework provides a flexible and adaptive methodology suited to the diverse and complex building stock in Sulaimani.

Based on the modular framework, a systematic survey of the building stock in the city of Sulaimani is conducted. For the optimize and efficiency of data collection for this study, senior undergraduate students in their fourth year were trained in the empirical framework developed for assessing buildings in Iraq [19]. This training equipped the students with the necessary skills to evaluate structural parameters and classify buildings according to the proposed modular framework.

After the training phase, the students carried out field surveys across the city. Each zone was allocated to specific groups of students, who were tasked with surveying buildings within their designated areas. During these surveys, students collected essential structural parameters, photographed the buildings, and classified them into types and vulnerability classes in accordance with the EMS-98 classification system [13], following the methodology outlined by [20]. The modular framework guided the data collection process, employing a random selection method to ensure representative sampling and facilitate subsequent verification and adjustments.

In total, data from 4,825 buildings were collected during the survey. After a thorough review and validation process, 4,772 entries (98.9% of the dataset) were approved, while 1.1% of the entries were removed due to unresolvable inaccuracies. Data entries identified as incorrect were adjusted where possible, and uncorrectable entries were excluded from the dataset. The resulting refined dataset reflects the classifications conducted in the field and serves as the foundation for future seismic risk analyses.

The methodology employed for executing the building survey in Sulaimani followed a structured series of steps, ensuring consistency, accuracy, and the reliability of the collected data. These steps included the systematic allocation of zones, the training of data collectors, the use of a modular framework for data collection and classification, and a comprehensive review and validation process to refine the dataset for subsequent analysis. Additional data was collected for each building to enhance the analysis. This included soil data sourced from the study by [6], which evaluated soil conditions in Sulaymaniyah using microtremor measurements, lithological data, and geotechnical datasets. The study classified soil according to EC8 and NEHRP soil classifications, providing critical insights into subsoil characteristics.

Given the distributed nature of soil sampling data in the study, soil data at various locations across the city required testing for interpolation methods to ensure accuracy. Three primary interpolation methods were considered: Inverse Distance Weighting (IDW), Kriging, and Radial Basis Functions (RBF). The performance of these methods was evaluated using metrics such as RMSE, MAE, and R^2, with IDW consistently demonstrating superior results across all tested parameters. This approach ensured the effective integration of soil data for each building.

Table 2. Results of Interpolation Methods for Soil Data

Method	RMSE	MAE	R^2	EVS	Max Error
IDW	0.2773	0.2185	0.7755	0.7786	0.8011
RBF	0.7925	0.5841	-0.8329	-0.7213	2.3468
Kriging	0.5844	0.5378	0.0033	0.0038	1.4814
Natural Neighbor	0.7405	0.4516	-0.6006	-0.4518	2
Spline	0.664	0.5305	-0.2869	-0.2604	1.8158
KNN	0.5917	0.5343	-0.022	-0.0217	1.5325

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The results in Table 2 shows that the selected IDW method performed significantly better than other methods, with the lowest RMSE and MAE and the highest R^2 and EVS values. In contrast, RBF exhibited poor performance, with high RMSE and negative R^2, failing to capture variance effectively. Kriging demonstrated moderate performance but struggled to generalize well, achieving near-zero R^2 and EVS values. The resulting dataset provided a comprehensive understanding of site conditions, facilitating the classification of buildings and enhancing the reliability of vulnerability assessment.

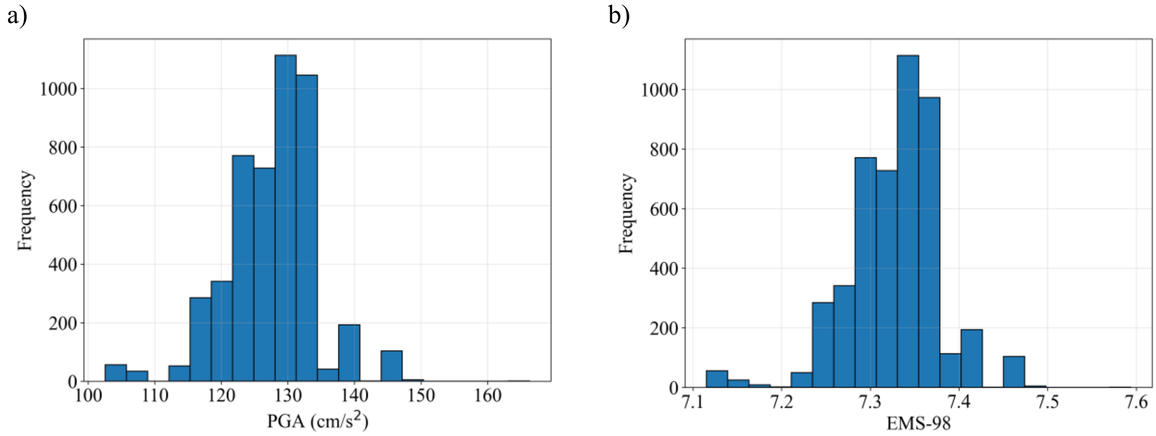

Figure 3. (a) Distribution of Peak Ground Acceleration (PGA) across Sulaimani city during the 2017 Iran-Iraq border earthquake, derived from the USGS ShakeMap [21] (b) Distribution of converted intensity values according to the EMS-98 scale, based on the correlation function of Zanini and Hoffer, 2019 [22]

In addition to the structural and soil data collected, information from past earthquakes was also integrated into the analysis. The survey integrated Peak Ground Acceleration (PGA) values for each building, derived from the USGS ShakeMap [23] model for the event [21]. The PGA values ranged from 100 to 160 cm/s² across the city, reflecting varying levels of ground motion during the earthquake. The distribution of PGA values is presented in Figure 3, which illustrates the frequency of PGA across the study area. This distribution helps in understanding the spatial variability of seismic impacts, forming a crucial input for the creation of damage models and risk assessment strategies.

The survey also included two additional questions aimed at capturing resident's experiences during the 2017 earthquake. Students asked homeowners to report the experienced earthquake intensity according to the EMS-98 scale and whether their houses sustained any damage. For those who reported damage, the survey collected details on the extent and level of damage observed. This firsthand information adds an important layer of empirical data, enhancing the understanding of building performance and community resilience during seismic events. Collection of data from previous earthquakes aids in future damage modeling which is further planned as part of seismic risk assessment in Iraq.

4. Survey Results

Based on the methodology described in the previous section, a detailed survey was conducted in Sulaimani, which resulted in a comprehensive dataset capturing both the structural and usage characteristics of buildings across the city. A total of 36 key attributes were collected, along with 10 supplementary parameters including soil class, soil frequency, and earthquake intensity, which were incorporated to refine the analysis. Figure 4 presents an overview of key parameters such as roof material, construction age, building location, and usage type. The survey revealed that 55% of the buildings are classified as non-engineered, while 45% were identified as engineered structures. Additionally, the majority of buildings were found to be in good (40.38%) or average (38.9%) condition, with a smaller proportion being newly constructed (12.8%) and some in bad condition (7.5%), as shown in Figure 4 (b). Understanding these material distributions is essential for evaluating the structural resilience of buildings against seismic events.

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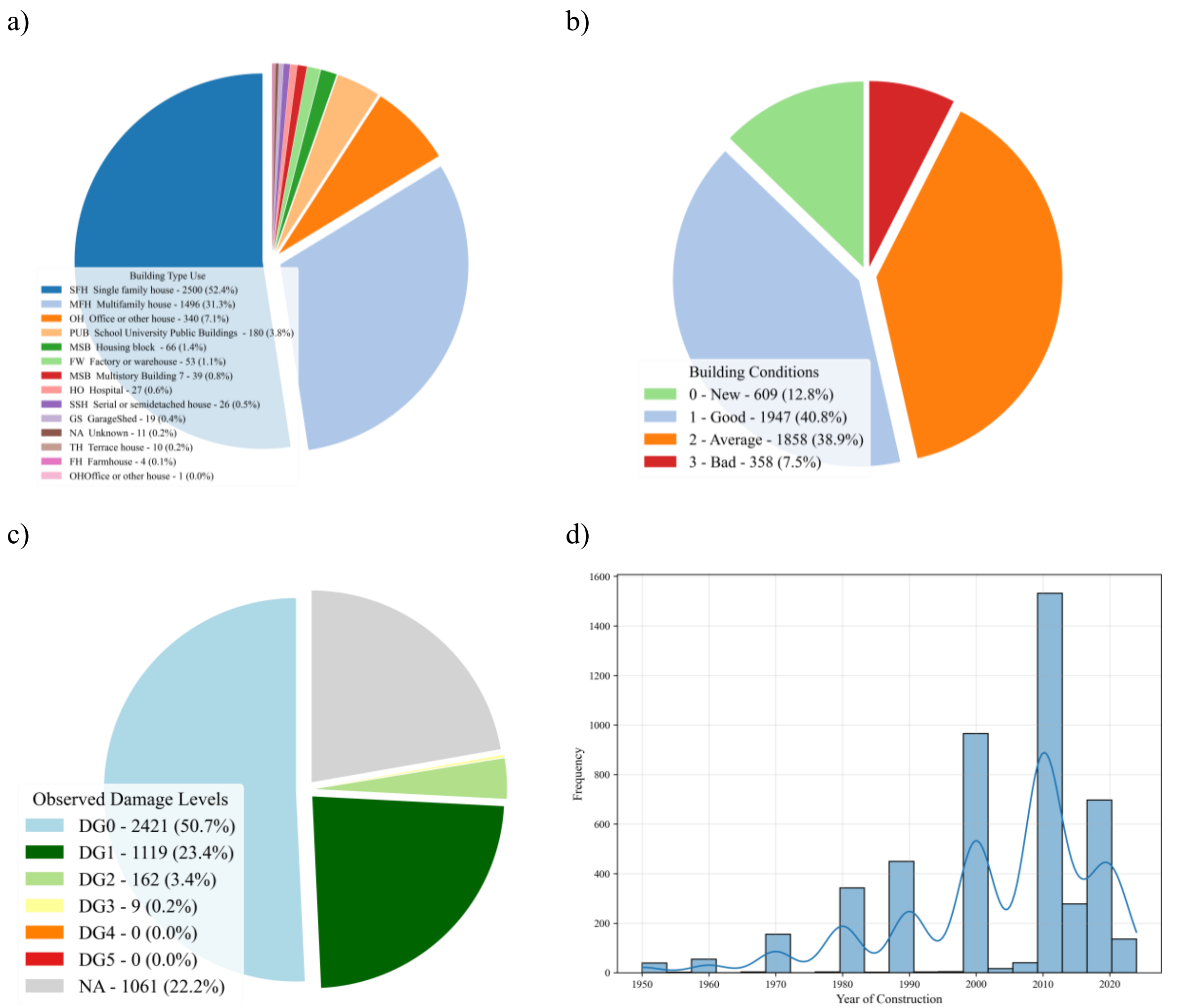

Figure 4. (a) Building types by use; (b) Building conditions; (c) Observed damaged during past earthquakes; (d) Year of construction trends.

The dataset also includes information on the year of construction for each building, Figure 4 (d). According to this dataset, a significant urban growth is observed in the 2000s and 2010s, with peaks in construction activities during these periods. This trend is visually represented in the histogram of construction years, which highlights the evolution of urban development over decades. The damages observed during the 2017 Iran-Iraq border earthquake are presented in Figure 4 (c), showing that at intensity level VII (see Figure 3) on the European Macroseismic Scale (EMS-98), a large number of buildings did not have any cases of damages while a number of buildings sustained minor cracks and negligible damage of damage grade 1, while a small number experiences damage of grade 3, indicating critical structural damages in these building that was later renovated or fixed. This classification provides valuable insights into spatial layouts and the density of residential zones, which are essential for urban planning and seismic risk analysis. Another key parameter recorded in the survey was building use. The results shows that single-family houses make up the majority of the city's building stock, which accounts for over half of the surveyed structures. These are followed by multifamily houses, public buildings, offices, and warehouses, as presented in the Figure 4 (a). This distribution reflects the city's mix of residential and commercial buildings, which are shaped by both planned development and natural growth.

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Additionally, Figure 5 shows the spatial distribution of the building types across different zones, which highlights significant regional variations in urban zoning and building use. According to the shown results, majority of building types are classified as M6 - Unreinforced with RC Floors (74.9%), which represents a common typology across most zones in the city. Other notable types include RC1-L - Frame without ERD (7.9%), M5 - Unreinforced, with manufactured stone unit (6.4%), and M7 - Reinforced or Confined (4.8%). The spatial distribution of the buildings shows that the buildings are scattered across specific zones, which represent local construction practices and architectural trends in different parts of the city.

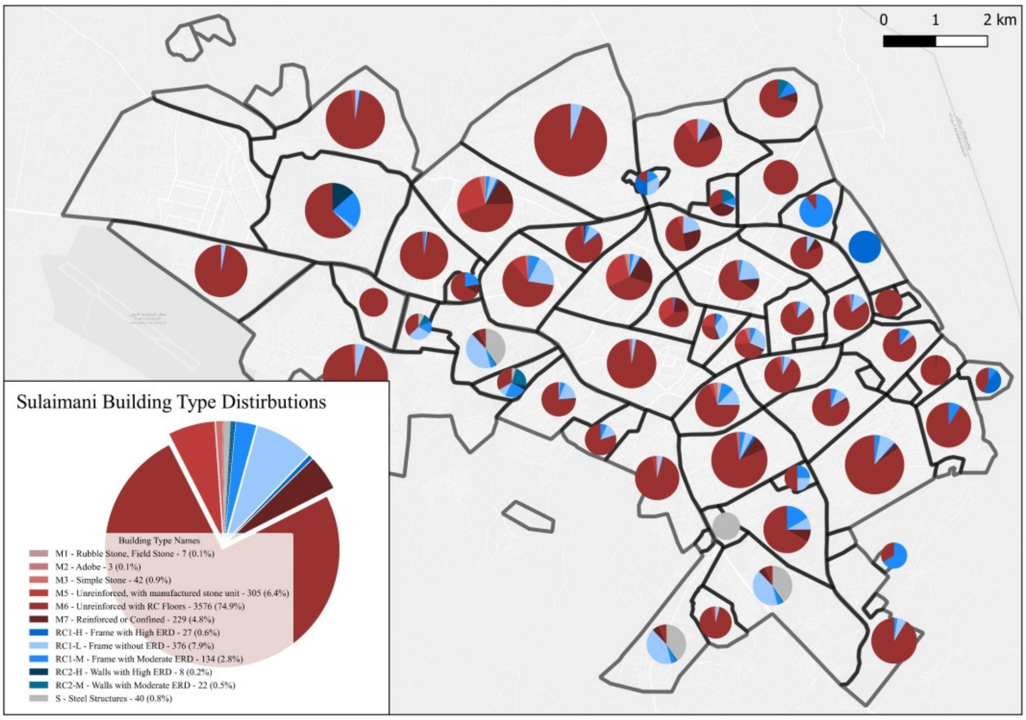

Figure 5. Spatial distribution of building types across zones in Sulaimani

Moreover, Figure 5 shows that some zones exhibit higher proportions of diverse building types, such as RC-M - Frame with Moderate ERD and M3 - Simple Stone, which reflect variations in structural design and urban planning. Conversely, in certain areas, a single typology of buildings is dominant, which is mainly zones of residential complex buildings where the structures are similar. This suggests the uniformity in development and standardized construction within these zones. This distribution provides critical insights into the zoning strategies and construction trends in Sulaimani, revealing areas with concentrated building types and others with a mix of structural designs.

Furthermore, each building was assigned a vulnerability class based on the EMS-98 system. Figure 7 presents the distribution of building vulnerability classes under optimistic and pessimistic scenarios, which provides a clearer picture of structural resilience across the city. In the optimistic scenario, the majority of buildings fall into vulnerability class C, which represents average vulnerability to earthquake actions.

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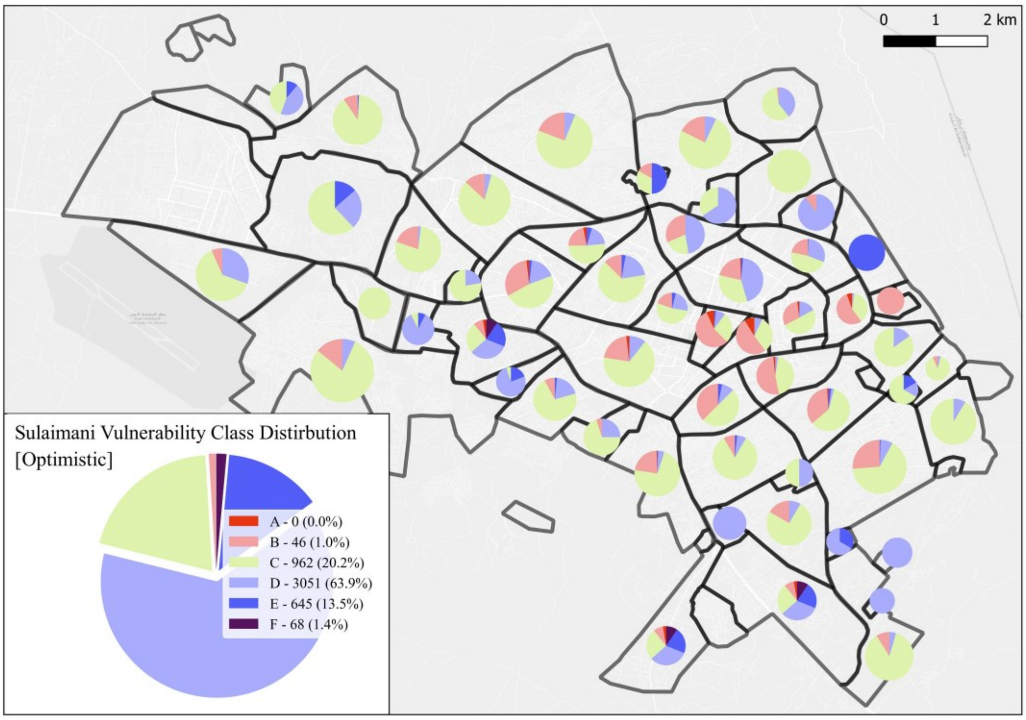
a)



b)

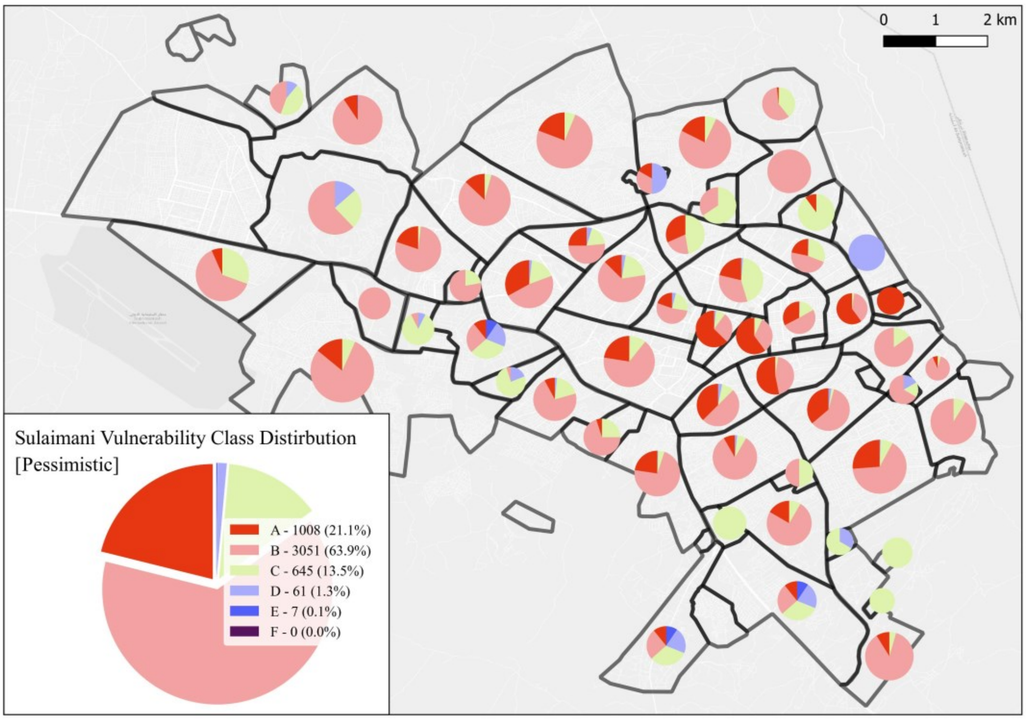


Figure 6. a) Distribution of building vulnerability classes under the optimistic scenario, b) Distribution of building vulnerability classes under the pessimistic scenario

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This classification pattern is mainly due to the high prevalence of masonry buildings, which are the most common building type in the region. Following this, class B and C are the next most common, representing moderate and low vulnerability, respectively. Only a small percentage of buildings are classified as E and F, which are considered very low and extremely low vulnerability structures. These buildings represent well-engineered and designed structures to withstand seismic forces effectively.

In the pessimistic scenario, where weaker construction quality and poor seismic detailing are considered, most buildings fall into vulnerability class B, meaning they have moderate vulnerability to earthquakes. This is followed by class A, which includes the most vulnerable structures, and class C, which remains common but less so than in the optimistic case. The shift in classifications highlights the impact of construction quality and regulatory enforcement on seismic risks, which emphasizes the need for retrofitting strategies and improved building standards to enhance earthquake resilience.

Moreover, the spatial distribution of vulnerability classes reveals notable differences across the city. The pessimistic scenario offers a realistic worst-case perspective and helps to understand which areas are most at risk. These insights are crucial for developing targeted mitigation plans, strengthening disaster preparedness, and reducing the impact of future earthquakes.

5. Conclusion

This study provides a comprehensive vulnerability assessment and seismic risk analysis of the building stock in Iraq, focusing on the city of Sulaimani as a case study. Utilizing an extensive field survey of 4,724 buildings, the study classified building types according to the EMS-98 system, providing a detailed understanding of building typologies and their vulnerabilities to seismic events in Iraq. A key contribution of this study is the modular classification framework, which enables an incremental refinement of vulnerability assessments in region with different level of data availability. This approach improves seismic risk assessment accuracy, especially in regions with limited data availability.

The findings revealed that 55% of the surveyed buildings are non-engineered, constructed with less adherence to engineering standards, thereby highlighting their vulnerability during seismic events. The dominance of unreinforced masonry and concrete block structures, coupled with the widespread use of reinforced concrete as the primary roofing material, underscores the critical need for structural retrofitting and enhanced construction practices. The spatial distribution of building types and vulnerabilities across Sulaimani revealed significant regional variations, reflecting differences in zoning strategies, construction trends, and material quality. By incorporating data from the 2017 Iran-Iraq border earthquake, the study further refines future damage modeling, integrating Peak Ground Acceleration (PGA) values and observed intensity levels into its analysis. This data, coupled with the survey responses on experienced damage and EMS-98 intensities, provides a valuable empirical basis for understanding building performance during seismic events.

The comparison of vulnerability distributions under optimistic and pessimistic scenarios illustrates the potential impact of material quality and construction practices on building resilience. The pessimistic scenario, in particular, serves as a vital tool for worst-case damage modeling, enabling targeted risk mitigation strategies and emergency preparedness measures. This research not only enhances our understanding of the seismic vulnerabilities in Iraq but also provides a systematic and scalable framework for future studies in similar regions. The digitized dataset and the methodology established in this study serve as critical resources for improving building codes, developing targeted retrofitting programs, and informing disaster risk management policies. By addressing the gaps in local data and integrating it into seismic hazard assessments, this study contributes significantly to improving Iraq's resilience to future earthquakes and fostering sustainable urban development in the region.

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