

EMPIRICAL SEISMIC ASSESSMENT OF URBAN SETTLEMENTS IN DEVELOPING COUNTRIES: CASE STUDY ERBIL (IRAQ)

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Abstract: *Urbanization in developing countries is often accompanied by inadequate surveillance, resulting in the increase of informal and non-engineered constructions, which are often associated with unsafe housing in regions affected by natural hazards, resulting in vulnerable and exposed communities. Following the World Housing Encyclopedia (WHE), this study seeks to enrich the knowledge of typical structures in Iraq by collecting and postprocessing building stock data from a survey performed in the City of Erbil. Moreover, the article serves as preliminary research to comply with one of the aims of the WHE, to explore the housing profiles from seismically active areas. The presence of Iraq's building taxonomies is yet to be added to the encyclopedia's database. In the past, the city has experienced several damaging earthquakes. This in addition to a diverse composition of building stock and continuous population growth, places the city in a vulnerable environment against seismic hazards where a quality model study could be extended to other regions. In this study a systematic documentation of the building stock data using a knowledge-based framework is performed following a Random Urbanization Method (RUM). A classification of building types is performed according to the EMS-98 guidelines, with adaptations to fit the typical construction techniques and materials used in Iraq. Vulnerability of surveyed buildings is assigned based on the EMS-98 vulnerability classes. The performed survey includes parameters to distinguish the non-engineered type of structures, information that is to be used in the future. In addition, the distinction between non-engineered and engineered buildings is further clarified by incorporating a survey question that addresses the involvement of professionals in the construction process, and a detailed evaluation of their composition was subsequently conducted. The preliminary results show that out of the 1.470 buildings surveyed, 45% can be classified as non-engineered primarily made of brick masonry and concrete blocks with flexible to semirigid diaphragms.*

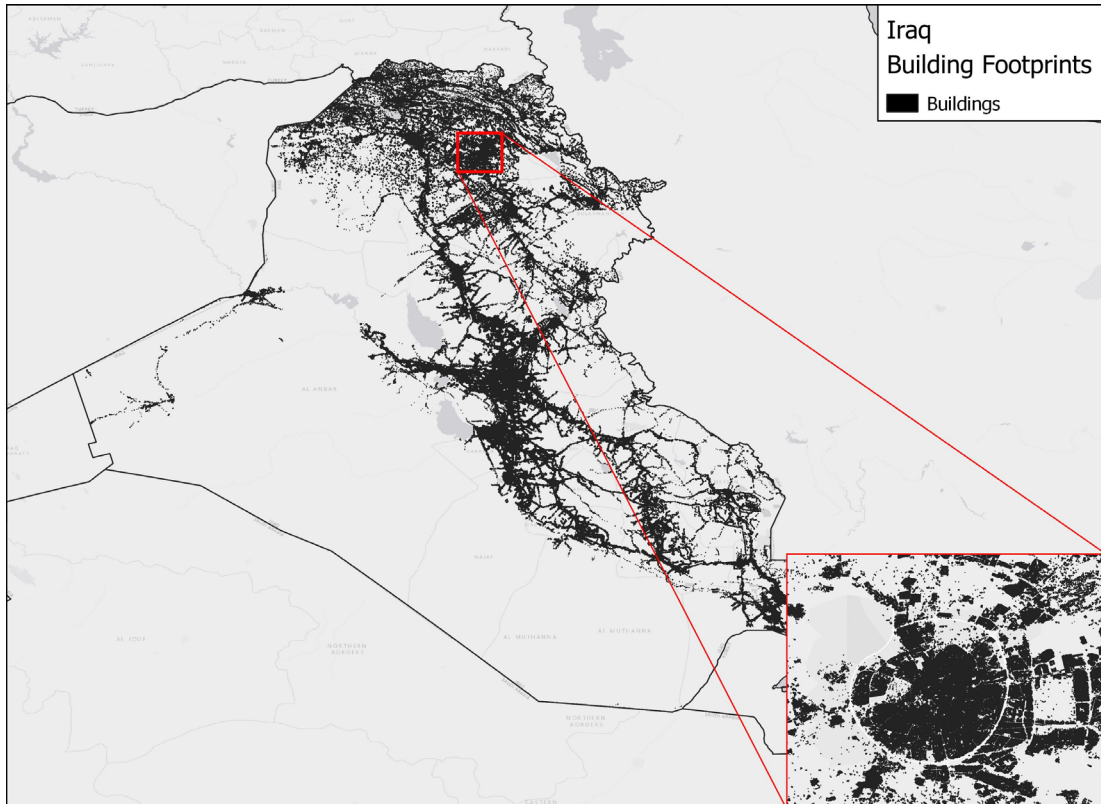
1 Introduction

Iraq 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. Due to Iraq's regional instability, the collection of geopolitical maps and building stock data have been neglected. This study is conducted to address the low level of data availability, especially with regard to building census data, where different levels of geological and geopolitical datasets are compiled from different studies, as well as the collection of building stock datasets through techniques of buildings stock surveys in the city of Erbil, Iraq as a study area to complete the knowledge of building census data in the region.

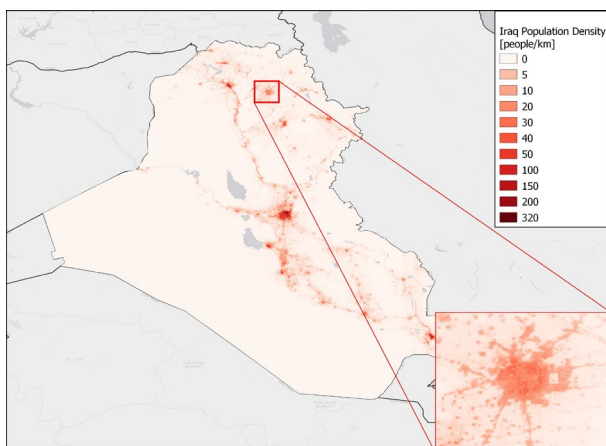
2 Case study

2.1 Geography and demography

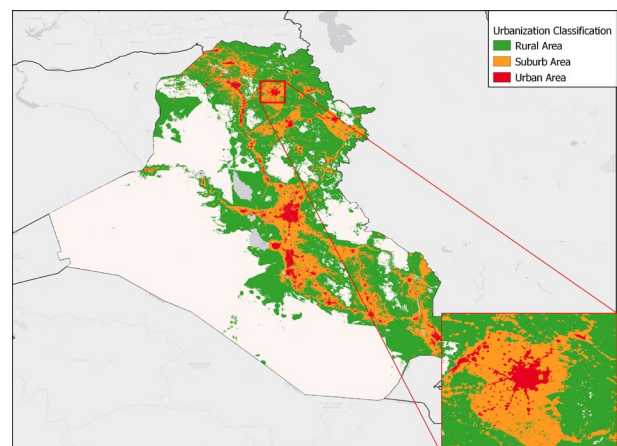
Iraq has a population of nearly 45 million individuals, living in a total area of 437,072 km², residing in over 19 governing states (World Population Review, 2023). Within this study, country's urban and rural areas are classified on the basis of building footprints and population density thresholds (see Figure 1) made available at a 1 x 1 km² grid (WorldPop, 2020). Moreover, while there are no accurate studies which map out or provide statistics of the number of buildings in Iraq, the Microsoft Planetary Computer (2023) has mined a total of 8,237,615 buildings using high quality satellite images and through recognizing building pixels on an aerial image using deep neural networks (DNNs).



a) Building footprints (Microsoft Planetary Computer, 2023).



b) Population density. (WorldPop, 2020)

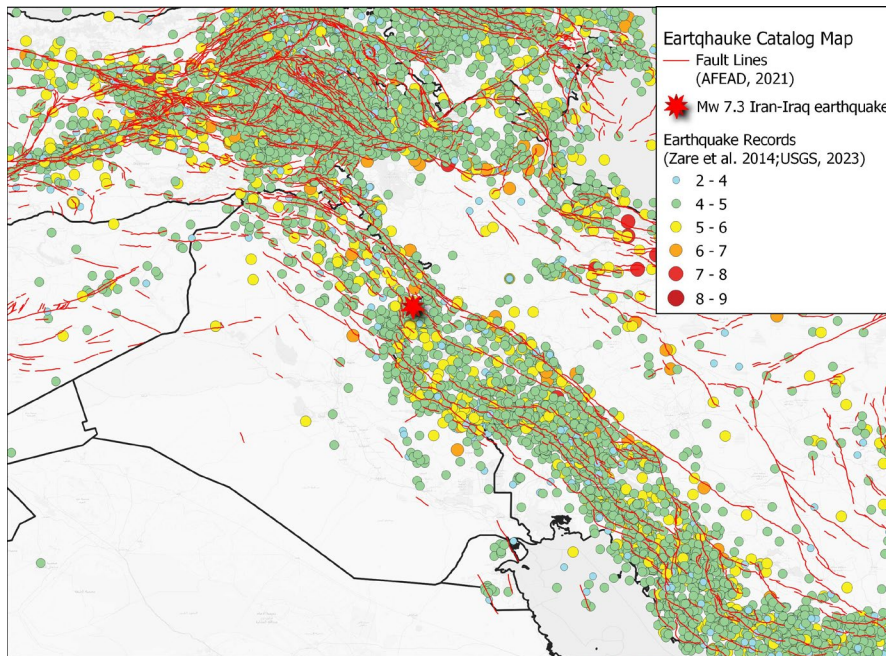


c) Urban-Rural classification.

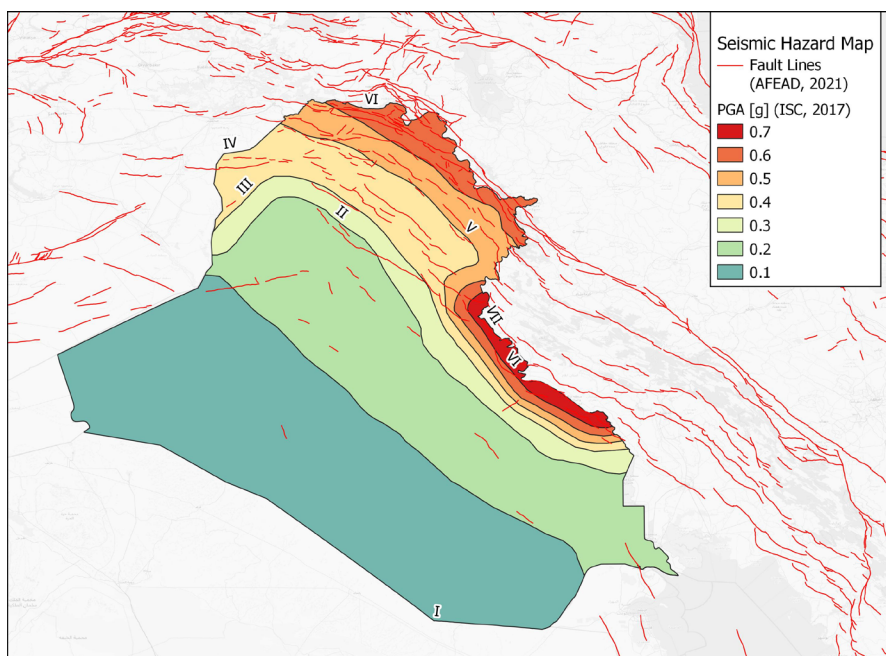
Figure 1. Demographic distribution of Iraq, visual representation to the distribution of the population and built environments within Iraq, highlighting the study area in a red square.

2.2 Earthquake catalogue and seismic code development

While an official earthquake catalogue for Iraq has not yet been released to date, numerous studies have focused on collecting historical instrumental and non-instrumental records of earthquakes that have affected the region (Zare et al., 2014; Omer et al., 2022; USGS, 2023), records of these events are visualized in Figure 2. The first Iraqi seismic code was published in 1997, which includes the preliminary seismic map developed by the building research centre of Iraq in 1988. Several updates have been made to the Iraqi seismic code, the next generation of seismic design code which is based on the International Building Code 2012 was published in 2017 (Iraqi Code Committee, 2017).



a) Earthquake catalogue (Zare et al., 2014; USGS, 2023).

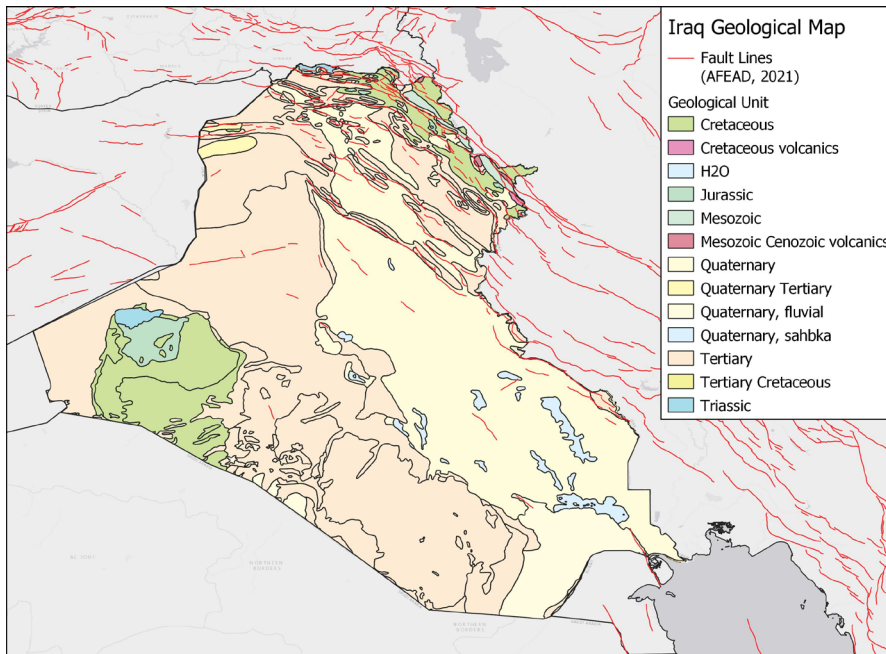


b) Seismic Hazard Map (Iraqi Code Committee, 2017).

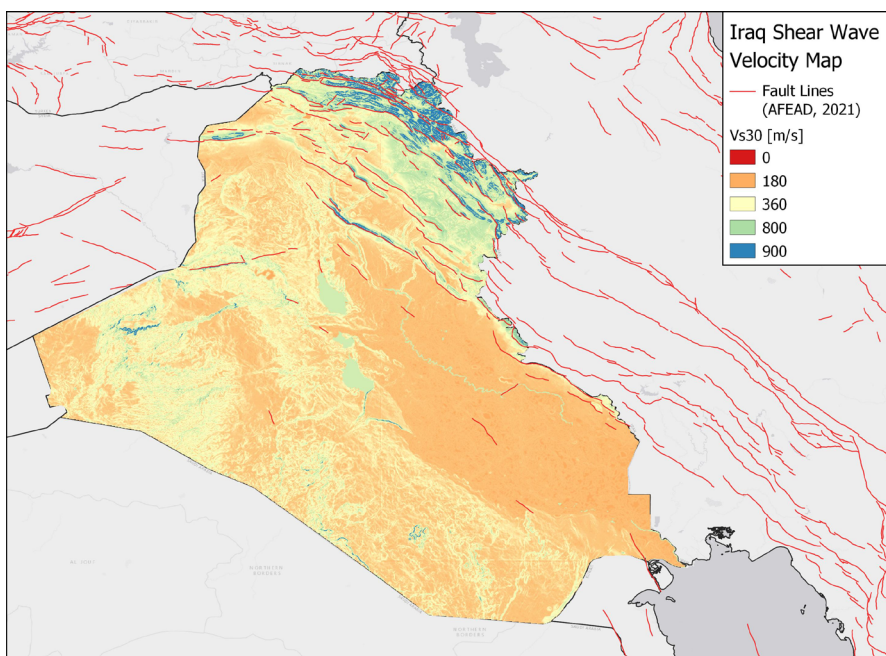
Figure 2. Comprehensive seismic zoning and historical earthquake catalog of Iraq.

2.3 Site effects

Iraq's geology is characterized by the significant Mesopotamian Basin, which contains sedimentary rock sequences ranging from the Precambrian to the Quaternary. These formations have made the region a major site for hydrocarbon exploration, with Iraq boasting some of the world's largest oil fields. Rock formations in Iraq span from the Precambrian to the present day, with Mesozoic rocks being especially crucial for oil exploration, the geological mapping has evolved over the decades due to collaborative efforts by both Iraqi and international experts Pollastro et al. (1999). As of the current date, a comprehensive soil study in the Erbil study area remains absent. Several initiatives are underway to examine the detailed microzonation with varying levels of data availability across different cities in Iraq, as documented by Ibrahim et al. (2024) see Figure 3.



a) Geological map of Iraq (Pollastro et al., 1999).



b) V_{s30} map (Becker et al., 2009).

Figure 3. Geology and microzonation studies for Iraq.

3 Building stock survey

3.1 Methodology

Systematic survey of building stock on a large scale requires significant organization of human resources. To optimize the efficiency of data collection for the study, senior undergraduate students (in their fourth year) were trained in the methodologies for building stock surveys, following the "Guidelines for Tagging Building Stock" (Beinersdorf, 2019).

After the training phase completed, the city of Erbil was segmented into multiple zones, according to the phases of urban development. Each zone was allocated to groups of students who were tasked with conducting field surveys within their designated areas (see Figure 5).

During these surveys, students collected key structural parameters and photographed the buildings (see Figure 4) selected based on random selection method, facilitating verifications and potential adjustments. Upon the completion of the data gathering phase, a thorough review and validation process was conducted. Data entries identified as incorrect were adjusted and uncorrectable entries were removed from the dataset. The processed dataset was used in the classification of the buildings within the region into distinct categories. Furthermore, each building was assigned a vulnerability class according to the EMS-98 (Grünthal et al., 1998). The methodology employed for executing the building survey in Erbil involved a structured series of steps, which are outlined as follows:

- Student Training: imparting necessary skills and knowledge to the participating students
- Urban Zoning: Study Area was divided into zones for systematic survey coverage.
- Data Gathering: Collection of relevant data from each zone.
- Data analysis: Review and examination and interpretation of the gathered data.
- Classification: Organizing data into defined categories



a) Engineered Masonry - Single Family Dwelling (EM-SFD)



b) Non-Engineered Masonry - Single Family House (NEM-SFD)



c) Multistorey Multipurpose Building



d) Highrise Building

Figure 4. Examples from representative building types.

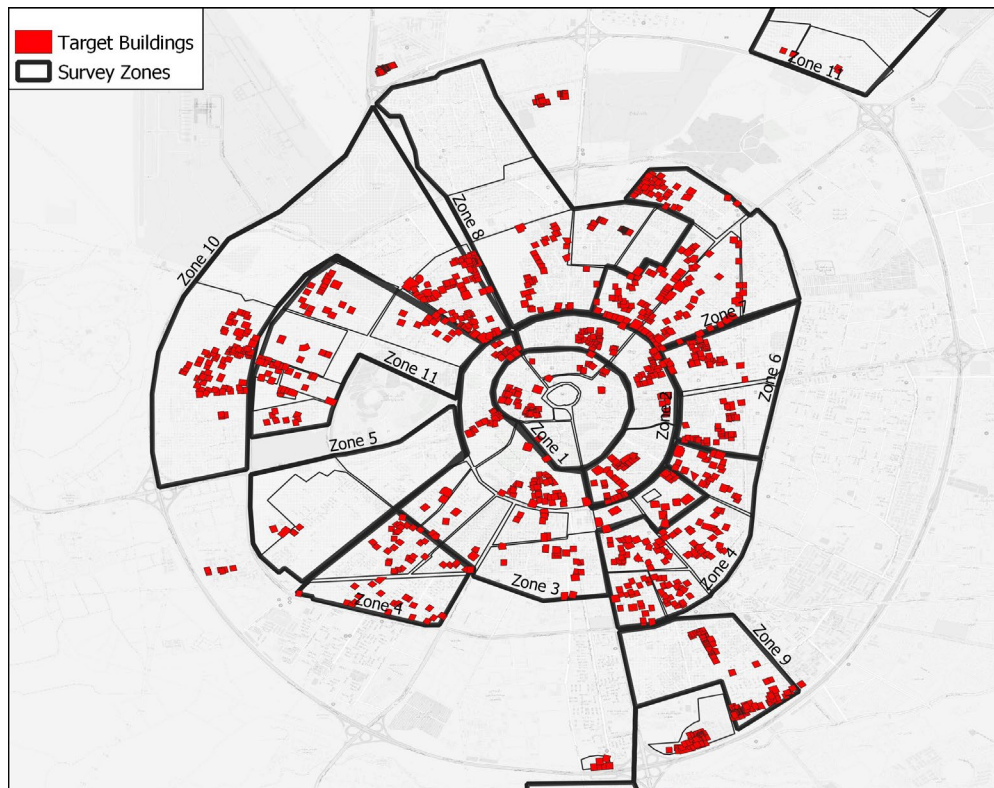


Figure 5. Study area by zones and target buildings selected for survey.

3.2 Definition of building types based on EMS-98 taxonomy

Following the procedure discussed by Lamadrid et al. (2023, 2024), the collected data was revised and summarized using 3 levels of detail as shown in Figure 7a. In such study, it is suggested that international building taxonomies can be transformed into EMS-98 (Grünthal et al., 1998) comparable building types. This is achieved in two stages, being the first one the identification of basic characteristics described by the EMS-98. This stage would refer to the assignment of vulnerability classes (VC) assuming one of three cases: the most likely, the pessimistic or the optimistic VC assignment; following the works from Abrahamczyk et al. (2013). The second stage refers to the engineering assignment of VC using six levels of detail to assign the most suitable VC within the EMS-98 proposed ranges given per building type. For the present study, a combination of both stages was implemented. On one hand a VC assignment was performed during the post-processing of the surveyed data, based on engineered expertise and observations. On the other hand, building types were identified based on material and structural characteristics, as well as correlated with the EMS-98 scheme.

For the first level of detail the buildings material was considered. With this categorization it was found that masonry is the dominant material within the studied building stock, followed by reinforced concrete and steel. For the second level of detail, structural characteristics were considered. In the case of masonry the type of masonry units was used as structural detail. A feature that can modify the seismic vulnerability of the building and therefore an important parameter taken from the field survey. Cement block being the most frequently found masonry units in Erbil. For reinforced concrete (RC), a distinction was initially made between vertical structural elements as done by the EMS-98: frames and walls. However, it was found that less than 0.5% of the sample could be identified with concrete walls, resulting in a classification that would only refer to RC frame structures. It is important to highlight that the survey includes information regarding masonry units found in RC infills, which should be considered for a VC assignment following Abrahamczyk et al. (2013) methodology. Nonetheless, this structural detail is here not addressed as no structural information aside from the load-resisting system is needed to identify EMS-98 RC types.

Table 1. Code level according to year of construction (Iraqi Code Committee, 1987; 1997; 2017)

Period of construction (or renovation)	Code Level (abbreviation)	Comments
<1997	Pre- (PC)	Seismic loads considered for design of RC structures
1997 - 2014	Low (LC)	First official seismic code (includes national seismic zones)
2014 - 2017	Moderate (MC)	Update [including Peak Ground Acceleration (PGA) maps]
>2010	High (HC)	Latest update

For the third level of detail, particular features from the EMS-98 descriptions were used to obtain the final comparable building type. For masonry structures, such features would imply the description of diaphragms, reinforcement or confinement. Considering this, masonry buildings were classified as reinforced or unreinforced. Finding that all surveyed cases with stone units were unreinforced. As preliminary observation it was assumed that all masonry with concrete units was reinforced (Type 3), as this is considered a typical construction detail from the region. This was later on confirmed through the post-processing of the data. It was also found that the rest of masonry (Type 1 and Type 2) did not have any reinforcement. Such reinforcement was also found in RC infills; however, it is here not further discussed.

For those masonry structures with unreinforced masonry units, it was necessary to identify the type of diaphragm for a direct EMS-98 correlation. This characteristic was not included in the survey as such detailed assessment of the building would imply the buildings' interior revisions, and most of the surveys consisted in exterior inspections. Nonetheless it is possible to assume, by experience, traditional masonry construction of the area includes the use of reinforced concrete slabs.

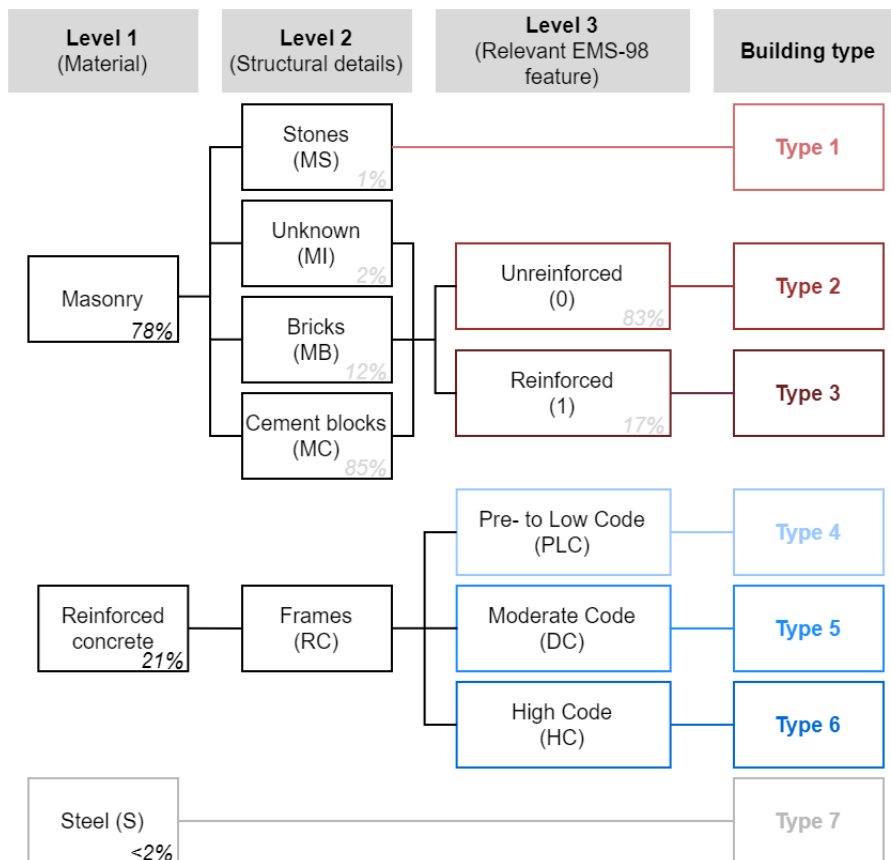


Figure 6. Information to define EMS-98 building types following workflow developed by Lamadrid et al. (2024).

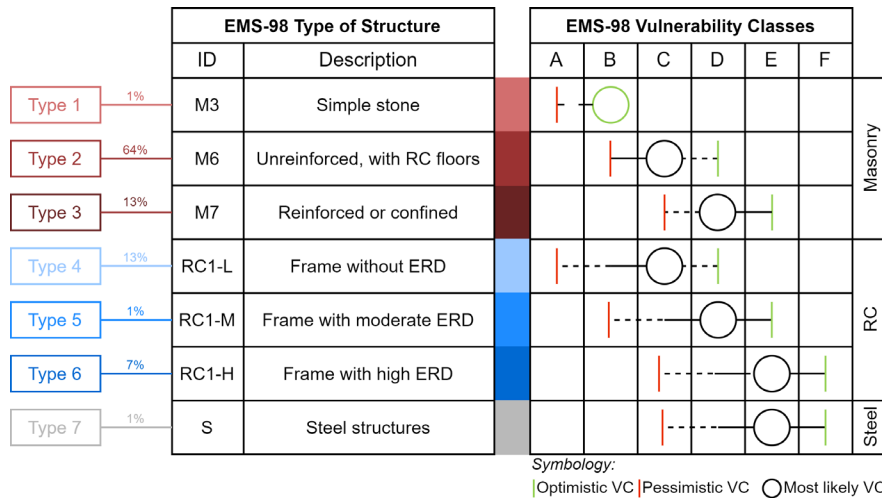


Figure 7. Classification of building types following EMS-98 scheme and lined to vulnerability classes (Lamadrid et al., 2024).

The earthquake resistant design level was considered as a relevant EMS-98 feature in reinforced concrete structures. The term used for the classification was code level, with four different classifications depending on the identified year of construction as shown in Table 1. Furthermore, it is here acknowledged that if a seismic design code is to be evaluated by the definition of classes identifying the level of earthquake resistant design, detailed investigation of limit states, spectra and implementation of the code is to be analyzed to have a fair evaluation of such code, a topic outside the scope of the present. As a result, Table 1 presents a simplified classification based on key points introduced or updated between code publications, in relation to seismic design. A detailed discussion regarding the topic can be found addressed by Haweyou et al. (2024).

Lastly, the identified building types were directly related to their equivalent EMS-98 types, with results shown in Figure 7. It is clear, that for vulnerability assignment the ranges of the EMS-98 may not represent an accurate description of the structural response of the studied sample as the composition and quality of materials is expected to differ from the European building stock. It is for this reason that further studies are necessary to study such possible variations.

3.3 Statistical overview

The final processed dataset contains 1470 buildings across 11 zones, The zones are divided based on the era of the city development as well the assumed type of buildings in the zone. The collected data provides a detailed overview of the building typology in Erbil, Iraq, including a variety of building characteristics such as type, construction year, height levels, and compliance with building codes. With a significant portion of the buildings being masonry types, it sheds light on predominant construction practices in the region. The inclusion of data on engineered and non-engineered buildings, along with their conditions, additional reinforcement and vulnerability classes, offers valuable insights into the structural integrity and potential seismic risks associated with these structures.

This dataset is a rich resource for understanding the housing typology in a specific urban context, contributing to the World Housing Encyclopedia resources. It allows for a comparative analysis of building practices over different periods, highlighting trends in construction methods and materials. The data on building conditions and vulnerability can inform guidelines for disaster resilience and retrofitting strategies, particularly relevant in areas prone to natural disasters. Additionally, collection of information such as number of occupancies in the building will be an additional parameter that can be used to quantify the uncertainties in Rapid Earthquake response estimated in SHAKEmaps. The insights derived from this dataset can aid policymakers, urban planners, and architects in devising informed, context-specific housing policies and construction standards to enhance the safety and sustainability of urban habitats.

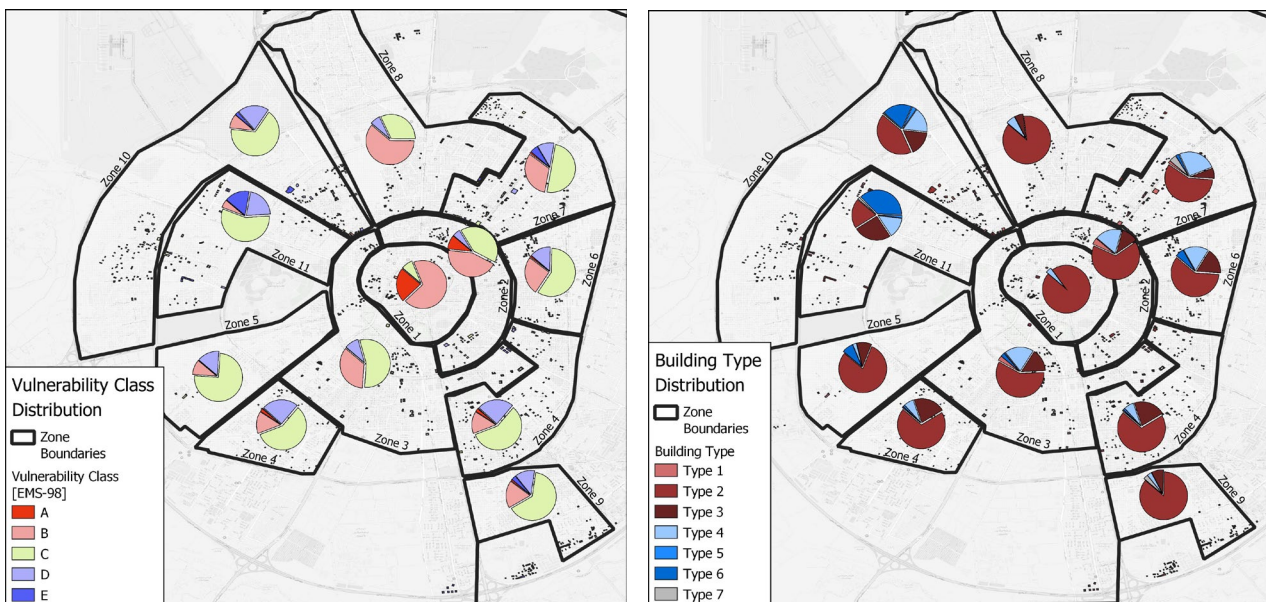
While the application of the EMS-98 guidelines as a starting point for classifying buildings in Erbil was insightful, it highlighted significant challenges due to the unique architectural and structural characteristics and construction practices in Iraq.

The EMS-98 classification, although effective in various global contexts, but not directly applicable for Iraq, efforts need to be done in the collection of the proper information such as confinement and diaphragm reinforcement. This limitation underscores the necessity for developing a regionally adapted classification scheme that can more accurately represent the diverse range of buildings in Iraq. Such a tailored approach is essential for enhancing the accuracy of seismic hazard assessments and the development of more effective mitigation strategies in this seismically active region.

In Figure 8, an elaborated geospatial representation outlines the variability of building vulnerability classes across outlined urban zones, utilizing pie charts overlaid on a map of Erbil to symbolize the distribution. The majority of the buildings across the zones predominantly fall within Vulnerability Class C, indicative of a moderate risk level according to the EMS-98 scale. Notably, the central zone diverges from this pattern, where buildings are primarily classified under Vulnerability Classes A and B, denoting a higher susceptibility to seismic events. As for the structural typologies, a substantial portion of the structures (i.e. predominantly Types 1 to 3) correlate with various masonry constructions, a typology inherently sensitive to seismic excitation. Furthermore, approximately 18 percent of these masonry structures are strengthened with supplementary confinement, such as retrofitting with beams and columns, potentially mitigating vulnerability. This detailed visualization underscores the heterogeneity of seismic risk within urban confines and is pivotal for targeted seismic reinforcement initiatives and optimized emergency response strategies.

Figure 9 presents probability distribution plots for key characteristics of buildings in the Erbil Building Survey Dataset. This dataset covers a diverse range of 39 characteristics, of which select ones such as 'Type/Use', 'Height Level', 'Year of Construction', etc., are visualized. For categorical variables (e.g., 'Type/Build', 'Building Type'), count plots are used to represent the frequency of each category. Numerical variables like 'Year of Construction' are shown using density plots, illustrating the spread of values over time. These characteristics are chosen for their relevance to understanding the architectural diversity and structural integrity of the building stock in the region. The plots collectively offer insights into the building stock of Erbil, underscoring variations in usage, structural features, and vulnerability - aspects vital for urban development and seismic risk management.

Following the definition by Narafu et al. (2010), non-engineered buildings can be distinguished from engineered ones depending on the quality of materials, the level of skills of the construction workers and the proper implementation of structural design during the construction process. As rapid urban growth takes place in many cities around the world (UN, 2023), it can be assumed that adequate housing is not economically feasible for all the population.



a) Vulnerability classes

b) Building types acc. EMS-98

Figure 8. Distribution of results from building stock survey across different zones in the city of Erbil, Iraq.

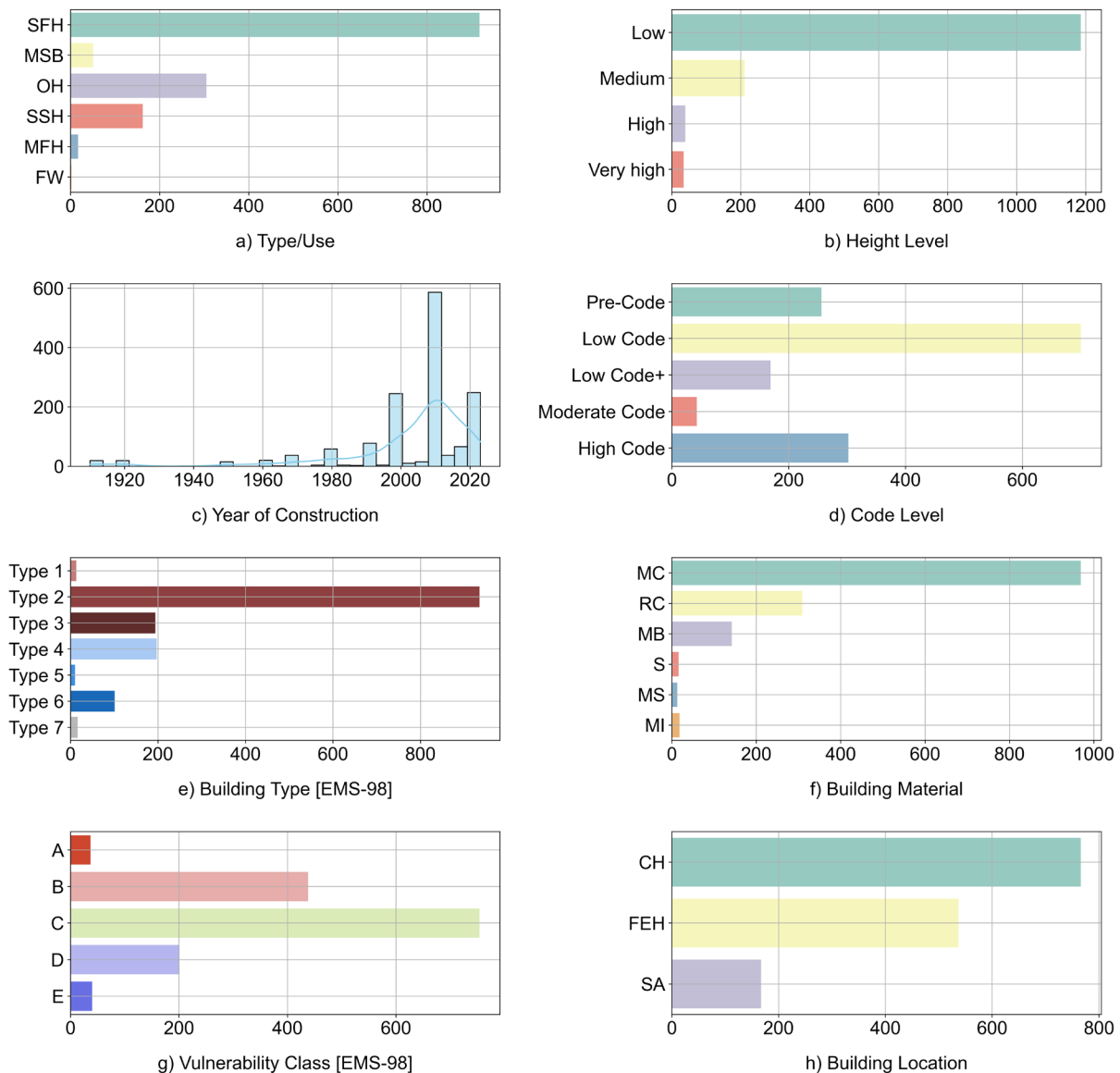


Figure 9. Distribution analysis of key building features in Erbil, Iraq.

Therefore, it can also be assumed that structural design is not always part of the construction process of single-family houses. In this direction, and to evaluate the presence of non-engineered structures in the target area, the survey included a question addressing the involvement of professionals in the construction of the inspected structures. With around 40% of the sample classified as non-engineered structures, it must be clarified that in some cases the presence (or absence) of structural design was confirmed through a consultation with property owners, while in some cases it was assumed due to exterior observations and the surveyors' acknowledgements of the common practices in the area (see Figure 4a and Figure 4b). It is also important to note that all identified non-engineered structures are located in formal settlements.

The sample classified as non-engineered was taken and a brief evaluation of the composition was performed, resulting in Figure 10. The height of the structure was classified according to building material. For masonry, low for 1 to 2 storey buildings, medium for 3 to 5 storey buildings and high for those with 6 or more storeys. Less than 0.5% of non-engineered masonry building were found with more than 4 storeys. For RC, those buildings with 5 to 10 storeys, were classified as high, while those with more than 10 were classified as very high.

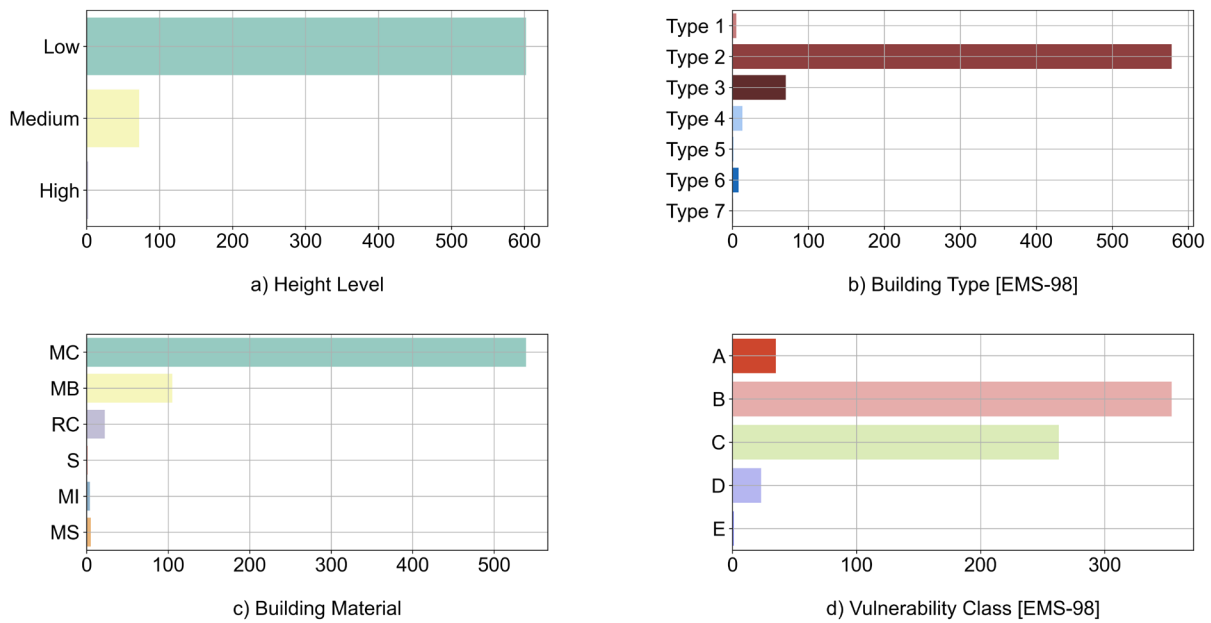


Figure 10. Distribution analysis of non-engineered structures in Erbil, Iraq.

4 Conclusions

This study provides a comprehensive analysis of the seismic vulnerability of the building stock in Erbil, Iraq, characterized by rapid urbanization. Through thorough documentation and analysis employing the Random Urbanization Method (RUM) and adapted EMS-98 guidelines, this research methodically documents and analyzes a significant portion of Erbil's building stock. Among the 1,470 buildings surveyed, a predominant construction pattern of concrete and brick masonry is observed. The classification of buildings into distinct categories and the subsequent vulnerability assessment according to EMS-98 classes provide a valuable framework for understanding the city's capacity to withstand seismic events. Moreover, the integration of geological, geopolitical, and urban development data has unveiled the complexities of seismic risk in an area marked by political instability and rapid, non-standardized urban growth.

This study also describes a clear typology of the local building stock into seven types, notably masonry and reinforced concrete structures, resonating with the structural features prevalent in Erbil as a starting point. The study bridges a significant gap in the World Housing Encyclopedia (WHE) coverage of Iraqi buildings. The comprehensive data and analysis of Iraqi buildings from this study provide a foundational framework for future WHE reports, enhancing the encyclopedia's coverage of seismic vulnerabilities in Iraq. Development of such a report, informed by the study's insights into structural vulnerabilities, could be contributory in understanding and addressing seismic risks in similar urban settings. Moreover, the study not only enriches the World Housing Encyclopedia with much-needed data on Iraqi buildings but also sets a precedent for future research.

Furthermore, the study focuses on non-engineered buildings, particularly those constructed with brick masonry and concrete blocks, which are prevalent in Erbil and likely other Iraqi regions. These buildings are notably susceptible to seismic events and should be a focus in seismic risk mitigation efforts. The integration of local construction practices into internationally recognized seismic vulnerability frameworks calls for a collaborative effort to tailor these models to Iraqi realities. This will be imperative for the development of informed, robust, and context-sensitive seismic codes and urban planning guidelines. As urbanization continues to outpace formal planning and engineering in Iraq, the implications of this research extend beyond academic discourse, extending to policymaking and disaster risk management, advocating for a proactive approach to urban resilience in seismically active regions.

5 Acknowledgment

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