URBAN SEISMIC VULNERABILITY IN BANGLADESH: AN ASSESSMENT OF RC BUILDINGS IN SYLHET CITY

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Urban Seismic Vulnerability in Bangladesh: An Assessment of RC Buildings in Sylhet City

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DECLARATION

We hereby certify that the work presented in this thesis is the product of our own joint work and that, to the best of our knowledge, it contains no material previously published or written by another person, nor material which has been accepted for the award of any other degree or diploma at Sylhet Engineering College, School of Applied Science and Technology, Shahjalal University of Science and Technology or any other educational institution, except where due reference and acknowledgement are made in the text. We further declare that the intellectual content of this thesis is the result of our collective effort, and all external contributions have been explicitly credited.

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Dedicated

to

"Our Beloved Parents"

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ABSTRACT

Urban areas in seismically active regions like Sylhet, Bangladesh, face significant risks due to building with varying levels of seismic resistance, yet a lack of detailed, validated vulnerability data at a local level impedes effective risk mitigation planning. This thesis addresses this critical gap by conducting a comprehensive seismic vulnerability assessment of 120 reinforced concrete (RC) buildings in Ward 13 of Sylhet City Corporation. To ensure a reliable and validated outcome, the assessment integrated the Seismic Vulnerability Index (SVI) simplified method with the Turkish Level I approach. The research framework encompassed systematic field surveys, the creation of a comprehensive GIS database, and the development of analytical models to figure out vulnerability, mean damage grades, and fragility curves. The study revealed a strong inverse correlation between the Vulnerability Index (I_v) from the SVI simplified method and the Performance Score (PS) from the Turkish method, confirming the concreteness of the assessment in consistently identifying the most at-risk structures. Key structural deficiencies, particularly soft-story mechanisms, plan and height irregularities, and poor apparent construction quality, were identified as the primary drivers of vulnerability within the local building samples. A significant outcome of this research is the development of a spatial vulnerability map that successfully delineates geographical hotspots where high-risk buildings are concentrated. Furthermore, fragility curves were developed to provide a probabilistic forecast of potential damage under various seismic scenarios. The findings provide a scientifically grounded and actionable basis for municipal authorities to prioritize retrofitting efforts, enhance building code enforcement, and improve disaster management planning, ultimately contributing to the seismic resilience of the urban environment in Sylhet.

ABBREVIATIONS

AQ	= Apparent Quality
ATC	= Applied Technology Council
BBS	= Bangladesh Bureau of Statistics
BE	= Edge Building
BIM	= Building Information Modeling
BM	= In-row Building
BNBC	= Bangladesh National Building Code
BS	= Base Score
DPM	= Damage Probability Matrix
EMS-98	= European Macroseismic Scale 1998
ERD	= Earthquake Resistant Design
G	= Corner Building
GIS	= Geographic Information System
GNDT	= Gruppo Nazionale per la Difesa dai Terremoti (Italian National Group for Earthquake Defense)
I	= Isolated Building
IoT	= Internet of Things
I_v	= Vulnerability Index
NL-THA	= Non-Linear Time History Analysis
PGA	= Peak Ground Acceleration
PGV	= Peak Ground Velocity
PS	= Performance Score
RC	= Reinforced Concrete
RVS	= Rapid Visual Screening
SA	= Spectral Acceleration
SCC	= Sylhet City Corporation
SVI	= Seismic Vulnerability Index
URM	= Unreinforced Masonry
VIM	= Vulnerability Index Method
VS	= Vulnerability Score
VSM	= Vulnerability Score Multiplier

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CHAPTER 1
INTRODUCTION

1.1 Background and Motivations

Earthquakes pose a threat to humanity as they become more destructive due to the growth of urbanization around the world's developing regions. In these areas where urban development outpaces preparedness efforts for disasters like earthquakes, according to Bilham (2019), the population is left vulnerable. Given this scenario highlighted by Paul & Bhuiyan (2010), evaluating the susceptibility of areas to seismic activity has shifted from being important to being crucial for safeguarding lives and livelihoods.

Bangladesh is situated at an intersection of several major tectonic plates and faces challenges as it falls within a region known for frequent seismic activity (Apu & Das, 2021). Looking back through its long history, the country experienced a pattern of enduring severe earthquakes that have resulted in noteworthy human suffering and economic hardships (Al Zaman et al., 2017; Kamal, 2013). The unbearable memories of disasters, like the 1918 Sreemangal earthquake, caused an estimated damage factor of 59% buildings, a maximum fatalities 7% at night and left millions homeless (Sarker et., 2010). In 2009, the Bay of Bengal earthquake, with a magnitude of 7.5, was strongly felt in Dhaka, causing widespread panic and tremors among residents, though no significant damage was reported (Islam et al., 2016). Such catastrophic events underscore the necessity for effective disaster risk reduction strategies tailored to local contexts (Pelling & Wisner, 2012).

The focus turns to Sylhet City Corporation (SCC), an area experiencing rapid urban development but also facing the looming threat of seismic activities (Mazumder & Salman, 2019). According to the World Bank (2023), approximately 40% of Bangladesh's population lives in urban areas, where Sylhet is a key hub for this demographic group as highlighted in reports. The rapid urban growth in these areas exacerbates vulnerabilities, as cities often expand without adequate planning for natural hazards (United Nations, 2018). Consequently, the effective management of seismic risk in Sylhet necessitates a deep understanding of the vulnerability inherent in its built environment, particularly within its dominant Reinforced Concrete (RC) building stock, as many of which were constructed without adherence to modern seismic codes or with insufficient quality control. This research, therefore, steps forward to address detailed assessments of their structural vulnerability, a gap that current generalized studies fail to address sufficiently.

1.2 Problem Statement

The need to carry out a vulnerability evaluation in the Sylhet City Corporation area arises from its geographic and socio-economic obstacles (Ara, 2013). Being one of Bangladesh's growing cities, Sylhet encounters the challenge of being at substantial risk for earthquakes because of its proximity to active tectonic fault lines. This is further complicated by the increasing dangers posed by its growth. Informal settlements and unauthorized construction practices have led to several buildings being susceptible to earthquakes in places around the world (Rahman et al., 2023). While there is a growing body of research on risks globally, there is still a gap when it comes to detailed studies focusing on urban areas in Bangladesh (Islam et al., 2016). Many current assessments tend to rely on approaches that struggle to capture the social and economic complexities of cities such as Sylhet.

Index-based vulnerability assessments have proven effective in classifying building types and assessing vulnerabilities in places like Lisbon (Xofi et al., 2024). However, a similar comprehensive approach has not been consistently used to analyse Sylhet's structure and its prevalent Reinforced Concrete (RC) buildings. The lack of research at this level hinders a deeper insight into the local manifestation of vulnerabilities and limits the effectiveness of disaster risk reduction efforts. Moreover, Geographic Information Systems (GIS), which have been extremely valuable in illustrating risk distribution in settings (Xofi et al., 2023), have not been fully utilized for creating detailed vulnerability maps in Sylhet yet. The absence of a vulnerability index to buildings in Sylhet's RC construction sector highlights a significant gap in research that this study aims to address. There is an evident requirement for information to inform policy-making at both local and national levels. To be well prepared for disasters and reduce vulnerability effectively requires an understanding of vulnerabilities in the community at hand.

1.3 Aim and Objectives

The primary objective of this study is to assess the earthquake susceptibility of Reinforced Concrete (RC) structures in Ward 13 of Sylhet City Corporation, utilizing the SVI simplified and Turkish Level I approaches. The primary purpose is to provide valuable insights and recommendations for effective disaster risk mitigation plans in the region. So, the study has been carried out with the following objectives:

1. To assess the seismic vulnerability of a selected area of Sylhet City.
2. To determine Mean Damage Grade and develop a Fragility Curve.
3. To develop a seismic vulnerability map of the surveyed area.

1.4 Scope of the Study

The study specifically looks at Ward 13 in Sylhet City Corporation to explore the vulnerability of Reinforced Concrete (RC) buildings using the SVI simplified along with Turkish Rapid assessment approach supported by field survey data and GIS spatial analysis methods. Around 120 typical RC buildings in this area will be assessed to gather reliable data for the study. In understanding this evaluation but focusing on aspects and gathered information instead of delving into intricate structural examinations or physical tests not within the current studies' practical limits; it is crucial to grasp the context of this analysis fully. Therefore, although the conclusions will reveal perspectives tailored to the selected structures, in Ward 13 of Sylhet City it is prudent to exercise caution when extending these outcomes to encompass all of Sylhet City without comprehensive inquiries.

1.5 Significance of Study

The significance of this research is twofold: academically, it adeptly addresses a critical lacuna in localized, detailed RC building vulnerability studies within Bangladesh, particularly for a high-risk urban centre like Sylhet. Practically, it aims to deliver actionable, spatially explicit data directly to local governmental bodies, urban planners, and disaster management agencies in Sylhet, thereby facilitating the formulation of more informed decisions regarding targeted mitigation interventions, prioritization of retrofitting initiatives, and the refinement of emergency response planning. Furthermore, it aims to increase awareness among building owners and the community by highlighting the risks in these structures to build a sense of readiness and resilience against future seismic dangers.

1.6 Organization of the Thesis

This thesis is structured into six distinct chapters, each addressing a specific aspect of the research in a logical sequence.

Chapter 1: Introduction provides the foundational context for the study. It outlines the research background, defines the problem statement, identifies key research gaps, and clearly states the objectives and scope of the work.

Chapter 2: Literature Review presents a comprehensive review of existing knowledge relevant to the study. It covers theoretical concepts of seismic vulnerability, discusses various assessment methodologies including the SVI and Turkish methods, and examines previous research conducted in similar contexts.

Chapter 3: Methodology details the systematic framework employed to achieve the research objectives. It describes the selection of the study area, the dual-methodology approach for data collection and analysis, the process for calculating vulnerability indices, and the techniques used for developing damage grades, fragility curves, and spatial vulnerability maps.

Chapter 4: Characteristics of the Surveyed Building presents the descriptive statistics of the sampled buildings. This chapter outlines the physical and functional attributes of the building, including age, height, and use, providing an essential baseline for the subsequent vulnerability analysis.

Chapter 5: Results and Discussion is the core analytical chapter of the thesis. It presents the detailed findings from both assessment methods, including a comparative analysis for validation, the derived fragility curves, and the spatial distribution of vulnerability. The discussion section interprets these results, highlighting the key drivers of seismic risk in the study area.

Chapter 6: Conclusion and Recommendations concludes the thesis by summarizing the key findings and their implications. It revisits the research objectives to highlight their fulfillment, acknowledges the limitations of the study, and provides actionable recommendations for future research and for stakeholders in urban planning and disaster management.

CHAPTER 2
LITERATURE REVIEW

2.1 Vulnerability Assessment

Vulnerability is defined as the degree of loss a component or system may experience when exposed to a specific hazard, quantified from 0 (no loss) to 1 (total loss) (Varnes & IAEG, 1984; UNDP, 1994, as cited in Sterlacchini, 2011). It can be categorized as high, moderate, or low based on the severity and geographic extent of expected impacts (NOAA, 1999).

i. High Vulnerability: An event occurring in such an area would result in severe impacts across large geographical extents or densely populated areas, incurring substantial financial repercussions for residents and businesses.

ii. Moderate Vulnerability: An event in this category would have confined impacts on the safety of residents and a discernible financial impact on residents and enterprises.

iii. Low Vulnerability: An event here would yield minimal impact on the safety of residents and negligible financial consequences.

Vulnerability assessment is essential for translating hazard exposure into actionable risk, requiring the evaluation of both structural and non-structural aspects such as population density, building stock, economic resources, and the environment (Schellnhuber, 2001; Cutter et al., 2000). Methods differ by scale and focus, including technical, community-based, and socio-economic perspectives, and are used to develop targeted strategies to reduce risk. Effective assessments consider not just hazard frequency but also differences in policy, infrastructure, preparedness, and demographic factors, as highlighted in Hazard Mitigation Plans and recent literature (Morrow, 1999; FDCA, 1997; Urban Regional Research, 1988). Long-term consequences such as socioeconomic disruption and environmental degradation are increasingly recognized, especially in rapidly urbanizing contexts like Bangladesh. As seismic events repeatedly reveal, understanding a region's specific vulnerabilities is foundational to both policymaking and disaster risk mitigation (Sterlacchini, 2011; Pelling & Wisner, 2012).

2.2 Vulnerability Assessment of Earthquake

Evaluating the seismic vulnerability of reinforced concrete (RC) buildings is crucial, especially in earthquake-prone regions where seismic design codes are emerging or inconsistently enforced (Ferreira et al., 2020). Improving the seismic resilience of RC structures is essential for ensuring both their operational functionality and the community's rapid recovery after an earthquake. Studies systematically examine and categorize assessment approaches into empirical, analytical, and experimental methods (Kazemi et al., 2023). Empirical techniques use observed data from previous earthquakes-such as historical damage databases—to estimate likely damage patterns. Analytical approaches involve computational simulations, generating fragility curves to quantify the probability of structural and non-structural damage as earthquake intensity increases. Experimental methods utilize physical tests, including shaking table and pseudo-dynamic tests, to validate modeling predictions and provide detailed insight into the behavior of RC structures under seismic loads (Masi & Vona, 2012).

Despite considerable progress, several challenges remain, such as limited access to quality data, computational constraints, and difficulties in realistically replicating earthquake scenarios in laboratory settings. Progress in this field requires the integration of advanced modeling techniques, regionally calibrated hazard characterizations, and enhanced experimental protocols. Addressing these gaps is vital to refine vulnerability assessment, improve existing and new RC building resilience, and strengthen overall disaster preparedness.

2.3 Relevant Research

Bangladesh lies in a seismically active region due to its proximity to the converging Indian and Eurasian tectonic plates. Multiple studies have identified the northeastern part, particularly Sylhet, as one of the most earthquake-prone zones in the country. The Geological Survey of Bangladesh and the Comprehensive Disaster Management Programme (CDMP) have marked Sylhet under Zone IV, the highest seismic risk zone in the Bangladesh National Building Code (BNBC, 2020). This inherent geological risk is amplified by rapid urban growth. This expansion has led to the widespread construction of multi-story RC buildings, often with insufficient adherence to seismic design codes, which significantly increases their vulnerability (Rahman et al., 2018).

Several scholars have conducted studies utilizing various approaches to ascertain the vulnerability of buildings in Sylhet (Ahmed et al., 2012; Mazumder et al., 2010). Multiple-level assessments of reinforced concrete frame structures using the Turkish Method were conducted in Sylhet City for educational institutes by Ahmed et al., 2012 and for residential buildings by Mazumder et al., 2010. Shadmaan and Popy's study used a multi-criteria decision-making approach known as the Analytical Hierarchy Process (AHP) to estimate the earthquake vulnerability of the Sylhet region (Shadmaan et al., 2023). Mazumder and Salman (Mazumder et al., 2019) estimated seismic damage by integrating RADIUS and GIS for the first time in Sylhet City. Damage to structures, as well as human casualties and injuries, was estimated by Ahmed et al., 2005 by using fragility curves for specific building types, and economic loss estimation by statistical methods was performed. Mazumder et al., 2011 worked on seismic risk analysis for some masonry and reinforced concrete school buildings of Sylhet City FEMA 310 method. Kairi & Ahmed researched to assess the seismic vulnerability of buildings in Srimangal, a town in the Sylhet region that experienced being the epicenter of the 1918 earthquake. They checked the applicability of the reliability-based model proposed by Shiga, T. (1977) and Shibata, A. (1980) for the Bangladesh context (Ashishbroto & Nuruzzaman, 2014). Seismic assessment of mid-rise RC buildings in Sylhet City was performed by Wahid et al. using 3 levels of the Japanese Index Method (Wahid et al., 2020). Mazumder and Ahmed used FEMA 154 to assess the vulnerability of reinforced concrete frame buildings in Ward (administrative units under a City Corporation) no. 9 in Sylhet City (Mazumder et al., 2010).

Given its high-risk profile, Sylhet City has been the subject of several key studies aimed at assessing the seismic vulnerability of its building inventory. A foundational report by the CDMP in 2009 provided an early, broad-stroke understanding of seismic risk across major Bangladeshi cities, including Sylhet, by adapting the HAZUS software package with country-specific data (Center, A. D. P. 2009). More detailed, ward-level research followed. A frequently cited study by Mazumder et al. on 194 RC frame buildings in Ward No. 9 employed a two-tier assessment. Their rapid visual screening found 26% of buildings had a low performance score, while a more detailed analysis revealed that 31% were in moderate to high-risk categories, with vulnerability increasing with building height.

A recent study by Kabir (2025) focused on 320 buildings in Ward No. 1 using the Modified Turkish Method. It quantified significant structural deficiencies, noting that 63 buildings had soft stories and 199 had short columns, and estimated that for a PGA value of 1g, 230 buildings would likely be damaged. Complementing this, research by Islam & Rahman in the densely populated Ward No. 14 highlighted that 42.8% of buildings were RC frame structures and estimated that a major earthquake could lead to 147 to 603 fatalities and approximately TK. 32.00 crore in building damage. Further demonstrating the application of screening tools, a study by Islam et al. (2024) used the Visual Rating (VR) method on twelve RC buildings in Sylhet. The study identified two vulnerable buildings, recommending them for more detailed seismic evaluation and confirming the utility of rapid assessment for initial prioritization.

2.4 Vulnerability Assessment Methods

Seismic vulnerability assessment methodologies are frequently grouped into three key categories: empirical/qualitative, analytical/quantitative, and experimental methods (Kassem et al., 2020).

2.4.1 Empirical and Qualitative Methods

Empirical methods rely on observed data from past seismic events, expert judgment, and rapid survey tools. These are cost-effective and scalable for large numbers of buildings. Notable approaches include Rapid Visual Screening (RVS) and the use of Damage Probability Matrices (DPMs).

Rapid Visual Screening (RVS): Developed by ATC (2009), RVS allows trained assessors to quickly categorize buildings using checklists, noting irregularities, evidence of past damage, and construction type. Its strengths are speed and low cost, but depth and predictive accuracy are inherently limited (FEMA, 2002).

Damage Probability Matrices (DPMs): DPMs utilize statistical correlations between ground motion intensity (e.g., Modified Mercalli Intensity) and observed damage states. Developed mainly from post-earthquake surveys (Giovinazzi & Lagomarsino, 2004), they remain central to loss estimation and risk mapping, particularly for large urban areas.

2.4.2 Analytical and Quantitative Methods

Analytical methods explicitly model the seismic response of structures using engineering principles and computational tools.

Nonlinear Static (Pushover) Analysis: This method incrementally applies lateral forces to a building model, tracking deformation and strength degradation. It identifies weak points and potential collapse mechanisms while quantifying the building's reserve capacity under increasing seismic demand (Fajfar, 2000).

Nonlinear Time History Analysis (NL-THA): NL-THA offers a dynamic, step-by-step simulation of response to actual or synthetic earthquake records. It captures complex phenomena like inelastic deformation, material deterioration, and higher mode effects, providing the most detailed predictions but at a significant computational cost (Rathod et al., 2020).

Development of Fragility Curves: Analytical simulations can be used to develop fragility curves—probabilistic relationships illustrating the likelihood that a building reaches or exceeds certain damage states as a function of seismic intensity measures (e.g., PGA, SA). These are foundational for quantitative risk assessments and loss estimations (Calvi et al., 2006).

2.4.3 Experimental Methods

Experimental methods involve physical testing to directly measure the seismic performance of components or entire structures. Shake Table Testing: Full- or reduced-scale models are subjected to recorded earthquake motions. These experiments provide insights into dynamic response, validating analytical assumptions and helping refine seismic codes (Mangliulo et al., 2012). Pseudo-Dynamic and Quasi-Static Cyclic Testing: Pseudo-dynamic tests blend analytical calculations for inertia with experimental measurements for restoring forces, while quasi-static tests apply repeated reversals of displacement. Both allow for detailed study of deformation, strength, ductility, and failure modes of connections and elements (Ozkaynak et al., 2011).

2.5 Empirical and Index-Based Seismic Vulnerability Assessment Methods

Empirical and index-based methodologies are especially valued for their efficiency when evaluating large building stocks.

2.5.1 Damage Probability Matrices

DPMs classify buildings' expected performance for a given intensity through statistical tables. These are particularly useful in hazard mapping for urban or regional analysis but rely on the availability and quality of post-disaster survey data for calibration (Giovinazzi & Lagomarsino, 2004).

2.5.2 Vulnerability Index Methods

Vulnerability Index Methods use a structured approach to rank relative susceptibility by scoring key structural and non-structural features.

2.5.2.1 *GNDT Method (Italian Method)*

Overview: The GNDT method involves two levels of survey. GNDT Level I offers a rapid qualitative assessment based on visible attributes (e.g., number of stories, construction era), while Level II is a semi-quantitative, parameter-driven assessment using in-depth field forms (Benedetti et al., 1988). This approach is widely used in Italy and has been adapted internationally, including for RC frames.

Parameters and Weighting: GNDT Level II assesses parameters such as the load-resisting system, regularity, presence of soft stories, infill conditions, quality of materials, plan configuration, and foundation type. Each is scored and weighted according to its seismic importance (Lagomarsino, 2006).

Vulnerability Index Calculation: For each building, a total vulnerability index (I_v) is calculated as the weighted sum of assessed parameters. The raw index, typically 0-600, is normalized to a 0-100 scale to rank vulnerability and enable mapping across regions (Ferreira et al., 2020).

2.5.2.2 *The European Macroseismic Scale (EMS-98) and RISK-UE*

EMS-98 directly matches building typologies (e.g., RC frame with infill, masonry box, precast) to vulnerability classes (A-F), each associated with damage descriptions and thresholds for different seismic intensities. The RISK-UE project extends EMS-98 to urban areas, allowing rapid estimation of probable losses considering building type distribution and local seismic hazard (Milutinovic & Trendafiloski, 2003).

2.5.3 Rapid Visual Screening (RVS)

As above, RVS methods—used in Turkey, Italy, the US, and elsewhere—classify buildings based on observable seismic deficiencies. The Turkish method, for example, evaluates the presence of shear walls, plan and vertical irregularities, construction quality, soft stories, and infill conditions. Points or penalties are assigned for each deficiency, summed into an index guiding prioritization for further engineering investigation or retrofitting (Yakut, 2004).

2.6 Analytical Assessment and Fragility Curves

Where detailed data and computational resources are available, analytical assessments yield more nuanced risk characterizations.

Nonlinear Analysis: Analyzing RC buildings under seismic loading requires modeling nonlinear (inelastic) behaviour. The pushover method and time history analysis, as outlined earlier, provide critical insights into the reserve capacity and damage progression of buildings, supporting performance-based design (Rathod et al., 2020).

Fragility Curves: Analytical or hybrid approaches develop fragility curves for specific building typologies. These express the probability that a structure exceeds defined damage limits under increasing seismic demand, allowing risk to be mapped probabilistically and used for scenario analysis or insurance loss modeling (Cherif et al., 2017).

2.7 Integration of Methods and Technological Advancements

Hybrid Approaches: Integrating empirical, analytical, and experimental approaches lies at the frontier of risk assessment. Hybrid methods use field data to inform or calibrate analytical models or fragility curves, improving reliability where local construction does not align with international typologies (Ortega et al., 2024).

Geographic Information Systems (GIS): GIS applications are increasingly crucial in managing large sets of vulnerability data, mapping risk spatially, and supporting response planning. Sophisticated GIS layers can relate individual building scores (from GNDT Level II, RVS, or similar) to hazard data, enabling authorities to prioritize interventions (Del Gaudio et al., 2014).

2.8 Comparison of Assessment Approaches

The choice between empirical, analytical, or experimental methodology depends on data availability, building stock size, resource constraints, and project scale. Empirical/index-based approaches (e.g., GNDT, RVS) are rapid, economical, and scalable, but may lack accuracy or specificity. Analytical methods (pushover, fragility curves) offer detail and predictive insight but are resource- and skill-intensive. Experimental methods provide the highest fidelity understanding of behavior but are feasible only for select research cases due to cost and logistics.

Hybridizing these approaches allows practitioners to benefit from each method's strengths: starting with rapid screening, followed by an in-depth study of critical cases.

2.9 Research Gaps

A comprehensive review of the existing literature on seismic vulnerability assessment, both globally and within the context of Bangladesh, reveals several key gaps that this thesis aims to address:

1. **Lack of Localized, High-Resolution Vulnerability Studies:** While seismic vulnerability has been studied in major Bangladeshi metropolises like Dhaka and Chattogram, there is a notable scarcity of detailed, ward-level vulnerability assessments for other seismically active urban centers such as Sylhet. Most existing research is either national in scope or lacks the granular detail required for effective local-level disaster risk reduction planning.
2. **Limited Comparative Application of Assessment Methodologies:** The majority of studies conducted in Bangladesh typically employ a single assessment methodology. There is a significant gap in research that applies and compares the outcomes of two distinct methods—such as a detailed quantitative index (SVI simplified) and a rapid screening protocol (Turkish Method)—on the same building stock. Such a comparative approach is critical for validating results and understanding the strengths and limitations of each method within the local construction context.
3. **Disconnect between Academic Research and Actionable Planning Tools:** Many academic studies on seismic vulnerability conclude with generalized recommendations but often stop short of producing practical, user-friendly tools for municipal authorities. There is a need for research that translates complex vulnerability data into clear, spatially defined outputs, such as a GIS-based seismic vulnerability map, which can be directly integrated into urban planning and emergency management frameworks by city corporations.

This thesis directly addresses these gaps by conducting a detailed, dual-method seismic vulnerability assessment in a specific ward of Sylhet City, identifying critical local parameters, and culminating in the development of a practical vulnerability map to support targeted risk mitigation efforts.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter delineates the methodological framework adopted for the seismic vulnerability assessment of reinforced concrete (RC) buildings within the designated urban study area. The following sections describe a sequential and rigorous process that integrates empirical survey instruments, direct field investigation, and advanced data analysis. A comparative dual-method strategy was employed: both the Seismic Vulnerability Index (SVI) simplified and the Turkish Level I assessment approaches were systematically applied to the building. This parallel implementation facilitated both the validation and the cross-examination of results, thereby contributing to a more robust and contextually sensitive understanding of earthquake vulnerability. The chapter is organized to detail each phase, starting from preliminary planning through to fieldwork, data handling, index computation, and spatial analysis. The adopted methodology is intended to be transparent, reproducible, and adaptable, addressing gaps in the literature related to empirical method calibration in diverse urban environments.

3.2 Methodology Overview

A multi-phase methodology was applied to accomplish the detailed comparative vulnerability assessment. The process started with the mapping and selection of the study area, followed by inventorying buildings of interest based on established criteria. Desk studies and reviews of technical documentation were first conducted to gather baseline information. Then systematic on-site inspections were performed, with standardized survey forms tailored for each method (eight-parameter index and Turkish method). All field and desk data were catalogued and digitized for further processing. Analytical calculations were subsequently performed to generate vulnerability indices and categories, with rigorous quality control at each stage. Finally, results were geospatially mapped and interpreted in the context of the urban setting. Figure 3.1 below presents the workflow as a flowchart, illustrating the entire process from initial planning to output generation.

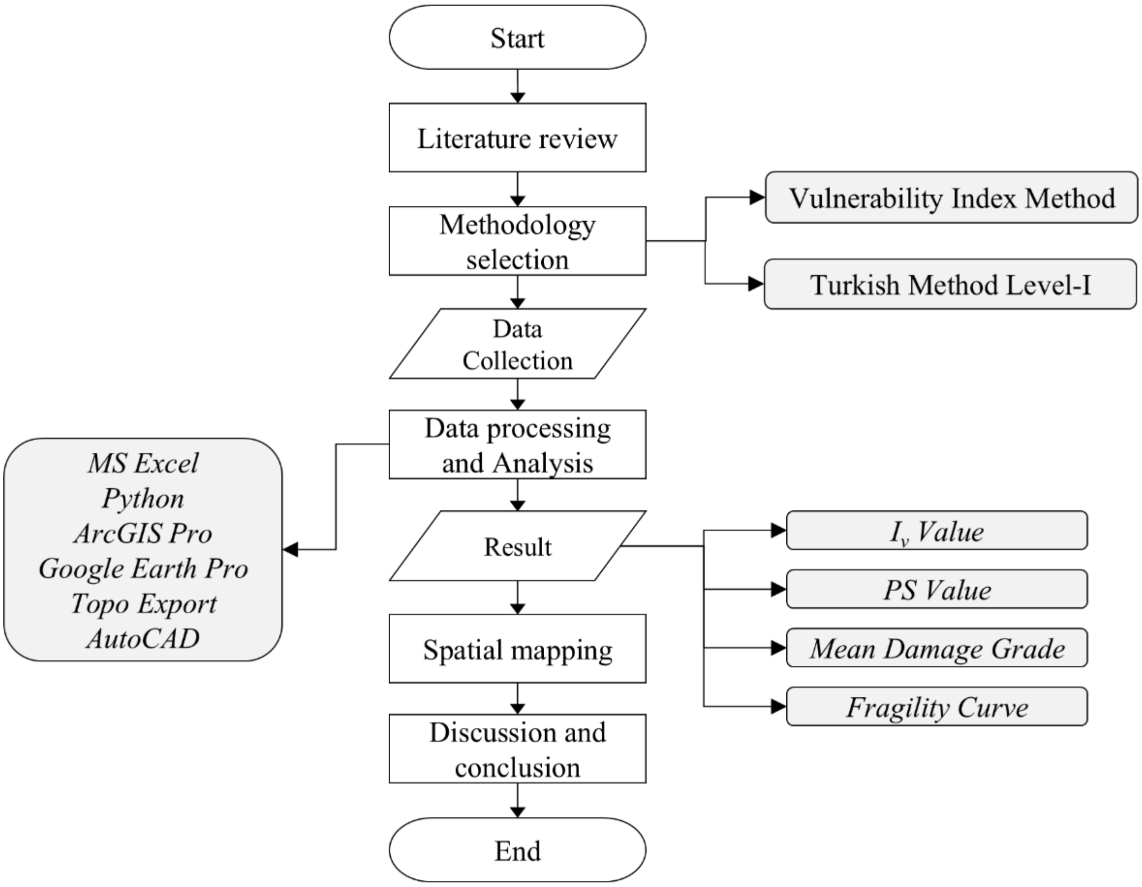

Figure 3.1: Flowchart of the thesis work.

3.3 Study Area

Sylhet, the fifth administrative division of Bangladesh, is situated near the northeastern border of the country. Covering an area of 3,452.07 km², the district has a population of 3,857,123, according to the 2022 Population and Housing Census (BBS, 2022). Sylhet City Corporation (SCC) is situated between the latitudes 24°36' and 25°11' north and the longitudes 91°38' and 92°30' east (BBS, 2022) on the northern bank of the Surma River and serves as the administrative center of the district. The SCC is divided into 27 administrative wards and has experienced rapid urbanization, making it one of the most densely populated cities in Bangladesh. Between 2001 and 2022, the population surged from 2,555,566 to 3,857,123 (Ara, 2014; BBS, 2001, 2022). A significant portion of the buildings in this area were constructed without adherence to seismic building code standards (Ara, 2014).

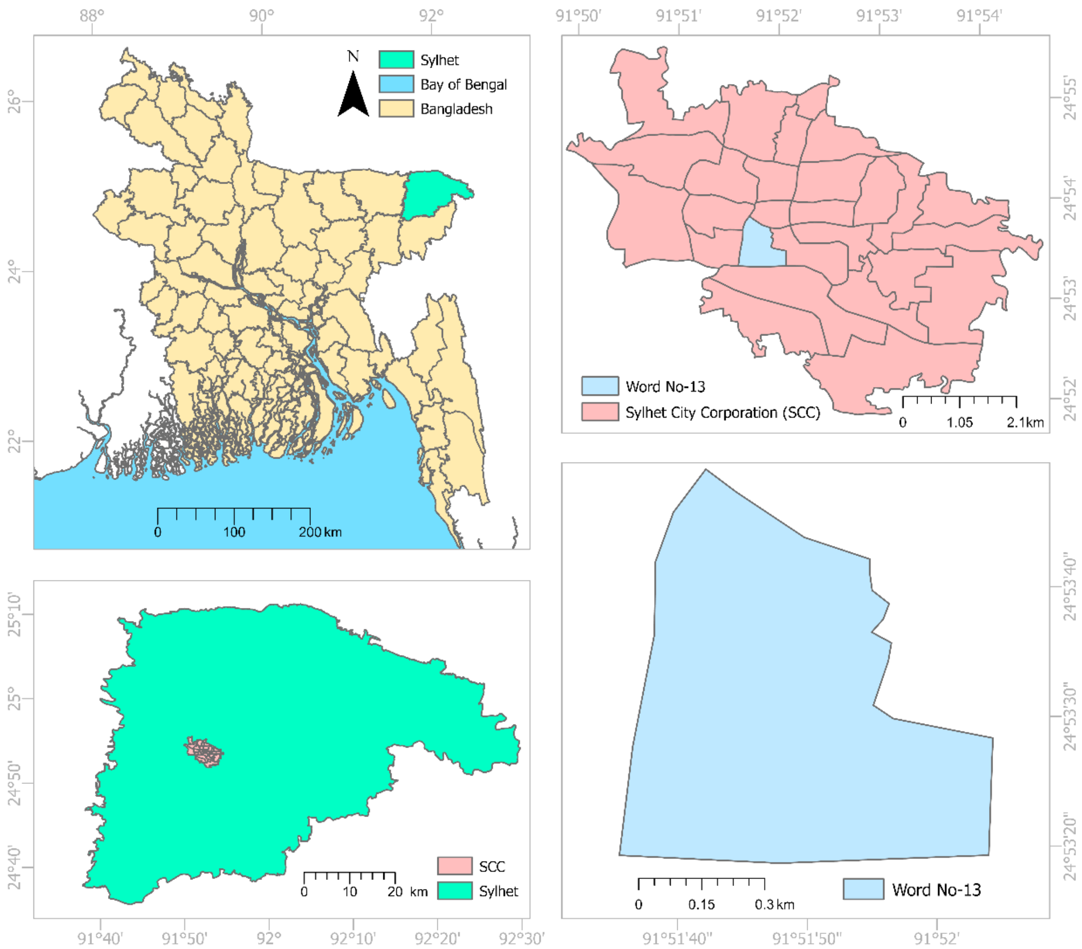

Figure 3.2: Study area maps of Ward no-13, SCC

For this research, Ward 13 of Sylhet City Corporation was purposively selected as the case study area due to its pronounced heterogeneity in building typologies, high density of both residential and critical functional structures, and ongoing construction activities that reflect typical urban development patterns observed across Sylhet. Notably, this ward encompasses older neighborhoods with numerous medium- and low-rise reinforced concrete buildings, many of which were constructed before the enforcement of seismic design provisions. Ward 13 presents a representative range of Sylhet's structural vulnerabilities in a manageable study area. Its high-activity, mixed-use makes it highly significant regarding potential seismic risks to both life and the economy. The selection of Ward 13, therefore, provides not only an opportunity for methodological application but also ensures that the findings are relevant for prioritizing mitigation strategies in other similarly composed urban districts within Sylhet.

3.3.1 Sampling

According to the 2022 Bangladesh Bureau of Statistics (BBS), Ward 13 contains a total of 2,316 buildings, within which 1,468 are reinforced concrete (RC) structures, 834 are tin shed constructions, and the remainder comprises other categories, including traditional, semi-pucca, and mixed-type structures. Given the large population of RC buildings and the logistical constraints inherent in detailed field-based vulnerability assessment, a representative sample was necessary to ensure the feasibility and manageability of the study while maintaining statistical validity. In determining an appropriate sample size for the field survey, both methodological rigor and practical feasibility were considered. For accurate representation, a sample size calculation was employed utilizing the following standard formula for surveys:

$$n = \frac{p(100-p)z^2}{E^2} \tag{3.1}$$

Where:

n = required sample size,
p = estimated percentage occurrence of the attribute under study (taken as 50% for maximum variability),
z = z-score corresponding to the desired confidence level (1.96 for 95% confidence),
E = is the margin of error expressed as a percentage.

For this study, values were chosen as follows:

p = 50; z = 1.96; E = 9

Substituting these values into the formula:

$$n = \frac{50 \times (100-50) \times (1.96)^2}{9^2} = \frac{9604}{81} \approx 119$$

Based on this calculation, a minimum sample size of 119 RC buildings was required to achieve a margin of error of approximately 9% at a 95% confidence level. In practice, 120 RC buildings were randomly selected for the survey, representing 8.2% of the RC building population in Ward 13. This proportion aligns with contemporary research standards for urban field surveys of this scale (Taherdoost, 2017; Nundy et al., 2022). Stratified random sampling was used to select a representative sample, ensuring the vulnerability assessment has the statistical validity and generalizability required for effective urban risk management.

3.4 Survey Form Design and Structure

The collection of field and documentary data in this study relied on two standardized survey forms, each tailored to one of the adopted vulnerability assessment methods: the eight-parameter index approach and the Turkish rapid assessment method. Meticulous survey form design was essential to ensure consistency, replicability, and the comparability of results between methodologies.

3.4.1 Eight-Parameter Index Survey Form

The eight-parameter index survey form was developed to systematically capture critical building features affecting seismic vulnerability. Each surveyed reinforced concrete (RC) building was evaluated against eight key parameters, each with defined vulnerability classes (A-D) and assigned weights, based on a combination of international best practice and extensive post-earthquake reconnaissance studies (Ferreira et al., 2020).

Table 3.1: Seismic Vulnerability Assessment Parameters with their classification

Code	Parameter	Description	Example Classes (A-D)
P1	Building implantation	Considers site, foundation, and soil class according to BNBC 2020	A: Good soil/robust foundation, D: Poor soil/slopes
P2	Building position	Relation to adjacent buildings (isolation, pounding risk)	A: In-row/constrained, D: Isolated/corner/pounding risk
P3	Building age	Construction era/seismic code compliance	A: After seismic code, D: Pre-code construction
P4	Irregularity in plan	Shape, regularity, potential for torsional amplification	A: Regular plan, D: Strong irregularity
P5	Irregularity in height	Vertical setbacks, sudden changes in mass/stiffness	A: Regular silhouette, D: Marked irregularity/soft story
P6	Soft-story mechanism	Presence of weak/soft stories, typically open ground floors	A: No soft story, D: Apparent soft story
P7	Short columns	Partial infills leading to vulnerable short columns	A: No short columns, D: Widespread short columns

P8	Presence of other vulnerable elements	Non-structural/brittle features (e.g., balconies, appendages)	A: Absent, D: Highly vulnerable elements present

Parameter definitions and rating guidance derived from Seismic Vulnerability Assessment of Existing Reinforced Concrete Buildings in Urban Centers (see full survey form in Appendix A).

Each parameter was rated during the site visit on a scale from A (least vulnerable) to D (most vulnerable), with clear guidance provided for each class. Corresponding weights, reflecting the relative importance of each parameter as established in empirical literature, were applied in the calculation of the final vulnerability index. The form included a field for the confidence level of each entry (direct observation, document-based, or extrapolation), thus allowing for data transparency and post-survey uncertainty analysis.

3.4.2 Turkish Level I Assessment Survey Form

In parallel, the Turkish rapid assessment survey form was utilized, which is widely recognized for rapid vulnerability screening of RC buildings in Turkey and similar contexts. Each observed vulnerability or deficiency was assigned a penalty point following Turkish assessment guidelines. The total penalty score for each building determined its vulnerability class (e.g., low, moderate, high) according to Turkish national standards.

Careful form design allowed standardized documentation of observed or reported features and for the annotation of cases in which scores were estimated due to inaccessible areas, consistent with international rapid-assessment best practice (Yakut, 2004). Both survey forms were pre-tested in a pilot phase for clarity, completeness, and usability. Surveyors underwent dedicated training sessions to ensure reliable and unbiased classification, as recommended in a recent survey methodology literature (Taherdoost, 2017).

3.4.3 Form Use and Integration

Completed forms were checked daily for completeness and accuracy. Both paper-based and digital versions were used, depending on site conditions and team preference. Data from both forms were subsequently entered into the project database for joint processing and analysis, as described in the next section.

3.5 Data Collection

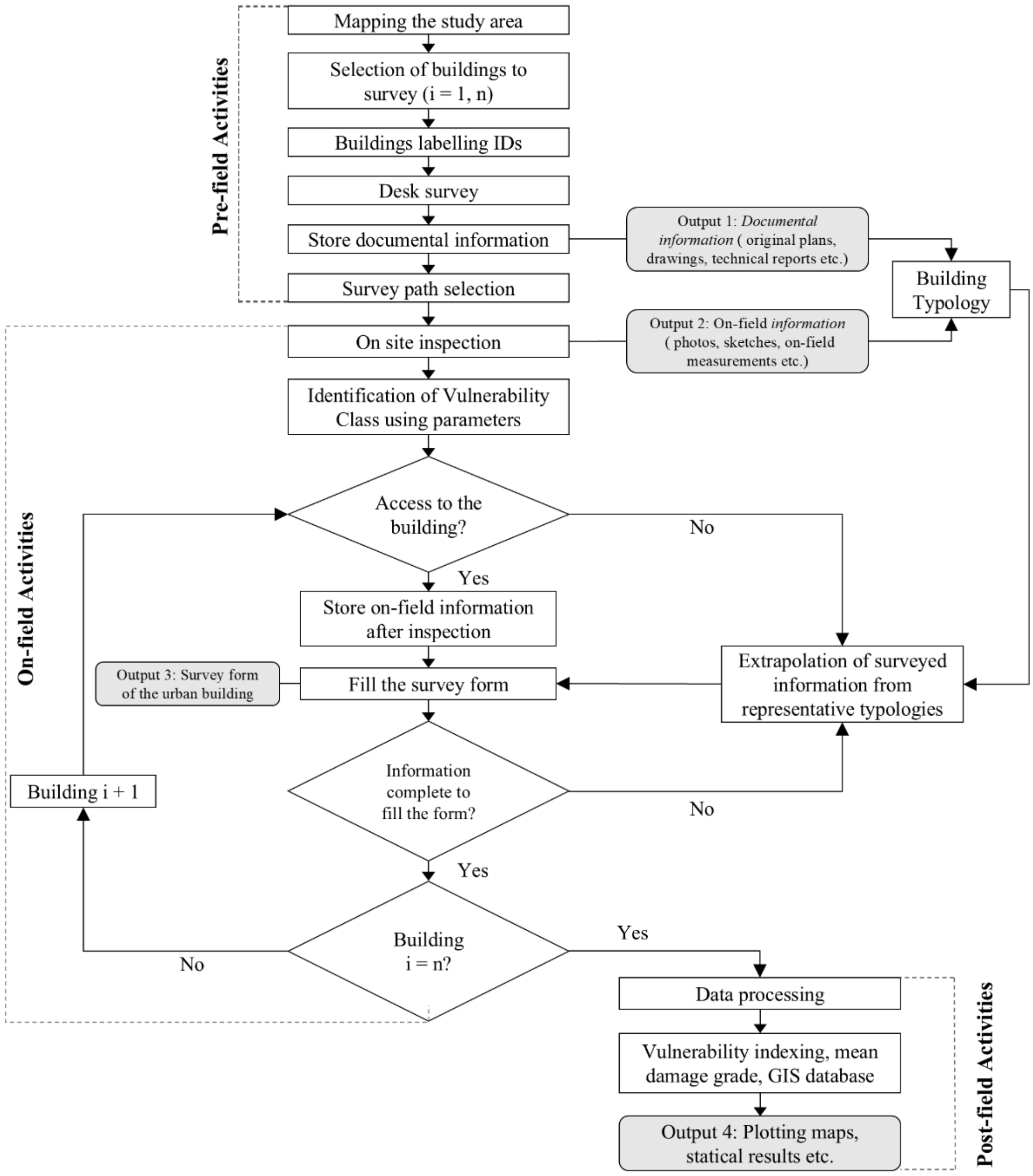

Figure 3.3: Flowchart of the data collection and analysis process.

A multi-layered data collection procedure was employed to systematically capture the required structural, typological, and contextual details for the seismic vulnerability assessment, the full workflow of which is illustrated in the figure 3.3.

3.5.1 Desk Survey and Preliminary Documentation

The initial step in data collection involved a comprehensive desk survey. Official records, architectural drawings, structural plans, and prior technical reports were gathered from city authorities and relevant municipal databases. This desk-based collation provided essential baseline information, including building footprints, construction years, number of stories, apparent usage, and pre-existing indications of structural type. As part of this stage, each building in the sample was assigned a unique identification code to streamline documentation and subsequent data integration.

3.5.2 Field Survey and On-Site Inspection

Field data collection was accomplished via systematic on-site inspections, employing two standardized survey instruments—the eight-parameter index form and the Turkish rapid assessment form—applied in parallel to each building. Survey teams, trained in both methodologies, visited each selected RC building to collect comprehensive information on structural attributes, vulnerability features, and observable deficiencies. During each site visit, the following actions were undertaken:

- **External and Internal Assessment:** Visual inspections were conducted to record essential structural features, including typology, vertical and plan regularity, infill wall characteristics, existence of soft or weak stories, and presence of short columns or non-structural hazards. Where possible, internal inspection supplemented data on reinforcement exposure, material deterioration, and past retrofitting.
- **Measurement and Documentation:** The survey team measured critical dimensions (building height, bay spacing, infill distribution) and photographed both overall facades and details relevant to vulnerability scoring. All field observations—both qualitative and quantitative—were logged using the survey forms and subsequently digitized.
- **Interview and Verification:** When feasible, contacts with building residents, managers, or caretakers provided additional information on construction history, structural interventions, or hidden defects not obvious from observation. These insights were used to clarify uncertainties and increase confidence in parameter scoring.

3.5.3 Handling Data Gaps and Extrapolation

In situations where access to a building was limited or particular attributes could not be confidently assessed, data were extrapolated from similar, previously surveyed structures within the same typological group. All extrapolations or estimates were indicated in the dataset and were considered during the analysis phase with appropriate confidence factors.

3.5.4 Data Entry, Storage, and Quality Assurance

Post-survey, all data from desk review and field assessment were cross-checked for consistency, completeness, and logical integrity. The integrated dataset was digitized and stored in a secure, structured database, with explicit traceability from raw field sheets to analytical outputs. Quality control steps included double entry of key fields, flagging of uncertain or estimated values, and systematic review by the research supervisor or a second analyst.

3.6 Data Processing and Analysis

The data processing and analysis phase was pivotal in transforming raw field observations and desk survey data into quantifiable seismic vulnerability metrics. This phase systematically integrated data organization, quality assurance, analytical computation of vulnerability indices, and preparation for both comparative analysis and spatial representation within a Geographic Information System (GIS).

3.6.1 Data Organization and Cleaning

Upon completion of all on-site inspections and data collection, the raw data, recorded on both the eight-parameter index forms and the Turkish rapid assessment forms, were meticulously digitized into a structured master database. This database was designed to allow complete traceability from each physical survey form to its corresponding digital record and unique building identifier. Rigorous data cleaning procedures were then initiated to identify and rectify any missing entries, logical inconsistencies, or out-of-range values. Data points flagged as ambiguous or uncertain during fieldwork were cross verified against field notes, photographic evidence, and, where possible, through direct consultation with the surveying teams. All entries derived from extrapolation, due to inaccessibility or partial observation, were explicitly marked within the database, ensuring transparency in subsequent analytical processes and the interpretation of results.

3.6.2 Calculation of Vulnerability Indices

3.6.2.1 *Seismic Vulnerability Index for RC Buildings*

The proposed methodology evaluates the vulnerability index for each RC building based on eight specific parameters (P1–P8), as presented in Table 3.2. These parameters were selected to capture critical features influencing the seismic response of buildings. Each parameter is classified into one of four vulnerability classes (C_{vi}): A, B, C, and D where Class A represents the least vulnerable condition and Class D represents the most vulnerable.

For each building under analysis, the vulnerability class that best described its observed characteristics was selected for each parameter. To each parameter, a specific weight (p_i) is associated, ranging from 0.5 for parameters considered less influential to 2.0 for parameters with the most significant impact on a building's seismic vulnerability. The assigned weights reflect empirical observations and expert consensus on their contribution to seismic performance.

Table 3.2: Parameters of the Vulnerability Index, I_v, with Respective Vulnerability Classes and Weights (Ferreira et al., 2020).

	Parameter	Class C_{vi}				Weight
		A	B	C	D	p_i
	Group 1. Foundations					
P1	Building implantation	0	5	20	50	1.5
	Group 2. Relative Position					
P2	Building position	0	5	20	50	0.5
	Group 3. Structural Features					
P3	Building age	0	5	20	50	1.5
P4	Irregularity in plan	0	5	20	50	2.0
P5	Irregularity in height	0	5	20	50	2.0
P6	Soft-story mechanism	0	5	20	50	2.0
P7	Short columns	0	5	20	50	2.0
P8	Presence of other vulnerable elements	0	5	20	50	0.5

The parameters included in Group 1 and Group 2 are related to the building's interaction with its site and adjacent structures. Specifically, Parameter P1, Building Implantation, combines the evaluation of soil type and the building's foundation conditions. Soil types are considered in accordance with Eurocode 8 classifications. As presented in Table 3.3, different combinations of soil type and building location (e.g., plain field, landfills, pronounced slope) dictate the vulnerability class. If soil information was unavailable, a soil type B was conservatively assumed.

Table 3.3: Vulnerability Classes of P1 (Building Implementation)

Type of Soil	Building Location		
	Plain Field	Landfills	Pronounced Slope
Soil type A	A	B	C
Soil types B and C	B	C	D
Soil types D and E	C	D	D

Parameter P2, Building Position, characterizes the building's vulnerability based on its relative placement within an urban aggregate. Four different positions are considered: in-row building (BM), isolated building (I), corner building (G), and edge building (BE). In-row buildings (Class A) are considered least vulnerable due to confinement, while isolated (Class B), corner (Class C), and edge buildings (Class D) generally exhibit higher vulnerability due to potential pounding effects and reduced confinement. As illustrated in Figure 3.2 (Figure 1 in your paper), these positions are critical. A significant difference in total height (more than one story) with adjacent buildings, or a floor misalignment exceeding 0.5 m with adjacent buildings of similar height, results in an increase of one vulnerability grade to account for potential severe damage due to interaction.

Figure 3.4: The Criteria to assess parameter P2, where BM stands for in-row building, I for isolated building, G for corner building, and BE for edge building.

Group 3 parameters relate to the intrinsic structural characteristics of the building. Parameter P3, Building Age, addresses the period of design and construction, which is correlated with the seismic provisions and codes applicable at the time. Table 3.4 outlines the class definitions based on design type, reflecting the evolution of seismic codes. If poor design or construction processes were detected, the vulnerability class was increased by one grade.

Table 3.4: Class Definition for Parameter P3 (Building Age)

Class	Design Type
A	With modern seismic design codes
B	With current seismic provisions
C	With minor seismic provision
D	Without seismic design

Parameters P4 and P5 evaluate the structural regularity of the buildings. P4, Irregularity in Plan, assesses the number of sources of plan irregularities (Table 3.5), drawing on concepts from Eurocode 8. Factors include the position of elevator shafts, building plan slenderness (largest side not exceeding four times the smaller side), and compact plan configuration.

Table 3.5: Class Definition for Parameter P4 (Irregularity in Plan)

Class	Plan Irregularity
A	Building regular in plan
B	Building with one source of plan irregularity
C	Building with two sources of plan irregularity
D	Building with more than two sources of plan irregularity

Parameter P5, Irregularity in Height, accounts for vertical irregularities such as setbacks, discontinuities in the vertical load path, and significant differences in floor heights.

Parameter P6, Soft-Story Mechanism, evaluates the potential presence of a soft story, typically found on the ground floor for architectural or commercial reasons. Such a mechanism leads to a concentration of deformation demand at the ground level, potentially causing unexpected collapse. Despite its inclusion within vertical irregularities (P5), its critical nature warrants a distinct parameter with a high weight, where Class D is assigned to buildings with a potential soft-story mechanism and Class A for those without. Parameter P7, Presence of Short Columns, identifies columns whose height is partially restricted by infill walls, leading to higher shear loads and potential brittle shear failure. Table 3.6 defines the vulnerability classes for P7.

Table 3.6: Class Definition for Parameter P7 (Presence of Short Columns)

Class	Short Columns
A	Building without short columns
B	Building with possible short columns in one of the upper floors
C	Building with possible short columns on the ground floor or in several stories of the upper floors
D	Building with possible short columns on the ground floor may lead to a story mechanism

Finally, Parameter P8, Presence of Other Vulnerable Elements, addresses secondary elements like balconies, parapets, cornices, and appendages (Table 3.7). These elements may increase risk to occupants or exacerbate structural damage during an earthquake.

Table 3.7: Class Definition for Parameter P8 (Presence of Other Vulnerable Elements)

Class	Identification of Non-Structural Components
A	Building without vulnerable non-structural components
B	Building with parapets and/or cornices and/or appendages
C	Building with balconies
D	Building with balconies and parapets or cornices or appendages

The raw vulnerability index, I_v is calculated as the sum of the products of each parameter's class score (C_{vi}) and its weight (p_i):

$$I_v^* = \sum_{i=1}^{8} C_{vi} \times p_i \qquad 3.2$$

The I_v ranges from 0 to 600. For more straightforward interpretation and use, this index is normalized to a range between 0 and 100, assuming the format I_v:

$$I_v = \frac{I_v^*}{600} \times 100 \qquad 3.3$$

As observed in Table 3.2, parameters P4, P5, P6, and P7—related to structural irregularities (plan and height), soft-story mechanisms, and short columns—are assigned the highest weight (2.0), reflecting their most significant influence on seismic vulnerability.

3.6.2.2 *Turkish Level I Method: Vulnerability Determination*

The Turkish Level I method, developed by (Sucuoglu and Yazgan, 2003), is a rapid walkdown evaluation procedure designed for the preliminary seismic screening of a large number of buildings. The methodology allows for the prioritization of high-risk structures that may require more detailed engineering analysis. The core of this method is the visual identification of key parameters that significantly influence a building's seismic performance.

Survey Parameters

The following structural and non-structural parameters are observed and recorded during the field survey:

a. Number of Stories: The total count of floors above the ground level, which influences the building's mass and dynamic response.
b. Soft Story: The presence of a story, typically a ground floor used for commercial purposes, that has significantly less stiffness and strength compared to the stories above it.
c. Heavy Overhangs: The existence of large, heavy balconies or overhanging floors can increase lateral seismic forces and overturning moments.
d. Apparent Building Quality: A visual assessment of the construction quality, categorized as 'Good', 'Moderate', or 'Poor', which has shown a strong correlation with damage in past earthquakes.
e. Short Columns: The presence of columns with reduced height due to partial infill walls makes them susceptible to high shear forces and severe damage.
f. Pounding Effect: The risk of adjacent buildings colliding during an earthquake due to insufficient separation distance, especially when floor levels do not align.
g. Topographic Effects: Location on or near steep slopes (e.g., greater than 30 degrees), which can lead to uneven ground distortions and adverse structural effects.
h. Local Soil Conditions: The intensity of ground motion at a particular site predominantly depends on the distance the causative fault and local soil conditions. As there exists a strong correlation between PGV and the shear wave velocities of local soils (Wald 1999), in this study, the PGV is selected to represent the ground motion intensity. The PGV map in the JICA (2002) report has contour increments

of 20 cm/s2. The intensity zones in Istanbul are expressed accordingly, in terms of the associated PGV ranges.

Zone I : 60<PGV<80 cm/s^2

Zone II : 40<PGV<60 cm/s^2

Zone III: 20<PGV<40 cm/s^2

Based on their number of stories and the seismic hazard level at the site, buildings are assigned different base scores as shown in Table 3.8.

According to current zoning map of seismic code, for Sylhet City (Zone I) the peak ground acceleration is around 0.25g on very firm soil, considering site New Technologies for Urban Safety of Mega Cities in Asia effects it can be taken as 0.30g or more. Corresponding PGV can be taken as between 60 cm/s to 70 cm/s (Wu et al., 2003). Hence for calculating performance score Zone I (60<PGV<80) is considered (Mazumder et al., 2011).

Table 3.8: Initial & Vulnerability Scores for Level - I Survey of RC Buildings (Ozcebe et al., 2006)

No. of Stories	Base Score (BS)			Soft Story	Heavy Overhang	Apparent Quality	Short Column	Pounding	Topography Effect
	60<PGV<80	40<PGV<60	20<PGV<40						
1, 2	100	130	150	0	-5	-5	-5	0	0
3	90	120	140	-15	-10	-10	-5	-2	0
4	75	100	120	-20	-10	-10	-5	-3	-2
5	65	85	100	-25	-15	-15	-5	-3	-2
6, 7	60	80	90	-30	-15	-15	-5	-3	-2

Building Seismic Performance

The final seismic Performance Score (PS) for each building is calculated to rank its relative vulnerability. The process begins by assigning a Base Score (BS) to each building based on its number of stories and the seismic hazard zone of its location, as shown in Table 3.8. This Base Score is then penalized by subtracting Vulnerability Scores (VS) associated with each negative parameter observed. The contribution of each vulnerability parameter is determined by a multiplier (VSM), as defined in Table 3.9. The final Performance Score is calculated using Equation 3.1.

$$PS = (BS) - \sum(VSM) \times (VS) \qquad 3.4$$

A lower final PS value indicates a poorer expected seismic performance and, consequently, a higher level of vulnerability, flagging the building for further, more detailed investigation.

Table 3.9: Vulnerability Parameters, (VSM) (Ozcebe et al., 2006)

Soft Story	☐ No (0)	☐ Yes (1)	
Heavy Overhang	☐ No (0)	☐ Yes (1)	
Apparent Quality	☐ Good (0)	☐ Moderate (1)	Poor (2)
Short Column	☐ No (0)	☐ Yes (1)	
Pounding Effect	☐ No (0)	☐ Yes (1)	
Topography Effect	☐ No (0)	☐ Yes (1)	
Local Soil Condition	☐ Stiff	☐ Soft	

3.6.3 Comparative Analysis of methodologies

To validate the reliability and consistency of the findings, a comprehensive comparative analysis was conducted between the two distinct assessment methodologies employed in this research: the quantitative SVI simplified method and the qualitative Turkish Level I rapid screening protocol. The primary objective of this comparison was to determine the degree of correlation between the outputs of these two methods. Specifically, the Vulnerability Index (Iv) obtained from the SVI method was plotted against the Performance Score (PS) from the Turkish method for each surveyed building. A strong and consistent inverse correlation—where high vulnerability indicated by one method corresponded to high vulnerability by the other-served to validate the overall assessment process and confirm the dependability of the identified at-risk structures.

3.6.4 Mean Damage Grade (μD)

Following the calculation of the Vulnerability Index (I_v) for each of the 120 reinforced concrete buildings in the study area, the next step in the methodology was to estimate the expected Mean Damage Grade (μD) under various seismic scenarios. This process establishes a crucial link between the calculated vulnerability of our building sample, the seismic action (macroseismic intensity), and the expected physical damage, which is defined according to the European Macroseismic Scale (EMS-98). (See on Appendix C). For this purpose, this research adopted the vulnerability function approach proposed and calibrated by Ferreira et al. (2020). This established method was applied to our dataset to relate the Mean Damage Grade (μD) - ranging from 0 (no damage) to 5 (collapse) - to the macroseismic intensity (I) and a normalized vulnerability index (V).

First, the Vulnerability Index (I_v) calculated for each of our 120 buildings was converted into a normalized vulnerability index, V, using the validated linear transformation from the source study. This is shown in Equation 3.2:

$$V = -0.02 + Iv \times 0.0104 \quad 3.5$$

With the normalized index *V* determined for each building, the Mean Damage Grade (µD) for a given macroseismic intensity (*I*) was then estimated using the pre-calibrated vulnerability function. This function, which takes the form of a hyperbolic tangent curve, is presented in Equation 3.3:

$$\mu D = 2.839 \times \left[1 + \tanh\left(\frac{I + 10.79 \times V - 11.6}{5}\right)\right] \quad 3.6$$

For the application in this thesis, the calibrated parameters from the source methodology were adopted, where a = 2.839, b = 10.79, and the ductility coefficient Q was taken as 5.0. This established formulation allowed for the development of vulnerability curves specific to our surveyed building stock, enabling the prediction of damage levels for different potential earthquake scenarios in Sylhet.

3.6.5 Fragility Curve

Following the estimation of the Mean Damage Grade (µD), fragility curves were developed for the surveyed buildings (Cherif et al., 2017). A fragility curve defines the probability of a structure reaching or exceeding a specific damage grade for a given level of seismic intensity. This was achieved by modeling the damage distribution using the beta probability distribution, a model suitable for variables bounded within a defined range. The probability density function (PDF) of the beta distribution, p_β, is defined as:

$$p_\beta = \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} \frac{(x-a)^{r-1}\,(b-x)^{t-r-1}}{(b-a)^{t-1}} \quad a \le x \le b \quad 3.7$$

The cumulative density function (CDF), $P_\beta(x)$, is obtained by integrating the PDF:

$$P\beta(x) = \int_a^x p_\beta(\varepsilon)\,d\varepsilon \quad 3.8$$

For this analysis, the parameters of the beta distribution were defined based on established methodologies:

a = 0 and b = 6, representing the bounds of the damage scale.
t = 8, a constant defining the overall shape of the distribution.
r, a parameter dependent on the Mean Damage Grade (μD), calculated as:

$$r = t(0.007\mu_D^3 - 0.052\mu_D^2 + 0.2875\mu_D) \qquad 3.9$$

The probability of being in a specific discrete damage state k was calculated by finding the difference in the cumulative probability between successive damage grades:

$$p_k = P_\beta(k+1) - P_\beta(k) \qquad 3.10$$

The fragility curve, representing the probability of exceeding a damage grade, was then derived directly from the cumulative beta distribution:

$$P(D \geq D_k) = 1 - P_\beta(k) \qquad 3.11$$

By applying these equations for different seismic intensities, a set of fragility curves was generated for the building sample, providing a comprehensive probabilistic assessment of expected seismic performance.

3.6.6 Data Integration and GIS Mapping

To visualize the geographical distribution of seismic vulnerability across the study area, a spatial vulnerability map was developed. This process involved integrating the calculated vulnerability results with the precise location of each surveyed building using a Geographic Information System (GIS) framework. The base map of the study area, including road networks and building footprints, was initially prepared using AutoCAD and subsequently georeferenced using high-resolution satellite imagery from Google Earth Pro. Each of the 120 surveyed buildings was then digitized as a distinct spatial feature within the ArcGIS Pro environment. The calculated Vulnerability Index (Iv) and Performance Score (PS) for each building were joined to its corresponding spatial feature in the attribute table, creating a comprehensive geodatabase. Finally, cartographic symbology was applied to classify and represent the buildings in distinct categories of vulnerability (e.g., low, moderate, high), resulting in a thematic map that clearly identifies the spatial location and concentration of at-risk structures.

3.7 Summary

This chapter outlined the comprehensive methodology for assessing seismic vulnerability in Ward 13, Sylhet. A dual-methodology approach was adopted, integrating the quantitative SVI simplified method with the Turkish Level I method to ensure a validated assessment. The analytical process involved calculating a Vulnerability Index (I_v) and a Performance Score (PS) for each building, followed by a comparative analysis of the two. The methodology culminated in the development of fragility curves, mean damage grade and a GIS-based spatial vulnerability map, translating the assessment data into actionable risk analysis tools.

CHAPTER 4
CHARACTERISTICS OF THE SURVEYED BUILDING

4.1 Introduction

This chapter provides a detailed description of the surveyed reinforced concrete (RC) buildings in Ward 13 of Sylhet City Corporation. Understanding the physical and functional characteristics of these structures is essential as a foundation for subsequent seismic vulnerability analysis. Various attributes, including location, topography, age, use, and height—were systematically documented to establish the context and representativeness of the sample and to facilitate meaningful comparison with regional trends.

4.2 Location of the Surveyed Buildings

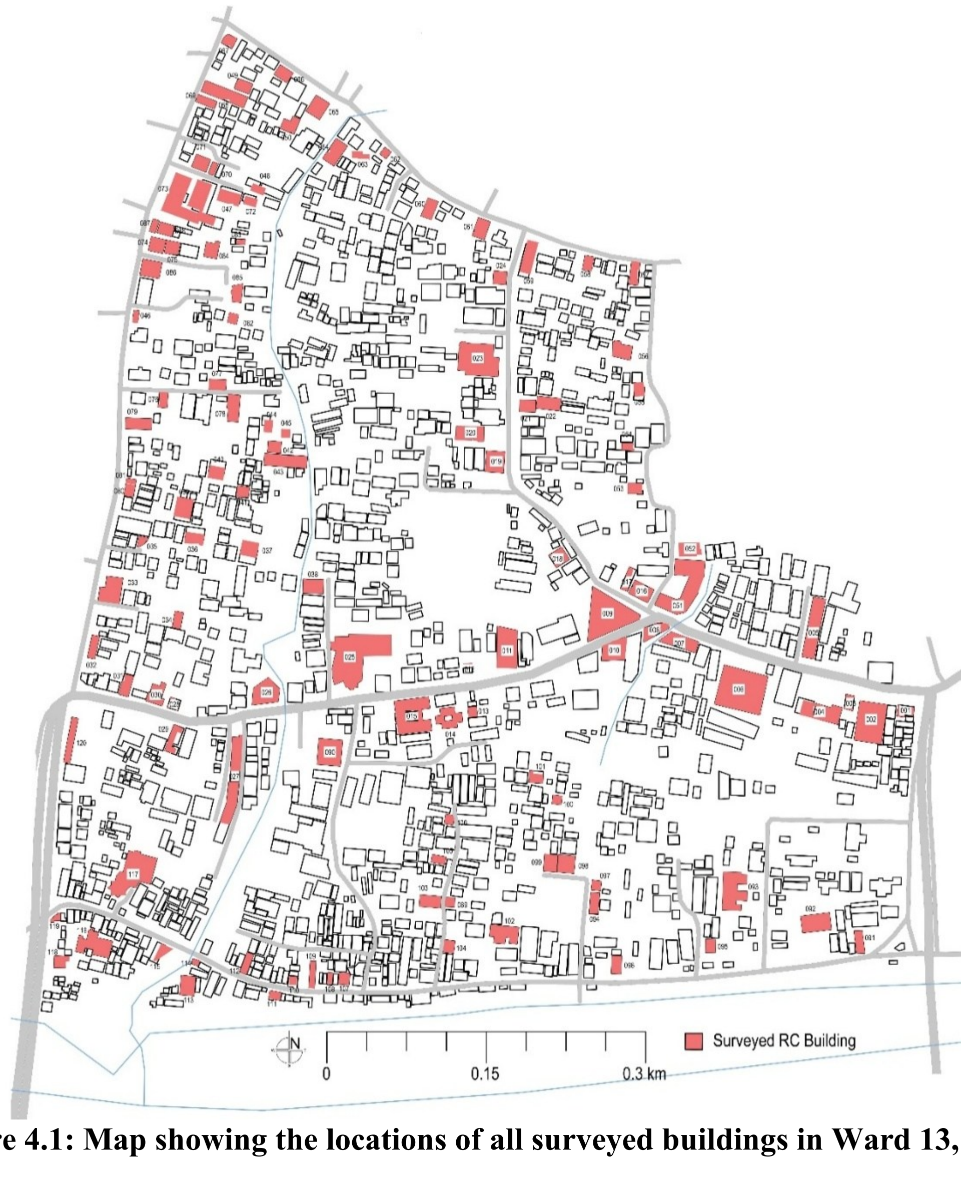

Figure 4.1: Map showing the locations of all surveyed buildings in Ward 13, SCC

Ward 13 of Sylhet City Corporation, selected for this study, is a densely developed urban area featuring diverse building uses and structural types. The ward includes both residential and mixed-use zones, with surveyed buildings strategically spread across different neighborhoods to reflect its spatial diversity. The topography is predominantly flat with some gentle slopes, influencing foundation choices. Most structures date from the 1980s to present, indicating a range of construction standards and code compliance. The building stock comprises mainly low- to mid-rise reinforced concrete (RC) buildings, generally two to six stories high, supporting a mix of residential, commercial, and institutional uses. The precise locations of all surveyed buildings in Ward 13 are presented in Figure 4.1.

4.3 Topographic Characteristics

The topographical setting of Ward 13 is characterized by relatively flat terrain interspersed with minor variations in elevation. The surveyed buildings typically occupy sites with gentle slopes, though some are located adjacent to water bodies or on slightly elevated land. These variations can influence building foundation design and, subsequently, seismic vulnerability, particularly concerning soil class and drainage characteristics.

4.4 Age of the Building

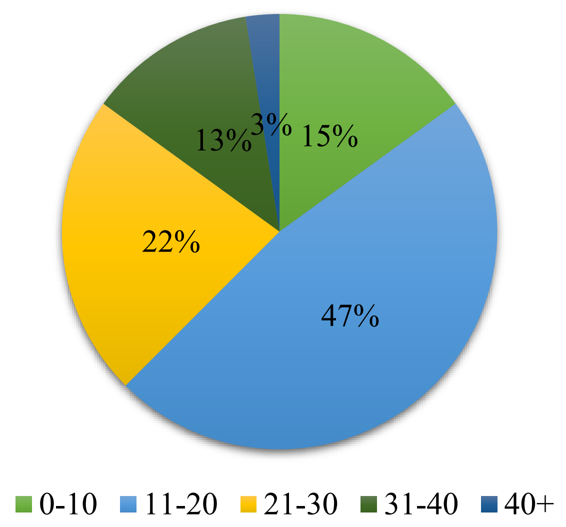

Figure 4.2: Age distribution of surveyed buildings in Ward 13, SCC.

The age distribution of surveyed buildings is shown in Figure 4.2. Almost half (47%) of the buildings are 11–20 years old, indicating a significant development phase in recent decades. Buildings aged 21–30 years make up 22%, while 15% fall within the 0–10-year range. Older structures, aged 31–40 years and 40+ years, account for 13% and 3% respectively. This predominance of mid-aged buildings suggests a mix of construction practices and varying adherence to modern seismic standards, with older buildings likely exhibiting higher vulnerability due to aging materials and possible lack of seismic detailing.

4.5 Use of the Building

The building survey demonstrates considerable functional diversity (Figure 4.3). Residential buildings are the most prevalent, accounting for 51 structures, while mixed-use buildings follow with 37. Commercial properties (15), government (9), educational (4), and both medical and mosque buildings (2 each) contribute to the mixed urban landscape. The dominance of residential and mixed-use structures reflects the ward's primarily residential character with a significant presence of businesses and community facilities. This variety is important for understanding differing occupancy patterns and assessing varied seismic vulnerabilities across building types.

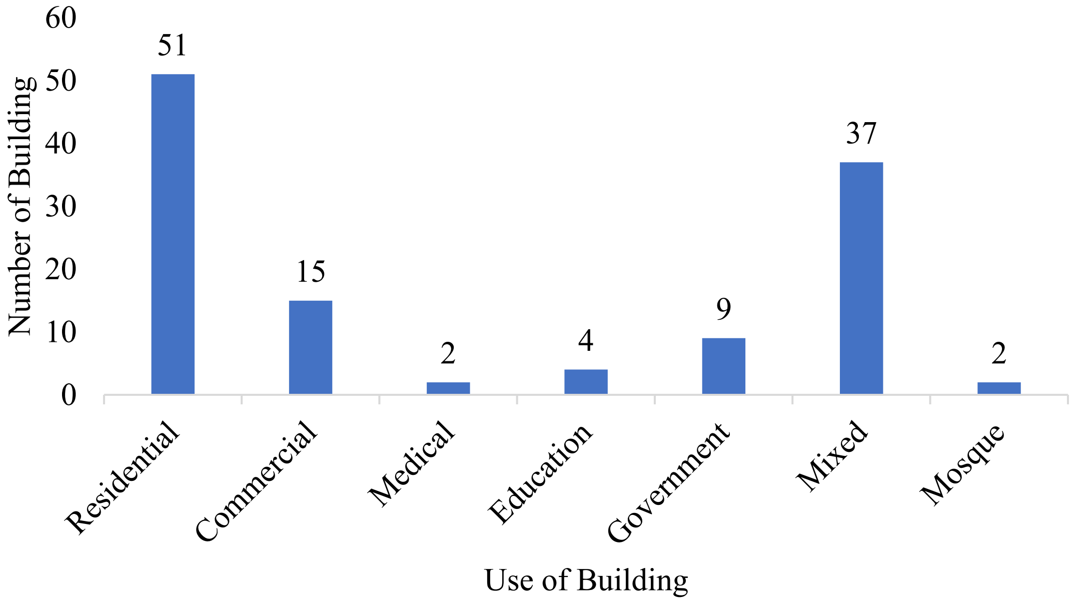

Figure 4.3: Distribution of surveyed buildings by use.

4.6 Stories of the Building

The analyzed building stock exhibits a significant dominance of mid-rise structures, with 3- and 4-story buildings comprising the largest portions—28 and 32, respectively—of the total sample. Lower-rise buildings with 2 stories account for 13, while 5- and 6-story buildings represent 19 and 14 cases each. High-rise buildings, with 7 and 7+ stories, are comparatively less common, totaling 14. This varied height distribution suggests a structural landscape where mid-rise forms prevail, a factor that directly affects seismic performance due to differences in mass, flexibility, and potential for soft-story effects.

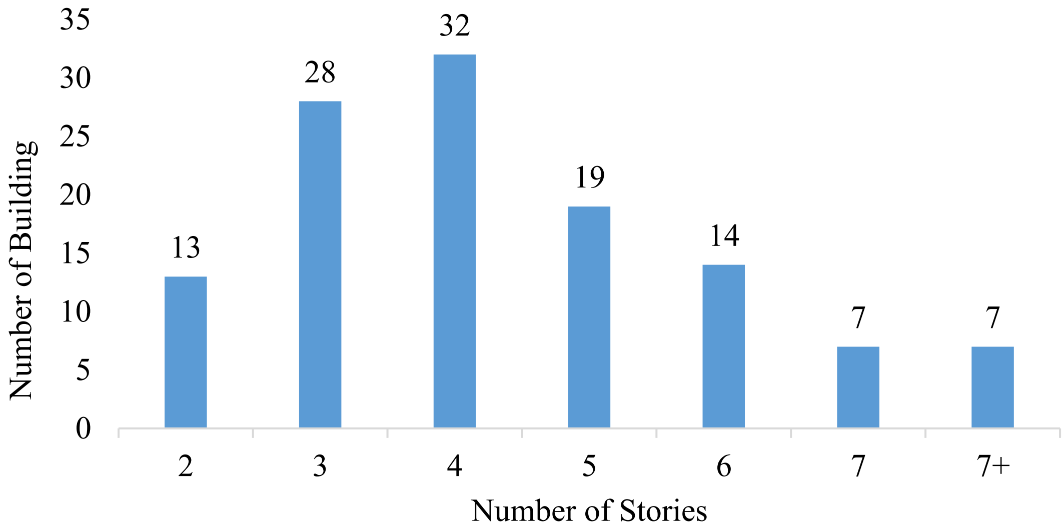

Figure 4.4: Distribution of surveyed buildings by number of stories.

4.7 Apparent quality

The visual assessment of apparent quality indicates that a significant majority (58.41%) of the surveyed buildings are of 'Moderate' quality. Buildings rated as 'Good' constitute 23.01% of the sample, while a concerning 18.58% are identified as being of 'Poor' quality. This distribution is critical, as a high prevalence of moderate to poor workmanship suggests potential deficiencies in construction and material integrity. Such conditions can compromise a structure's capacity to withstand seismic loads, thereby increasing its overall vulnerability.

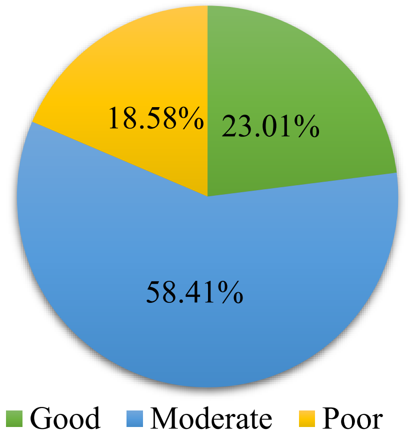

Figure 4.5: Apparent quality of the surveyed buildings.

4.8 Building Vulnerability Parameters in the Turkish method

The analysis of specific vulnerability parameters highlights several recurring structural deficiencies across the surveyed buildings. The most widespread issue is heavy overhang, observed in 80 buildings, which represents a major architectural and structural risk. This is followed by the pounding effect in 62 buildings, reflecting the risks associated with inadequate spacing and high urban density. Poor apparent quality is identified in 21 buildings, while soft story conditions are present in 32 buildings, both of which significantly increase susceptibility to seismic damage. Additionally, topography effect is evident in 22 buildings, and short column issues are recorded in 11 buildings.

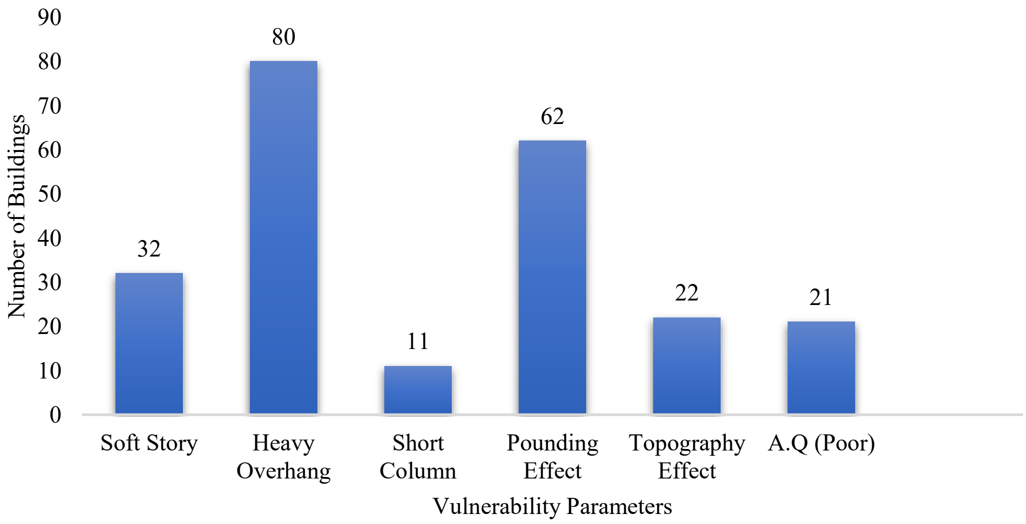

Figure 4.6: Vulnerability Parameters in Turkish method.

4.9 Summary

This chapter summarizes the structural characteristics and seismic-related aspects of the surveyed buildings in the study area. Before conducting detailed analyses of seismic vulnerability, it is essential to understand the key physical attributes—such as location, age, use, and number of stories—that directly influence seismic performance. By outlining these structural features, the chapter establishes a foundational context for interpreting vulnerability assessment results and supports a focused evaluation of potential seismic risks in the following chapters.

CHAPTER 5
RESULTS AND DISCUSSIONS

5.1 Introduction

This chapter presents and interprets the key findings from the seismic vulnerability assessment of reinforced concrete buildings in the study area. The results section provides detailed outputs from both the eight-parameter index and Turkish rapid assessment methodologies, highlighting patterns in vulnerability scores, spatial distributions, and building typologies. In the discussion, these findings are analyzed in the context of local structural characteristics and seismic risk, drawing comparisons between assessment methods and relating outcomes to broader urban resilience strategies. Together, the results and discussion provide a comprehensive understanding of the seismic performance of the surveyed building and inform recommendations for effective risk mitigation.

5.2 Distribution of Vulnerability

5.2.1 Seismic Vulnerability Index (SVI) simplified Method

The distribution of the Vulnerability Index (I_v) for the surveyed buildings, as calculated using the SVI simplified method, is shown in Figure 5.1. The majority of buildings fall within the 10-20 (34 buildings) and 20-30 (33 buildings) I_v ranges, indicating that most structures have low to moderate seismic vulnerability. A notable number (22 buildings) are found in the 30-40 range, with decreasing counts in higher index categories. Very few buildings exhibit high vulnerability (I_v above 50), and none are observed in the 80+ range. This spread suggests that while a significant portion of the building stock is not immediately at high risk, there remains a substantial minority requiring further assessment and potential intervention, especially among buildings with higher I_v values.

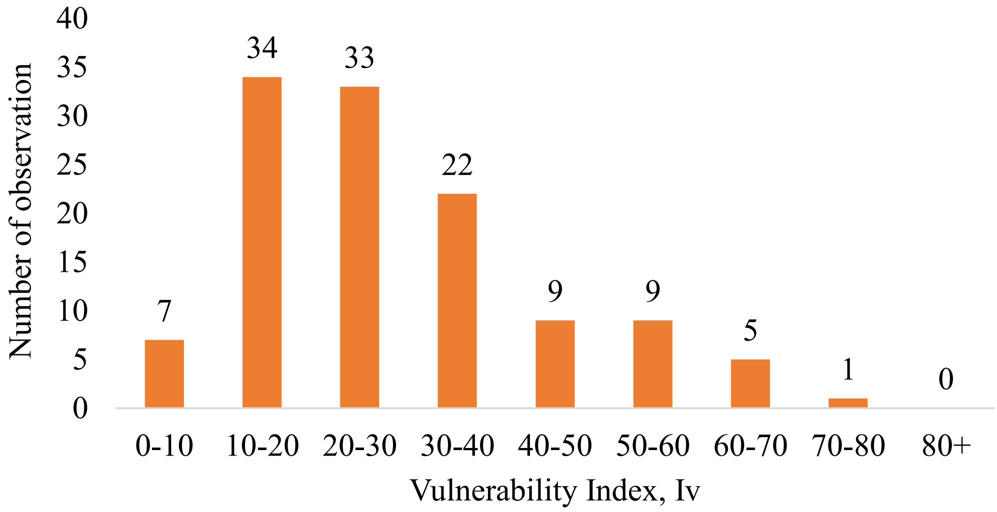

Figure 5.1: Distribution of analyzed building across ranges of Vulnerability Index, I_v

5.2.2 Turkish Method

The distribution of Performance Scores (PS) derived from the Turkish Method is presented in Figure 5.2. This assessment reveals a broad spectrum of expected seismic performance across the sample. The highest concentration of buildings (21) is found in the 60-70 PS range, indicating that a significant portion of the structures are anticipated to have adequate performance. However, since a lower PS score signifies higher vulnerability, the presence of 14 buildings with a score of 30 or less highlights a critical subset of highly vulnerable structures that require immediate attention and further detailed analysis.

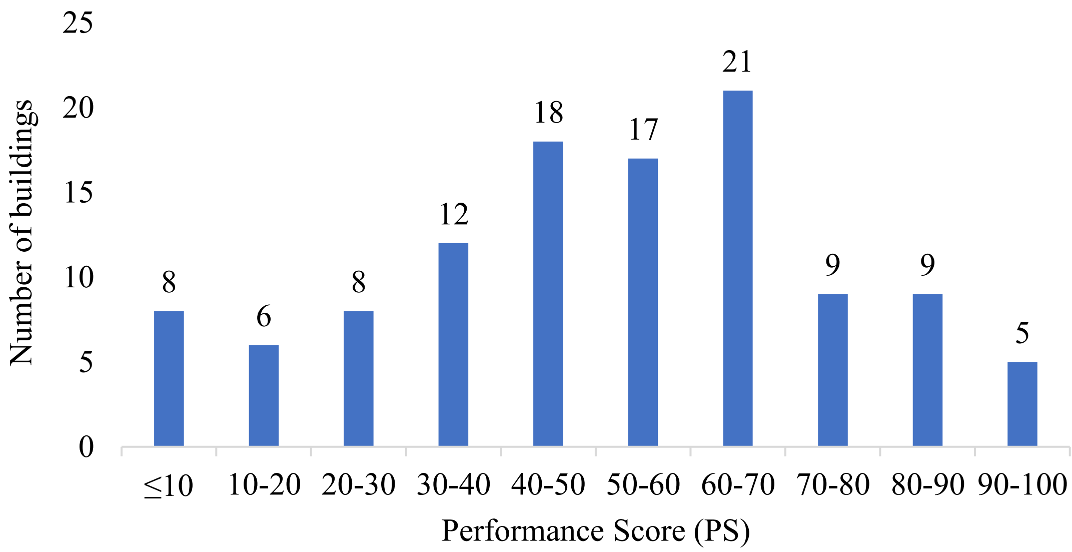

Figure 5.2: Building frequency across Performance Score ranges from the Turkish Method.

Table 10: Calculated Performance Scores of RC buildings having 7 stories of less.

No. of Stories	Performance Scores				Total
	PS≤30	30<PS≤60	60<PS≤100	100<PS	
1&2	0	0	13(100)	0	13(100)
3	0	8(28.57)	20(71.43)	0	28(100)
4	2(6.25)[1]	19(59.38)	11(34.38)	0	32(100)
5	8(42.11)	11(57.89)	0	0	19(100)
6	7(50)	7(50)	0	0	14(100)
7	5(71.43)	2(28.57)	0	0	7(100)
Total	22(19.47)	47(41.59)	44(38.94)	0	113(100)

[1]Entries in parenthesis indicate the expected risk distribution in percentages.

5.3 Parameter-Wise Vulnerability Assessment Results

5.3.1 Building Implantation (P1)

Analysis of building implantation reveals that a majority of structures (67.5%) fall under Class C, indicating moderate vulnerability due to suboptimal site conditions. Class D, which represents the highest risk category, comprises 26.67% of the buildings, while only a small number (5.83%) are in Class B. Notably, no buildings achieved Class A status, highlighting a general lack of optimal site selection and implantation practices across the study area. This distribution underscores the importance of addressing building placement and its role in overall seismic vulnerability within the surveyed stock.

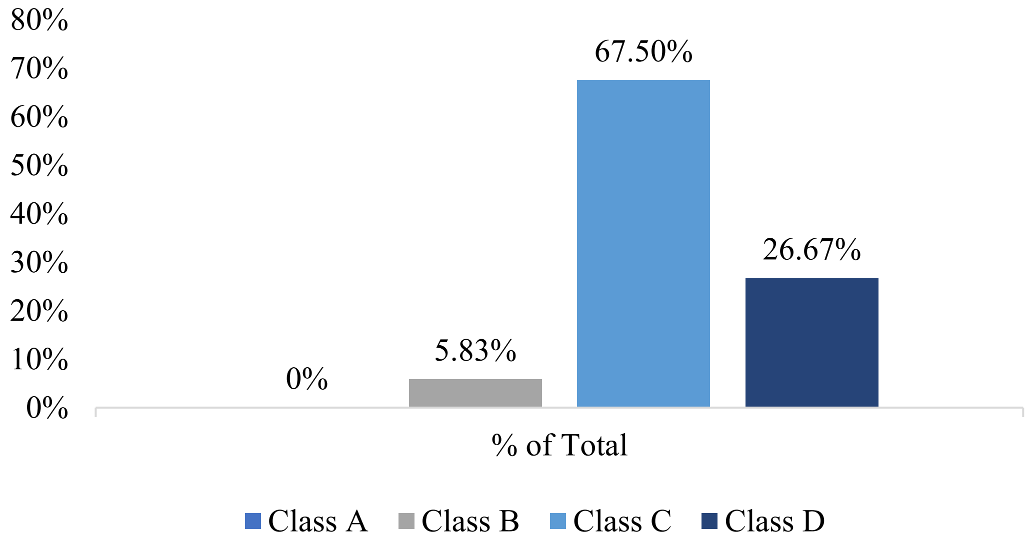

Figure 5.3: Distribution of vulnerability class for Building Implantation (P1).

5.3.2 Building Position (P2)

The distribution of building positions reveals that 30.83% of structures are in Class A, indicating the safest placement concerning seismic exposure. Class B (26.67%) and Class C (24.17%) buildings represent intermediate positional safety, while 18.33% fall into Class D, the most vulnerable category. This relatively balanced spread suggests that although nearly one-third of buildings are well-positioned, a significant fraction remains at moderate or high risk due to less favorable site locations, increasing the potential for seismic vulnerability.

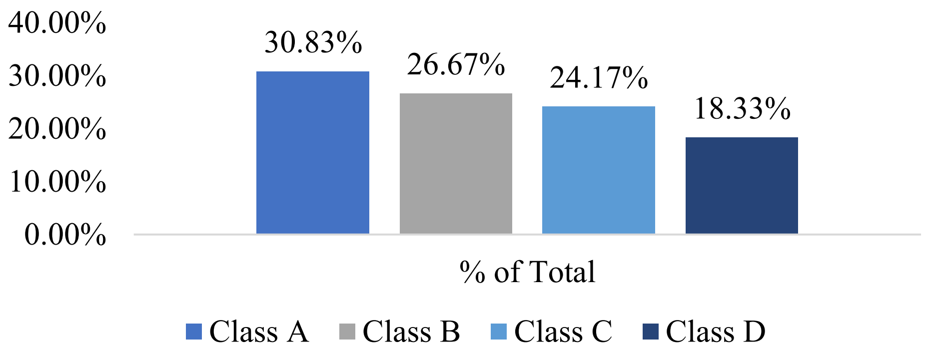

Figure 5.4: Building position class distribution (P2).

5.3.3 Building Age (P3)

The age analysis of surveyed buildings (Figure 5.4) shows that nearly half (48.33%) fall into Class B, representing structures built with moderate seismic provisions. Class C buildings, often constructed before full code adoption, make up 35%, while only 4.17% are in Class A and 12.5% in the most vulnerable Class D. This pattern indicates that most buildings are of intermediate age and potentially susceptible to outdated design standards, highlighting the possible risk of inadequate seismic resistance in a substantial part of the building stock.

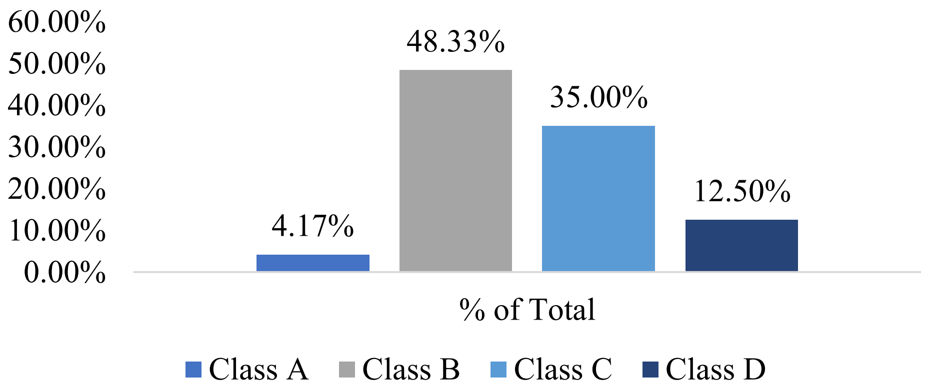

Figure 5.5: Building age class distribution (P3).

5.3.4 Irregularity in Plan (P4)

The distribution of "Irregularity in Plan" (P4) indicates that only 20.83% of the surveyed buildings have a regular plan (Class A). A significant majority exhibit some form of irregularity: 44.17% have one irregularity (Class B), 27.50% have two (Class C), and 7.50% have more than two (Class D). These irregularities, such as torsional irregularity or re-entrant corners, can negatively impact seismic performance by causing uneven stress distribution and concentration of damage. The high prevalence of Class B and C buildings suggests that plan irregularities are a widespread concern, increasing the overall seismic vulnerability of the building stock.

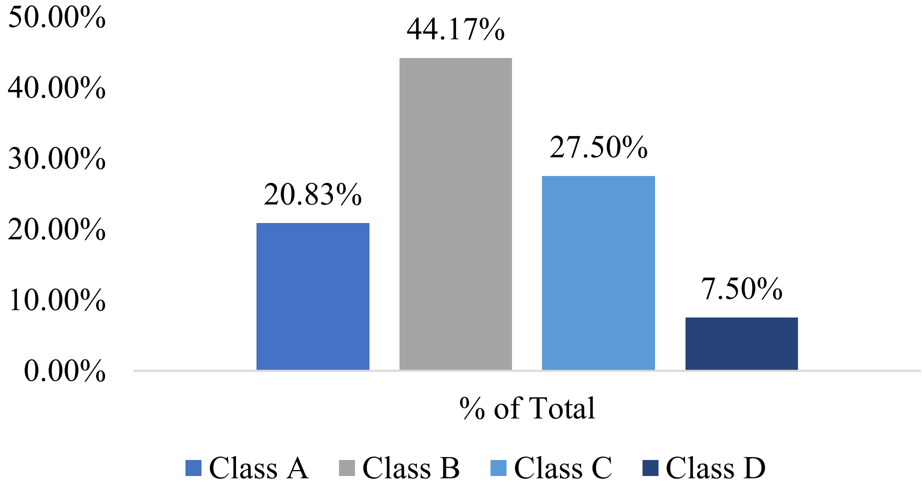

Figure 5.6: Building plan irregularity distribution (P4).

5.3.5 Irregularity in Height (P5)

The assessment revealed that 34.17% of the buildings exhibited no significant vertical irregularity (Class A), while 32.50% showed minor irregularities (Class B). A notable 25.00% fell into Class C, indicating pronounced height inconsistencies, and 8.33% were classified as highly irregular (Class D). The presence of one-third of the buildings in Classes C and D indicates a considerable vulnerability due to vertical discontinuities, which can amplify seismic demand. These findings underscore the importance of addressing height irregularities in seismic design and retrofitting strategies for RC buildings in urban areas like Sylhet.

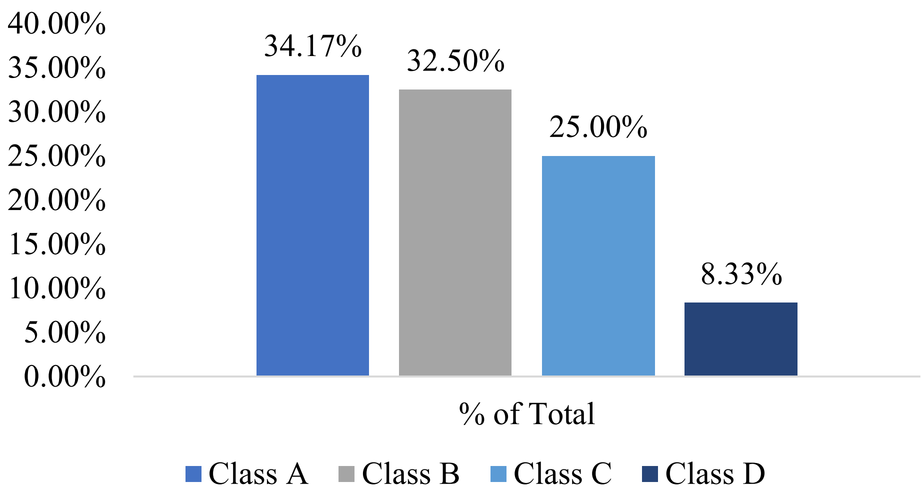

Figure 5.7: Distribution in height irregularity (P5).

5.3.6 Soft-story Mechanism (P6)

Analysis of the soft-story mechanism revealed that 68.33% of the surveyed buildings were classified as Class A, indicating no apparent soft-story vulnerability. In contrast, 32.50% were categorized as Class D, exhibiting pronounced soft-story characteristics, often due to open ground floors. No buildings fell under Classes B or C, suggesting a distinct separation between compliant and vulnerable structures. The prevalence of Class D buildings highlights the need for focused retrofitting strategies to address this critical seismic weakness.

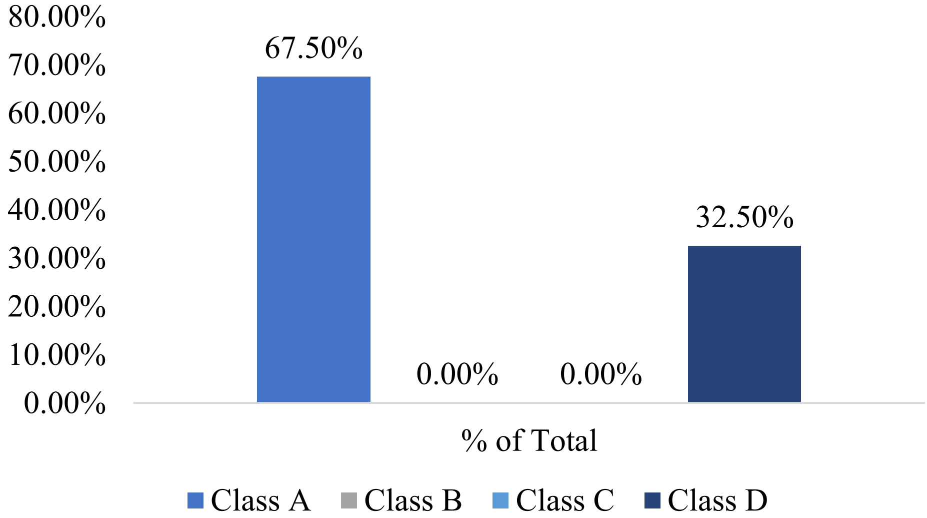

Figure 5.8: Soft-story mechanism.

5.3.7 Presence of Short Columns (P7)

The analysis demonstrated that short columns were overwhelmingly present in buildings classified as Class A, accounting for 90.00% of the surveyed structures. In contrast, Classes B, C, and D comprised only 4.17%, 5.00%, and 0.83%, respectively. The pronounced dominance of Class A indicates that the majority of buildings are at a heightened risk due to the widespread occurrence of short columns, which are known to increase seismic vulnerability. This distribution underscores the need for targeted mitigation strategies focusing on the predominant structural deficiencies within this class.

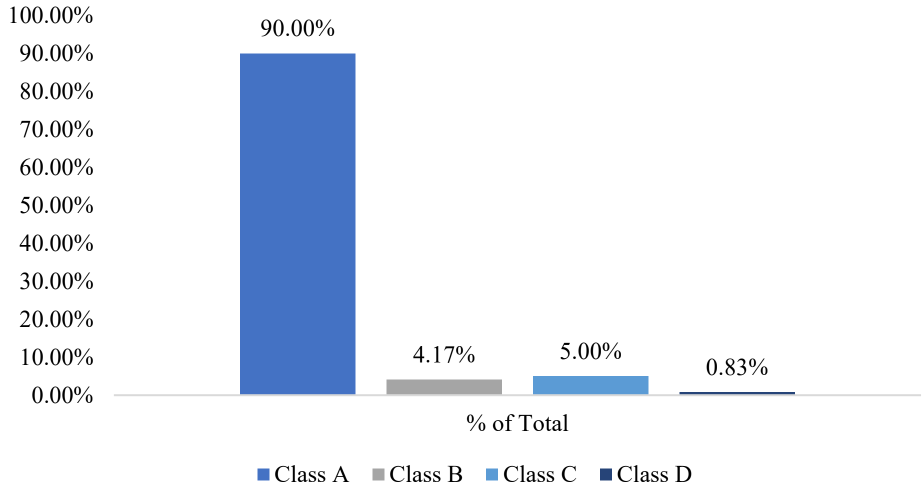

Figure 5.9: Short column class distribution (P7).

5.3.8 Other Vulnerable Elements (P8)

The analysis revealed a significant concentration of other vulnerable elements within Class D buildings, which constituted 67.50% of the total surveyed stock. Class B accounted for 25.83%, while Classes A and C represented only 4.17% and 2.50%, respectively. The predominance of Class D indicates that the majority of vulnerable structural elements are concentrated within the highest risk category. This pattern highlights an urgent need for targeted intervention within Class D buildings to mitigate overall seismic risk in the area.

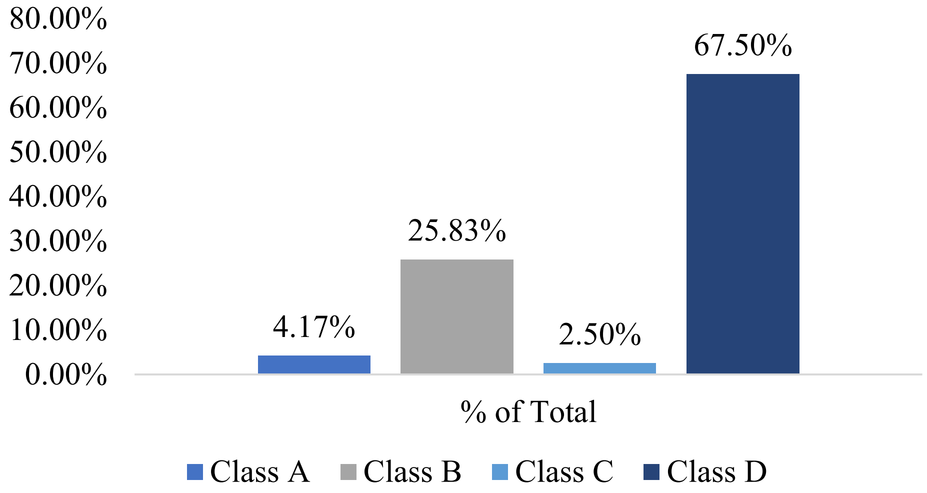

Figure 5.10: Presence of other vulnerable elements (P8).

5.4 Composite Vulnerability Index

The Composite Vulnerability Index (CVI) integrates the frequency distribution of seismic vulnerability classes (A, B, C, D) across multiple structural and non-structural evaluation parameters (P1–P8), as depicted in the stacked bar chart. By aggregating class frequencies for each parameter, the CVI offers a holistic measure that encapsulates the cumulative risk profile of the surveyed building stock. The chart reveals varying class dominance across parameters, with Class C notably prominent in P1–P5 and Class D in P1, P6, and especially P8, while Class A dominates P7. This multidimensional assessment enables prioritization of intervention strategies, ensuring that mitigation efforts address both prevalent and parameter-specific vulnerabilities for more resilient urban planning.

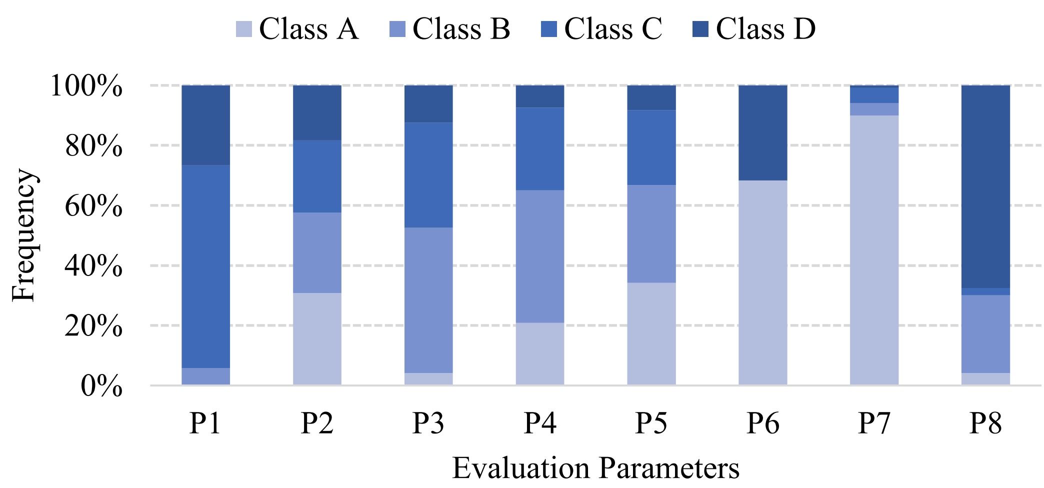

Figure 5.11: Influence of each one of the evaluation parameters on the final value of I_v

5.5 Comparative Analysis and Validation of Vulnerability Assessment Methods

To ensure the robustness and reliability of the seismic vulnerability assessment, a comparative analysis was conducted between the detailed Vulnerability Index (I_v) derived from the SVI simplified method and the Performance Score (PS) from the Turkish method. This section presents the results from both methodologies individually and then compares them to validate the overall findings.

5.5.1 Vulnerability Index (I_v) Distribution

The Vulnerability Index (I_v), calculated for each of the 120 surveyed buildings, is presented in Figure 5.12. The graph illustrates a significant fluctuation in vulnerability across the sample, with I_v values ranging from a low of 10 to a high of approximately 72 (Building B051). While many buildings exhibit low to moderate vulnerability (I_v < 40), several distinct peaks (e.g., at buildings B007, B025, B051, B083, and B117) indicate structures with a high combination of risk factors. This detailed method provides a nuanced quantification of vulnerability based on a weighted average of eight key parameters.

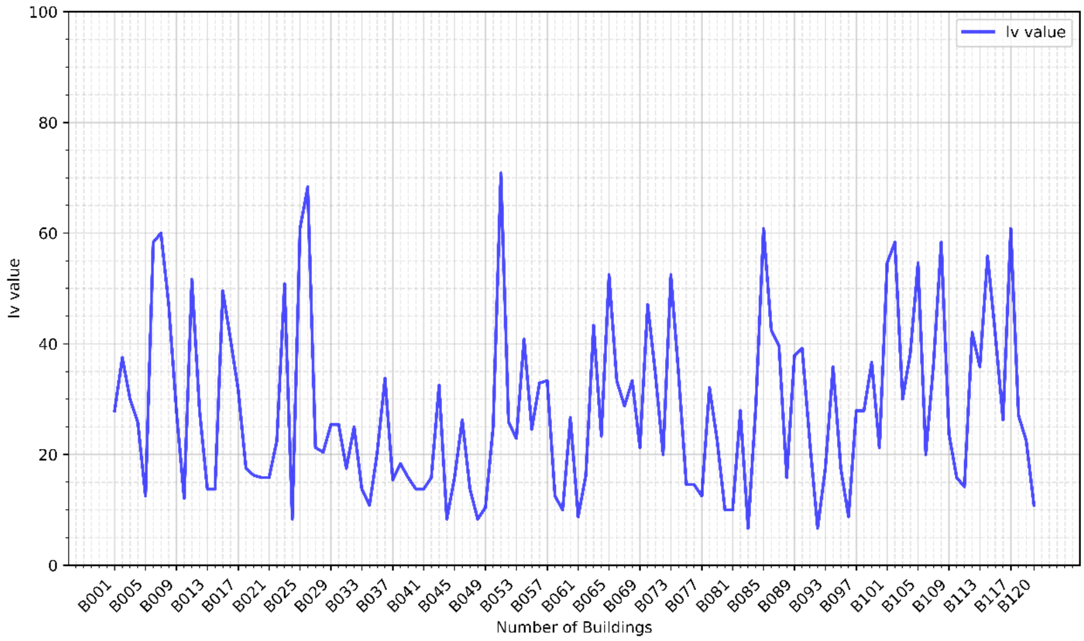

Figure 5.12: Vulnerability Index (I_v) Across Surveyed Buildings.

5.5.2 Performance Score (PS) Distribution

The Performance Score (PS), derived from the Turkish rapid assessment protocol, evaluates a building's expected seismic performance, where a lower score indicates higher vulnerability. The distribution of PS values for the surveyed buildings is illustrated in Figure 5.13. The graph reveals a wide and dynamic range of scores, from a negative value of approximately -15 to a maximum of 100. This broad spectrum effectively differentiates between buildings with robust seismic features (high PS) and those with critical deficiencies (low PS). It should be noted that the analysis using the Turkish method excluded seven buildings taller than seven stories (Building ID: 002, 016, 023, 025, 026, 057, and 068).

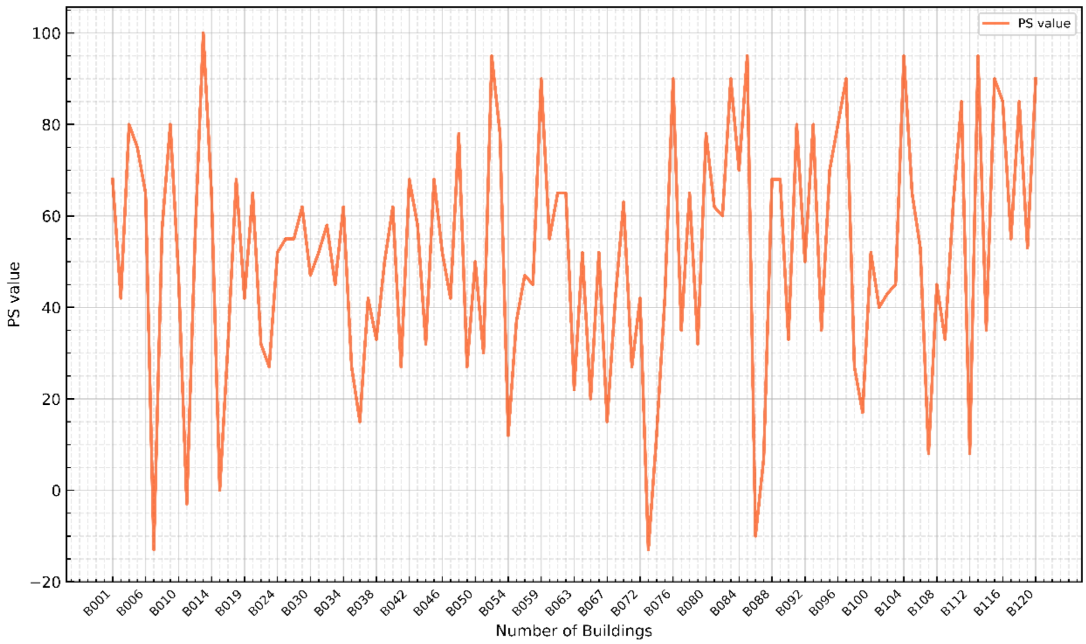

Figure 5.13: Performance Score (PS) for Each Surveyed Building.

The sharp fluctuations highlight the method's sensitivity to specific, heavily penalized flaws. For instance, buildings with very low scores (e.g., B010, B034, B076) are identified as highly vulnerable due to one or more significant structural weaknesses. Conversely, numerous buildings achieved high scores, suggesting good, anticipated performance. This method, therefore, acts as a potent screening tool, quickly pinpointing the most at-risk structures within the sample.

5.5.3 Comparative Analysis and Methodological Validation

A direct comparison of the Vulnerability Index (Iv) and the Performance Score (PS) for each building, as plotted in Figure 5.14, serves as a powerful tool for methodological validation. It is crucial to note the inverse relationship between the two metrics: a high I_v value indicates high vulnerability, whereas a low PS value indicates high vulnerability. Therefore, successful validation should demonstrate a strong inverse correlation, where peaks in the I_v graph correspond to troughs in the PS graph for the same building.

Observing Figure 5.14, this inverse relationship is evident. For example, buildings such as B025, B051, B083, and B117, which exhibit prominent peaks in their I_v values, consistently show significant dips or low points in their corresponding PS values. Conversely, buildings with low I_v scores, such as B018, B045, and B063, generally display high PS values, indicating they are assessed as less vulnerable by both methods.

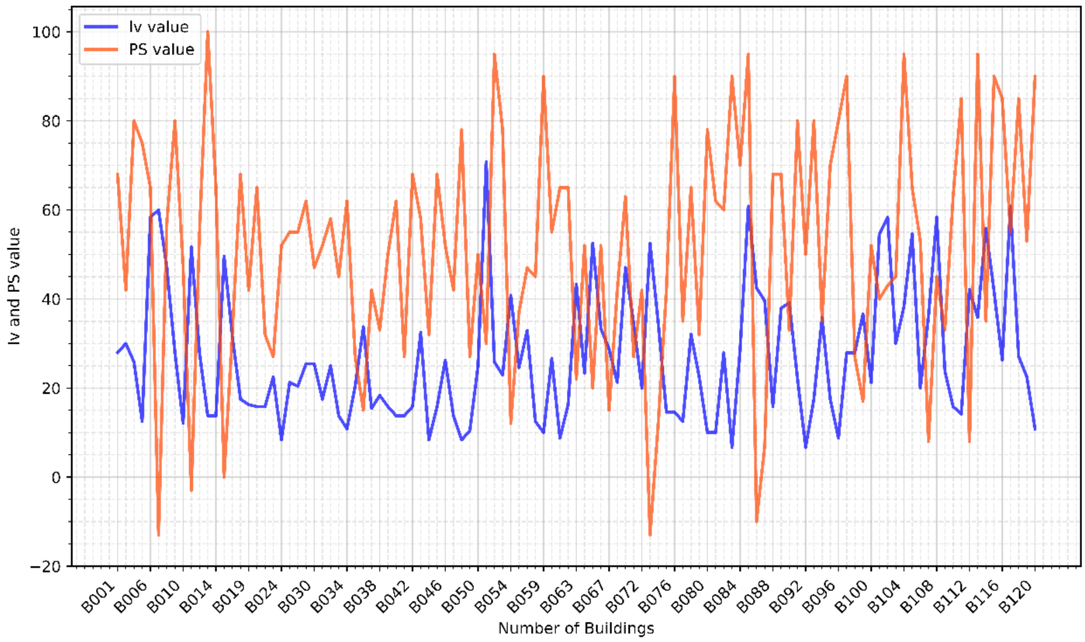

Figure 5.14: Comparative Plot of I_v and PS Values for Methodological Validation.

This consistent inverse correlation between the detailed, quantitative SVI method and the Turkish method is a significant finding. It demonstrates that despite their different approaches, both methodologies are effectively identifying the same buildings at the extreme ends of the vulnerability spectrum. The ability of two independent assessment techniques to converge on similar conclusions regarding the most and least at-risk structures provides strong validation for the overall reliability of this study. It should be noted that the comparison of these two methods excluded seven buildings taller than seven stories (Building ID: 002, 016, 023, 025, 026, 057, and 068).

5.6 Mean Damage Grade

The Mean Damage Grade (μD) establishes a quantitative link between the calculated vulnerability of the building sample and the potential for physical damage under various seismic scenarios. This analysis, which correlates seismic intensity with expected damage levels according to the EMS-98 scale, provides a predictive forecast of building performance and forms a critical component of the overall risk assessment.

Figure 5.15 presents the best-fit curve plotted against the mean damage grades calculated for the surveyed buildings at various macroseismic intensities (EMS-98). The light blue scatter points represent the damage grade for each building, while the line illustrates the clear, positive correlation between increasing seismic intensity and the average level of damage. The mean damage grade progresses from μD = 1.19 (slight to moderate damage) at an intensity of V, steadily increasing to μD = 4.34 (very heavy damage to near collapse) at an intensity of XII. This demonstrates a predictable escalation in damage severity as the intensity of ground shaking increases.

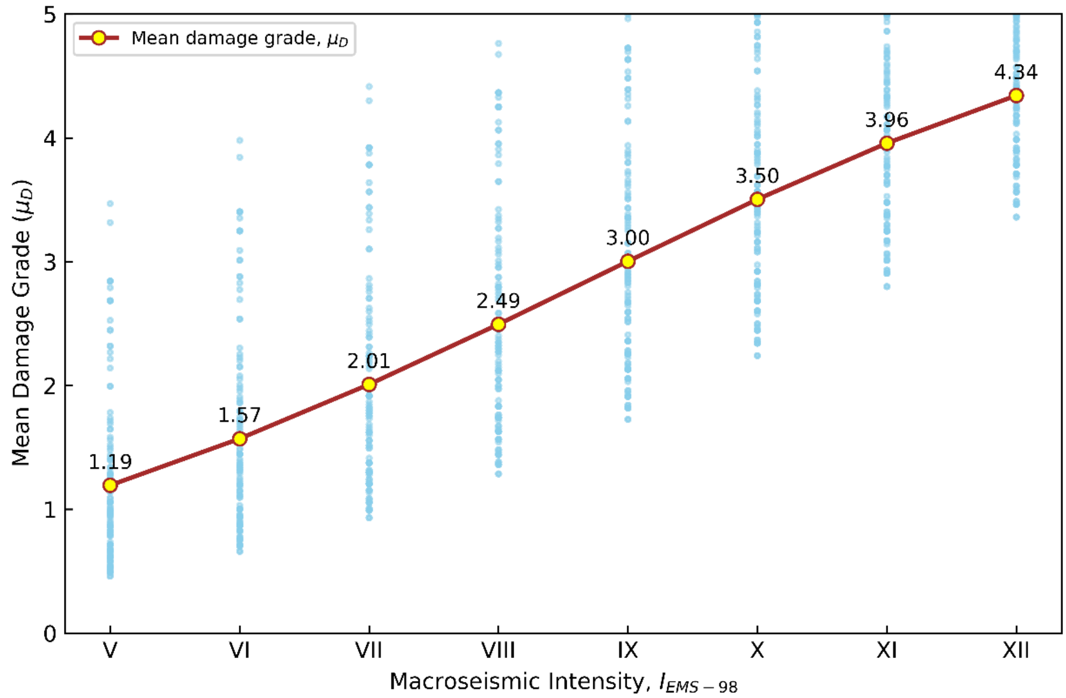

Figure 5.15: Best curve fit to the average values of the assessed buildings with damage.

Building on this relationship, a set of vulnerability curves was developed for the reinforced concrete building sample, as shown in Figure 5.16. These curves depict the expected mean damage grade as a function of seismic intensity for buildings with varying levels of vulnerability. The central curve represents the expected damage for a building with the average vulnerability index of the sample (I_v, mean = 28.39). The upper and lower curves illustrate the expected damage for more vulnerable (I_v, mean + Std = 43.76) and less vulnerable (I_v, mean - Std = 12.99) buildings, respectively. This set of curves is a powerful predictive tool, clearly showing that for any given seismic intensity, a building with a higher vulnerability index will suffer significantly higher damage. For instance, at an intensity of IX, the average building is expected to sustain damage of μD ≈ 3.5, while a more vulnerable structure may approach μD ≈ 4.2.

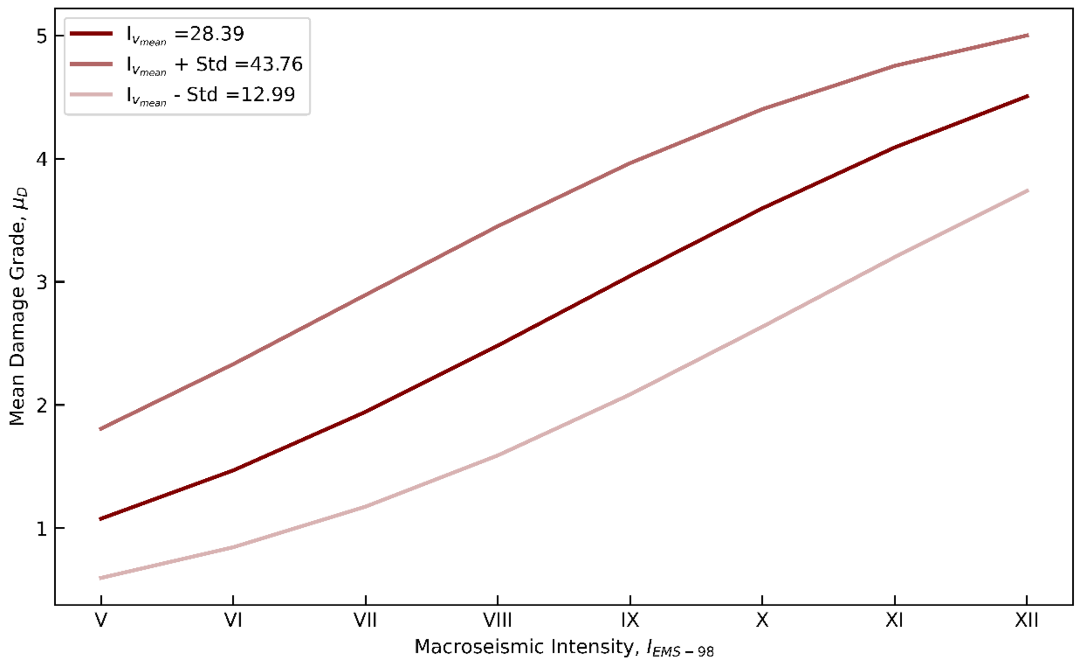

Figure 5.16: Vulnerability curves for Reinforced Concrete buildings.

5.7 Fragility Curve

The fragility curves, developed for building samples, are presented in Figure 5.17. These curves are a critical output of the probabilistic risk assessment, illustrating the probability that a building will reach or exceed a specific damage grade as a function of increasing macroseismic intensity (I, EMS-98).

The set of five curves demonstrates that for any given damage state, the probability of exceedance increases with higher seismic intensity. The curve for D1 (slight damage) shows a very high probability of damage even at low intensities, with a 69% chance of occurrence at an intensity of V and reaching near certainty (98%) at an intensity of VIII. This indicates that most buildings will experience at least minor damage in moderate seismic events.

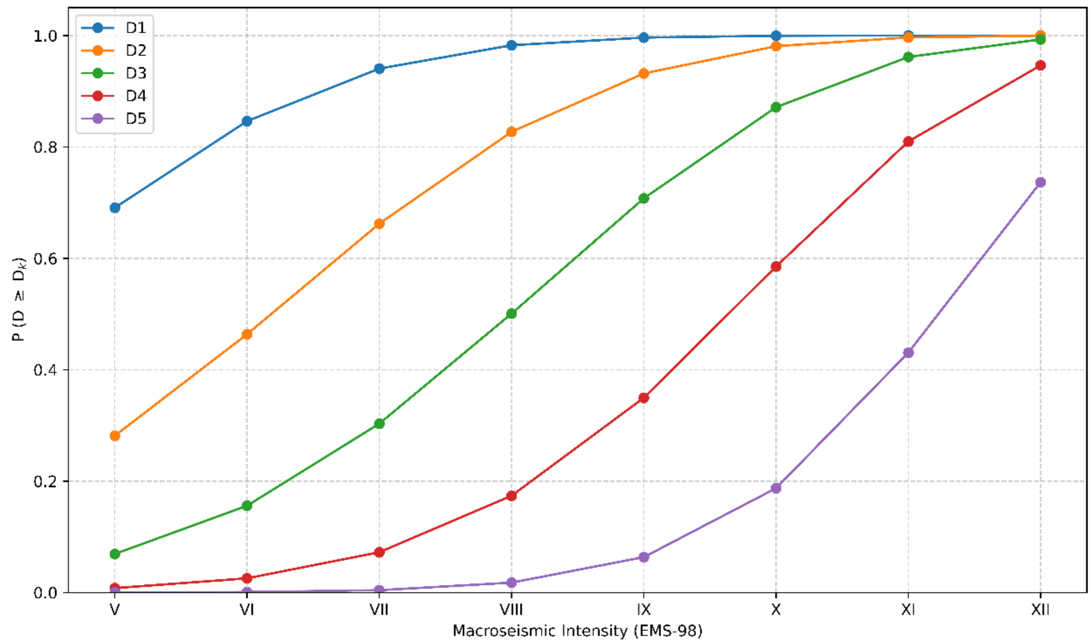

Figure 5.17: Fragility curves for the building sample by damage grade exceedance.

As the damage level increases, the curves shift to the right, signifying that a higher intensity is required to induce more severe damage. For D3 (substantial to heavy damage), the probability is negligible at low intensities but rises sharply, reaching approximately 50% at an intensity of VIII.

The curves for severe damage states, D4 (very heavy damage) and D5 (destruction/collapse), show very low probabilities at intensities below VIII. However, the risk escalates significantly in strong ground shaking. The probability of collapse (D5) remains near zero until an intensity of VIII but increases to 19% at intensity X and reaches a critical 74% at intensity XII.

These fragility curves are essential for seismic risk management, as they provide a quantitative basis for forecasting damage, estimating potential losses, and prioritizing retrofitting efforts for the most vulnerable structures under credible earthquake scenarios.

5.8 Spatial Distribution of Vulnerability

5.8.1 Vulnerability Index (I_v)

The spatial distribution of seismic vulnerability, as determined by the Vulnerability Index (Iv), is presented in Figure 5.18. The map provides a clear geographical representation of risk across the study area, color-coding each surveyed building according to its calculated vulnerability level. While a large number of buildings exhibit low to moderate vulnerability (indicated by lighter shades), several distinct clusters of high-vulnerability structures (darker reds) are evident. These "hotspots" are primarily concentrated in the western and central portions of the ward, identifying specific zones where seismic risk is highest. This spatial analysis is a critical tool for urban planning and disaster management, as it allows for the direct visualization of high-risk areas, enabling authorities to prioritize detailed structural assessments and target retrofitting interventions effectively.

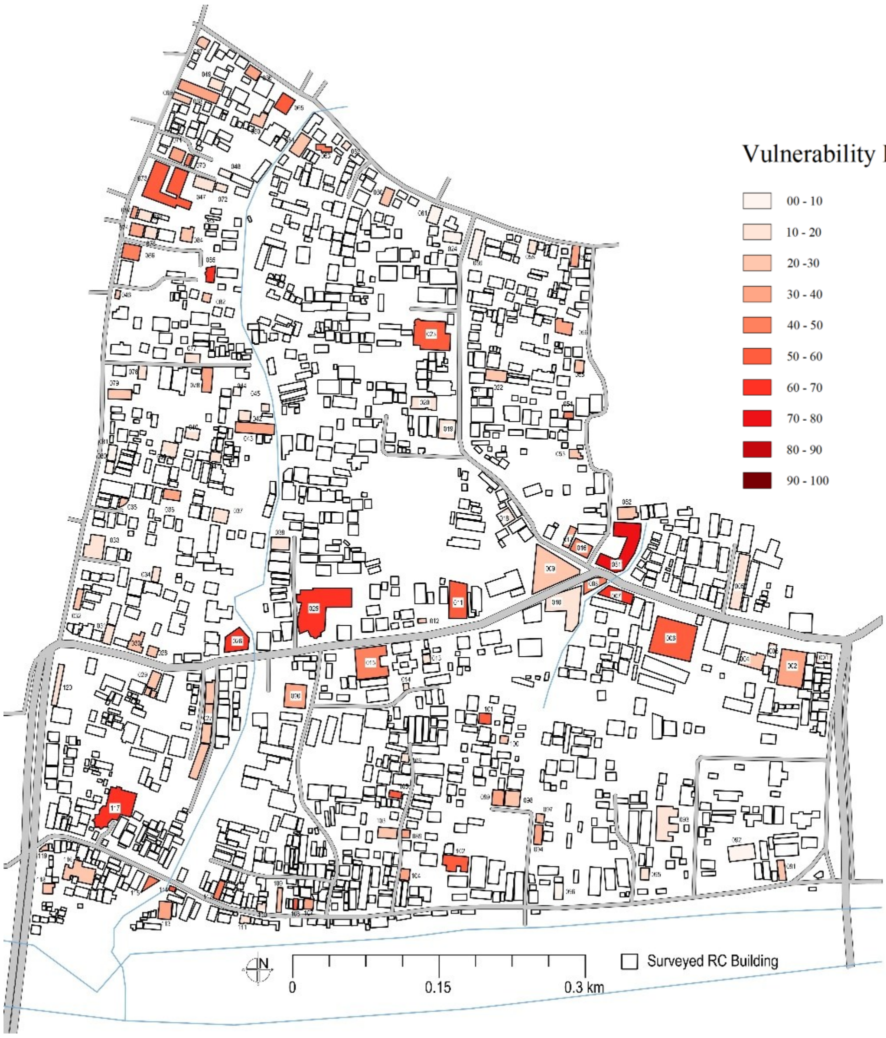

Figure 5.18: Spatial distribution of seismic vulnerability in Ward 13 based on the Vulnerability Index (I_v).

5.8.2 Turkish Method (Performance Score)

Figure 5.19 illustrates the spatial distribution of seismic vulnerability based on the Performance Score (PS) from the Turkish method. In this visualization, buildings are color-coded to represent their expected performance, where lower scores (indicated by darker shades of red) signify higher vulnerability.

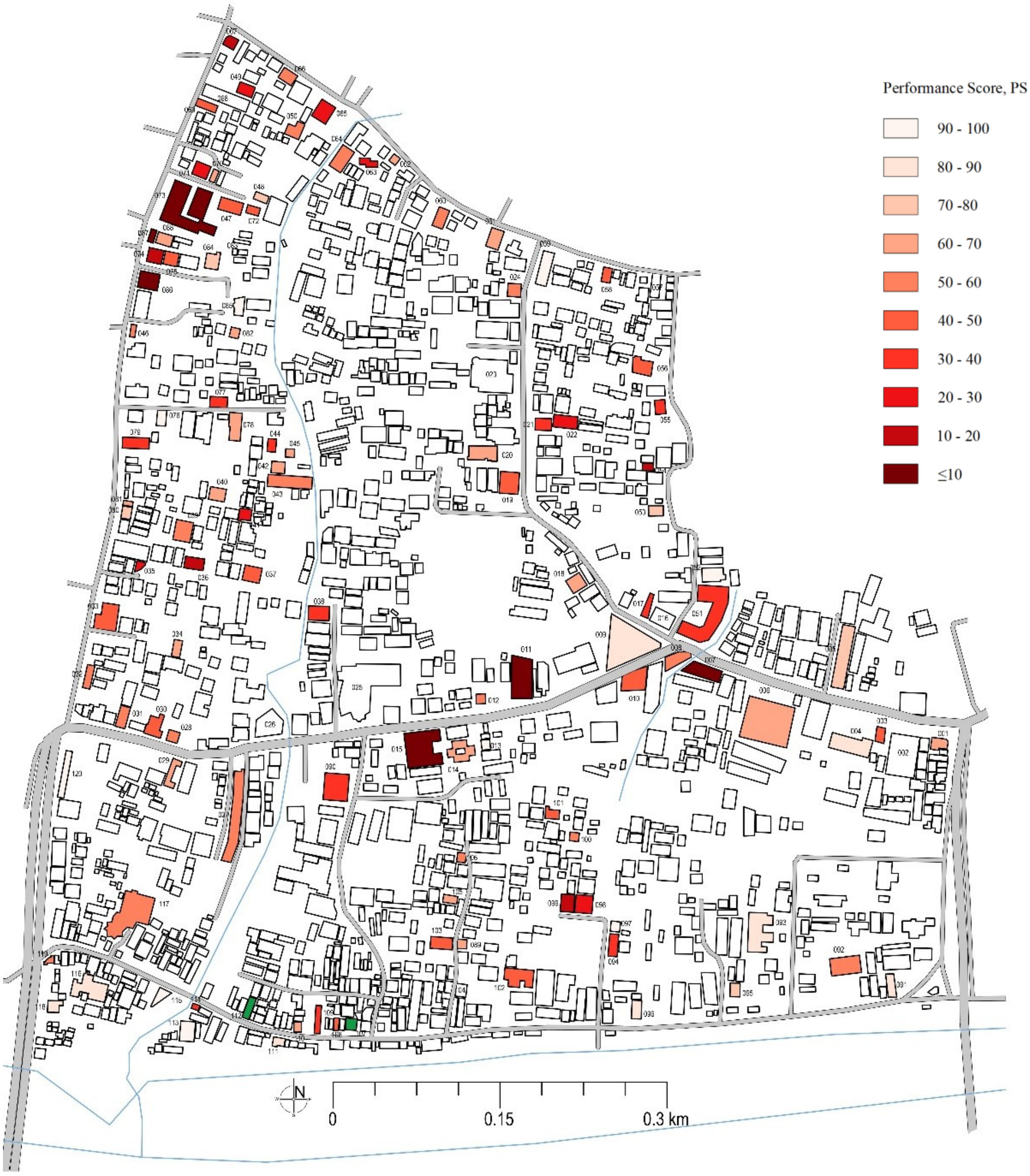

Figure 5.19: Spatial distribution of seismic vulnerability based on the Performance Score (PS).

A visual inspection of the map reveals a strong correlation with the vulnerability patterns identified by the Vulnerability Index (Iv) map (Figure 5.18). The same clusters of high-risk buildings are evident, particularly in the western and central parts of the ward. Buildings with low PS values consistently correspond to those with high I_v values, confirming the reliability of both assessment methods in identifying critical structures.

5.9 Discussion

The results presented in this chapter provide a multi-faceted and validated assessment of the seismic vulnerability of the reinforced concrete building stock in Ward 13 of Sylhet City. The analysis reveals that while the majority of structures exhibit low to moderate vulnerability, a significant and critical subset of buildings poses a high risk, warranting immediate attention. This discussion interprets the key findings, their implications for seismic risk management, and their alignment with the research objectives.

A detailed analysis of the individual vulnerability parameters reveals the primary causes of seismic risk within the study area. The high prevalence of vulnerabilities such as Heavy Overhangs, Irregularity in Plan and Height, and the potential for Pounding Effect points to systemic issues in local architectural design and urban planning practices. Most critically, the identification of a Soft-Story mechanism in a substantial portion of the sample highlights a widespread and dangerous structural flaw. Similarly, the widespread classification of buildings under 'Moderate' or 'Poor' Apparent Quality suggests deficiencies in construction practices and material quality control, which directly compromise the seismic resilience of structures.

The spatial analysis, culminating in the vulnerability maps, translates these numerical scores into an actionable planning tool. The maps fulfill a key research objective by providing a visual basis for municipal authorities to prioritize detailed inspections, implement targeted retrofitting programs, and refine emergency response plans for the areas of greatest risk.

Finally, the development of fragility curves provides a crucial probabilistic dimension to the assessment. By quantifying the probability of exceeding specific damage states at various seismic intensities, these curves move the analysis from a deterministic assessment to a forecast of potential losses. The curves indicate that even a moderate seismic event (e.g., Intensity VII-VIII) could cause substantial damage to many buildings in the ward, while a major earthquake could lead to catastrophic failures, especially among the most vulnerable structures. This information is invaluable for policymakers, engineers, and disaster managers for conducting realistic risk scenarios and advocating for proactive seismic risk reduction policies.

5.10 Summary

This chapter presented the detailed results of the seismic vulnerability assessment, validating the dual-methodology approach through a strong correlation between the Vulnerability Index (I_v) and the Performance Score (PS). The analysis identified soft-story mechanisms, plan irregularities, and poor construction quality as the primary drivers of risk within the surveyed buildings. Spatial mapping successfully delineated geographic "critical spots" of high vulnerability, providing a visual tool for targeted planning. Finally, the development of fragility curves quantified the significant probability of widespread damage under moderate to strong seismic intensities, underscoring the urgent need for mitigation efforts in the study area.

CHAPTER 6
CONCLUSIONS AND FUTURE WORKS

This final chapter synthesizes the findings of the research, presents the main conclusions drawn from the analysis, acknowledges the inherent limitations of the study, and provides concrete recommendations for future work. The chapter aims to consolidate the contributions of this thesis to the field of seismic risk assessment in the context of urban Bangladesh.

6.1 Conclusions

This research set out to conduct a comprehensive seismic vulnerability assessment of reinforced concrete buildings in Ward 13 of Sylhet City Corporation, utilizing a dual-methodology approach for validation. The study successfully achieved its objectives, yielding several key conclusions:

a. **Validated Vulnerability Assessment:** The dual-methodology approach was successfully validated through the assessment between the SVI simplified and Turkish methods, confirming the reliable identification of the most at-risk structures.
b. **Identification of Critical Risk Parameters:** The study identified critical risk parameters, including soft-story mechanisms, structural irregularities, and poor construction quality, which indicate systemic deficiencies in local building practices that require attention.
c. **Development of an Actionable Risk Map:** A key outcome was the creation of a spatial vulnerability map that delineates high-risk "hotspots," providing a practical, data-driven tool for municipal authorities for targeted planning and risk mitigation.

In summary, this thesis provides conclusive evidence that a significant portion of the RC building in urban Sylhet possesses high seismic vulnerability due to identifiable and recurring structural flaws. The study not only quantifies this risk but also provides a validated methodological framework that can be replicated in other urban areas to support proactive disaster risk reduction efforts.

6.2 Limitations of the Study

Despite the rigorous methodology, this assessment has several inherent limitations. The study provides a structural vulnerability assessment but does not extend to a quantitative loss estimation for potential seismic events. During the field survey, practical challenges within the dense and busy environment of Ward 13 occasionally impeded full physical access to all buildings, which placed constraints on the uniformity of visual inspections. Furthermore, as a rapid assessment, the methodology relies on observable parameters and does not include detailed analytical structural modeling or laboratory material testing, which were beyond the scope of this research. These factors define the boundaries within which the study's findings should be interpreted.

6.3 Recommendations for Future Works

Based on the findings and limitations of this study, the following recommendations are proposed for future research and practical application:

1. Expand the Study Area: Extend the assessment to all wards of Sylhet City Corporation to create a comprehensive, city-wide seismic risk profile for municipal planning.
2. Include Other Building Typologies: Incorporate vulnerability assessments for other common building types, especially high-risk unreinforced masonry (URM) structures prevalent in older city areas.
3. Develop a Localized Retrofitting Manual: Research to create a cost-effective, context-specific retrofitting manual that addresses the typical deficiencies (e.g., soft-story conditions) identified in this study.
4. Integrate Socio-Economic Data: Enhance the physical vulnerability maps by integrating them with socio-economic data, such as population density, to develop more holistic and comprehensive seismic risk models.

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APPENDIX

Appendix A

Seismic Vulnerability Assessment Form for RC Buildings: GNDT Level II Methodology

Generation Information		
ID:		Notes: GPS: X = Y = Length = Width = Avg. Storey Height = Plan & Elevation:
Address	Street Name : Street Number: City : Ward :	
Use	☐ Residential ☐ Governmental ☐ Commercial ☐ Touristic ☐ Industrial ☐ Unoccupied ☐ Medical ☐ Mixed ☐ Education	
Occupants	☐ 0 – 10 ☐ 10 – 100 ☐ >100	

P-1: Soil and Foundation Conditions			
Type of Soil	Type of Foundation	Building Location	Class
☐ B (Rock) ☐ C (Very Dense) ☐ D (Stiff) ☐ E (Soft)	☐ Shallow ☐ Pile	☐ Plain Field ☐ Landfills ☐ Pronounced Slope	☐ A ☐ B ☐ C ☐ D

P-2 Building Position		
Type	Class	Note:
In -Row (BM)	☐ A	
Isolated (I)	☐ B	
Corner (G)	☐ C	
Edge (BE)	☐ D	

Figure 1: The criterion to assess parameter P2, where BM stands for in row building, I for isolated building, G for corner building, and BE for edge building.

P-3 Building Age		
Year of Construction =		Class
Design Type	1.With modern seismic design codes	☐ A
	2.With current seismic provisions	☐ B
	3.With minor seismic provision	☐ C
	4.Without seismic design	☐ D

P-4 Irregularity in Plan		
Category	Class	Note:
☐ Regular plan	☐ A	1. Torsional Irregularity
☐ 1 irregularity	☐ B	2. Re-entrant corners 3. Diaphragm discontinuity
☐ 2 irregularities	☐ C	4. Out- of-plane offsets of shear wall 5. Non-parallel systems of shear wall
☐ >2 irregularities	☐ D	

P-5 Irregularity in Height		
Category	Class	Note:
☐ No vertical irregularities	☐ A	1. Soft story
☐ 1 irregularity	☐ B	2. Mass irregularity 3. Vertical geometric irregularity (setback structures)
☐ 2 irregularities	☐ C	4. Vertical In-Plane Discontinuity in Vertical Elements Resisting Lateral Force
☐ >2 irregularities	☐ D	5. Weak story

P-6 Soft Story Mechanism	
Category	Class
1. Without a possible soft story	☐ A
2. Potential soft-story mechanism (Commercial/parking)	☐ D

P-7 Presence of short columns	
Category	Class
1. No short columns	☐ A
2. Possible short columns in upper floors only	☐ B
3. Possible short columns on ground floor or multiple upper floors	☐ C
4. Short columns on ground floor likely to cause story failure	☐ D

P-8 Presence of other vulnerable elements	
Category	Class
1. Building without vulnerable non-structural components	☐ A
2. Building with parapets and/or cornices and/or appendages	☐ B
3. Building With balconies	☐ C
4. Building with balconies and parapets or cornices or appendages	☐ D

Turkish Methodology Adopted Survey Form for Vulnerability Assessment of RC Buildings

Table A: Initial & Vulnerability Scores for Level - I Survey of RC Buildings

No. of Stories	Initial Score (On Soil Zoning)			Soft Story	Heavy Overhang	Apparent Quality	Short Column	Pounding	Topography Effect
	60<PGV<80	40<PGV<60	20<PGV<40						
1, 2	100	130	150	0	-5	-5	-5	0	0
3	90	120	140	-15	-10	-10	-5	-2	0
4	75	100	120	-20	-10	-10	-5	-3	-2
5	65	85	100	-25	-15	-15	-5	-3	-2
6, 7	60	80	90	-30	-15	-15	-5	-3	-2

Table B: Vulnerability Parameters

Parameter			
Number of Stories			
Soft Story	☐ No (0)	☐ Yes (1)	
Heavy Overhang	☐ No (0)	☐ Yes (1)	
Apparent Quality	☐ Good (0)	☐ Moderate (1)	Poor (2)
Short Column	☐ No (0)	☐ Yes (1)	
Pounding Effect	☐ No (0)	☐ Yes (1)	
Topography Effect	☐ No (0)	☐ Yes (1)	
Local Soil Condition	☐ Stiff	☐ Soft	

General Equation for Seismic Performance Scores (PS) for both Levels ("cut-off" PS = 50):

PS = (Initial Score) − Σ (Vulnerability Parameter) × (Vulnerability Score)

Appendix B

Table 6.1: Summary of total 120 surveyed building

Building ID	Latitude	Longitude	Purpose	Construction Year	Stories	Soil Type	I_v (0–100)	PS
B001	24.890345	91.867813	Commercial	1980	3	C	27.92	68
B002	24.89039	91.867418	Mixed	2005	14	D	37.50	NA
B003	24.890434	91.867235	Mixed	1990	4	D	30.00	42
B004	24.890376	91.866893	Government	1988	3	D	25.83	80
B005	24.890919	91.866871	Government	1997	4	D	12.50	75
B006	24.890504	91.866269	Government	1980	4	D	58.33	65
B007	24.890898	91.865646	Commercial	1995	5	D	60.00	-13
B008	24.890976	91.865415	Mixed	1997	4	E	47.08	57
B009	24.891142	91.865200	Mixed	1985	3	E	27.92	80
B010	24.890760	91.864944	Mixed	2004	5	D	12.08	47
B011	24.890778	91.864066	Mixed	1986	7	D	51.67	-3
B012	24.890699	91.863818	Commercial	2005	4	D	27.92	55
B013	24.89024	91.864101	Government	2002	2	C	13.75	100
B014	24.890269	91.863495	Government	2005	4	C	13.75	65
B015	24.890219	91.863097	Commercial	2011	6	D	49.58	NA
B016	24.891303	91.865325	Commercial	2004	9	D	40.83	NA
B017	24.891385	91.865219	Mixed	2010	4	D	31.67	32
B018	24.891608	91.864576	Education	2005	3	D	17.50	68
B019	24.892499	91.863948	Residential	2006	7	D	16.25	42

Building ID	Latitude	Longitude	Purpose	Construction Year	Stories	Soil Type	I_v (0–100)	PS
B020	24.892693	91.863717	Mixed	2000	4	D	15.83	65
B021	24.892908	91.864183	Mixed	1998	5	D	15.83	32
B022	24.892886	91.864404	Residential	2001	6	D	22.50	27
B023	24.893275	91.863901	Commercial	2016	8	D	50.83	NA
B024	24.894013	91.863997	Residential	2008	4	C	8.33	52
B025	24.890712	91.862589	Medical	2013	14	D	60.83	NA
B026	24.890524	91.861815	Residential	2007	16	E	68.33	NA
B027	24.889635	91.861513	Education	1995	4	E	21.25	55
B028	24.890406	91.860944	Mixed	2003	4	D	20.42	55
B029	24.890142	91.860813	Education	1995	4	D	25.42	62
B030	24.890427	91.860772	Residential	1994	5	D	25.42	47
B031	24.890504	91.860503	Mixed	1997	4	D	17.50	52
B032	24.890791	91.860183	Commercial	1985	3	D	25.00	58
B033	24.891322	91.860407	Residential	2019	6	D	13.75	45
B034	24.891076	91.860981	Residential	2020	4	D	10.83	62
B035	24.891711	91.860575	Residential	2010	7	D	20.42	27
B036	24.891690	91.861384	Residential	2007	7	D	33.75	15
B037	24.891639	91.861604	Residential	2018	6	D	15.42	42
B038	24.891382	91.862254	Residential	2011	5	E	18.33	33
B039	24.891975	91.860999	Residential	1998	4	D	15.83	50

Building ID	Latitude	Longitude	Purpose	Construction Year	Stories	Soil Type	I_v (0–100)	PS
B040	24.892326	91.861331	Residential	2006	4	D	13.75	62
B041	24.892177	91.861610	Residential	2009	6	D	13.75	27
B042	24.892598	91.861856	Residential	1995	3	D	15.83	68
B043	24.892483	91.861889	Residential	1988	3	D	32.50	58
B044	24.892795	91.861794	Residential	2010	5	D	8.33	32
B045	24.892707	91.861711	Residential	1992	3	D	15.83	68
B046	24.893676	91.860574	Commercial	1984	4	D	26.25	52
B047	24.894661	91.861461	Residential	2010	6	D	13.75	42
B048	24.894739	91.861640	Residential	2006	3	C	8.33	78
B049	24.895581	91.861525	Residential	2007	6	E	10.42	27
B050	24.895296	91.862013	Residential	2017	5	E	25.00	50
B051	24.891226	91.865625	Commercial	1992	6	E	70.83	30
B052	24.891756	91.865749	Residential	1993	2	E	25.83	95
B053	24.892953	91.86531	Residential	2007	3	D	22.92	78
B054	24.89259	91.865201	Residential	2022	6	E	40.83	12
B055	24.89305	91.86528	Residential	2011	6	D	24.58	37
B056	24.893435	91.865151	Residential	2010	5	D	32.92	47
B057	24.894004	91.865214	Mixed	2006	9	E	33.33	NA
B058	24.894154	91.864795	Residential	2013	6	D	12.50	45
B059	24.89428	91.864229	Education	2006	3	D	10.00	90

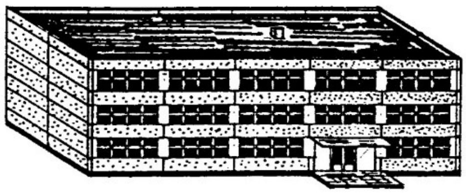
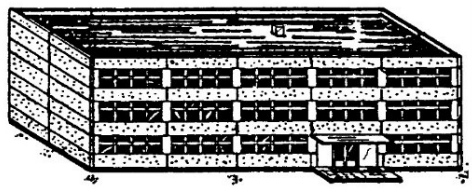
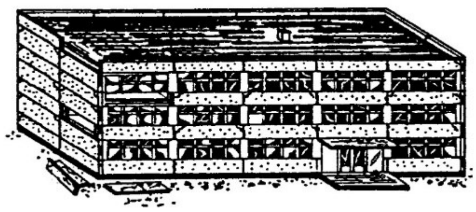
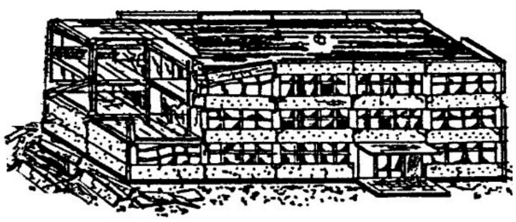
Building ID	Latitude	Longitude	Purpose	Construction Year	Stories	Soil Type	I_v (0–100)	PS
B060	24.89462	91.863323	Mixed	2005	4	D	26.67	55
B061	24.894455	91.86379	Residential	2007	4	C	8.75	65
B062	24.895068	91.86289	Mixed	1996	4	E	16.25	65
B063	24.894922	91.86269	Residential	2024	5	D	43.33	22
B064	24.895104	91.862433	Residential	1997	4	E	23.33	52
B065	24.895457	91.862228	Mixed	1998	4	E	52.50	20
B066	24.895707	91.861907	Mixed	2019	4	E	33.33	52
B067	24.895993	91.861417	Mixed	1990	6	D	28.75	15
B068	24.895527	91.861258	Mixed	2010	10	D	33.33	NA
B069	24.895458	91.861178	Mixed	2006	6	D	21.25	42
B070	24.894829	91.861268	Residential	2018	3	E	47.08	63
B071	24.894924	91.861160	Residential	2005	7	D	34.58	27
B072	24.894640	91.861180	Residential	1995	6	D	20.00	42
B073	24.89457	91.861192	Residential	2000	5	E	52.50	-13
B074	24.894237	91.860702	Mixed	2006	7	D	34.58	12
B075	24.894182	91.861041	Residential	2005	7	E	14.58	42
B076	24.892923	91.861067	Residential	2017	2	E	14.58	90
B077	24.893106	91.861335	Mixed	2010	5	E	12.50	35
B078	24.892901	91.861492	Mosque	2010	3	E	32.08	65
B079	24.892865	91.860527	Mixed	2000	5	E	22.50	32

Building ID	Latitude	Longitude	Purpose	Construction Year	Stories	Soil Type	I_v (0–100)	PS
B080	24.891911	91.860474	Mixed	2012	3	E	10.00	78
B081	24.891966	91.860493	Mixed	2019	4	D	10.00	62
B082	24.893454	91.861418	Residential	2003	3	D	27.92	60
B083	24.894344	91.861466	Residential	2011	2	E	6.67	90
B084	24.894193	91.861455	Residential	1985	3	D	28.75	70
B085	24.893866	91.861488	Government	2012	2	D	60.83	95
B086	24.894057	91.860663	Mixed	2017	5	D	42.50	-10
B087	24.894369	91.860727	Mixed	2006	5	D	39.58	7
B088	24.894388	91.860799	Residential	1995	3	E	15.83	68
B089	24.888657	91.863535	Residential	2013	3	D	37.92	68
B090	24.889965	91.862409	Residential	2003	5	E	39.17	33
B091	24.888385	91.867336	Medical	2005	3	D	22.08	80
B092	24.888572	91.866873	Mixed	2010	5	D	6.67	50
B093	24.888746	91.866134	Government	1998	3	D	17.50	80
B094	24.888392	91.865688	Mixed	2019	4	D	35.83	35
B095	24.888249	91.865492	Government	2010	3	D	17.50	70
B096	24.888147	91.865081	Mixed	2011	3	D	8.75	80
B097	24.888854	91.864905	Mixed	2011	2	D	27.92	90
B098	24.889033	91.864573	Residential	2011	4	D	27.92	27
B099	24.889026	91.86446	Residential	2000	5	D	36.67	17

Building ID	Latitude	Longitude	Purpose	Construction Year	Stories	Soil Type	I_v (0–100)	PS
B100	24.889456	91.864518	Residential	2019	4	D	21.25	52
B101	24.888280	91.864254	Residential	2005	3	D	54.58	40
B102	24.888444	91.863980	Government	2008	4	D	58.33	43
B103	24.888463	91.863431	Residential	1998	3	D	30.00	45
B104	24.882828	91.863515	Residential	2012	2	D	38.33	95
B105	24.889043	91.863427	Residential	2014	3	D	54.58	65
B106	24.889377	91.863520	Residential	2012	4	D	20.00	53
B107	24.887988	91.862561	Mixed	2005	5	D	36.25	8
B108	24.887976	91.862373	Mixed	1990	3	D	58.33	45
B109	24.888084	91.862274	Mixed	2005	4	D	23.75	33
B110	24.888086	91.861758	Mixed	2015	4	D	15.83	63
B111	24.887974	91.861603	Mixed	2022	2	D	14.17	85
B112	24.888235	91.861491	Mixed	1985	5	D	42.08	8
B113	24.887958	91.861168	Mosque	2005	2	D	35.83	95
B114	24.888211	91.861133	Commercial	1988	4	E	55.83	35
B115	24.888251	91.860949	Mixed	2020	2	E	41.67	90
B116	24.888320	91.860326	Commercial	2014	2	D	26.25	85
B117	24.888782	91.860468	Commercial	2010	3	D	60.83	55
B118	24.888008	91.860270	Commercial	2008	2	D	27.08	85
B119	24.888549	91.859946	Commercial	2005	3	D	22.50	53
B120	24.890058	91.859997	Commercial	2018	2	D	10.83	90

Appendix C

Classification of Damage to RC buildings.

Classification of damage to buildings of reinforced concrete	
	**Grade 1: Negligible to slight damage** **(no structural damage,** **slight non-structural damage)** Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills.
	**Grade 2: Moderate damage** **(slight structural damage,** **moderate non-structural damage)** Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels.
	**Grade 3: Substantial to heavy damage** **(moderate structural damage,** **heavy non-structural damage)** Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of conrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels.
	**Grade 4: Very heavy damage** **(heavy structural damage,** **very heavy non-structural damage)** Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.
	**Grade 5: Destruction** **(very heavy structural damage)** Collapse of ground floor or parts (e. g. wings) of buildings.

Short form of the European Macroseismic Scale, EMS-98

EMS intensity	Definition	Description of typical observed effects (abstracted)
I	**Not felt**	Not felt.
II	**Scarcely felt**	Felt only by very few individual people at rest in houses.
III	**Weak**	Felt indoors by a few people. People at rest feel a swaying or light trembling.
IV	**Largely observed**	Felt indoors by many people, outdoors with very few. A few people are awakened. Windows, doors and dishes rattle.
V	**Strong**	Felt indoors by most, outdoors by few. Many sleeping people awake. A few are frightened. Buildings tremble throughout. Hanging objects swing considerably. Small objects are shifted. Doors and windows swing open or shut.
VI	**Slightly damaging**	Many people are frightened and run outdoors. Some objects fall. Many houses suffer slight non-structural damage like hair-line cracks and fall of small pieces of plaster.
VII	**Damaging**	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many well-built ordinary buildings suffer moderate damage: small cracks in walls, fall of plaster, parts of chimneys fall down; older buildings may show large cracks in walls and failure of fill-in walls.
VIII	**Heavily damaging**	Many people find it difficult to stand. Many houses have large cracks in walls. A few well-built ordinary buildings show serious failure of walls, while weak older structures may collapse.
IX	**Destructive Damaging**	General panic. Many weak constructions collapse. Even well-built ordinary buildings show very heavy damage: serious failure of walls and partial structural failure.
X	**Very Destructive**	Many ordinary well-built buildings collapse.
XI	**Devastating**	Most ordinary well-built buildings collapse, even some with good earthquake resistant design are destroyed.
XII	**Completely devastating**	Almost all buildings are destroyed.

Appendix D

Figure 6.1: Pounding effect.

Figure 6.2: Apparent quality (Poor).

Figure 6.4: Heavy overhang.

Figure 6.5: Irregularity in height

Figure 6.3: Irregularity in plan.

Figure 6.6: Buildings in different position.

Figure 6.7: Data collection moments.