Qualitative Methodology for Earthquake Disaster Risk Assessment of the Existing Buildings

Thesis submitted in partial fulfilmentof

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by

Bharat

2019810001

bharat.prakke@research.iiit.ac.in

International Institute of Information Technology (IIIT)

Hyderabad,Hyderabad – 500032, India.

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Certificate

It is certified that the work contained in this thesis, titled “ **Qualitative Methodology for Earthquake Disaster Risk Assessment of the Existing Buildings** “ submitted by *Bharat Prakke, by* Roll No. 2019810001, has been carried out under my supervision and is not submitted elsewhere for a degree.

6 July 2024

Date

Advisor: Prof. R Pradeep Kumar
Professor
Earthquake Engineering Research Centre
International Institute of Information Technology
Hyderabad

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Abstract

India has experienced some of the world's most devastating earthquakes. In the past thirty years, earthquake losses in the country have been substantial, and the collapse of buildings is the principal cause of life loss. The experience of past earthquake events indicates that even moderate earthquakes caused significant property damage and fatalities. Most existing buildings in India are of the vernacular housing type and were constructed with limited or no engineering input. The remaining structures are considered engineered buildings of Reinforced Concrete type, but many of them were built without the assistance of professionals or trained assistance from the builders, placing them outside the scope of formal building codes. Rapid urbanization places pressure on the housing industry to expedite building structures. The expansion of urban areas because of population growth and migration results in unplanned and uncontrolled urban infrastructure, jeopardizing the built environment's safety. About 57% of the land area in India lies within the moderate-to-severe seismic zone, where approximately 80% of the population resides. Consequently, a substantial proportion of India's buildings are at risk due to seismic hazard and building stock in seismically active regions. Thus, pre-earthquake safety assessment of the built environment significantly reduces damage and losses by identifying buildings prone to earthquakes and implementing appropriate mitigation measures. Given the large number of existing buildings in cities and towns, conducting a detailed assessment of each structure is challenging. Therefore, two qualitative methods for assessing earthquake disaster risk, with a focus on building level and projection onto a city scale, provides a thorough understanding of risk and the ability to prioritize mitigation measures.

The Earthquake Disaster Risk Index (EDRI) is a first-cut method for estimating the earthquake risk of a city's-built environment. It is a nonlinear combination of the existing earthquake hazard representing the spatial aspects , vulnerability of the building's thematic characteristics and the exposure representing temporal characteristics. The method is based on a detailed visual survey of the building stock of specific typologies and reflects hazard, exposure, and vulnerability factors contributing to earthquake risk . The risk of individual buildings evaluated is used to calculate the average risk of each building type in the city. The Earthquake Disaster Risk Index of the surveyed buildings is computed. The overall EDRI of the city/town is estimated using the housing census data. risk of an individual building is estimated in terms of Demand Factor and Capacity Factor of the building. The seismic design coefficient from 1893 (Part 1):2016, is the Demand Factor. The Capacity Factor is from the Level 2 Detailed Qualitative Assessment of buildings built in the Town or City. A final qualitative earthquake rating is assigned to the building by calculating the Capacity Factor/Demand Factor. The method helps in understanding, managing, and reducing seismic risk overtime.

In this study, the data collected from fifty cities by National Disaster Management Authority (NDMA) and the International Institute of Information Technology Hyderabad (IIIT H) is used for analysis. Two types of data were gathered: building information and city

information, where the former is collected by Rapid Visual Screening (RVS) and photographs of the building and the latter by collected by visiting the municipal office.

Risks associated with cities in Seismic Zones III, IV and V are compared. This aids in the identification of techniques for retrofitting buildings in such regions; improving local construction techniques and adhering to the Indian Standard Code of Practice, as well as regularizing construction on hilly regions, will reduce the seismic risk of these cities.

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1
Introduction

1.0 INTRODUCTION

Over the past two decades, the world has experienced over 7,348 natural disasters, caused significant losses and affecting billions of people. Among these events, earthquakes account for 8 percent, leading to 58 percent of total fatalities. The economic impact of earthquakes is substantial, contributing to the $2.97 trillion in damages incurred globally (Figure 1.1) (Cred, 2020). Particularly in developing countries, the urban population is increasingly at risk from earthquakes. In 1950, just over half of the population in developing nations was at risk, but by 2000, this figure had increased to over 85 percent. During the first half of the 20th century, developing and industrialized nations experienced approximately twelve thousand deaths per deadly earthquake. However, in the latter half of the century, industrialized nations saw a significant reduction in fatalities per earthquake (Tucker et al., 1994; GHI, 2001). In developing nations, the loss of life remains a primary concern, with earthquake disasters significantly impeding progress. For instance, in the aftermath of various earthquakes, such as the Mw7.7 Bhuj earthquake in 2001, which resulted in over 13,800 fatalities; the Mw7.6 Kashmir earthquake in 2005, claiming 73,338 lives; the Mw6.3 Yogyakarta earthquake in 2006, in Indonesia with 5,778 casualties; the Mw7.9 Wenchuan earthquake in 2008 resulting in 87,476 deaths; the Mw7.0 Haiti earthquake in 2010 causing 2,22,570 fatalities, and the Mw7.8 Gorkha Nepal earthquake in 2015 leading to 8,831 deaths, the loss of life remains a significant concern (Spence and So, 2013).

Buildings are a crucial component of the built environment, serving multiple societal needs by providing shelter for people in their homes and workplaces, housing commercial and industrial operations, and serving as essential facilities such as schools and hospitals . Urbanization, a complex phenomenon that change the built environment by converting rural areas into urban centres redistributing the population from rural to urban regions (United Nations, 2018).Currently, more than 56 Percent of the world population living in the urban areas as compared to the 18 percent in the 1950s, and the world's population could add more than 2.5 billion to the urban areas by 2050 (United Nations, 2018). In many countries, rapid urbanization is leading to construction of numerous new buildings without compliance to the earthquake resistant design standards or building built in a manner reminiscent of rural construction techniques (Spence, 2019). Thus, the earthquake risk is increasing , creating a context for large earthquake disaster in the future.

Past earthquakes have highlighted the significant life and economic losses that result primarily from damage to buildings. It's estimated that 75 percent of deaths during earthquakes are due to building collapses and continue to be the dominant causes of deaths in earthquakes (Marano et al. 2010, Daniell et al. 2012, So et al. 2018).

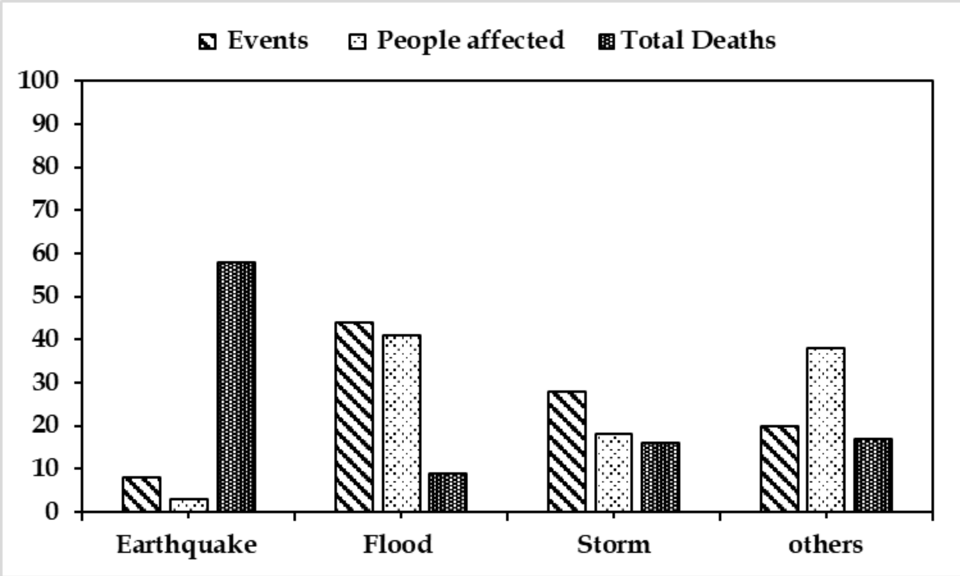


Figure 1.1 *Disaster Events and Consequences expressed as percentage (2000-2019)*

India has experienced some of the world's most devastating earthquakes, resulting in significant losses (Jain, 2016) (Table 1.1)(Figure 1.2). Over the past three decades, India experienced 16 earthquake events, resulting in the loss of nearly 50,000 lives, injuries to around 2.14 lakh individuals, and rendering approximately 21.5 lakh people homeless, affecting a total of more than 85 lakh individuals (Cred,2020). For instance, the 1993 Killari earthquake caused 7,928 human fatalities (Gurme, 2017). The 2001 Bhuj earthquake resulted in approximately 13,800 deaths (Singh et al., 2002). However, a common factor among all earthquakes is the extensive loss of life, which is entirely attributed to the collapse of the physical infrastructure. A key observation highlights that it was the moderate earthquakes that caused the most significant losses and damage. One of the main reasons for such a high number of casualties is the lack of earthquake awareness among the population and the prevalence of poor building practices. In India, it's quite common for people to build their homes without seeking professional help, often overlooking crucial seismic safety measures.

India has over 1.5 billion population (United Nations, 2022) . About 59 percent of India's land area, with over 78 percent of its population living in it, is prone to moderate to strong earthquake shaking intensities (BIS, 2023). As per census 2011 more that 31 percent of the population lives in the urban areas (NITI Aayog, 2021). By 2050 more than 50 percent of the population in India reside in urban areas. Almost half of the 7933 'urban' settlements are census towns, that is, they continue to be governed as 'rural' entities. Small and medium towns face vulnerabilities due to rapid growth and inadequate planning. To safeguard built environments against such disasters, it is imperative that new constructions are designed to be earthquake-resistant, and existing buildings are strengthened by retrofitting. Focus on mitigation is pivotal in minimizing the extent of disaster impacts and preventing any loss of life resulting from disasters. Mitigation encompasses five interrelated aspects: Typology, Education, Safety, Practice, and Policy. These aspects work together to enhance the resilience of the built environment against earthquakes.

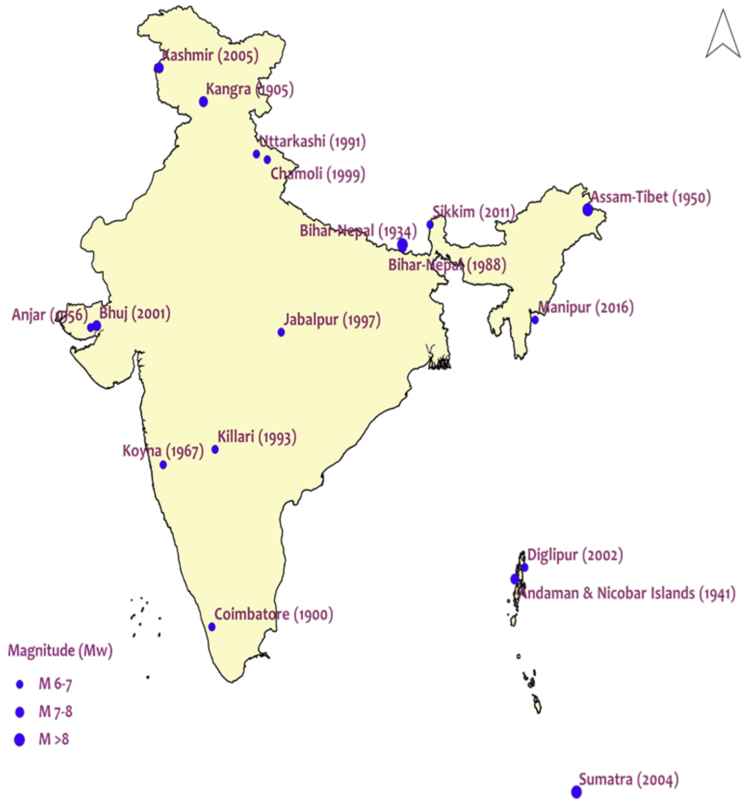


Figure 1.2 *Location of major earthquakes in India*

i) *Typology* involves understanding the different types of buildings and their vulnerabilities to earthquakes. This knowledge helps in designing buildings that can withstand seismic forces.

ii) *Education* is about raising awareness among stakeholders, including builders, homeowners, and the general public, about the importance of earthquake-resistant constructions and the steps they can take to mitigate risks.

iii) *Safety* emphasizes the implementation of construction standards and regulations that ensure buildings are built or retrofitted to resist earthquakes effectively.

iv) *Practice* refers to the application of knowledge, skills, and technology in the construction and retrofitting of buildings to make them more resilient.

v) *Policy* involves the development and enforcement of laws and regulations that mandate earthquake-resistant construction and retrofitting practices.

Establishing widespread public awareness about earthquake risks, fostering what can be termed as 'safety culture,' is a fundamental initial step for enhancing the earthquake safety of the buildings.

Risk indexing plays a pivotal role within this framework. It helps policymakers understand the earthquake disaster potential of a region and its various dimensions. This understanding enables them to commission detailed studies for the evaluation and retrofitting of buildings, thus making informed decisions to enhance the resilience of the built environment.

Table 1.1 *A brief overview of some significant earthquakes in the Indian subcontinent*

Date	*Location*	*Magnitude / MSK Intensity*	*Remarks*
8 February, 1900	Coimbatore	6.0/VII	Shock was felt throughout south India. Coimbatore and Coonoor worst affected.
4 April, 1905	Kangra	8.0/X	~19,000 deaths. Considerable damage in Lahore. High intensity around Dehradun and Mussorie VIII
15 January,1934	Bihar-Nepal	8.3/X	~7,000 deaths in India and ~3,000 deaths in Nepal. Liquefaction in many areas.
26 June, 1941	Andaman & Nicobar Islands	7.7/VIII	Triggered Tsunami-1.0m high on the east coast, causing many deaths.
15 August, 1950	Assam-Tibet	8.6/XII	About 1,500 deaths in India and ~2,500 in China. Caused huge landslides which blocked rivers and later caused flood.
21 July, 1956	Anjar (in Kutch)	6.1/IX	About 115 deaths. Part of Anjar on rocky sites suffered much less damage comparatively.
10 December, 1967	Koyana, Maharashtra	6.5/VIII	About 180 deaths. Caused significant damage to the concrete gravity dam.
21 August,1988	Bihar-Nepal	6.6/IX	About ~709 deaths.
20 October, 1991	Uttarkashi	6.4/IX	~750 deaths. 56m span Gawana bridge 6 km from Uttarkashi collapsed.
30 September, 1993	Killari, Maharashtra	6.2/IX	~8,000 deaths. Most deadly earthquake in India since Independence.
22 May, 1997	Jabalpur	6.0/VIII	~40 deaths and ~1,000 injured. Concrete frame buildings with

			open ground storey suffered damage.
26, January, 2001	Bhuj (Kutch)	7.7/X	~13,800 deaths. Numerous modern multistorey buildings collapsed. Number of medium and small earth dams severely damaged.
26, December, 2004	Sumatra	9.4/VI (in Andaman)	Caused most devastating Tsunami in thehistory resulting in ~2,27,898 deaths in 14 countries.
8, October, 2005	Kashmir	7.6/VIII	Poor performance of masonry buildings caused many life losses. Unique construction found in this region Dhajji Diwari showed very good seismic performance.
28, September, 2011	Sikkim	6.9/VI	~80 deaths. Large number of landslides, significant damage to the buildings and infrastructure.
4, January 2016	Manipur	6.7/VII	Loss of damage to life and property,08 deaths and 78 injured in Manipur and Assam. 1825 buildings damaged in Manipur

1.1 PAST EARTHQUAKES IN INDIA

The 1991 Uttarkashi earthquake, occurred in the Himalayan region of the then Uttar Pradesh, resulted in 768 fatalities and 5,066 injuries. It also led to the complete destruction of 20,184 homes and caused damage to an additional 74,714 houses. Nearly 4,25,000 people in 2,093 villages were adversely affected. There were numerous landslides in the area of strong shaking. Predominant wall materials are field stone with mortars of clay mud or lime-sand, and concrete blocks with lime or cement mortars. Building types and their damage can be described. Damage was observed in the Unreinforced masonry buildings and *Reinforced Concrete (RC)* frame structures. Extensive damage was observed in the rural stone houses of pitched roofs consisting of slates resting on wood purlins and round wood rafters. Intermediate floors made of wooden planks resting on the wood logs and joists were observed in such houses. A notable trend identified in the epicentral area was the complete destruction of stone houses built with random rubble masonry walls with RC slab roofs. These buildings collapsed, trapping people beneath them. The large mass due to concrete roofs and higher stiffness attracted large seismic forces in the buildings and the low shear and zero tensile strength of the wall material coupled with lack of strong bond between the stones of the masonry houses initiated the severe damage and collapse of the buildings. Houses constructed from random rubble masonry walls using lime and mortar, as well as those made from concrete blocks with RC slabs, also suffered significant damage. In these cases, the walls showed extensive cracking, and the roofs collapsed. However, several one storey and two storey loads bearing walled buildings, with roofs are made sloping with either CGI sheet covering on wood purlins in reinforced concrete slab construction, have shown excellent performance except for minor cracking in the joints. This is due to the provision of lintel band, roof band and gable bands. The area has one of the lowest population density in the state, and hence the rather low number of deaths and injuries.(Arya,1994; SK Jain, 1994).

The 1993 killari earthquake was one of the most devasting earthquakes occurred in India. The quake was centred near Killari village of Latur district of state of Maharashtra of central India, an area deemed to be non-seismic, and placed in the lowest seismic zone, zone I, by the Indian code IS:1893-1984. (Murty,1994). The area is in the Deccan plateau region . The earthquake resulted in a devastating loss of life, with more than 8,000 deaths, around 16,000 injuries, and over a million people left without homes. Roughly 67 villages were destroyed and caused severe destruction to around 700 villages in the Latur district and 600 in the Osmanabad district. Additionally, eleven other districts in Maharashtra experienced significant damage to both private and public properties. The estimated total property loss amounted to approximately US $333 million. In the region, the majority of houses were built using locally sourced uncoarsed random rubble stones and masonry as the main material for load-bearing walls. Mud mortar was commonly used, although some houses also utilized cement mortar. Most of these houses were single-story structures with a unique roofing system. This system included wooden joists covered with wooden planks, on top of which a 30-60 cm thick layer of clay was applied to protect against rain and heat. However, this construction method offered poor resistance to lateral forces and stability. The heavy roofs attracted large inertia forces during an earthquake, leading to the failure and collapse of the weak walls due to their inability to support vertical loads. Many houses experienced complete or near-total collapse, with severe damage and cracking observed in the houses up to 75 km from the epicentre. Another type of construction in the region used wooden load-bearing frames with stone masonry for partition walls. Post-earthquake, these wooden frames remained intact, but the partition walls fell due to lateral shaking. Many traditional houses in the region feature roofs made of reinforced concrete, which, during such constructions, have been observed to collapse entirely as a single unit, leading to significant casualties. This pattern of damage and its devastating effects were similarly noted in the aftermath of the Uttarkashi earthquake.

The 2001 Gujarat earthquake, with a magnitude of Mw 7.7, caused extensive damage across the region. The earthquake, which occurred on January 26, resulted in the destruction of approximately 300,000 houses and damaged another 700,000. The affected buildings primarily consisted of non-engineered dwellings with load-bearing masonry walls and reinforced concrete (RC) frame buildings with unreinforced masonry infills, most of which did not comply with seismic code provisions due to lack of enforcement. The earthquake also led to widespread liquefaction in areas such as the Great Rann, Little Rann, Banni Plains, Kandla River, and the Gulf of Kachchh, manifesting as sand boils, lateral spreads, and collapse features. This liquefaction caused significant damage to infrastructure, including the Ports of Kandla and Navlakhi, various bridges, and numerous embankment dams. For instance, the Kandla port experienced severe undulations of floor tiles at the container terminal and lateral translation of piles due to lateral spreading of the liquefied soil .

The Mw 6.9 earthquake that struck near the Nepal-Sikkim border on September 18, 2011, caused significant damage across Sikkim and surrounding areas. The earthquake's magnitude and the region's geological features led to extensive destruction. In Gangtok, the seismic event registered a peak ground acceleration (PGA) of 0.15g, with projections showing up to 0.35g in the meisoseismal region. The intense shaking resulted in severe structural damage to both residential and government buildings, with notable failures in reinforced concrete (RC) and unreinforced masonry (URM) structures. Pancaking of multiple-story buildings and shear failures were common, particularly in areas with non-engineered constructions.

Additionally, the earthquake triggered numerous landslides and instances of liquefaction. Landslides significantly increased north of Dikchu, with about 354 new and 48 reactivated slides documented. Liquefaction phenomena were observed in several regions, further exacerbating the damage to buildings and infrastructure. Consequently, over 600 school buildings suffered extensive damage or collapse, and critical facilities like hospitals were severely impacted, disrupting essential services and necessitating emergency measures.

This seismic event underscores the need for rigorous earthquake-resistant design and construction practices in Sikkim and similar regions, highlighting the importance of retrofitting existing structures to withstand such natural disaster (Murty et al. , 2012)

1.2 HAZARD

The Indian subcontinent is a seismically active region and has experienced numerous moderate to severe earthquakes in the past. The seismicity map of India indicates that the Andaman-Nicobar Islands, the Northeast region, and the Himalayas experience higher levels of seismic activity compared to the rest of Peninsular India (Figure1.3). The activity in the Himalayan region is associated with the collision between the Indian and the Eurasian plates that led to the subduction of the Indian plate to the Eurasian plate. Several key fault systems recognized within the Himalayas include the Indus Tsangpo Suture Zone (ITSZ), along with the Main Frontal Thrust (MFT), Main Central Thrust (MCT), and Main Boundary Thrust (MBT). In the western syntaxis region, notable fault lines include the Main Karakoram Thrust (MKT) and Main Mantle Thrust (MMT). The MKT delineates the southern boundary of the Hindu Kush and the Karakoram Mountain ranges. Meanwhile, the MMT, extending from the Hazara syntaxis, represents the western continuation of the Main Central Thrust (MCT). These fault systems have triggered numerous catastrophic earthquakes in history. Examples include the 1905 Mw7.8 Kangra earthquake, the 1934 Mw8 Bihar-Nepal earthquake, the 1991 Mw6.8 Uttarkashi earthquake, the 1999 Mw6.8 Chamoli earthquake, the 2011 Mw6.9 Sikkim earthquake, and the 2015 Mw7.9 Nepal earthquake. Northeast India and its surrounding regions represent one of the world's most complex tectonic regions. The majority of seismic events in this area stem from the movements of the Indian plate, primarily in south–north and west–east directions. A notable characteristic of this region is the abrupt curvature of the Himalayas at the Assam syntaxis, followed by their continuation in a general north-south direction towards eastern Burma, merging with the Andaman arc, thus forming a multifaceted plate boundary. Additionally, the Brahmaputra River flows nearly parallel to the Main Boundary Thrust (MBT) along the Assam valley, before sharply altering its course at a 90^0 angle, aligning itself with the Dhubri fault. The Shillong plateau and Mikir hills are remnants of the Peninsular Shield, displaced eastward along the Dauki fault. Due to their proximity to the Himalayas and the Burmese arc, seismic events in the Shillong Plateau and Assam valley are often classified as plate-boundary earthquakes. This region also suffers from very high seismicity and has produced the 1950 Mw 8.6 Assam-Tibet earthquake. Additionally, the Andaman-Sumatra-Sunda arc highlights the boundary between tectonic plates, leading to significant seismic hazards, including tsunamis. Besides the regions mentioned earlier, the stable continental area has also witnessed several significant intraplate earthquakes, such as the 1967 Mw6.5 Koyna earthquake and the 1993 Mw6.2 Killari earthquake, along with others like the 1997 Mw6 Jabalpur earthquake and the 2001 Mw7.6 Bhuj earthquake. Within the shield region, there are various local zones of vulnerability, including the Kutch rift zones and the Son-Narmada-Tapti lineaments. The Himalayan region and peninsular India are separated by the sedimentary plains of the Indo-Gangetic foredeep, characterized by low seismic activity. Figure 1.4 shows the seismo-tectonic map of India.

The Indian Standard IS 1893:2016 categorizes regions into four seismic zones: II, III, IV, and V. Zones indicate the level of seismic shaking that has been observed in the past, with Zone II experiencing low intensity and Zone V experiencing high intensity. The map shows most of the peninsular region is in zones II and III (Figure 1.5) .

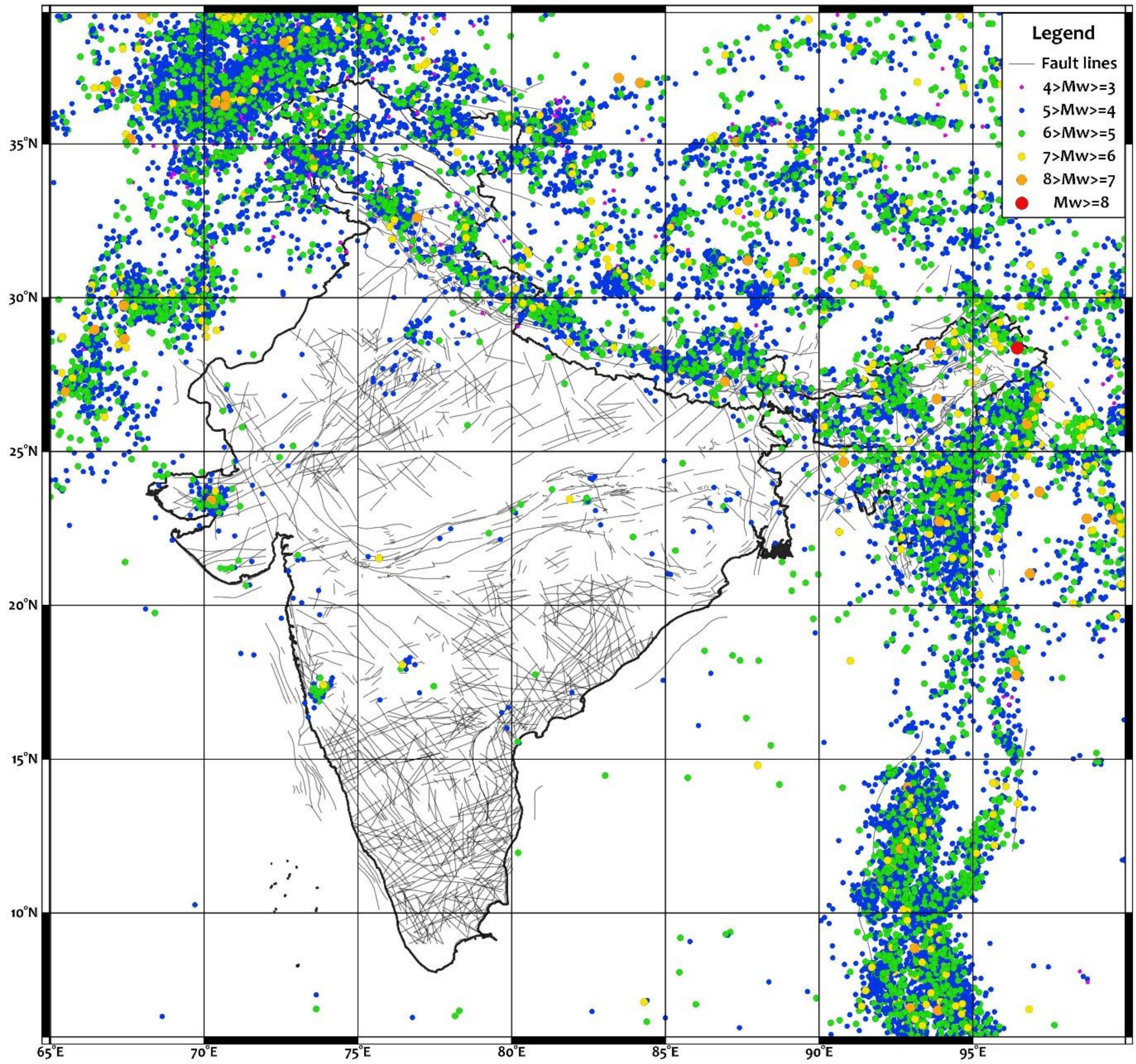


Figure 1.3 *Seismicity map of India*

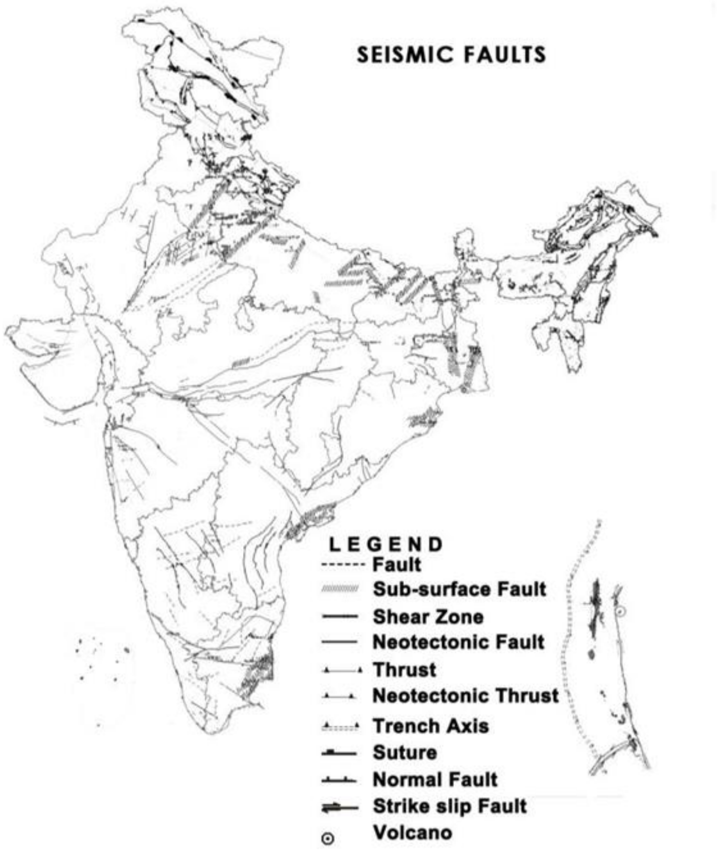


Figure 1.4 *Seismic faults in India (Ramancharla & Murty, 2014)*

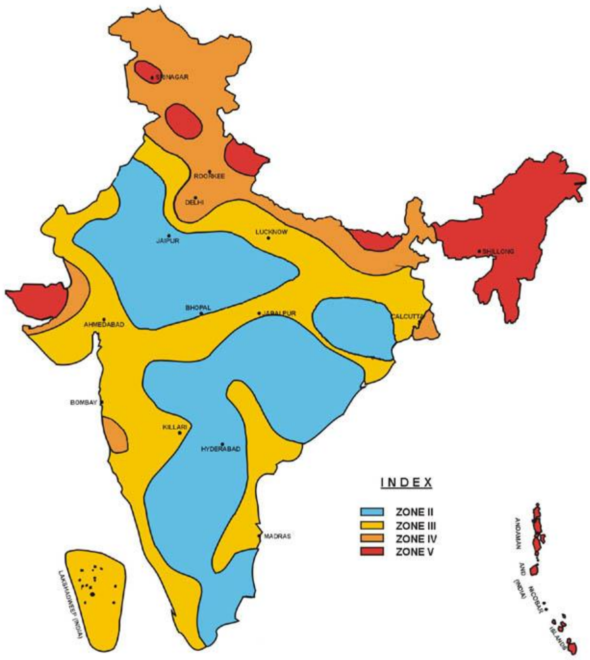


Figure 1.5 *Seismic zone map of India (Ramancharla & Murty, 2014)*

1.3 HOUSING IN INDIA

In the present scenario, India boasts over 300 million census houses, as indicated by the Census 2011 data. This represents an increase of approximately 18-25% compared to the previous decade, although there's a declining trend evident. However, the absolute number of houses is steadily rising, with a notable surge observed in the past decade, recording an increase of about 43.8% from 2001 to 2011. The predominant choice of construction materials across the nation is depicted in Table 1.2, with a preference for natural materials being predominant. Rural areas predominantly rely on locally available natural materials for roofing and walling, while urban areas tend to favor cement-based materials. Comparing the construction materials used in 2001 and 1991, there's a noticeable decline in the use of traditional materials like grass, thatch, bamboo, and wood, accompanied by an increase in concrete usage, including the introduction of plastics in construction. Despite these shifts, the earthquake resistance of these newly introduced materials remains a subject of concern when utilized for structural purposes. Different housing typologies have been adopted across India, each with various sub-typologies. Initially, after Independence, traditional technologies and locally sourced materials were widely employed, particularly in rural areas, resulting in cost-effective and sustainable housing solutions. However, over the past two decades, the introduction of new materials and building technologies, primarily in urban areas, has gradually permeated rural regions without adequate caution or preparation, often leading to suboptimal outcomes. Examples include the indiscriminate use of burnt clay bricks in cement masonry and reinforced concrete slabs in roofs, integrated into traditional construction methods without sufficient engineering judgment or consideration of consequences.

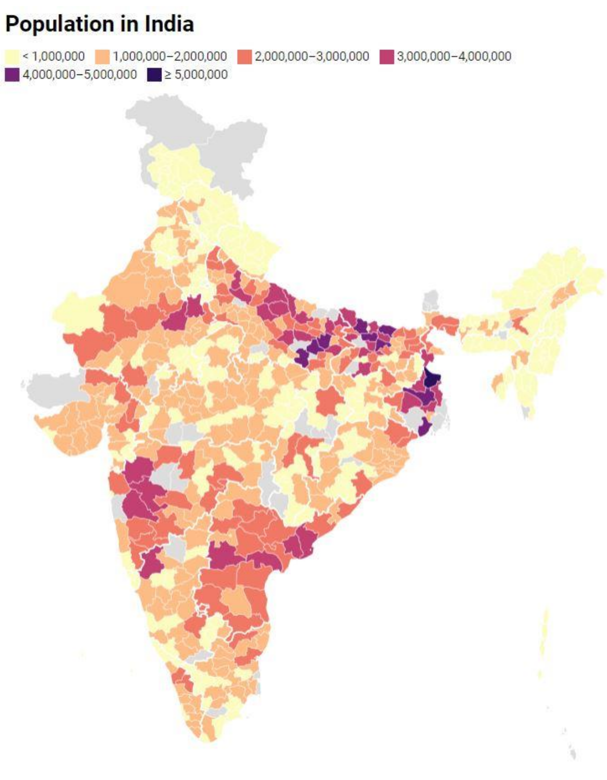


Figure 1.6 *District wise population of India*

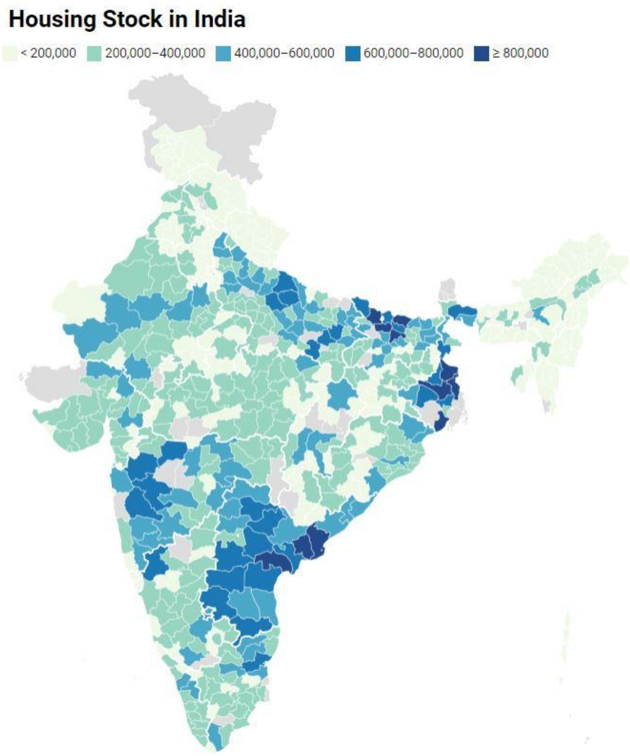


Figure 1.7 *District wise housing stock of India*

1.4 LEVELS OF SAFETY ASSESSMENT

One of the major factors contributing to the vulnerability of buildings in India is , a prevalent self-styled approach to development, where buildings are constructed at the owner's convenience without the involvement of competent engineers or architects, leading to suboptimal structural design and construction. Also, general lack of awareness regarding earthquake standards for design and construction with the substantial portion of the country's land area under the threat of *moderate* to *severe* earthquakes, makes buildings vulnerable.

Four levels of assessments are envisaged for evaluating the earthquake safety of the buildings (NDMA,2020).

(1) Level 1: Using RAPID QUALITATIVE Assessment of Vulnerability.

The primary goal of this assessment is to analyze the risk that a community, town, or city faces regarding the potential collapse of houses during anticipated earthquake shaking in the local area. Typically, a proficient team of assessors should spend approximately 15-30 minutes per building, conducting observations from the exterior without entering and avoiding technical calculations. This assessment approach serves to envision a scenario, providing a preliminary estimate of potential damage based on the expected intensity of shaking in the building's region. It relies solely on visual observations, offering a comprehensive understanding of safety while acknowledging its limitation in ensuring high accuracy. It is evident that precise earthquake safety evaluations for buildings require detailed assessments.

(2) Level 2: Using DETAILED QUALITATIVE Assessment of Vulnerability.

The primary objective of the Rapid Visual Screening (RVS) method is to conceptually assess various aspects of a building, specifically focusing on:

(a) Site and Soil Features,

(b) Architectural Form and Material Choices,

(c) Structural System,

(d) Construction Details, and

(e) Maintenance Quality.

The study aims to comprehend and address factors contributing to potential structural deficiencies within these five domains. The RVS method conducts a Base Level Technical Evaluation of a house before an earthquake to anticipate its performance during strong seismic activity. This sequential approach involves two evaluations:

(a) Safety Index, assessing overall safety (life safety) based on global parameters in the event of an earthquake, and

(b) Seismic Performance Rating, estimating the extent of damage (economic losses) during an earthquake based on structure components and house contents.

The Seismic Performance Rating is conducted only if a building passes the initial Safety Index evaluation, recognizing that economic assessment becomes meaningful only when basic safety is assured. This assessment method serves two main purposes: (a) as an initial evaluation exercise before detailed retrofitting, and (b) to evaluate the safety and performance of individual houses of a specific typology.

(3) Level 3: Using RAPID QUANTITATIVE Assessment of Vulnerability

Evaluating the structural safety of standing buildings is crucial, especially in seismic zones susceptible to moderate to severe seismic shaking, a concern heightened by recent earthquakes in India. The vulnerability of buildings to lateral earthquake shaking is evident, and multiple factors contribute to this susceptibility, including:

(a) Inadequate structural configuration, exemplified by unreinforced masonry buildings and reinforced concrete moment frame (RC MRF) structures with open ground storeys lacking sufficient infills.

(b) Deficient structural design and detailing, where there is a lack of mechanisms to ensure compliance with national seismic design standards, even if the initial design considered only gravity load actions.

(c) Subpar quality control and assurance during construction, evidenced by insufficient supervision during ongoing construction and the continued use of 90-degree hook ends in transverse reinforcement.

Hence, assessing the structural safety of existing buildings with these prevalent deficiencies becomes imperative. This chapter outlines a procedure for a Simplified Quantitative Assessment (SQA) of structural safety for existing buildings. The SQA predominantly focuses on shear capacity, with a specific emphasis on safeguarding against abrupt brittle failures—a critical failure mechanism.

(4) Level 4: Using DETAILED QUANTITATIVE Assessment of Vulnerability.

The DQA (Demand-Capacity Quantification) method relies on leveraging three fundamental virtues inherent in structures: strength, stiffness, and ductility. Recognizing that buildings may exhibit deficiencies in one or more of these virtues, the DQA assesses them by comparing the demand on the building with its capacity. The demand is determined by estimating the actual seismic hazard according to Indian Standards, while the capacity is computed using classical structural theory, considering equilibrium, compatibility, and constitutive law. NDT (Non-Destructive Testing) is essential, conducted at pertinent locations/elements in the building, facilitating subsequent safety checks at both the overall building level and each component level.

The DQA employs nonlinear structural analyses to evaluate the building's capacity, requiring detailed information such as as-built dimensions, reinforcement details of all structural elements, and material and soil properties. The assessment involves calculating various parameters on both the demand and capacity sides:

Demand Side:

(a) Distribution of lateral forces using the equivalent static method,

(b) Eccentricity between the Centre of Resistance and Centre of Mass,

(c) Storey Shear Force Demand,

(d) Shear Force Demand on each structural element, and

(e) Deformation Demand in each storey.

Capacity Side:

Axial Force, Shear Force, Bending Moment, and Torsional Capacity of all structural elements, and safety checks for:

(a) All structural members, including the Strong-Column Weak-Beam check, and

(b) Storey Drift of the building.

This assessment method is applicable both before and after earthquakes, serving the purpose of understanding structural deficiencies at both component and overall levels. It aids in undertaking retrofit measures before earthquakes and improving design standards post-earthquake events.

1.5 RESEARCH QUESTIONS

The research aims to address three critical questions regarding earthquake disaster risk and its mitigation strategies in built environments. Firstly, the study seeks to develop a comprehensive model for assessing pre-earthquake disaster risk at various levels—region, ward, city, district, state, and national—enabling its applicability to a broad spectrum of stakeholders, including the general public, policymakers, and other concerned entities. Secondly, it endeavours to identify and analyse the multifaceted factors that influence the earthquake disaster risk of built environments. Understanding these factors is crucial for devising effective mitigation and preparedness measures. Lastly, the research aims to evaluate the utility of earthquake disaster risk assessments in understanding the impact of seismic events and strengthening mitigation and preparedness efforts at the regional level. By addressing these research questions, the study endeavours to contribute significantly to enhancing the resilience of built environments against seismic hazards and fostering informed decision-making among stakeholders.

1.6 RESEARCH OBJECTIVES

The research objectives of the thesis encompass a comprehensive exploration of earthquake risk within existing built environments. Firstly, the study aims to develop a nuanced understanding of the earthquake risk associated with current building structures, focusing on assessing vulnerabilities and potential hazards. Secondly, it endeavours to create an Earthquake Disaster Risk Index tailored to the specific context of cities, towns, or regions, facilitating a comprehensive evaluation of seismic vulnerabilities within these built environments. Additionally, the research seeks to delve into the underlying parameters of earthquake disaster risk, particularly exploring dimensions such as hazard, vulnerability, and exposure to identify their respective roles in influencing overall risk levels. Furthermore, the study intends to assess the effectiveness and validity of the proposed Index in accurately measuring earthquake disaster risk, ensuring its practical utility for stakeholders. Finally, the research aims to investigate the spatial and temporal variations of earthquake risk within the studied areas, utilizing the Index as a tool to analyze and understand these fluctuations over time and across different geographical locations. Through these objectives, the thesis endeavours to contribute significantly to enhancing earthquake resilience in built environments.

1.7 SCOPE OF RESEARCH

- The research thesis aims to address two primary questions: How to model the pre-earthquake disaster risk of various administrative levels—region, ward, city, district, state, and national—within built environments, and what factors influence the earthquake disaster risk.

- The central objective of the thesis is to develop an Index that provides insight into earthquake disaster risk at both individual building and regional levels, fostering awareness among stakeholders. The study focuses on understanding the hazard, housing typologies, earthquake resistance of buildings, and exposure to seismic risks.

- Hazard variables such as zone factor and building importance factor, along with exposure measured through Floor Area Ratio, will be analyzed. Additionally, the capacity of buildings will be assessed based on deviations in architectural and structural features from ideal earthquake-resistant standards.

- The research will specifically consider Reinforced Concrete, Brick Masonry buildings with concrete roofs, and Brick Masonry buildings with other roof types.

- The outcomes of this research will be beneficial for individual building owners, policymakers, and builders, providing them with insights into the earthquake risk of their buildings and regions. Moreover, it will enable stakeholders to commission detailed risk analyses and implement appropriate mitigation strategies.

1.7 ORGANIZATION OF THE THESIS

The thesis is structured into six chapters. Chapter 1 introduces the subject matter of the research and the overall idea. In Chapter 2, a brief review of pertaining literature is presented, gap areas of the study identified, and objectives and scope of the present study outlined. In Chapter 3 the framework and the proposed methodology are described. The evaluation of EDRI for various cities is computed and the results are presented in Chapter 5. Further, Chapter 6 introduces sigmoid function-based model for assessing earthquake disaster risk and discusses the factors influencing the earthquake disaster risk index, using a sigmoid function of probabilities of damage of the surveyed buildings. Finally, summary and conclusions are presented in Chapter 7. Scope of future work in the subject area is also discussed.

2
Review of Literature

2.0 INTRODUCTION

A hazard is a phenomenon or process that can cause life loss, injury, health-related issues, property damage, economic disruption, and environmental degradation. Earthquake hazards are physical phenomenon associated to earthquakes that detrimental impact on human activities. Every hazard is characterized by its likelihood of occurrence, intensity, affected area, duration, and potential consequences. The vulnerability is the extent of loss or damage to the assets that may incur due to their susceptibility to the impacts of earthquake hazard. Assets cover physical items like people, animals, properties, and businesses, as well as intangible yet valuable aspects like social cohesiveness and peace, public trust, political stability, education, and mental health, all of which are important to protect from loss or damage. From social domain perspective, vulnerability refers to more lack of capacity of the populations and systems to cope with the disaster. Exposure means the situation of the people, infrastructure, housing, production capacities, and other tangible human assets in hazard-prone areas (UNDRR, 2019). , seismic risk analysis is the combination of three main factors – hazard, vulnerability, and asset value (exposure).

Seismic hazard arises from the combined likelihood of earthquakes happening, the effects of those earthquakes at a specific site, and the unique conditions at that site. Human-made structures and resources, known as assets, often intersect with natural hazards. These assets encompass people, buildings, infrastructure, and operations. Each asset possesses various characteristics, such as age, location, and functionality, which influence its vulnerability to earthquakes. While assets are typically human creations, even natural environments can suffer losses due to earthquakes, affecting their intrinsic value. Vulnerability or fragility functions are created for each asset, considering the overall or specific seismic resistance traits of the asset.

Methods of seismic risk assessment involve empirical methods, analytical methods and hybrid models. Empirical methods involve looking at past events and observations of similar assets to understand their performance during earthquakes. These can be categorized into three types:

a) Field survey data, which records damage observed in actual earthquakes.

b) Experimental and laboratory data, gathered from tests on components or small-scale models.

c) Expert opinions, where knowledgeable individuals share their insights based on firsthand experience with earthquake performance.

Analytical methods, on the other hand, analyze asset properties using theoretical models based on mechanics or other frameworks. Ideally, both approaches should align or be used together. When empirical data is used to fine-tune an analytical model, it's called a hybrid model, but there are relatively few of these.

Creating vulnerability functions empirically entails gathering damage observations and data for diverse structures or assets at risk. This involves organizing the assets into a schema, either before or after collection, and then analysing the observations and data within each category to establish a relationship between vulnerability and a hazard measure. In the earliest studies of earthquake damage and potential losses, researchers began laying the groundwork for estimating earthquake hazards in a probabilistic manner. They examined 1,139 buildings damaged during the M7.6 Kern County earthquake of July 21, 1952, and its aftershocks, aiming to determine the fraction of structures—categorized by construction type and level of lateral bracing—that were demolished, repaired, or remained undamaged. This involved creating a matrix associating different building construction classes with earthquake intensities, each containing data on repair costs and the likelihood of experiencing specified damage. Subsequent studies investigated earthquakes like the 1967 Caracas Venezuela earthquake and the 1971 San Fernando earthquake, analyzing factors such as building design coefficients and spectral accelerations to correlate with observed damage. Various methodologies were developed, including the Damage Probability Matrix (DPM) and empirical estimation methodologies for different types of buildings. The MIT Seismic Design Decision Analysis (SDDA) project introduced sophisticated seismic studies and multi-attribute decision-making techniques. In Japan, extensive literature documented earthquake damage, with studies correlating building characteristics with observed damage ratios. Notable publications like ATC-13 provided valuable data on earthquake damage evaluation, influencing seismic research and mitigation efforts.

The Federal Emergency Management Agency (FEMA) in the United States developed several guidelines for seismic risk assessment and rehabilitation of buildings. For the rapid visual screening of buildings, FEMA 178 (1992), FEMA 310 (1998), and FEMA 154 (2005, 2015) are available. The Basic Structural Hazard Scores were calculated using expert opinion and ground motion maps that specified a 10% chance of exceeding effective peak acceleration ground motion in 50 years. The PMFs were also assigned values based on expert opinion (FEMA 154,1988; FEMA 178, 1989; FEMA 178, 1992; FEMA 310 ,1998; FEMA 154; 2002). A rapid and straightforward seismic risk assessment procedure for vulnerable urban building stocks is proposed. Essentially, it is a sidewalk survey procedure based on observing selected building parameters from the street and calculating a performance score for determining the risk priority of buildings. Using a database of 454 damaged buildings surveyed after the 1999 Düzce earthquake in Turkey, statistical correlations have been determined for measuring the sensitivity of damage to the assigned performance score. The results demonstrated that the proposed screening procedure provides a simple yet effective method for identifying structures with a significant risk of damage. For a final determination on the seismic risk level of these structures, a more detailed assessment is required (Sucuoglu H et.al., 2007, Ozcebe G et.al.,2006). A distinct RVS procedure based on fuzzy logic was developed to classify buildings into five distinct damage grades (Sen Z ,2010; SIA-2018,2004; Demartinos K and Dristos S, 2006)This method was utilised on 102 buildings damaged by the 1999 Athens earthquake. A fuzzy inference system was used to determine the damage score at the conclusion. National Research Council of Canada proposed an alternative RVS method based on a seismic priority index. This method considers both structural and non-structural factors, such as soil conditions, building occupancy, building significance, falling hazards, occupied density, and occupancy duration (NRCC , 1993). In India, there have been some efforts to develop RVS methods A method for RVS of ten distinct building types was developed in 2006 [Jain et.al., 2010] The procedure requires the identification of the primary structural load carrying system and the building characteristics that are anticipated to modify the expected seismic performance of the lateral load resisting system being considered. A statistical analysis has been performed to develop Expected Performance Score (EPS) for RC buildings based on the rapid visual surveys in Ahmadabad, India (Jain CK,2006; Keya M, 2008).

Earthquake risk assessment helps in preparedness and in enabling mitigation efforts for future earthquake event. Many conceptual approaches of risk have their origin in technology, which were extrapolated to the scenario of natural disasters in the early 1960s from the perspective of ecology, geography, and social impacts of nuclear disasters on societies (Quarantelli,1987; Kates R W 1971). The damage assessment methods from the perspective of civil engineering entailing the developments of physical risk were attempted in 1973. This has led to the development of many seismic risk methodologies all over the world. The UNDRO report on Natural Disasters and Vulnerability Analysis, based on the Expert Meeting held in 1979, proposed the unification of disaster-related definitions as a Hazard (H), Vulnerability (V), Exposure (E) of built environment, and Disaster Risk (R), and suggested that disaster risk be estimated as $R = H \times E \times V$ (UNDRO,1980).

In 1997, the Federal Emergency Management and Agency (FEMA) of USA developed software Hazard of United States (HAZUS), which addresses different hazards, including earthquakes. The International Decade for Natural Disaster Reduction (IDNDR 1990-2000) of United Nations launched the initiative Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters (RADIUS), to improved decision-making towards reducing seismic disasters in urban areas, particularly in developing countries [40]. Earthquake risk assessment addressed either loss estimation or earthquake damage scenario projections. The results are presented in the form of expected impact of a possible earthquake in a selected region; the data requirements are high in this model. In 1997, a composite Earthquake Disaster Risk Index (EDRI) was developed, to estimate the relative risk of the cities across the world (Davison, 1997). It employs a multidisciplinary approach and considers factors of hazard, exposure, vulnerability, emergency response & recovery capabilities, and external content (i.e., the interaction of the city with other parts of the world). Thus, the EDRI is fundamentally different from the earthquake assessment models of loss estimation and earthquake damage scenarios; the former looks at multi-disciplinary aspects, while the latter address limited aspects (Cardona, 2001).

In 2001, a seismic risk index was developed for urban cities, from a holistic perspective, considering both hard and soft risk variables (Carreño et.al., 2007). The model considers the physical risk, exposure, and socio-economic factors & their degree of resilience. The model was improved to estimate risk at a local level and global scale. In 2011, based on the holistic approach of seismic evaluation, a new seismic risk index was proposed for cities in Iran (Hajibabaee et.al., 2014). In 2012, a earthquake disaster index was proposed using Bayesian Neural Networks; the importance was highlighted of using computational techniques for estimation of risk.

2.1 A MULTIDISCIPLINARY URBAN EARTHQUAKE DISASTER RISK INDEX

A multidisciplinary earthquake risk index model is developed for urban areas with an aim to estimate the risk of earthquake disaster and factors contributing to the risk[40]. The EDRI is used to estimate the relative risks of the cities. The index helps to allocate the mitigation resources according for cities, to industrialists to take a decision about the city characteristics to establish the industry, for structural engineers to estimate the vulnerability of the physical infrastructure etc. The index developed is a composite index, a mathematical combination or aggregation of indicators or sub indicators. In the development of EDRI, the factors that contribute to the earthquake disaster risk, like hazard, vulnerability of structures.

The Earthquake Disaster Risk Index (EDRI) is constructed in five steps, listed below.

Factor identification

Conceptual framework

Indicator selection

Mathematical combination

Data gathering and evaluation.

Five main factors, Hazard, Exposure, Vulnerability, External content and Emergency Response and Recovery Capability are identified. Figure 2.1 illustrates conceptual framework of earthquake disaster risk. Each of these five main factors is disaggregated into more specific factor components until further disaggregation is not possible. The indicators representing the factor components are selected. X`x

Three criteria are used for indicator selection as enumerated,

Represent the concept they purport to report.

Be quantitative and objective.

Be measured data that is easy to collect.

The selected indicators along with the main factors and factor components are shown in the Figure 2.2 . The EDRI is computed as a linear combination shown below

$$\mathrm{EDRI}=\sum_i w_i x_i \tag{2.1}$$

Where w_i, is the weight shows importance of the corresponding factor is to overall earthquake risk which is subjective to expert assessment x_i is the scaled value of the i^{th} indicator. The indicators scaled into compatible units of measurement using the following method.

$$x_{ij} = \left[\frac{x'_{ij} - (\bar{x}_i - 2S_i)}{S_i}\right] \quad (2.2)$$

where x_{ij} scaled value of indicator i of city j.

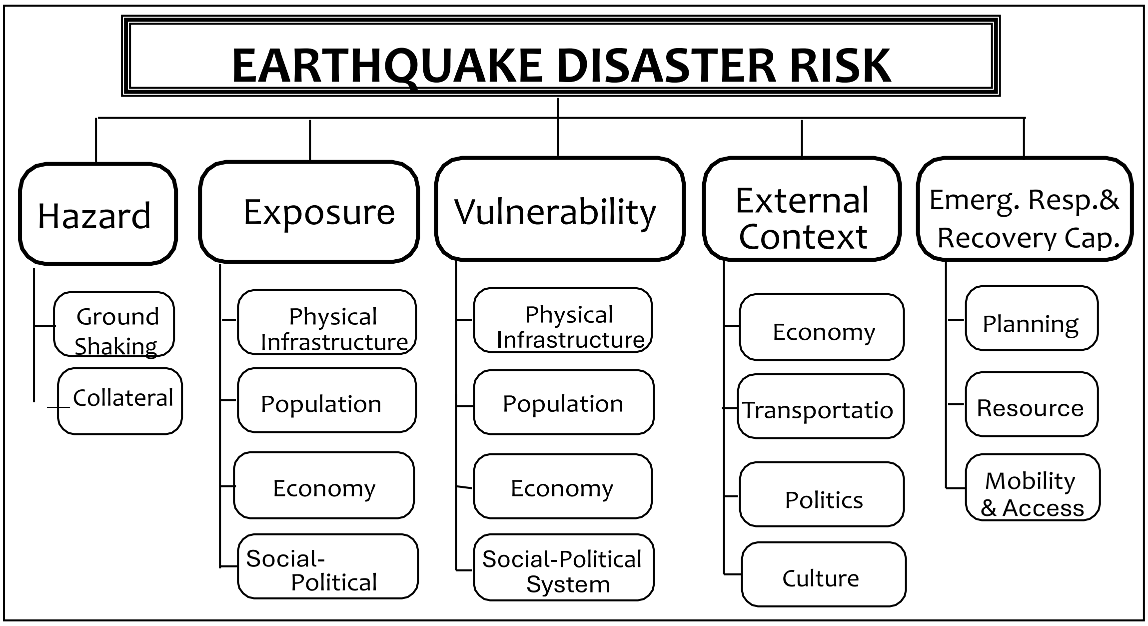


Figure 2.1 *Framework of Earthquake Disaster Risk Index*

Raw data is collected in a table with row for each indicator and column for each city as shown in Table 2.1

Table 2.1 *Schematic indicator-city table*

Indicator	Cities				
	A	B	. . . j . . .	Y	Z
Ind. 1 Ind. 2 ⋮ Ind. i Ind. n	*City A values*	*City B values*	x_{ij}	*City Y values*	*City Z values*
EDRI	$EDRI_A$	$EDRI_B$		$EDRI_Y$	$EDRI_Z$

The following equations are used to evaluate EDRI

$$EDRI = w_H H + w_E E + w_V V + w_C C + w_R R \quad (2.3)$$

$$H = w_{H1}x'_{H1} + w_{H2}x'_{H2} + w_{H3}x'_{H3} + w_{H4}x'_{H4} + w_{H5}x'_{H5} + w_{H6}x'_{H6} + w_{H7}x'_{H7} + w_{H8}x'_{H8} \quad (2.4)$$

$$E = w_{E1}x'_{E1} + w_{E2}x'_{E2} + w_{E3}x'_{E3} + w_{E4}x'_{E4} + w_{E5}x'_{E5} + w_{E6}x'_{E6} \quad (2.5)$$

$$V = w_{V1}x'_{V1} + w_{V2}x'_{V2} + w_{V3}x'_{V3} + w_{V4}x'_{V4} + w_{V5}x'_{V5} + w_{V6}x'_{V6} \quad (2.6)$$

$$C = w_{C1}x'_{C1} + w_{C2}x'_{C2} + w_{C3}x'_{C3} \quad (2.7)$$

$$R = w_{R1}x'_{R1} + w_{R2}x'_{R2} + w_{R3}x'_{R3} + w_{R4}x'_{R4} + w_{R5}x'_{R5} + w_{R6}x'_{R6} + w_{R7}x'_{R7} + w_{R8}x'_{R8} + w_{R9}x'_{R9} \tag{2.8}$$

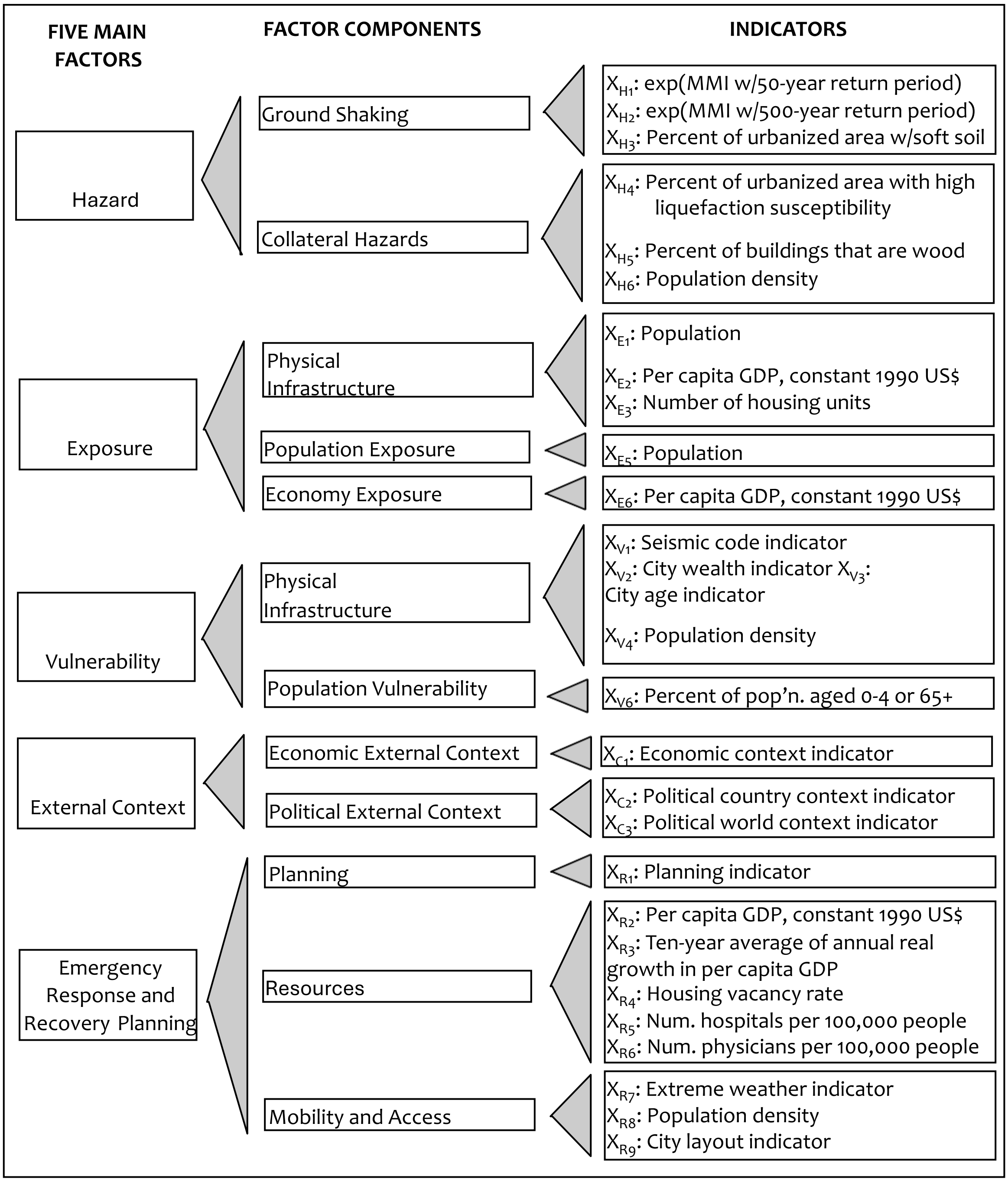


Figure 2.2 *Indicators*

The EDRI is used to estimate the relative risks of the cities. The result is a unitless number. The variation of the five factors within a specified city and among cities are also displayed. The Figure 2.3 to 2.6 represent the results.

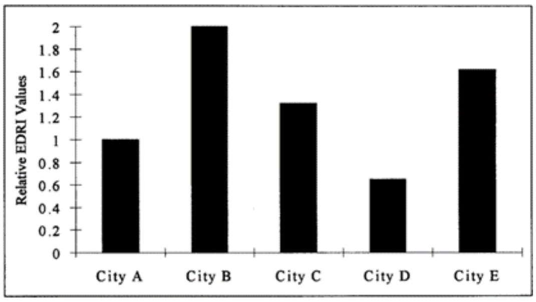


Figure 2.3 *Overall EDRI values of different cities*

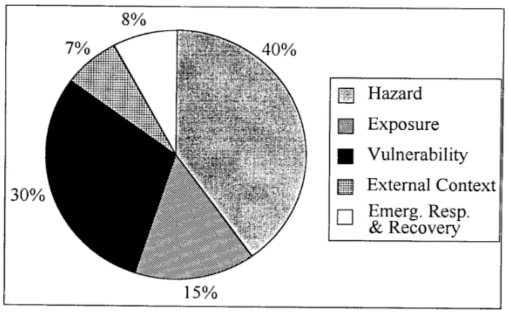


Figure 2.4 *Relative contributions of five main factors within a city*

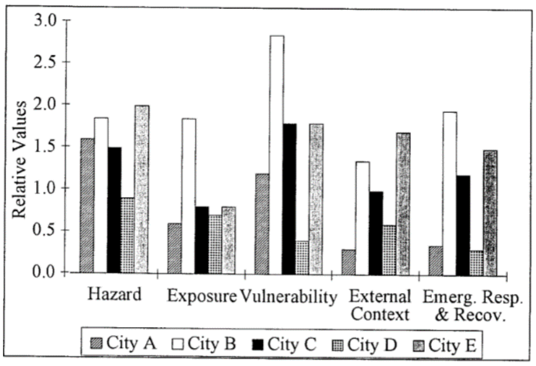


Figure 2.5 *Relative values of five main factors*

2.2 HOLISTIC ESTIMATION OF SEISMIC RISK USING COMPLEX DYNAMIC SYSTEMS

A comparative and holistic seismic risk index was proposed in 2001. A multidisciplinary approach including social, economic issues besides the seismological and engineering parameters viewing not only the expected physical damage of the buildings but the lack of social fragilities and the lack of resilience of the exposed community. The risk is evaluated as the convolution of the hazard and the vulnerability. The hazard and vulnerability is defined as follows. "*Once known the hazard or threat Hi, understood as the probability that an event may occur with an intensity larger or equal to i during an exposition period t, and known the vulnerability V_e, understood as the intrinsic predisposition of the exposed elements e to be affected or of being susceptible to suffer a loss as a result of the occurrence of an event with intensity i, the risk R_{ie} can be understood as the probability that a loss can occur over the element e, as consequence of the occurrence of an event with an intensity larger or equal to i, that is, the probability to exceed some social and economic consequences during the given period of time t .*"

$$R_{ie}\,|_t = (Hi \,.\, V_e)\,|_t \qquad (2.10)$$

The seismic risk variables are divided as "Hard risk" and "Soft risk" Variables. Hard risk variables are obtained from the estimation of losses or urban scenarios of earthquake damages and are the result of the convolution of the seismic hazard, or microzoning of the city, and the physical vulnerability of the buildings and of the infrastructure. "soft" risk was valuated, resulting from the estimation of relative seismic hazard descriptor and its convolution with the vulnerability of the context descriptor, which is based on indicators of exposure, social fragility and relative resilience of the analysis units conforming the urban centre.

2.2.1 Methodology

The risk is estimated as a total risk as given in the following equations.

$$IRT_k = IRH_k \,.\, \delta IRH_k + IRS_k \,.\, \delta IRS_k \tag{2.11}$$

where IR_{Hk}, is the hard seismic risk index of physical seismic risk, which is based on descriptor obtained from the estimation of the urban potential losses caused by future earthquakes; IRS_k , is the soft seismic risk index or context seismic risk, obtained from the scaled product of seismic hazard and of context vulnerability descriptors, and δIR_{Hk}, δIR_{Sk} are the participation factors of each index for each analysis area k.

$$IR_{Hk} = \Sigma_i X_{IRi} \,.\, \delta_{IRi} \tag{2.12}$$

where X_{IRi} is the value of each indicator i obtained from the information of the scenarios of losses and δ_{IRi} the participation factor of each indicator i, for each analysis area k

$$IR_{Sk} = \alpha\left((H_{Sk} - \beta)(V_{Sk} - \beta) + \beta\right) \tag{2.13}$$

H_{Sk} the descriptor of seismic hazard of the context, V_{Sk}, the descriptor of vulnerability of the context, and α, β constants of visualization related to the average and the standard deviation of the values

$$V_{Sk} = \Sigma\, i\, X_{Hi} \,.\, \delta_H \tag{2.14}$$

X_{Hi} the value of the indicators i obtained from the study of urban seismic microzoning and δ_{Hi} the participation factor of each indicator i, for each analysis area k.

$$V_{Sk} = E_{Vk} \,.\, \delta_{Ek} + F_{Vk} \,.\, \delta_{Fk} + R_{Vk} \,.\, \delta_{Rk} \tag{2.15}$$

E_{Vk} , F_{Vk} , R_{Vk} are indicators of exposure, social fragility, and lack of resilience, and δEk , δ_{Fk} , δ_{Rk} are their participation factors for each analysis area k

$$V_{Sk} = (\Sigma\, i\, X_{Ei} \,.\, \delta_{Ei})\, \delta_{Ek} + (\Sigma\, i\, X_{Fi} \,.\, \delta_{Fi})\, \delta_{Fk} + (\Sigma\, i\, X_{Ri} \,.\, \delta_{Ri})\, \delta_{Rk} \tag{2.16}$$

X_{Ei}, X_{Fi}, X_{Ri}, the values of the indicators i which compose the exposure, social fragility, and lack of resilience and δ_{Ei}, δ_{Fi}, δ_{Ri}, the participation of each indicator i, for each analysis area k, respectively .The participation factors for each index are also presented. The participation factors are obtained from the subjective assessment of the experienced people in the field. The descriptors or indicators of each of the component.

The indicators values are scaled to make the values commensurable. The indicators selected are independent and mutually exclusive. The weights are obtained from the experts in the field. The results are estimated as relative risk and represented as shown in Figure 2.7.

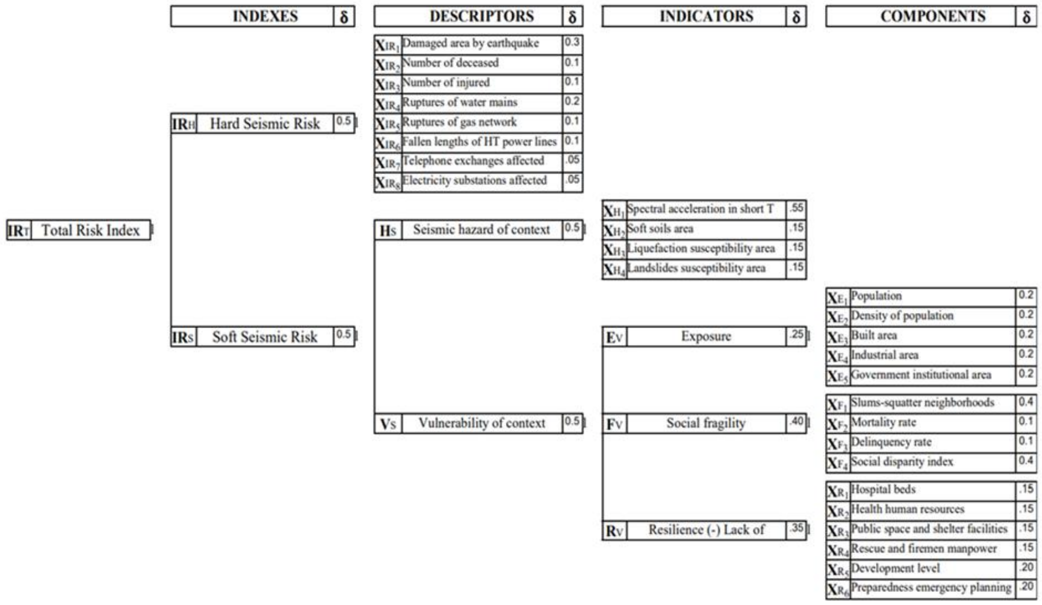


Figure 2.6 *Relative seismic risk indexes defined for the different districts of Bogotá with the participation factors used.*

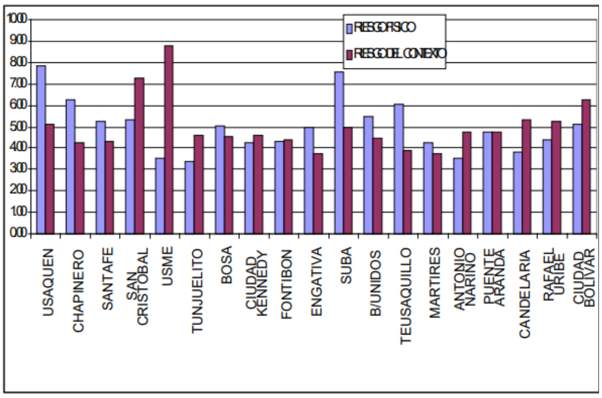


Figure 2.7 *Relative hard and soft seismic risk indexes*

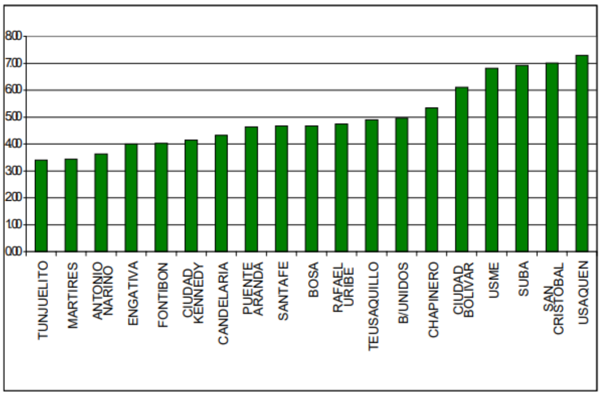


Figure 2.8 *Total seismic risk index of cities in ascending order*

2.3 SEISMIC RISK ANALYSIS USING BAYESIAN BELIEF NETWORKS

The EDRI is developed is based on the EDRI methodology of "A Multidisciplinary Urban Earthquake Disaster Risk Index." The key performance indicators used to quantify the hazard, exposure, vulnerability, external context, and emergency and recovery planning as shown in Figure 2.9. In aggregating through a hierarchical structure, there is a potential for loss of information due to exaggeration and eclipsing. Exaggeration occurs when all input parameters are of relatively low importance, yet the aggregated score comes out unacceptably high. Eclipsing is the opposite phenomenon, where one or more of the input parameters are of relatively high importance, yet the aggregated score comes out as unacceptably low.

The Figure 2.8 illustrates the framework of evaluating EDRI using Bayesian Neural Networks.

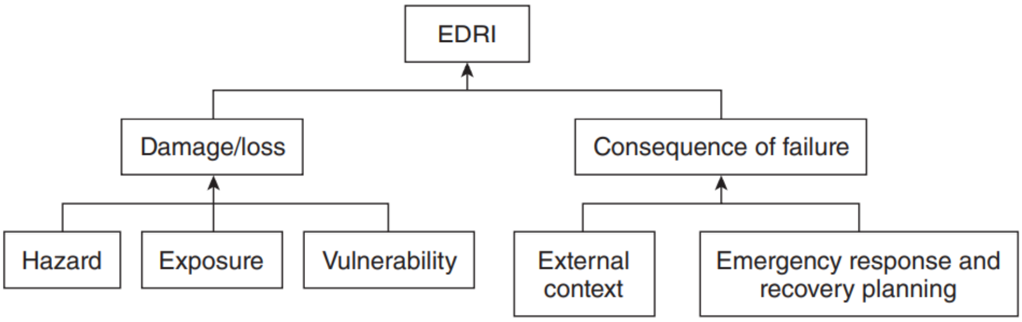


Figure 2.9 *Framework for earthquake disaster risk index*

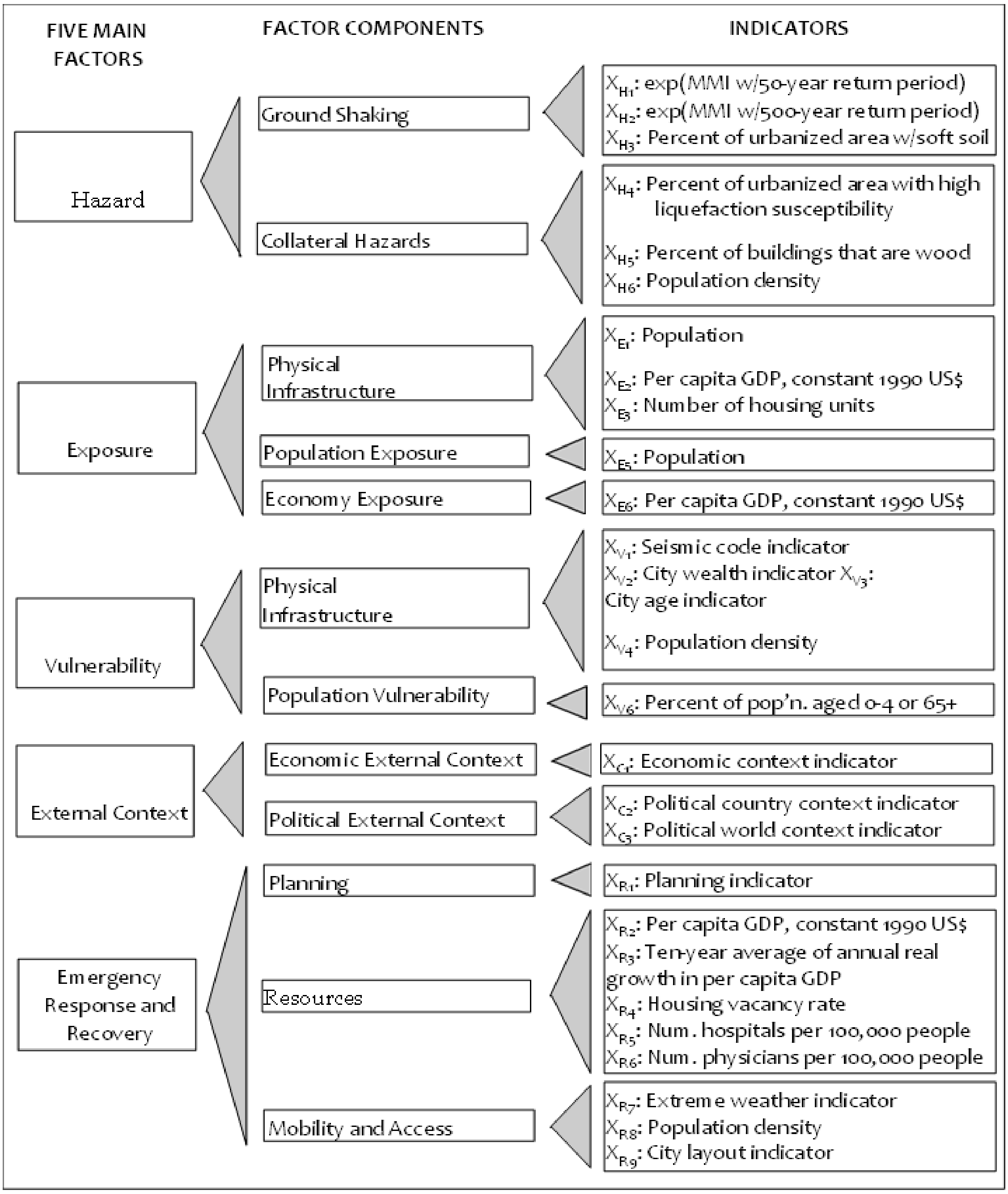


Figure 2.10 *EDRI Indicators*

The EDRI is calculated for 11 Cities in Canada. Using Bayesian Belief Networks (BBN) of the hierarchical structure depicted in Figure 2.9 and input parameters described in Figure 2.8, the EDRI model is developed. The input parameters are transformed using scaling techniques in commensurable units using

$$x_{ij} = \left[\frac{x'_{ij} - (\bar{x}_i - 2S_i)}{S_i}\right] \qquad (2.17)$$

An initial probability for very low(VL), low(L), medium(M), high(H) and very high(VH) cases at bottom nodes in the hierarchy are initiated based on expert

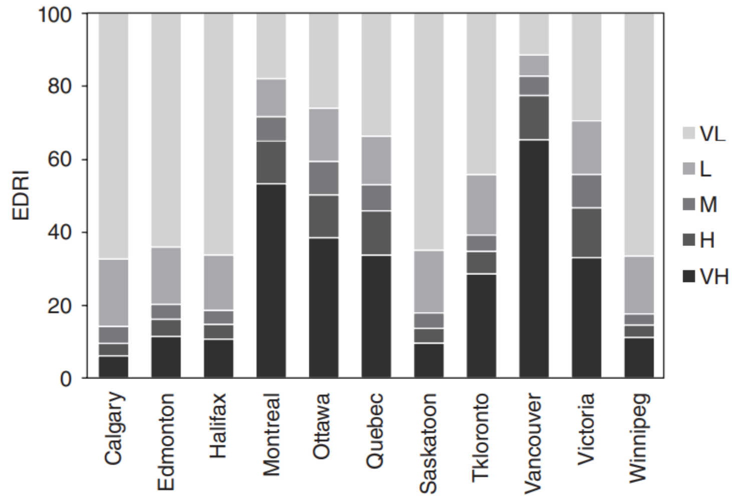


Figure 2.11 *Earthquake disaster risk index (EDRI) values for 11 Canadian cities*

opinion. Then the probability at each node all the cases is computed. Five states of EDRI values , $EDRI^{VL}$, $EDRI^{L}$, $EDRI^{M}$, $EDRI^{H}$, $EDRI^{VH}$ are computed. The results obtained for the 11 cities are shown in the Figure 2.10.

The EDRI model depicted showed cities located in high seismic hazard zones (e.g., Vancouver and Montreal) show higher EDRI values, as compared with cities in moderate and low seismicity (e.g., Calgary and Halifax). Furthermore, for similar magnitude of seismicity, the consequence of failure dictates the EDRI values. Vancouver has the highest EDRI value, followed by Victoria and Montreal. The contribution of the indicators and the factors for each city can also be compared. The EDRI obtained by BBN are compared with the EDRI model proposed by Rachael Davidson WAM stands for Weighted Average Method). The results are shown in the Figure 2.11.The anomalies described in the linear aggregation method and the weights, and the equal weights assigned to the five factors are reason for relatively higher scores of EDRI for cities. The BBN model provides more realistic and intuitive evaluations of relative risks, and the proposed new hierarchical structure have improved these shortcomings.

2.4 Earthquake risk assessment in urban fabrics based on physical, socioeconomic and response capacity parameters (a case study: Tehran city)

A model was proposed to calculate the relative seismic risk index (RSR*i*) of urban fabrics by considering hazard, vulnerability, and response capacity indicators. A comprehensive set of physical and socioeconomic indicators are employed. In this approach, estimation of the risk is performed by combination of vulnerability indicators with their directly related hazard factors. the methodology is improved by considering the effect of pre- and post-earthquake response capacity. The hazard factors (Ground motion and Ground failure parameters) are established based on available data. The physical, human life and socioeconomic vulnerabilities as well as response capacity indicators are evaluated. The total RSR*i* is calculated by weighted combination of risk and response capacity indicators. The model has also the ability to reassess the total risk after taking some mitigation strategies (by assuming new values for indicators of vulnerability, response capacity and hazard factors), to measure the effectiveness of mitigation decisions. The weight for each indicator and its sub-components is determined by applying AHP (analytical hierarchy process) method and, in some cases, by engineering judgments. Figure 2.12 represents the approach to estimate the Relative Seismic Risk index (RSR*i*).

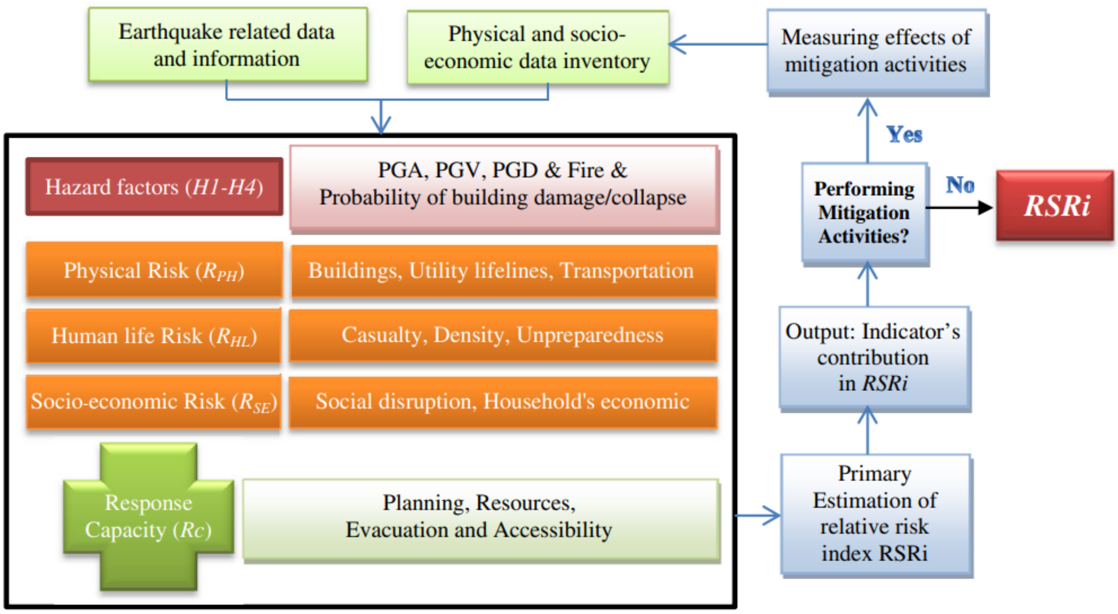


Figure 2.12 *Approach to estimate the Relative Seismic Risk index (RSRi)*

The RSR*i* are computed as

$$\text{RSR}i = \frac{(w_{PH}\, xR_{PH} + w_{LS}\, xR_{LS} + w_{SE}\, xR_{SE})}{(1+\ln\,(R_C\,))}$$

(2.18)

where R_{PH}, R_{HL} and R_{SE} are physical, human life and socioeconomic risk indices, respectively. The model was implemented for 22 municipal districts in in Tehran, Iran. The range of RSRi 0 to 4 without the response capacity indicators. Adding response capacity indicators reduces the risk. All the districts are ranked as shown in the Figure 2.13.

Rank	Main indices						
	R_{PH}	R_{HL}	R_{SE}	*Rc*	***RSRi*** ***without Rc***	***RSRi*** ***with Rc***	
	District number						
1[st]	15	15	6	4	15	**15**	Highest risk
2[nd]	20	20	18	2	20	**17**	
3[rd]	12	16	15	5	18	**18**	
4[th]	16	12	20	1	16	**12**	
5[th]	18	17	17	6	12	**19**	
6[th]	11	18	19	3	17	**11**	
7[th]	19	11	16	7	11	**20**	
8[th]	10	14	4	20	19	**16**	
9[th]	14	10	5	15	14	**10**	
10[th]	4	19	21	22	10	**9**	
11[th]	21	8	2	13	6	**14**	
12[th]	17	7	3	16	4	**8**	
13[th]	6	4	12	8	8	**21**	
14[th]	2	13	7	14	7	**7**	
15[th]	8	9	11	21	21	**6**	
16[th]	7	6	9	18	2	**13**	
17[th]	3	21	14	12	9	**4**	
18[th]	5	2	10	11	13	**3**	
19[th]	22	3	8	10	5	**5**	
20[th]	1	5	13	19	3	**2**	
21[st]	13	1	1	9	1	**22**	
22[nd]	9	22	22	17	22	**1**	Lowest risk

Figure 2.13 *District rank for the main indices*

2.5 EARTHQUAKE DISASTER RISK INDEX REPORT -50 TOWNS & 1 DISTRICT IN SEISMIC ZONES III, IV AND V

In 2019 National Disaster Management Authority, India released a report on a study conducted by International Institute of Information Technology-Hyderabad (IIIT-H), India. Earthquake Disaster Risk Index (EDRI) forecasts the relative risk within a city and across cities based on three important factors i.e., topographical condition (known as Hazard), total number of people and buildings spread in the topography (known as Exposure) and the present condition of the buildings (known as Vulnerability). This forecast of risk within a city projects the overall damage or loss that city may experience in expected earthquakes in future and the necessary precautions to be taken. Vulnerability is assessed through a Level 2 Detailed Qualitative Assessment (DQA) of buildings built in the Town or City, with a penalty point for the missing features of the earthquake resistance with reference to an Ideal building. Figure 2.14 represents the conceptual framework of the method.

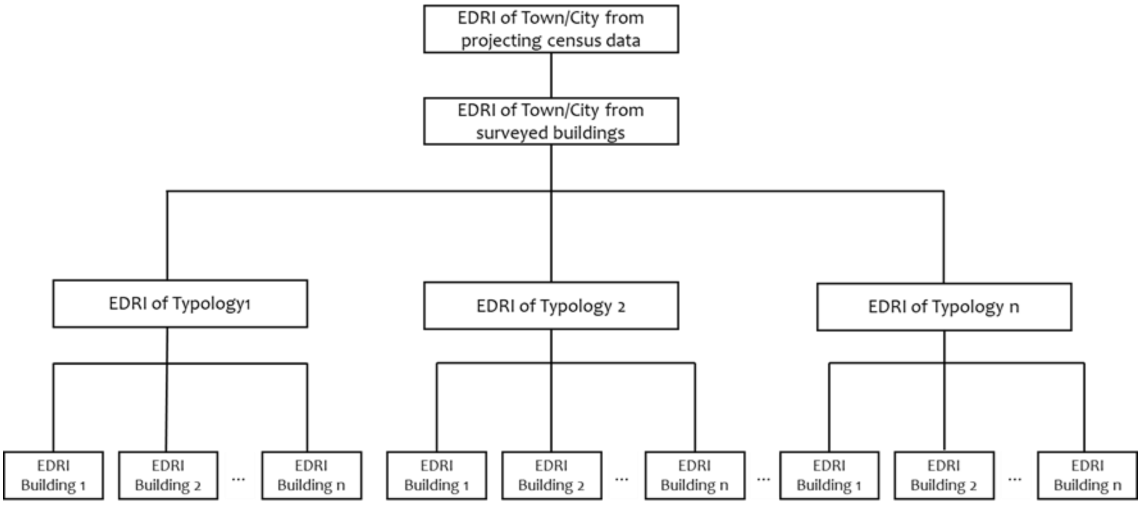


Figure 2.14 *Framework of Earthquake Disaster Risk Index*

There are two components of earthquake hazard factors, namely, hazard due to ground shaking (H_g) which is primary, and the collateral hazard. The hazard due to ground shaking is computed from the seismic zone factor (Z), soil type(S_{ta}), and the spectral shape (S_a) and is given as H_g =Z x S_t x S_a. The values of parameters mentioned are obtained from IS 1893. The range of H_g is [0.2,1.5]. If the buildings are in the regions susceptible to liquefaction, landslide/rockfall, or fire hazard, the building is declared as the one with 100 percent risk. The flowchart for the estimation of hazard is given in Figure 2.15 . The exposure of a building is expressed as Eb = I x FAR. I is the important factor, and as per IS 1893[23], I is 1 for ordinary buildings, 1.25 for offices, and 1.5 for important buildings like hospitals. FAR is Floor Area Ratio specified in the municipal byelaws. The range of the Eb is [1.33, 4.0]. The flowchart for the estimation of exposure is shown in the Figure 2.16. The earthquake vulnerability of the building, the amount of damage induced by the expected intensity of the earthquake shaking are quantified in terms of Life-Threatening Factors (LTF) and Economic Loss Inducing Factors (ELIF). The LTF is a condition the jeopardizes life, and hence the house is declared unsafe. Both the structural elements of the house and the utilities of the house contribute to the LTF. LTF is quantified in terms of size, form, and strength. The building is declared as the one with 100 percent risk if any of the indicators are present. The ELIF again has contributions from the structural element aspects and the utilities of the building. An ideal earthquake-resistant building in each typology is defined and taken reference to evaluate the buildings under study. The factors and their indicators representing ELIF are drawn from the clauses of relevant Indian standard standards. The flowchart for the estimation of the vulnerability of the building is shown in

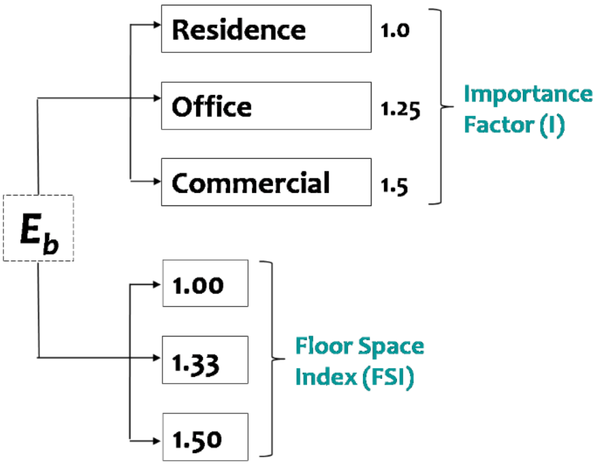


Figure 2.17 *Flow chart representing an estimation of exposure factor*

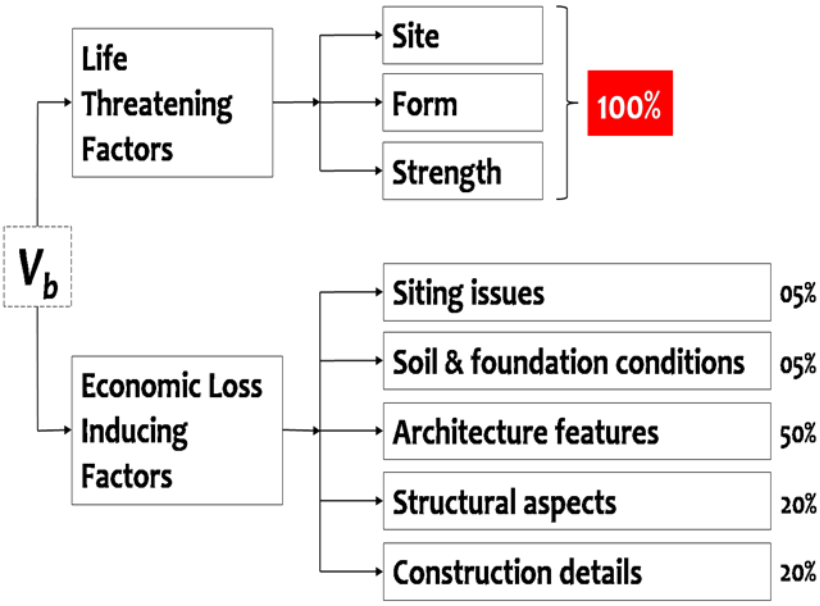


Figure 2.18 *Flow chart representing an estimation of vulnerability factor*

The EDRI of each building is calculated from the risk of each building, as

$$\text{Risk} = H_b \times V_b \times E_b \tag{2.19}$$

Table 1 presents the correlation of EDRI score to the level of risk/damage of building.

***Table 2.2**:Comparison of Final Score and Level of Risk/Damage of Building*

Score	Level of Risk/Damage
0.0 – 0.2	No Damage
0.2 – 0.4	Slight Damage
0.4 – 0.6	Moderate Damage
0.6 – 0.8	Severe Damage
0.8 – 1.0	Collapse

Substituting the minimum and the maximum values of hazard, exposure, and vulnerability, the EDRI of a building, has a range of 0 to 9.

$$EDRI_b = \begin{bmatrix}0.2\\1.5\end{bmatrix} \times \begin{bmatrix}0\\1\end{bmatrix} \times \begin{bmatrix}1.33\\6.0\end{bmatrix} = \begin{bmatrix}0\\9\end{bmatrix} \quad (2.20)$$

The EDRI of a town /city is obtained as

$$EDRI_{Town} = \frac{N_1 R_{b1} + N_2 R_{b2} + .. + N_T R_{bT}}{N_1 + N_2 + .. + N_T} \quad (2.21)$$

Where $EDRI_{Town}$ is the Earthquake Disaster Risk Index of Town, N_1 the number of buildings of typology 1, R_{b1} the summation of risks of buildings of typology.

2.6 Literature Gaps

Observations from past earthquakes indicate that a significant proportion of earthquake-related fatalities result from the collapse of buildings. Evaluations of the earthquake resilience of built environments are thus crucial. Rapid visual screening does not account for all factors that contribute to the risk of individual buildings rather. Existing risk indexing methods emphasise the holistic assessment of a region's risk, with less emphasis on the components of large existing building stocks. Given the technical expertise and lack of availability of skilled manpower needed, qualitative assessment methods provide a detailed understanding of the housing typologies, construction practises prevalent in a region, and urban planning aspects contributing to the earthquake risk, as well as aiding in the segregation of buildings requiring special attention for level 3 and level 4 qualitative assessments. A comprehensive assessment method that gives overall risk of a region in the form of an earthquake disaster risk index along with identifying the factors contributing to the risk and hotspots, which is consistent with time is necessary. This helps the stakeholders to address the identified issues. Also, developing a method that assists users with the perception of the risk of their building and the causes of the buildings' lack of earthquake resistance helps them in commissioning a quantitative assessment and adopted appropriate retrofitting strategies.

2.7 CONCLUSIONS

The comprehensive study outlined above delves into the multifaceted nature of seismic risk and the methodologies employed to assess and mitigate it. By defining key concepts such as hazard, vulnerability, and exposure, the framework establishes a holistic understanding of earthquake risk. Seismic hazards arise from the interaction of earthquake sources, paths, and site-specific conditions, while vulnerability and exposure highlight the susceptibility of various assets, both tangible and intangible, to these hazards.

Various methodologies for seismic risk assessment are discussed, including empirical, analytical, and hybrid models. Empirical methods, such as field surveys, laboratory experiments, and expert opinions, provide data-driven insights into past earthquake impacts. Analytical methods utilize theoretical models to predict potential damages, and when combined with empirical data, form hybrid models offering more robust risk evaluations.

The development of vulnerability functions through historical data and damage probability matrices has laid the groundwork for modern seismic risk assessments. Significant contributions from agencies like FEMA and international collaborations, such as the IDNDR and RADIUS initiatives, have advanced the understanding and implementation of seismic risk mitigation strategies globally.

The Earthquake Disaster Risk Index (EDRI) presents a multidisciplinary approach to assessing urban earthquake risks, incorporating factors like hazard, exposure, vulnerability, emergency response, and recovery capabilities. This composite index aids in resource allocation, industrial planning, and structural engineering by providing a relative risk evaluation across different cities.

Recent advancements, such as Bayesian Belief Networks (BBN), have refined the assessment models, addressing limitations of traditional linear aggregation methods. The EDRI model, validated through studies in various cities, emphasizes the significance of integrating physical, socioeconomic, and response capacity parameters to obtain a comprehensive risk profile.

Overall, the detailed methodologies and case studies discussed provide a robust framework for understanding and mitigating earthquake risks. By combining empirical data, analytical models, and expert insights, these approaches enable more effective preparedness and resilience planning, ultimately reducing the adverse impacts of earthquakes on urban environments.

3
Conceptual Framework

3.0 INTRODUCTION

Protection of the built environment from earthquakes necessitates an important starting step: create *awareness of the earthquake risk* among key stakeholders, including policymakers, urban planners, building contractors, individual building owners, and other relevant participants. A well-constructed *earthquake risk index* serves as a valuable tool, contributing significantly to the achievement of this objective. It enables the selection and assessment of various components contributing towards a region's earthquake disaster risk, facilitating effective communication of the level of risk and comparisons of changes in risk over space and time. In the development of the current risk index, three primary elements of risk—*Hazard*, *Vulnerability*, and *Exposure*—are chosen.

3.1 HOUSING TYPOLOGIES

In this research study, we focus on evaluating earthquake safety assessments for two distinct building typologies, specifically highlighting their structural characteristics and vulnerabilities during seismic events. The first typology is Brick Masonry buildings, a traditional construction style where the primary load-bearing structures are made from individual bricks bonded together with mortar. The second typology is *Reinforced Concrete Moment Resisting Frame (RC MRF)* buildings. These are modern structures where the load-bearing framework is constructed from reinforced concrete, designed to resist bending moments, shear forces, and axial loads, especially during seismic activities.

Further, we categorize Brick Masonry buildings based on the type of roofing material used. This distinction results in two sub-types: *Brick Masonry Concrete Roof (BMCR)* and *Brick Masonry Other Roof (BMOR)*. BMCR buildings are characterized by their concrete roofs, which add significant weight and rigidity to the structure, potentially influencing how these buildings behave during an earthquake. On the other hand, BMOR buildings utilize different roofing materials, which could be lighter and may impact the building's seismic performance differently. Understanding these differences is crucial for accurate earthquake safety assessments, as the roof structure plays a significant role in the overall seismic response of masonry buildings. This study aims to delve into these typologies to better comprehend their behavior under seismic stress and to develop more effective strategies for enhancing their earthquake resilience.

Figure 3.1 *Brick masonry with concrete roof building*

Figure 3.2 *A three storey brick masonry with concrete roof*

Figure 3.3 *Brick Masonry with titled roof*

Figure 3.4 *Brick Masonry with other roof*

Figure 3.5 *An under construction RC MRFzbuilding*

Figure 3.6 *Typical View of RC MRF building*

3.2 HAZARD

The earthquake *hazard* is defined by the likelihood of a damaging earthquake occurring during the expected lifespan of a residential structure in a particular geographic area. *Ground shaking* is the primary seismic hazard, directly affecting structures and giving rise to other hazards. Secondary hazards, known as *collateral hazards*, arise as consequences of the initial shaking and encompass phenomena such as *liquefaction*, post-earthquake *fires*, *landslides*, *rockfalls*, and *tsunamis*. An informed assessment of hazard at the individual building level is essential for conducting a meaningful risk assessment.

3.2.1 Ground Shaking

Seismic waves, originating from an earthquake's source, travel through the earth's layers, reaching the surface and causing ground shaking. This shaking, which can last from a few seconds to several minutes, varies in strength and duration based on factors like the earthquake's magnitude, its epicentral location, and the geological characteristics of the affected region. The nature of ground motion differs depending on proximity to the earthquake source. Near the epicentre, the ground experiences a mix of low and high-frequency waves, leading to potentially catastrophic damage. In contrast, distant locations predominantly encounter high-frequency waves with a more random motion pattern.

Three characteristics of ground motion amplitude, frequency content, and duration of motion are important from engineering purposes.

Ground shaking is quantified using parameters such as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Peak Ground Displacement (PGD). Additionally, the local soil conditions significantly influence ground shaking. Depending on their properties, soils can either amplify or attenuate seismic waves, thus affecting the shaking experienced at the surface. This variation in soil response is a key factor in seismic risk assessment.

Understanding ground shaking is essential for seismic risk evaluation in any geographic area. It not only aids in the development of earthquake-resistant infrastructure but also plays a vital role in preparing communities for earthquakes, thereby safeguarding human lives and property. This comprehensive understanding of seismic hazard and ground shaking is indispensable for advancing research in earthquake engineering and for enhancing disaster preparedness and mitigation strategies.

3.2.2 Liquefaction

Liquefaction is a phenomenon in which the strength of soil significantly decreases, leading to its inability to support structures or maintain stability. This occurrence is most commonly observed in granular and saturated soils, especially in areas near rivers, coasts, and other water bodies, particularly during strong earthquakes . Liquefaction of saturated soils has been reported in a number of earthquakes worldwide, 1964 Alaska earthquake (USA), 1964 Niigata earthquake (Japan), and 1995 Kobe Earthquake (Japan). In India, Liquefaction was observed in 1934 and 1988 Bihar-Nepal earthquakes, and the 2001 Bhuj earthquakes.

Figure 3.7 *Extensive liquefaction at a three-story RC frame office building near Kandla port; building sustained only minor cracks in the walls, but settled down by about 70mm (Source: EERI)*

Figure 3.8 *Surface water due to liquefaction, Banni Plains (Source: EERI)*

Figure 3.9 *Liquefied soil has left cars stranded, much like an awful winter snowstorm (Source: EERI)*

Figure 3.10 *Effects of soil liquefaction caused by the earthquake on apartment buildings in Niigata (Source: Wikipedia)*

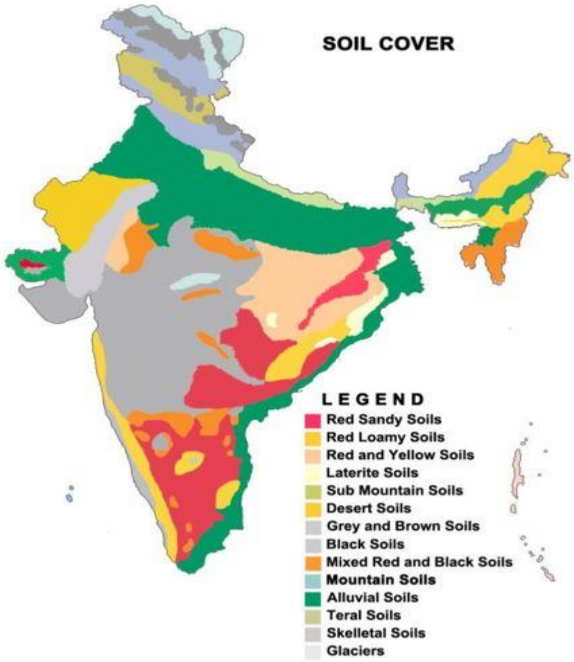


Figure 3.11 *Soil cover [BMTPC, 2014]*

3.2.3 Landslides

Landslides refer to the movement of materials on slopes, including rocks, debris, and soil, as they slide downward and outward. Various landslide types, including debris slides, debris flows, rockslides, and rock falls, can be triggered by multiple factors. These triggers include rainfall, slope undercutting due to flooding or excavation, earthquakes, snowmelt, and other natural as well as human-made causes. Landslides can happen in different terrains if the conditions of soil, rock, geological structure, and slope inclination are favourable.

Landslides that are either triggered or induced due to earthquakes are called co-seismic landslides. An earthquake-triggered landslide is when an existing, previously formed landslide is reactivated or set in motion due to the shaking or seismic activity of an earthquake. An earthquake-induced landslide refers to a new, first-time landslide that is directly caused by an earthquake. The most common types of earthquake-induced landslides are rock falls and slides on steep slopes. Other mass movements related to earthquakes include rock avalanches on steep, weak slopes, and mud flows or earth flows triggered by tremors.

Co-seismic landslides often occur in the Himalayan and North-Eastern regions of our country. Notable examples include landslides triggered by the Shillong earthquake in 1897, the Kangra earthquake in 1905, the Assam earthquake in 1950, the

Uttarkashi earthquake in 1991, and the Chamoli earthquake in 1999. These earthquakes caused widespread landslides. Similarly, the Kashmir earthquake in October 2005 resulted in numerous landslides in both Pakistan and India (NDMA, 2010). The Sikkim earthquake in 2016 triggered landslides and caused road blockages.

Landslide hazard map indicates those areas that are, or could be, affected by landslides, assessing the probability of such landslides occurring within a specific period of time, while landslide inventory is documentation of all the known landslide incidences including stabilised, dormant, reactivated, and most recent slides. Figure X shows the landslide hazard map of India, and it can be noticed that most of the areas is in higher seismic zone. In India, landslides mostly affect three major areas. The Northwest Himalayas are the most impacted, accounting for 66.5% of the country's landslides. Following this, the Northeast Himalayas see about 18.8% of landslides. The Western Ghats experience 14.7% of the landslides in India. Some areas of Eastern Ghats experience landslides (Figure 3.12).

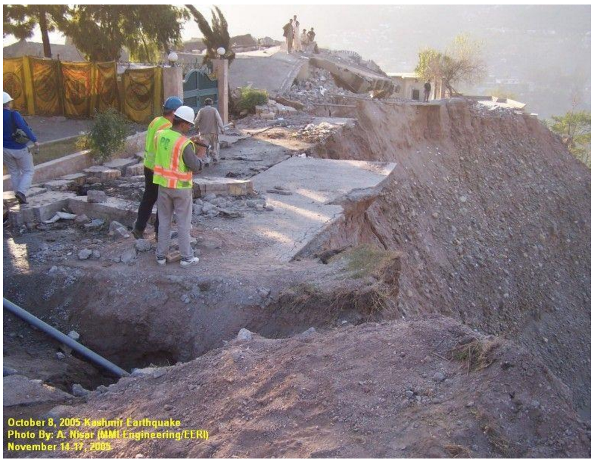


Figure 3.12 *Landslide in 2005 Kashmir Earthquake (Source EERI)*

Figure 3.13 *Damage to a building due to rock fall (Source EERI)*

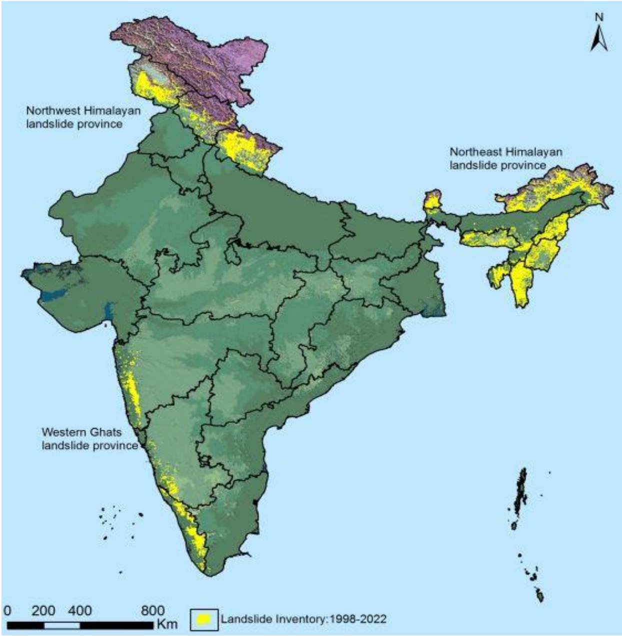


Figure 3.14 *Landslide incidence map (ISRO,2020)*

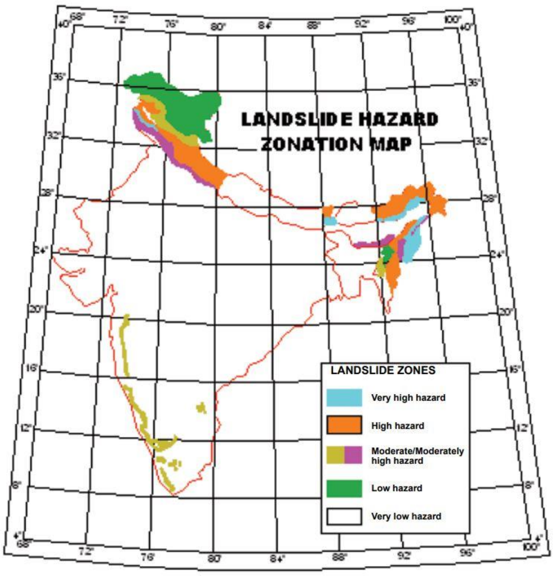


Figure 3.15 *Landslide hazard map*
(NDMA,2010)

3.2.4 Post-earthquake Fire

Post-earthquake fires are among the most destructive events following earthquakes, especially in urban areas. Though scattered and not always extensive, the post-earthquake fires sometimes lead to catastrophic outcomes. In the recent times, immediately after the 1994 Northridge earthquake 110 fire events originated mostly in the residential buildings were reported. The cause of the fire was attributed to the short either gas leaks or short circuits. None of the fire turned into a conflagration due to timely response of fire brigades, supporting weather conditions with weak winds, the nature of the building material and the separation between the buildings. The 1995 Kobe earthquake, soon after the shocks nearly 53 fires broke out that developed into number of conflagrations, where most of them lasted for more than 24 hours with few of them burned for more than 2 days (Figures 3.16 to 3.18). The fires destroyed about 5000 buildings over an area of approximately 660,000 m^2. Major reasons for development of fire and its spread are broken gas pipes, short circuits, and demolished buildings. Though the city had advance fire control centre to respond to the fire, the interruption of telephone lines and blockage of the roads led to delay in response to the fires.

The main components of the fire hazard due to earthquakes are , the location and ignition sources, and the types of materials used in buildings, along with weather conditions. The common ignition sources are , short circuits, damage to the electrical equipment's, gas leaks and flammable liquids. The impact of fires on the buildings is dual: first, from the burning of valuable combustible materials, and second, from the excessive load on structural elements causing further damage. Post-earthquake, the effectiveness of built-in fire extinguishing systems is often compromised, as these systems can be severely damaged. Additionally,

Figure 3.16 *Aerial view of the city devastated by the post-earthquake fires. By the time the fires died out, large areas of Kobe had been destroyed, 1995 Kobe earthquake (Source EERI)*

Figure 3.17 *All fires were burning freely, several with flames 20 ft. or more in height. Fire spread was via radiant heat and flame impingement, building to building in the densely built-up areas, 1995 Kobe earthquake (Source EERI)*

Figure 3.18 *Aerial view of the city devastated by the post-earthquake fires. By the time the fires died out, large areas of Kobe had been destroyed., 1995 Kobe earthquake (Source EERI)*

building collapses can block roads, making it harder for rescue teams to reach and assist those trapped in fires. Consequently, the number of casualties in fires following earthquakes tends to be much higher than in other fire incidents.

3.3 VULNERABILITY

Vulnerability means the degree of loss to a given element at risk or set of such elements resulting from an earthquake of a given magnitude or intensity which is usually expressed on a scale from 0 (no damage) to 10 (total loss). Vulnerability refers to the potential for the physical infrastructure to be damaged or destroyed. Vulnerability of the built environment is a crucial factor because it determines the extent of damage a city might suffer which indirectly affects post-earthquake response activities.

3.3.1 Life Threatening Factors

3.3.1.1 Siting Issues

Buildings on or near hill slopes, including those on flat areas close to slopes, are at risk of damage from debris falling from above. This risk increases if nearby or uphill structures move or collapse, sending debris down, which can severely impact buildings below. Buildings on steeper slopes are more likely to be damaged during earthquakes.

Figure 3.19 *Damage to houses due to rolling boulder at Lingzya and Chungthang , 2001 Sikkim earthquake (Source EERI)*

Figure 3.20 *Classic damage in lower stories of RC frame building with large block masonry infill panels at ITBP quarters at Chungthang, 2011 Sikkim Earthquake (Source EERI***)**

Figure 3.21 *Common hillside construction on precipitous slopes near Chautara, 2015 Nepal Earthquake (Source EERI)*

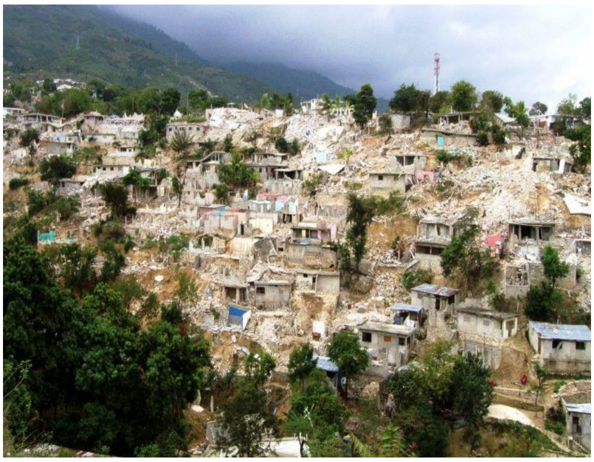


Figure 3.22 *Ground effects, 2010 Haiti Earthquake (Source EERI)*

3.3.1.2 Pounding

In the context of urban structural, the issue of buildings in proximity, or different parts of the same building, colliding or pounding during an earthquake is of utmost concern. The issue of adjacent buildings or sections of a single building colliding during an earthquake is associated with two main factors: the presence of separation joints, in cases where the buildings are architecturally integrated into a single structure, and the stiffness of the buildings , as this influences drift, which in turn determines the necessary separation distance to avoid contact). Pounding has been noted in several earthquakes of the past. In Nepal lack of planning and oversight in construction practices has led to disorderly building developments with inadequate spacing between structures. Consequently, in 2015 Nepal earthquake, many buildings that might have remained intact from the earthquake's effect incurred significant harm due to collisions with neighbouring buildings. Pounding was noted during the 2023 Kahramanmaraş earthquakes. Even with measures taken following the 1999 earthquakes, this recognized flaw persists because of insufficient design and construction regulation. It was seen that many buildings shared a wall with the one next to them, showing there was no gap between neighbouring buildings (Figure 3.23).

Figure 3.23 *Pounding , 2015 Nepal earthquake*
(Source EERI)

3.3.1.3 Open Ground Storey

Many apartment buildings feature a design where the ground level is allocated for either commercial use or vehicle parking. This design choice results in an open floor plan, with no infill walls as in the upper stories, and with increased height, and such buildings are commonly referred to as *Open Ground Storeys*. This feature is more commonly observed in reinforced concrete moment resisting framed buildings. The feature in the building may cause

i) Soft storey effect—the ground floor of these buildings is much more flexible compared to the upper floors. This means that the ground floor can move horizontally more than the floors above it when subjected to forces like earthquakes.

ii) Weak story effect—reduced Strength on the ground floor in terms of withstanding horizontal forces such as those experienced during earthquakes, the ground floor is weaker than the upper floors. The columns on this floor can carry less of these horizontal forces compared to the floors above. Therefore, the open ground floor is not only flexible but also weak.

Open ground storey buildings have consistently performed poorly during past earthquakes across the world. Many such structures have collapsed, while a vast number have sustained damage, ranging from minor to severe . During recent 2023 Kahramanmaraş earthquake, the formation of a storey mechanism has been the reason of collapse of many RC buildings . Few buildings have open ground storeys (Figure). During the 2001 Bhuj earthquake in India, many open ground storey buildings in cities such as Ahmedabad, Bhuj, and Gandhidham experienced extensive damage or were completely collapsed. (Figure 3.24). Damage to the buildings due to the soft storey effects was observed in 2016 Manipur EQ .

Figure 3.24 *Typical RC MRF Building with open ground storey*

3.3.1.4 Structural Aspects

In the construction of reinforced concrete structures, stirrups in beams and ties in columns are traditionally equipped with 90^0 hook ends. As per IS 13920:2016, closed ties with 135^0 hooks are recommended. By bending vertical links into a 135^0 hook and extending them adequately into the surrounding confined concrete, the risk of the links opening out under seismic forces is significantly reduced. It helps in preventing the opening of loops, thereby reducing the potential for buckling in the vertical reinforcement bars.

According to the IS 13920:2016, the width of columns should not be less than 300mm. This requirement addresses potential issues arising from insufficient column dimensions, such as:

i) a significantly reduced moment capacity due to a narrow lever arm distance between tension and compression reinforcements, and

ii) ii) inadequate anchorage for the longitudinal reinforcements of beams at both external and internal column connections. However, A column width of up to 200mm is allowed if the unsupported length is less than 4m and beam length is less than 5m.

3.3.2 Economic Loss Inducing Factors

3.3.2.1 Siting Issues

Characteristics like the emergence of ground cracks because of the surface expression of fault lines or due to soil movements, as well as landslides and the destabilization of slopes, especially when they occur near a building, significantly increase the risk of additional harm or even structural failure, thus compromising safety.

3.3.2.2 Soil and Foundation Condition

(a) Suitability of Soil

The soil conditions beneath a building are a significant factor in its behavior during an earthquake. Soft and weak soils do not provide strong support for buildings, which can lead to greater movement and shaking compared to buildings on firm ground. This can cause more damage to the building's structure. Similarly, soils with high moisture content or those with a high-water table can also be problematic during earthquakes. When saturated with water, soils can lose strength and stiffness, leading to a phenomenon known as liquefaction. Liquefaction occurs when the soil behaves more like a liquid than a solid, which can cause buildings to tilt, sink, or collapse. Additionally, the presence of water can amplify seismic waves, exacerbating the shaking and the potential for damage. Therefore, buildings on soft, weak, or moist soils require special design considerations to improve their earthquake safety.

(b) Foundation

During earthquakes, the foundation system of a building critically influences its performance. Footings on non-uniform soil without tie beams are highly vulnerable, as they offer little resistance to the differential movement caused by seismic activity, leading to a high risk of structural damage . Conversely, adding tie beams to footings on non-uniform soil can mitigate some of this risk by providing additional lateral support and helping to maintain the structure's integrity during shaking .

For buildings with footings on soft soil, the absence of tie beams can be particularly detrimental . Soft soil amplifies seismic waves and can cause significant settlement or tilting of the foundation, and without tie beams, the footings are not effectively connected, which can lead to uneven settlement and more extensive damage. Including tie beams with footings on soft soil can somewhat improve performance by ensuring that the footings behave more cohesively during an earthquake, thus reducing the risk .

A mat foundation, which is a large concrete slab that supports several columns or an entire building, on non-uniform soil can offer a better performance than individual footings. It distributes the load over a larger area, reducing the differential movement and potential for severe damage. However, on non-uniform soils, there is still a risk of uneven settlement, though to a lesser extent than individual footings without tie beams.

3.3.2.3 Architectural Features

(a) Plan Shape

The shape of a building plays a crucial role in how it performs during an earthquake. Buildings with simple, symmetrical shapes are generally more resistant to earthquake forces. In contrast, buildings with *large rooms*, *irregular orientation of rooms* , complex overall shapes, and *re-entrant corners* are more vulnerable. When a building's design is large and though simple, during earthquake it might not respond as a unit. Increasing a building's size increases the stress on floors. In case of the large floor diaphragms, the forces are not effectively transferred from the floor to the stronger structural elements that has capacity to take stresses generated due to the earthquakes.

Re-entrant corners can concentrate stress, leading to cracking and structural weakness. Therefore, the design of a building, including its plan shape and the configuration of its rooms, significantly affects its ability to withstand earthquakes.

(b) Elevation Profile

The features of a building significantly impact its performance during an earthquake. Buildings with a wider top and narrower bottom are unstable as the mass is not evenly distributed, leading to a top-heavy structure that is prone to tipping or collapsing.

Large projections or overhangs, such as balconies or extended roofs, can also pose risks during an earthquake. A split roof creates discontinuities in the mass and stiffness of the building, which can lead to complex seismic responses that the structure may not withstand.

Buildings with large storey heights or differences in storey heights can experience increased seismic forces on the taller storeys, leading to potential damage as these floors move more than the lower ones. The unsymmetrical location of staircases can similarly create an irregular distribution of mass and stiffness, which can result in torsional movement and additional stresses during an earthquake.

The most significant risk is posed by an open ground storey that is not designed to resist earthquake shaking. This is often seen in buildings with parking or open commercial spaces on the ground floor, which lack the necessary walls or bracing. Such a 'soft' storey is extremely vulnerable to collapse, as it lacks the strength to support the storeys above during seismic shaking. This feature poses the greatest risk to structural integrity during an earthquake.

(c) Door and window Openings in walls

The placement and size of openings in a building, such as windows and doors, affect its structural performance during an earthquake. A single window close to corners may slightly compromise the integrity of that corner, but the overall effect on the building's performance is typically minimal. However, if about half or more of the building's openings are close to corners, the risk increases . Concentrating openings near corners can significantly weaken these load paths.

The larger the area of window and door openings, the greater the reduction in wall area that provides lateral resistance against seismic force. Large openings mean less wall material to resist earthquake forces, leading to a higher risk of structural failure, especially if these openings are not reinforced or designed to accommodate seismic movements.

(d) Parapets

Large and heavy projections and overhangs present another challenge. These elements can act as pendulums during an earthquake, exerting additional forces on the structure as they sway. This can lead to stress concentrations at the connection, potentially causing those parts of the building to fail. Moreover, if these projections or overhangs collapse, they can cause significant damage to lower parts of the building and pose a serious hazard to people nearby.

3.3.2.4 Structural Aspects

(a) Frame Grid

The performance of buildings during earthquakes is significantly influenced by their structural framework and symmetry.

When a building has a grid of parallel planar frames only along one plan direction, it means that it may be well-supported in that direction but could be vulnerable to seismic forces coming from perpendicular directions. This can lead to asymmetric shaking and torsional movements, causing damage to the structure.

If there is no grid of parallel planar frames along both plan directions, the building lacks a uniform framework to distribute seismic forces evenly. This absence can result in a lack of support during lateral shaking, making the building highly susceptible to damage or collapse from earthquakes.

A building whose frames have symmetric lateral stiffness along one plan direction may perform well when faced with seismic forces in that direction, as the stiffness helps resist deformation. However, if the forces come from a different direction, the building could experience more movement and potential damage.

In contrast, frames that don't have symmetric lateral stiffness along any plan direction would likely perform poorly during an earthquake. Without symmetric stiffness, the building would be prone to uneven lateral movement, leading to increased stress on the structure and a higher risk of failure.

Similarly, frames with symmetric lateral strength along one plan direction can resist seismic forces well in that orientation but may not in others. Strength symmetry helps in handling the seismic loads, reducing the likelihood of structural failure.

Frames that don't have symmetric lateral strength along any plan direction are at a severe disadvantage in an earthquake. Such a building would lack the necessary resistance to seismic forces from any direction, increasing the probability of damage and structural failure. Therefore, for optimal earthquake performance, it is crucial for buildings to have balanced and symmetrical frames that provide even stiffness and strength in all directions.

(b) Slab Design

The performance of buildings during earthquakes can be significantly affected by the characteristics of their roof and floor slabs:

A heavy roof or floor slab can have a negative impact on the performance of a building during an earthquake. The excess weight increases the forces exerted on the building's structure when the ground shakes, potentially leading to a higher risk of collapse.

A pitched roof or floor slab, typically with two sloped sides meeting at a peak, may perform better than flat heavy slabs because they often weigh less and can distribute the seismic forces more efficiently. However, the effectiveness can vary depending on the construction details and the materials used.

A split roof or floor slab, which means the slab is divided into sections, may perform poorly during an earthquake. The discontinuity can lead to differential movement between the sections, putting additional stress on the connections and potentially leading to structural failure.

Roof or floor slabs with large size openings, particularly when these are located along the edges, can be problematic during seismic events. The openings can weaken the slab's structural integrity, and when these are near the edges, the reduction in continuous support makes the slab more susceptible to damage or failure under seismic shaking.

(c) Roof/floor – column connection

No/insufficient anchorage of horizontal reinforcement from beams to columns at roof/floor levels: The lack of proper anchorage can lead to a failure in the connection between beams and columns, resulting in the beams becoming detached and increasing the likelihood of partial or total collapse of the floors.

Column weaker (in moment capacity) than beams framing into it at each joint: Columns are the main vertical supports, and if they are weaker than the beams they connect to, they may buckle or collapse under the earthquake forces. This can lead to a "soft-story" collapse, where an entire floor gives way.

No/insufficient anchorage of reinforcement from columns to foundation: The connection between columns and the foundation is vital for the stability of the building. Without sufficient anchorage, columns may move or sway separately from the foundation, potentially leading to a catastrophic failure of the structure.

All longitudinal bars in column lapped at the same location: This creates a weak point in the column, and during an earthquake, this is the likely location where the column would fail. The uniform weakness across the height of the column could lead to its inability to support the building, causing severe structural damage or collapse.

(d) Staircase

Unsymmetrical location: Staircases located asymmetrically within the building plan can create an irregular distribution of mass and stiffness. This can result in torsional, or twisting, movements during an earthquake, which can cause additional stress on the structure, leading to damage not evenly distributed across the building.

Both top and bottom integrally built into the building frame: If the staircase is integrally built into the building frame at both the top and bottom, it can help with the overall stiffness and stability of the building. However, if the staircase is damaged during an earthquake, it can compromise the integrity of the building frame, potentially leading to a more significant structural failure.

Staircase not adequately separated from the house: Staircases that are not separated from the house might cause a chain reaction of damage if they fail during an earthquake. Since they are connected to the main structure, the failure of a staircase could lead to further damage within the building, exacerbating the overall structural damage and possibly blocking escape routes.

(e) Large water tanks

If a building has large water tanks that are not anchored to the structural system, the performance of the building during an earthquake can be significantly compromised. Unanchored tanks can move or slide during seismic activity, potentially causing damage to the supporting structure or to other non-structural elements. The movement of heavy tanks might also lead to punctures or ruptures, which can result in water leaks that could further weaken the building materials or lead to additional hazards for occupants. Moreover, the dynamic forces generated by the sloshing of water within the tanks can introduce unexpected loads on the building structure, which may not have been accounted for in the design, thus increasing the risk of structural failure. It is essential for such tanks to be properly anchored and integrated with the building's design to ensure stability during an earthquake.

3.3.2.5 Construction Details

(a) Types of Material

The quality of materials used in construction has a direct impact on a building's behaviour during an earthquake. If the sand in concrete mixtures is of poor quality, it can lead to weaker concrete with less durability and reduced strength, making the building more susceptible to cracks and damage during seismic activity. Similarly, poor quality aggregates can compromise the concrete's integrity, as they may not bond well with the cement, leading to a reduction in the overall strength of the material.

Poor quality cement can greatly reduce the structural strength of concrete, as cement is the binding agent that holds the sand and aggregate together. If the cement is not able to perform this function effectively, the concrete will be weak and prone to failure under the stress of an earthquake.

Lastly, poor quality bricks can be detrimental to the stability of masonry buildings. They may crumble or crack under seismic forces, leading to a loss of wall integrity and potentially causing the collapse of the structure.

(b) Workmanship

Buildings with poor geometries of masonry and roof structures are at a disadvantage during earthquakes. Irregular shapes and asymmetrical designs in masonry work can lead to stress concentrations and inadequate load paths, which can cause premature cracking or collapse when the building is shaken. Inadequately designed roofs may also fail to properly transfer seismic forces to the walls, leading to potential roof collapse or separation from the supporting structure.

Insufficient curing of concrete is another critical issue. Curing is the process of maintaining adequate moisture, temperature, and time to allow concrete to achieve its designed strength. Insufficient curing can result in weaker concrete that may not perform as expected during seismic events. Such concrete may exhibit poor bonding with the reinforcement, reduced toughness, and increased brittleness, making the structure more vulnerable to cracking and failure under the dynamic loads of an earthquake.

(c) Concrete Mix

When concrete is prepared using a nominal mix, it means that the components are proportioned based on common practice and experience rather than precise calculations or laboratory tests. This can result in a mix that may not have the optimal strength or durability needed for seismic resistance. During an earthquake, such concrete might be more prone to cracking, spalling, or even catastrophic failure under the stress of seismic forces due to potentially inadequate strength or inconsistency in the mix.

Similarly, measuring concrete ingredients by volume batching can lead to variations in the mix from batch to batch, as volume measurements are less accurate than weight measurements. The inconsistency in the mix quality can affect the concrete's strength, leading to weak spots that may fail under the dynamic loads of an earthquake.

Buildings constructed with concrete that has been prepared using these methods may not perform as well as those where the concrete mix is carefully designed and measured by weight. It's important that the concrete mix is consistent and meets the structural requirements to ensure the building can withstand the stresses of seismic activity.

3.4 Exposure

Exposure refers to the number of people living, infrastructure, houses, and other tangible human assets in the hazard-prone area . From the perspective of the built environment, the number of people living in the houses, the total number of houses, the population density, and the housing density are significant exposure indicators that contribute to the risk. In the present study, Floor Area Ratio (FAR), is chosen as the indicator. Floor Area Ratio is the ratio between the total built up area to the plot area/lot area available. The city specific FAR and ground coverage regulations are provided in the local municipal byelaws. They indicate the limitations of the building's area and height. In a city/town, FAR is fixed and the height of the building depends on the plot area. For example, if the FAR in some city is 1 and a plot area of 100 unit^2 , there is a one storey building constructed. If the plot area is 50 unit^2 , a two-storey building in the area is to be constructed to maintain FAR as 1. As the plot area decreases the height of the building increases. Similarly, if FAR value calculated for an existing building is greater than the recommended value, it is an indication that the building height is exceeding the limits and it affects planning of other infrastructures like roads, drainage systems, powerlines etc. FAR is a common variable in the cities and it results in varying pattern of development of urban form, space, and the degree of development. Figure 3.25 shows the land area and the floor area of a general building having N floors, and FAR of a building is given by equation 3.2, where

L = Length of the plot,

B = Breath of the plot,

$(B - S_{Bi})$ = Breath of built up area at the ith floor, and

$(L - S_{Li})$ = Length of built up area at the i^{th} floor,

in which S_{Bi} and S_{Li} are total offsets of the building from the plot boundary along the breadth and length directions of the building.

$$FAR = \frac{Total\ area\ built\ up\ in\ all\ floors\ together}{Plot\ area} \tag{3.1}$$

$$\text{FAR} = \frac{\sum_{i=1}^{N}(B - S_{Bi})(L - S_{Li})}{BL} \tag{3.2}$$

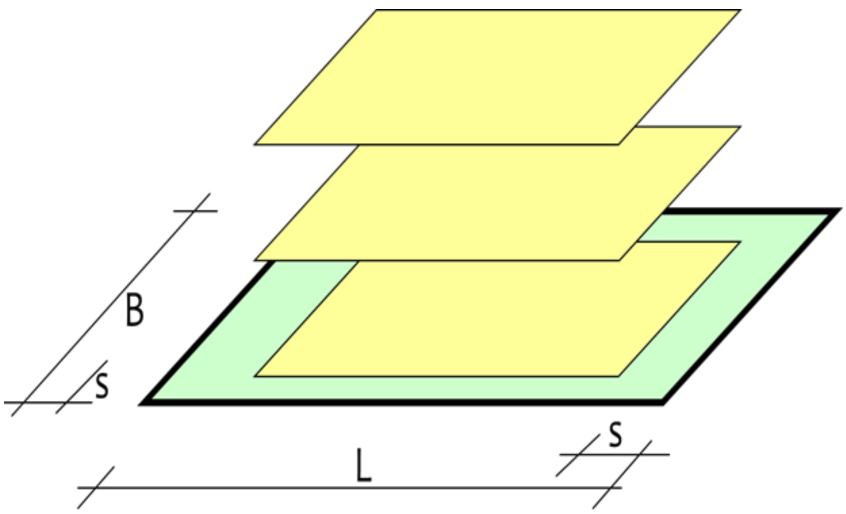


Figure 3.25 *Floor area and land area of a building*

3.5 Conclusion

The protection of the built environment from earthquakes requires a comprehensive understanding of hazard, vulnerability, and exposure. By focusing on these three primary elements, the development of an earthquake risk index can effectively communicate the level of risk and guide the implementation of mitigation strategies. Housing typologies and their structural characteristics play a crucial role in assessing and enhancing earthquake resilience. A well-constructed risk index facilitates informed decision-making and prioritizes actions to reduce the risk of earthquake disasters, thereby safeguarding lives and properties.

4
Proposed Methodology

4.0 INTRODUCTION

This chapter presents the proposed methodology for assessing earthquake disaster risk for buildings. The methodology involves several key factors and calculations designed to evaluate the capacity and demand factors of buildings, as well as their overall risk. The Capacity Factor evaluates the building's resistance to earthquake damage, considering various critical and economic loss-inducing factors. The Demand Factor assesses the expected seismic forces on a building, incorporating components such as the Seismic Zone Factor, Response Acceleration Coefficient, Importance Factor, and Response Reduction Factor. The risk of individual buildings is computed using these factors, alongside the Floor Area Ratio (FAR) to determine the building's exposure. The Earthquake Disaster Risk Index (EDRI) is then calculated for different building typologies and the overall built environment of a city or region. The final section of this chapter classifies buildings based on their demand factor and capacity, providing a general-purpose formula for estimating the risk of buildings across various seismic zones. This methodology aims to identify vulnerable buildings, facilitating comparative risk assessments and enhancing earthquake resilience in urban areas.

4.1 CAPACITY FACTOR

The capacity factor refers to a building's resistance to damage from earthquake shaking and is a measure of how well a building of a specific typology (type and design) can perform during an earthquake. This factor is derived from a technical evaluation of the building's features and conditions that contribute to its earthquake resistance. The factors affecting earthquake safety are divided into two categories: Life-Threatening Factors (LTFs) and Economic Loss-Inducing Factors (ELIFs). LTFs are critical issues that directly impact the building's safety and can lead to catastrophic failure or collapse during an earthquake. These factors are related to the structural integrity and overall stability of the building. Examples of LTFs include poor siting, such as buildings on slopes prone to landslides, inadequate soil and foundation conditions like liquefiable soil, and structural flaws such as unanchored roofs, weak connections between walls, and inadequate reinforcement. On the other hand, ELIFs may not cause the building to collapse but can lead to significant economic loss due to damage. These factors are related to both structural and non-structural elements of the building. For instance, structural ELIFs can include improper architectural features like large unanchored projections and construction details such as the use of mud mortar, while non-structural ELIFs may involve unanchored heavy objects inside the building, unprotected gas cylinders, and poorly secured electrical wiring.

An ideal earthquake-resistant building is designed and constructed to include all necessary features that minimize the impact of seismic forces. This includes appropriate siting, strong soil and foundation conditions, optimal architectural features, robust structural aspects, and meticulous construction details. Deviations from this ideal result in penalty points. The system quantifies the absence of earthquake-resistant features by assigning penalty points for each missing feature compared to the ideal building. A 100% penalty is assigned if any LTF is present, indicating that the building is unsafe. The penalty points for ELIFs vary based on the building typology and the specific factor. For example, in load-bearing masonry buildings, predetermined penalties are assigned for each ELIF, such as 5, 5, 40, 20, and 30. These points are determined using the Delphi Method, a structured communication technique involving a panel of experts. The P_{Bi} are penalty factors and $P_{Bi,j}$ are the penalty for the indicators of the factors. V_B is vulnerability of the individual building , and C_B is the capacity of the individual building. The maximum capacity of the buildings C_{Bmax} is 100. The range of capacity factor 0 to 100.

$$V_B = \frac{\left(\sum_{i=1}^{5} P_{Bi}\right)}{100} \tag{4.1}$$

$$V_B = \frac{\left[\sum_{i=1}^{5}\left(\sum_{j=1}^{N_{pi}} P_{Bi,j}\right)\right]}{100} \tag{4.2}$$

$$C_B = C_{Bmax} - V_B \tag{4.3}$$

$$C_B = 100 - V_B \tag{4.4}$$

4.2 DEMAND FACTOR

The Demand Factor is a critical measure used to assess the expected seismic forces on a building. This factor is calculated as a product of several key components. First, we have the Seismic Zone Factor (Z), which indicates the Peak Ground Acceleration (PGA) at the building's location. PGA is a vital measure that shows the maximum expected ground movement during an earthquake.

Next, the Response Acceleration Coefficient (Sa/g) is considered. This coefficient measures how a structure is likely to respond to the ground shaking, based on its specific characteristics. Then, the Importance Factor (I) is included in the calculation. This factor varies depending on the building's role and function. For instance, buildings essential for emergency services might have a higher importance factor.

Additionally, the Demand Factor calculation includes the Response Reduction Factor (R). This factor reflects the building's ability to reduce the seismic forces through its inherent design and construction qualities, such as ductility and energy dissipation capacity.

For buildings in India, the values for these components are derived as per the standards set in IS 1893 (Part 1): 2016. This code provides detailed guidelines to ensure buildings are designed to withstand seismic forces appropriate to their location and importance. By using these factors in combination, engineers can determine the level of seismic forces that a building must be prepared to handle, ensuring safety and resilience in earthquake-prone areas.

$$D_B = 100\, Z \left(\frac{S_a}{g}\right)\left(\frac{I}{R}\right) \tag{4.5}$$

4.3 RISK OF INDIVIDUAL BUILDING

The risk of an individual building is computed as shown in the equation 7, where ρ_B represents risk of an individual building, and $\frac{\text{FAR}}{\text{FAR}_{\text{Allowed}}}$ represents the exposure of the building.

$$\rho_B = 100\left(1 - \frac{\text{Capacity factor}(C_B)}{\text{Demand factor }(D_B)}\right)\left(\frac{\text{FAR}}{\text{FAR}_{\text{Allowed}}}\right) \tag{4.6}$$

4.4 EARTHQUAKE DISASTER RISK INDEX OF TYPOLOGY

The risk of a building of certain typology is estimated as the average of the risk values of the buildings. The $EDRI_T$ of the typology is a representative of the risk of that typology in the region. The N_T is the number of buildings in the typology.

$$\text{EDRI}_T = \frac{\sum_{b=1}^{N} \rho_{bT}}{N_T} \tag{4.8}$$

4.5 EARTHQUAKE DISASTER RISK INDEX OF A BUILT ENVIRONMENT

The EDRI of a City/Town/Region with M typologies of buildings is estimated in equation 8

$$\text{EDRI}_{\text{Town}} = \frac{N_{T1}\text{EDRI}_{T1} + N_{T2}\text{EDRI}_{T2} + \ldots + N_{TM}\text{EDRI}_{TM}}{N_{T1} + N_{T2} + \ldots + N_{TM}} \tag{4.9}$$

4.6 RISK CLASSIFICATION

Seismic design base shear coefficient, demand, for various classes of buildings Residential (R), Office (O), and Critical (C) in different zones as described as per IS 1983 (Part1) : 2016 were computed.

The capacity is categorized as Very Low (0-20), Low (20-40), Medium (40-60), High (60-80), Very High (80-100).

The objective of the study is to generate a general-purpose formula to estimate the risk of a building present in any zone . The estimation of risk is based on experience from the past earthquake data and Design code provisions. The attempt to develop a formula is to identify buildings that are vulnerable and risky from a code provisions and design philosophy, an engineering formula. It facilitates to compare the risk of any two building irrespective of the zone and the values of risk generate are absolute in nature.

Table 4.1 *Computation of risk values for various demand and capacities*

Capacity	Zone II			Zone III			Zone IV			Zone V		
	R	O	C	R	O	C	R	O	C	R	O	C
	Demand			Demand			Demand			Demand		
	25.00	31.25	37.50	40.00	50.00	60.00	60.00	75.00	90.00	90.00	112.50	135.00
100	4.00	3.20	2.67	2.50	2.00	1.67	1.67	1.33	1.11	1.11	0.89	0.74
80	3.20	2.56	2.13	2.00	1.60	1.33	1.33	1.07	0.89	0.89	0.71	0.59
60	2.40	1.92	1.60	1.50	1.20	1.00	1.00	0.80	0.67	0.67	0.53	0.44
40	1.60	1.28	1.07	1.00	0.80	0.67	0.67	0.53	0.44	0.44	0.36	0.30
20	0.80	0.64	0.53	0.50	0.40	0.33	0.33	0.27	0.22	0.22	0.18	0.15
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

5
Data Collection and Evaluation

5.0 INTRODUCTION

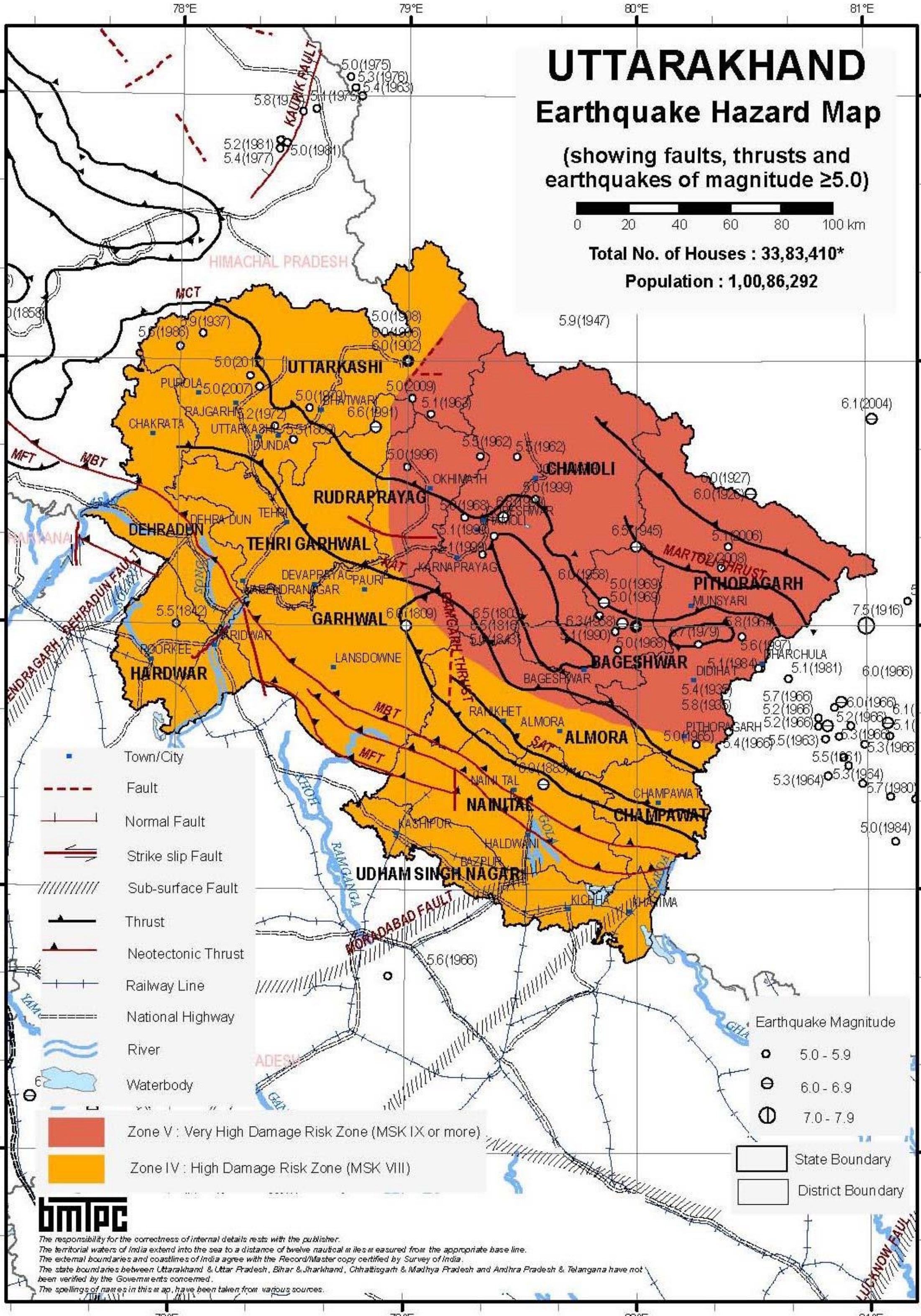
The previous chapter established the foundational groundwork, encompassing a conceptual framework, carefully selecting indicators, and identifying the theoretical components essential for deriving the earthquake disaster risk index. The next phase involves systematically collecting data pertaining to each designated indicator within the city. The data collection methodology, the inherent challenges linked to obtaining information for each designated indicator, and the reliability of the datasets are discussed in this chapter.

According to the Census of India, cities and towns within the country are classified into three distinct categories based on population size. These classifications include (i) semi-urban centres, encompassing populations ranging from 10,000 to 99,999, (ii) urban centres, comprising populations falling within the range of 100,000 to 999,999, and (iii) metro cities, characterized by populations exceeding 1,000,000.

5.1 EARTHQUAKE DISASTER RISK INDEX OF PITHORAGARH

5.1.1 SEISMOTECTONIC SETTING AND SEISMICITY

Pithoragarh, situated within the core of the Himalayas, is located at a latitude of 29.58^{0}N and a longitude of 80.22^{0}E. The town stands at an average altitude of 1,514 m and extends across a valley that spans an area of 7,110 sq.km .The region has limited flat land and has predominantly sloping landscapes. The territory within Pithoragarh's Municipal Boundary includes mainly slopes, alongside narrow and wide mountain valleys. About 48% of the area features steep mountain slopes. Slopes that are very steep to extremely steep cover 55% to 60% of the land. Uttarakhand, located in the seismic-prone area of the Himalayas in India, is characterized by its position along several active thrust faults. Notably, the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) are two key active faults in the region. These and other faults have been responsible for significant earthquakes, with magnitudes over 7.5, in the past. Other smaller faults, such as the Yamuna Fault near Haridwar and the Alaknanda Fault near Rudraprayag, have shown activity in the Holocene period. The actual boundary between the Indian and Eurasian plates is the Indus-Tsangpo Suture Zone in southern Xizang (Tibet), not the MBT and MFT, which are sometimes incorrectly regarded as the plate boundary.



BMTPC : Vulnerability Atlas - 3rd Edition : Peer Group, MoHUA, GOI; Map is Based on digitised data of SOI; Seismic Zones of India Map IS:1893 (Part I): 2002, BIS; Earthquake Epicentre from IMD; Seismotectonic Atlas of India and its Environs, GSI; Houses/Population as per Census 2011; *Houses including vacant & locked houses. Disclaimer: The maps are solely for thematic presentation.

Figure 5.1 *Hazard map of Uttarakhand (BMTPC, 2019)*

Table 5.1 *Past earthquakes near Pithoragarh*

Date	*Epicentral Distance (km)*	*Magnitude (Mw)*	*Latitude*	*Longitude*	*Remarks*
16 June 1902	126.4	6.0	30.00^0N	79.00^0 E	-
13 June 1906	196.2	6.1	31.00^0 N	79.00^0 E	-
28 August 1916	88.56	7.1	30.00^0 N	81.00^0 E	The shock caused severe damage to civil structures in Dharchula located 90 km form Pithoragarh city
27 July 1926	103.3	6.5	30.50^0 N	80.05^0 E	-
08 October 1927	103.3	6.1	30.50^0 N	80.05^0 E	-
04 June 1945	82.46	6.5	30.30^0 N	80.00^0 E	-
28 December 1958	23.03	6.1	29.50^0 N	80.00^0 E	-
27 June 1966	59.29	6.2	29.62^0 N	80.83^0 E	-
29 July 1980	84.32	6.5	29.60^0 N	81.09^0 E	Around 150 - 200 persons were killed, and hundreds injured. The shaking caused damage in Pithoragarh area also killing 13 people and injuring 40. The shock was felt even in Kathmandu and New

					Delhi.
20 October 1991	190.4	6.8	30.77^0 N	78.79^0 E	-
05 January 1997	42.04	5.6	29.84^0 N	80.53^0 E	Shaking is strongly felt in many parts of Uttarakhand, namely Nainital, Kumaon and the Terai. Many houses were damaged in western Nepal, and it was also felt at Dadeldhura, 45 km form. Pithoragarh city.
29 March 1999	120.1	6.4	30.40^0 N	79.41^0 E	-

5.1.2 Built Environment

In the Himalayan town of Pithoragarh, within Pithoragarh district, Uttarakhand, the built environment, as defined by the Census of India 2011, comprises 16,412 houses. Of these, 87% feature concrete roofs while the remaining 13% have various other types of roofing. Wall materials predominantly consist of burnt brick, accounting for 88% of houses, with nearly 2% constructed with concrete walls. A specific subset, 1.68% of buildings, incorporates both concrete roofs and walls. The majority, 81.6%, combines concrete roofs with burnt brick walls. In terms of usage, 69% of buildings serve as residential spaces, 16% as shops and office buildings, and 1.2% as hospitals and similar institutions. From 2001 to 2011, there was an 18.6% increase in the number of buildings, with a notable shift in roofing materials: the prevalence of lightweight and heavyweight sloping roofs decreased by 9% and 37%, respectively, whereas buildings with flat roofs (concrete and burnt brick) increased by 26%. Concurrently, Pithoragarh's population rose from 44,964 in 2001 to 56,044 in 2011, reflecting both urban development and demographic growth.

5.1.3 Sample Survey

The visit focused on conducting a Detailed Visual Survey (DVS) of buildings. This survey aimed to understand the risk distribution across the city. During the survey, a total of 348 buildings were examined. These buildings included Reinforced Concrete Moment Resisting Frames (RC MRF), Brick Masonry with Concrete Roof (BMCR) and Brick Masonry Other Roof (BMOR). The survey covered 15 different wards within the city. The survey covered 15 different wards within the city.

Table 5.2 *List of Wards in Pithoragarh City with Census Data and Number of Buildings considered*

Ward No.	*Ward*	*Census Population*	*Census Household*	*No. of Buildings*
1	Bhatkot	4,207	1,028	18
2	Vin Jackni	3,775	945	31
3	Kumound	3,817	1,016	51
4	Cinema Line	2,581	591	38
5	Pandgav	3,435	831	24
6	Bhajeti	4,801	1,193	2
7	Cimalgier	4,031	998	18
8	Khadkot	3,939	996	21
9	Cera pundi	1,772	397	16
10	Luntyunda	1,981	449	21
11	Shivalaya	3,509	909	24
12	Tildookri	4,985	1,303	16
13	Naya Bazar	3,895	975	21
14	Takana	4,592	1,142	22
15	Chandrabhag	4,724	1,263	25



Figure 5.2 *Typical buildings in Pithoragarh*

4.1.4 Observations

In the city, several factors contribute to the potential economic loss in reinforced concrete moment-resisting frame (RC MRF) buildings during seismic events. A significant portion of these buildings, approximately 50.54%, have large area door and window openings, which are an architectural feature that can lead to increased damage and higher repair costs in the event of an earthquake. Nearly as many buildings, at 47.67%, have staircases that are not adequately separated from the main house structure, a structural factor that can result in a compromised escape route and additional structural damage. Variations in storey heights, present in 44.09% of buildings, can cause irregular distribution of seismic forces, potentially leading to uneven damage across floors. Furthermore, 48.39% of the buildings are constructed in close proximity to each other, allowing for the possibility of impact and collective damage during strong ground shaking. These factors are significant in assessing the vulnerability and economic impact on RC MRF buildings in the city when faced with an earthquake.

In the city's building inventory, particularly brick masonry (BM) buildings with concrete roofs, there are several critical factors that not only pose economic risks but also threaten the lives of occupants in the event of an earthquake. A significant majority of these buildings, 67.44%, lack structural reinforcements such as lintel and sill bands, which are crucial for maintaining the integrity of openings like doors and windows during seismic activity. Additionally, 65.12% of buildings with flat roofs do not have a roof band, an architectural feature that helps tie the structure together, increasing the risk of collapse under earthquake forces. The close construction of homes, with 60.47% of buildings touching each other, can lead to a domino effect of damage as structures impact one another during shaking. Variances in story heights, found in 58.14% of buildings, contribute to uneven force distribution during quakes, which can exacerbate structural failures. These factors collectively highlight a heightened risk to economic assets and human safety in the city's BM concrete roof buildings.

For buildings with brick masonry (BM) and various other types of roofing in the city, several factors have been identified that could threaten economic stability and human life during seismic events. The presence of large door openings is seen in 46.15% of these buildings, which can compromise the structural framework during an earthquake due to the reduced wall area available to resist seismic forces. Similarly, 30.77% of buildings have large window openings that can similarly reduce the structural integrity of walls. Around 23.08% of buildings have approximately half of their openings near corners, a feature that can significantly weaken those critical junctures and make them susceptible to cracking or failure during seismic shaking. Another 23.08% of buildings have split roofs, which can create discontinuities in the structure and lead to an uneven distribution of forces during an earthquake, increasing the risk of damage. Additionally, 19.23% of the buildings are constructed near each other, which can result in amplified damage due to the collision of buildings swaying or toppling onto one another. These architectural and structural vulnerabilities highlight the need for careful seismic assessment and retrofitting to mitigate potential economic and life-threatening risks.

5.1.5 EARTHQUAKE DISASTER RISK INDEX

Following a thorough building survey, individual building risks are assessed. The Estimated Damage Risk Index (EDRI) for each building typology is calculated by averaging the risks of all buildings within that typology. The EDRI of a typology reflects its overall risk within the region. Utilizing census data, the city's overall EDRI is determined (Table 4.3). The distribution of the risk score of the individual RC and BMCR buildings is presented. For RC buildings 25 percent of the buildings are falling in the higher risk category.

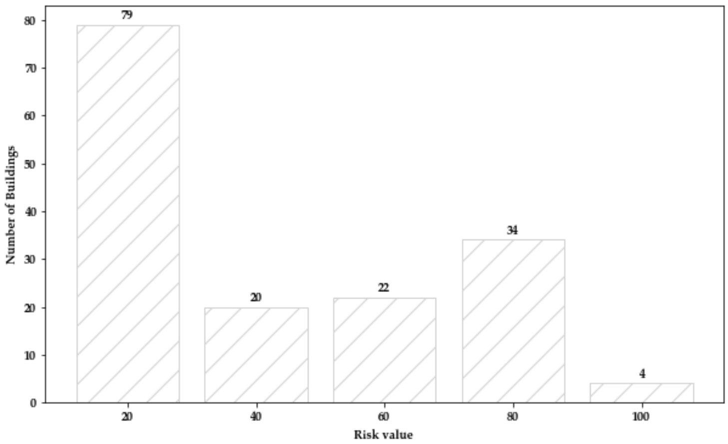


Figure 5.3 *Distribution of the RC buildings*

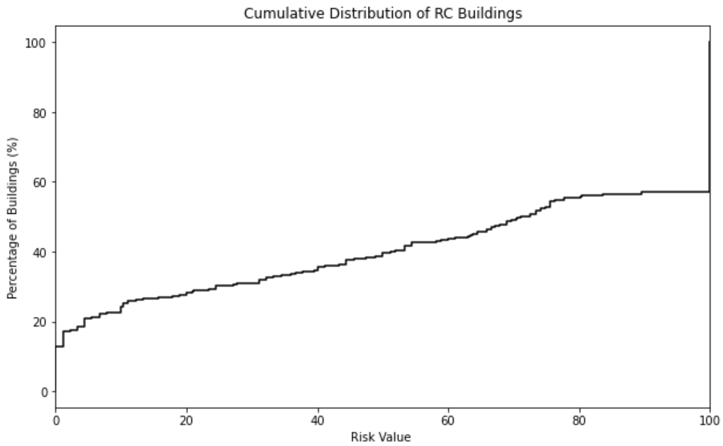


Figure 5.4 *Cumulative distribution of the RC buildings*

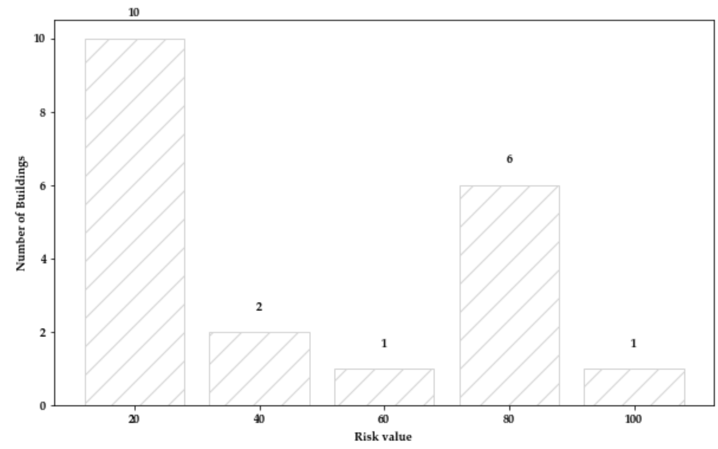


Figure 5.5 *Distribution of the BMCR buildings*

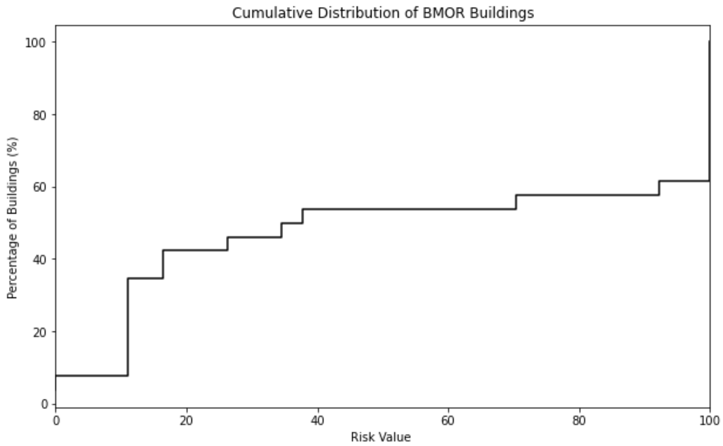


Figure 5.6 *Cumulative distribution of the BMCR buildings*

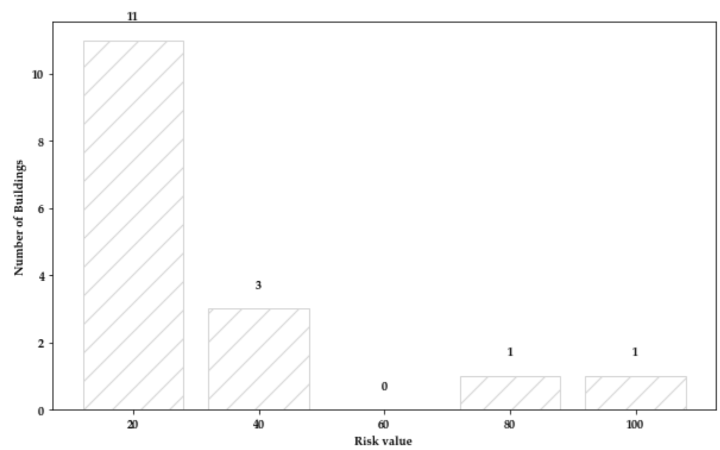


Figure 5.7 *Distribution of the BMCR buildings*

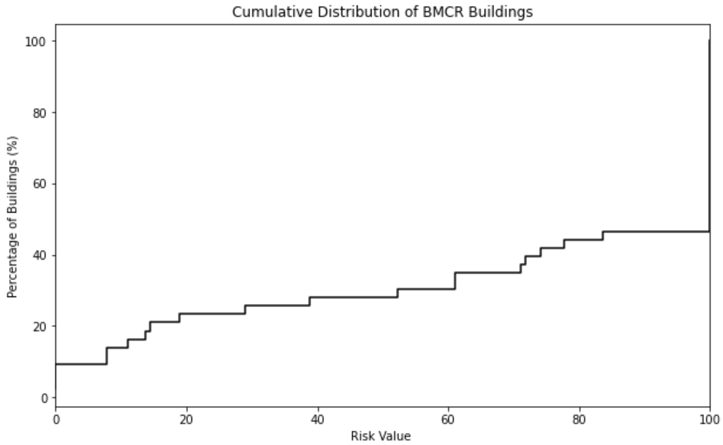


Figure 5.8 *Cumulative distribution of the BM0R buildings*

5.2 EDRI OF CITIES

For demonstration of EDRI, three cities in India Vijayawada, Chandigarh, Pithoragarh present in Zone III, Zone IV, and Zone V, as per IS 1893:2016 are considered in the study.

Vijayawada is located on the banks of a river with a flat topography bounded by hills. The soil profile of the city varies within the city and ranges from soft to medium type. There has been a rapid growth of population in the past three decades with a growth rate of 27% every decade. There were incidents of landslides in the region. There are around 22 seismic sources within 300km of the city with a prominent active fault. There is a possibility of collateral hazards. Vijayawada city has its distinct approach to house construction, with a predominant mix typology observed in most single-story residences. The choice of materials for these constructions varies across different areas. For example, in certain regions, houses are erected using bricks for walls, cow dung for binding, and G.I. sheets for roofing. Conversely, in other localities, dwellings are fashioned from stone or wood for walls, cement for binding, and bamboo for roofing. These types of housing are commonly found in slum areas and are often termed non-engineered buildings. Additionally, the city boasts engineered structures, typically characterized by reinforced concrete. A survey conducted in Vijayawada covered a total of 87 buildings, with masonry typologies being the predominant type of construction. Regarding reinforced concrete (RC) buildings, notable findings include the fact that more than a quarter of them have ground floors left open for parking, and around 13% are built in such close proximity that they nearly touch each other, highlighting the densely packed nature of the city’s-built environment. Furthermore, around 27% of the buildings show variations in storey heights, with 16% having particularly significant discrepancies. Common characteristics observed in RC buildings in the area include large window openings and inadequate separation between staircases and the main living spaces. Similarly, brick masonry buildings often lack lintel bands and sill bands, and also exhibit differences in storey heights. The floor area ratio (FAR) exceeds regulations in 94% of RC buildings and 83% of brick masonry and concrete reinforced (BMCR) buildings.

Chandigarh sits close to the base of the Himalayas and is at high risk of earthquakes. The soil here is considered medium in type. With more people moving in, the city's population is growing, leading to urban areas spreading out into the suburbs. In Chandigarh, a study looked at 569 buildings.. Nearly all of these buildings have big windows, usually near the corners, which is common in both RC and BMCR buildings. Another thing they share is being very close together, with 62% of RC and 87% of BMCR buildings nearly touching. Many buildings have noticeable overhangs or projections, seen in 87% of RC and all BMCR buildings. Most RC buildings 73% and nearly half of BMCR buildings 48% have a higher floor area ratio than allowed . The Earthquake Disaster Risk Index (EDRI) for RC buildings is 94, influenced by building capacity, and for BMCR buildings, it's 62, also influenced by capacity. The vulnerability and exposure of buildings affect Chandigarh's EDRI.

Table 5.3 *Number of houses surveyed and those as per 2011 Census in three cities.*

Housing Typology	Number of Houses					
	Vijayawada		**Chandigarh**		**Pithoragarh**	
	Surveyed	Census	Surveyed	Census	Surveyed	Houses
RC MRF	81	12,477	187	9,763	279	6,565
BMCR	6	70,815	382	1,66,496	43	3,282
BMOR	-	-	-	-	26	1,641

Table 5.4 *EDRI of buildings surveyed and those as per 2011 Census in three cities.*

<table>
<tr><th rowspan="3">Housing Typology</th><th colspan="6">EDRI</th></tr>
<tr><th colspan="2">Vijayawada</th><th colspan="2">Chandigarh</th><th colspan="2">Pithoragarh</th></tr>
<tr><th>Surveyed</th><th>Census</th><th>Surveyed</th><th>Census</th><th>Surveyed</th><th>Census</th></tr>
<tr><td>RC MRF</td><td>77</td><td rowspan="2">57</td><td>94</td><td rowspan="3">64</td><td>78</td><td rowspan="3">73</td></tr>
<tr><td>BMCR</td><td>54</td><td>62</td><td>76</td></tr>
<tr><td>BMOR</td><td>-</td><td>-</td><td></td><td>49</td></tr>
</table>

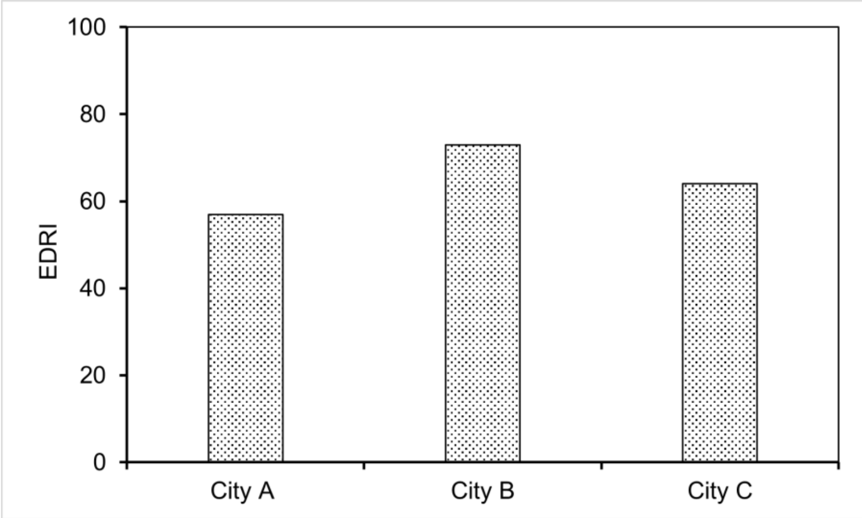


Figure 5.9 *EDRI of the Cities*

5.3 Conclusions

A significant number of the RC buildings in Pithoragarh show higher risk values. For example, slightly more than 50 percent of the buildings have risk values greater than 60, indicating high and very high, risk categories. Majority of the buildings are almost touching each other , some are having staircase not adequately separated from the house, buildings built on hill slopes, complex overall shape with re-entrant corners are some of the irregularities observed. Nearly 2 percent of the buildings, (more than 130 buildings in total) are having open ground storey and require attention for simplified quantitative assessment. The BMCR buildings also show significant number of the buildings in the high and very high risk. The buildings close to each other, lack of lintel bands, large projection overhangs, unsymmetrical staircase location with respect to the house plan are major contributors. The EDRI of the town is 73, indicating the higher risk. In this high hazard region, higher vulnerability of the buildings contributes the EDRI.

In Chandigarh, more than 95 percent of the RC and BMCR buildings exceed the allowable FAR limits. Buildings with heavier top , large overhangs, and large window and the door openings are the irregularities. The EDRI of the town indicates high risk with exposure factor contributing to the EDRI.

Though Vijayawada region has lower hazard, it has experienced ground shaking to past earthquakes. The higher exposure and high vulnerability of the buildings puts the built environment in the moderate risk. The buildings close to each other and open ground storey in the RC buildings and lack of lintel bands in the masonry buildings are the major contributing factors to the EDRI. Since the city falls in the Zone III category as per IS 1893:2016 (Part 1), the adjacency problem and lack of lintel bands are not implemented. But the Vijayawada city is on the banks of Krishna River, surrounded by hills on one side and there are nearly 18 municipal wards on hillside and river side together. An earthquake that occurred like the 1993 Killari earthquake or the 1997 Jabalpur earthquake, in the region has potential to create severe damages to the buildings in the built environments. Hence commissioning a detailed assessments is required to identify important buildings with lack of earthquake resistant features and implement retrofitting methods.

6

Sigmoid Function-Based Model for Assessing Earthquake Disaster Risk

6.0 INTRODUCTION

The chapter introduces a mathematical model that utilizes the sigmoid function to express earthquake risk. This model calculates the probability of various degrees of damage to different types of buildings within a region. The model helps us in understanding the effect of factors on the earthquake risk of a region. Three factors Underestimation of Earthquake Hazard (UEH), the impact of Floor Area Ratio (FAR), indicating how building density can exacerbate the consequences of seismic events, and the role of Retrofitting of the buildings, an intervention measure that significantly alters a building's vulnerability profile by enhancing its seismic resistance. By studying these factors, the thesis aims to provide a nuanced understanding of earthquake disaster risk, offering insights into how risks can be effectively managed and mitigated through informed urban planning and building practices. This approach seeks not only to safeguard physical structures but also to enhance the resilience of communities against the devastating impacts of earthquakes.

6.1 SIGMOIDAL MODEL

The sigmoid function is a mathematical model used to describe relationships in various scientific and engineering fields. It produces an "S"-shaped curve, also known as a sigmoid curve, which is especially useful for modeling the probability of events and understanding complex relationships. In the context of assessing earthquake risk for buildings in different regions, the sigmoid function helps to predict the likelihood of buildings falling into certain risk categories based on specific risk values.

The general form of the sigmoid function used in this study is given as:

$$P[R]=\frac{A}{1+e^{\left(-k(R-R_0)\right)}} \tag{6.1}$$

Where ,

P[R]: This is the probability of a building falling under a certain risk category when the risk value is R. It tells us how likely it is that a building will be classified as being at a particular level of risk.

A: This is the upper asymptote of the function, which represents the maximum probability value that can be reached. Essentially, it's the highest point on the curve, indicating the limit that the data (in this case, the probability of risk) can achieve.

k: This parameter controls the steepness of the curve. A larger value of k means the curve will respond more quickly to changes in the risk value (R), resulting in a steeper ascent or descent at the inflection point. Conversely, a smaller k value produces a flatter curve, indicating a slower response to changes in R.

R: This is the risk value for which the probability is being calculated. It's a measure of how likely it is that a building will experience a certain level of damage or loss due to an earthquake.

R_0: This is the value of R at the curve's inflection point, where the growth rate of the probability begins to change more significantly. It marks the transition between the lower and upper parts of the curve, where small changes in R can lead to large changes in the probability P[R].

The curve's inflection point (R_0) is particularly important because it represents a critical threshold in the risk assessment. At this point, the probability of being classified within a certain risk category begins to increase more rapidly with small increases in the risk value. This region is crucial for understanding how sensitive the probability of risk is to changes in the risk value (R).

The sigmoid function is adept at modelling spatially varying data, which does not change over time but varies from one location to another. This characteristic makes it particularly suitable for earthquake risk assessment, where the risk to buildings is determined more by their location's specific characteristics (such as soil type, construction quality, and proximity to seismic faults) than by temporal factors.

By using the sigmoid function to model the probability of earthquake risk, researchers and policymakers can gain insights into how risk distribution varies across different regions. This understanding can inform targeted interventions and mitigation strategies, prioritizing areas that fall within the sensitive transition region of the curve where improvements can significantly reduce the overall risk.

6.2 SAMPLE DATA

The survey conducted in an urban centre located in Zone V, as per the Indian Standard IS 1893 (Part 1):2016, aimed to assess the earthquake risk associated with different building typologies. This urban centre was chosen due to its high seismic risk, and the survey focused on three main types of buildings: Reinforced Concrete Moment Resisting Frames (RC MRF), Brick Masonry with Cement Mortar and Reinforcement (BMCR), and Brick Masonry with Other Reinforcement (BMOR). A total of 93 RC MRF buildings, 39 BMCR buildings, and 49 BMOR buildings were evaluated.

The collected data covered various aspects that contribute to earthquake risk, including the city's topography, soil conditions, population density, potential collateral hazards such as soil liquefaction, landslides, and fire, as well as the usage of buildings (e.g., residential, office, commercial), Floor Area Ratio (FAR), and overall vulnerability of each building typology.

For RC MRF buildings, the survey identified specific risk factors such as:

- Frames having symmetric lateral stiffness only in one plane direction.

- Staircases not being adequately separated from the main structure.
- Unsymmetrical location of staircases with respect to the building plan.
- Presence of open ground storeys not properly designed.

In the case of BMCR and BMOR buildings, the primary risk contributors were found to be:

- Walls being unsymmetrical in one direction, which could lead to uneven distribution of seismic forces.
- Close proximity of houses to each other, which increases the risk due to pounding.
- Use of construction procedures, lacking standardized safety measures.

Given the limited number of data points for BMCR and BMOR buildings, the dataset was expanded using the bootstrap method. This statistical technique enhances the robustness of the analysis by generating additional data points from the existing sample through random sampling with replacement. This approach helps in creating a more comprehensive dataset for further analysis.

The enhanced dataset was then used to create a sample dataset for applying sigmoidal regression analysis. Sigmoidal regression is a statistical method that models the relationship between a set of independent variables and a binary dependent variable. In this context, it was utilized to analyse the frequency of buildings within each damage state category (e.g., minor, moderate, severe) for each building typology, and to calculate the cumulative probability of occurrence for these categories.

6.3 APPLICATION

The analysis conducted with the sample dataset aims to predict the damage state probability and the expected number of buildings for each typology (RC MRF, BMCR, and BMOR) in an urban centre located in a high seismic risk zone. Sigmoidal curve fitting was applied to each building typology using Origin Pro 2023b (Learning Edition), a sophisticated tool for such statistical analysis. This method models the relationship between the risk values indicative of damage states and the cumulative probability of these states occurring.

For all three typologies, the upper asymptote (A) value was set at 1, underpinning the assumption that the probability cannot exceed 1. The Levenberg-Marquardt algorithm facilitated the iterative process, with initial weights determined for each risk range. The goodness of fit was evaluated by the coefficient of determination (R^2), and residuals were analyzed to assess model performance and the influence of outliers.

6.3.1 Analysis of Results

6.3.1.1 RC MRF Buildings

The R^2 value of 0.96 reflects a high correlation between observed and predicted probabilities across different risk values. The curve's inflection point at a risk value of 48.17 suggests that 50% of buildings fall below this risk level, indicating a balanced distribution across damage states. The equation provided, shows a slower response to increasing risk values, with the transition occurring around the middle of the risk spectrum.

$$P[R] = \frac{1}{1 + e^{(-0.058(R-48.17))}} \tag{6.2}$$

6.3.1.2 BMCR BUILDINGS

With an R^2 of 0.96, similar to RC MRF buildings, the analysis for BMCR buildings indicates a good fit but reveals a bimodal distribution, as seen in the deviation from the line in the normal probability plot. The inflection point at a risk value of 26.30, along with a higher k value, signifies a rapid initial increase in probability, followed by a slower growth at higher risk values. The equation, highlights a quicker response to changes in risk values at the lower end of the spectrum.

$$P[R] = \frac{1}{1 + e^{(-0.12(R-26.30))}} \tag{6.3}$$

6.3.1.3 BMOR BUILDINGS

The highest R^2 value among the three, at 0.98, indicates an almost perfect fit between the model and the observed data, suggesting a normal distribution of the data. The growth of the curve is gradual, with a slower increase for risk values above 40, as described by the equation

$$P[R] = \frac{1}{1 + e^{(-0.091(R-37.98))}} \tag{6.4}$$

This equation indicates a more moderate response to changes in risk values across the spectrum.

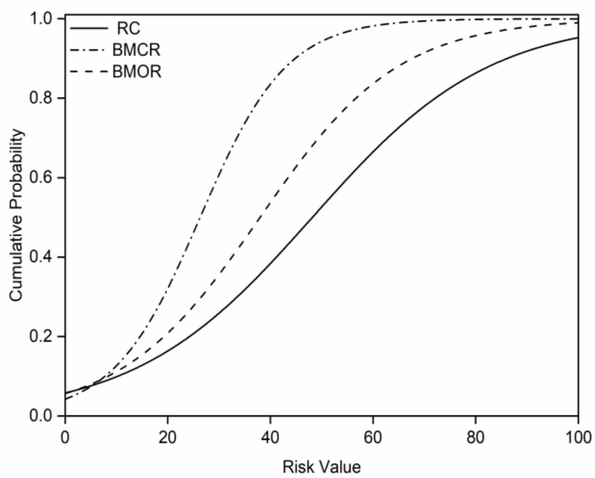


Figure s6.1 *Sigmoidal fit for RC MRF, BMCR, and BMOR typologies of the city*

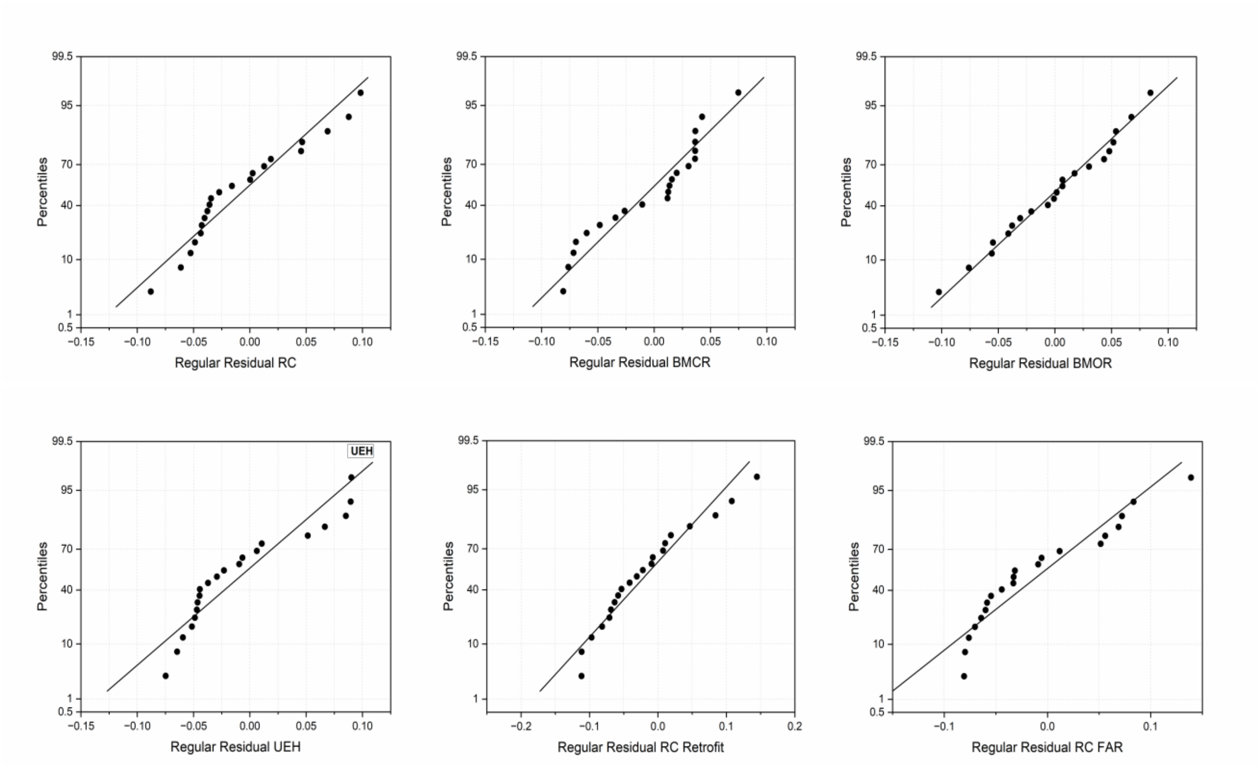


Figure 6.2 *Normal Probability plot of residuals for RC MRF , BMCR, BMOR typologies, and factors influencing RC MRF typology.*

6.3.2 COMMENTS

The comparative analysis of the sigmoidal equations for each building typology reveals distinct characteristics in how each respond to seismic risk. The RC MRF buildings exhibit a balanced risk distribution, with a moderate response to changes in risk value. In contrast, BMCR buildings show a rapid response at lower risk values, indicating a potentially higher sensitivity to initial seismic activity but a plateau at higher risk levels. BMOR buildings, with their gradual and consistent response across a wider range of risk values, suggest a different pattern of vulnerability to seismic events.

These differences underline the importance of tailoring earthquake mitigation strategies to specific building typologies. The rapid increase in risk probability for BMCR buildings at lower risk values suggests a need for immediate intervention at lower thresholds of seismic activity. Meanwhile, the more evenly distributed response of RC MRF and BMOR buildings across the risk spectrum indicates a broader range of intervention points may be effective. This analysis, by providing a nuanced understanding of each building typology's response to seismic risk, enables targeted and efficient planning for earthquake preparedness and mitigation efforts, ultimately aiming to reduce the potential impact on human lives and property.

6.4 UNDER ESTIMATION OF HAZARD

The geology and earthquake mechanics (seismotectonic) vary across different parts of the country, meaning some areas are more likely to experience damaging earthquakes than others. Therefore, a seismic zone map is essential to indicate the expected level of earthquake shaking in various regions. These maps are updated over time (Figure 1) as we learn more about the country's geology, earthquake mechanics, and seismic activity (Murty, 2005). The first seismic zone map by the Indian Standards was released in 1962 and updated in 1966. The initial map (IS:1893, 1962) divided India into seven seismic zones (O, I, II, III, IV, V, and VI), with zone O being considered a non-seismic zone (Figure 6.3). The second map (IS 1893, 1966) adjusted the boundaries between these zones without changing their main features (Figure 6.4).

After observing the damage caused by earthquakes in areas thought to have low seismic risk, like the 1967 Koyna and 1969 Bhadrachalam earthquakes, the map was revised in 1984 (IS 1893, 1984) to five zones (I, II, III, IV, and V) (Figure 6.5). This update combined the previously non-seismic zone O with zone I and merged zone VI with zone V (Table 6.1). It also made significant adjustments in the peninsular region, especially along the western and eastern coasts affected by the 1967 and 1969 earthquakes. The new classification defined zones by the maximum expected earthquake intensity, from V or less to IX and above. The highest risk areas, zone V, included parts of the Himalayan boundary and the Kachchh area in the west.

The 1993 Killari earthquake ,Maharashtra, Central India , which happened in the previous zone I and caused about 8,000 deaths, led to public demand for revising the seismic zone map in peninsular India. The 2001 Bhuj earthquake, occurring in the highest risk zone V, resulted in approximately 13,805 fatalities. These events prompted the Bureau of Indian Standards to update the seismic zone map in 2002 (Figure 6.6), now featuring four seismic zones – II, III, IV, and V (IS 1893, 2002). The update merged the areas of the former zone I with zone II and made changes to the peninsular region's zoning, for example, moving Madras to zone III from its previous classification in zone II.

Thus the entire Indian landmass, susceptible to different levels of earthquake hazard, has been classified into four Seismic Zones, namely Seismic Zones II, III, IV and V, as per the Seismic Zone Map of India given in IS 1893 (Part 1): 2016. A revision is underway of the seismic hazard of India. In general, the current earthquake hazard is considered to be underestimated in the country. Considering the current hazard to be underestimated, the demand factor is increased by 1.33 times. In such a case, the effect is studied of the current under estimation of hazard on the earthquake disaster risk of the city.

$$\mathrm{P[R]} = \frac{1}{1 + \mathrm{e}^{(-0.059(\mathrm{R}-71.13))}} \tag{6.5}$$

Comparing with the RC MRF original equation , both have similar k-values, -0.059 for the underestimation of hazard and -0.058 for RC MRF buildings, indicating nearly identical rates at which the probability of risk increases with respect to the risk value (R). This similarity suggests that the responsiveness of the probability to changes in risk value is almost the same for both scenarios. There is a significant difference in the inflection points: 71.13 for the underestimation of hazard and 48.17 for RC MRF buildings. The inflection point represents the risk value (R) at which the probability of damage shifts from being less likely to more likely. A higher inflection point for the underestimation of hazard indicates that the recognition of buildings being at risk occurs at a higher threshold. In practical terms, it means that for underestimation of hazard, the probability of acknowledging a building as

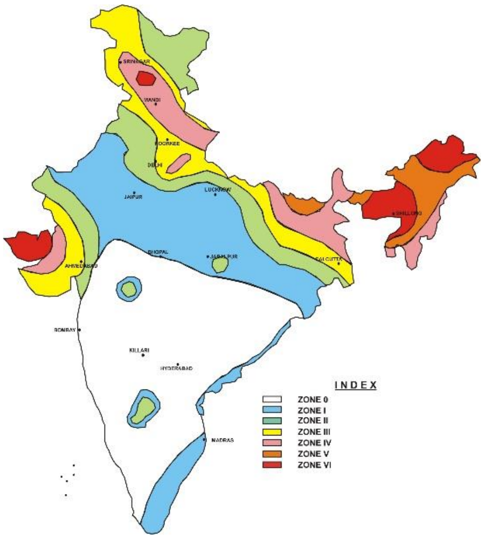


Figure 6.3 *Indian Seismic zone maps 1962 edition*

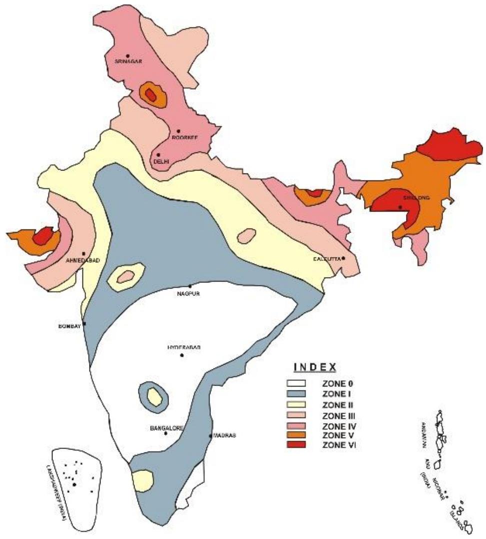


Figure 6.4 *Indian Seismic zone maps 1966 edition*

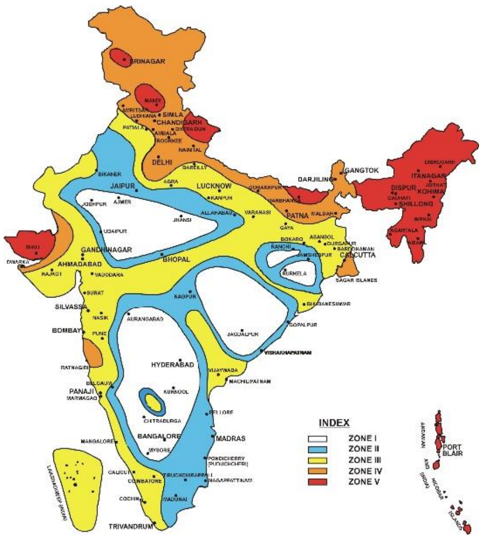


Figure 6.5 *Indian Seismic zone maps 1984 edition*

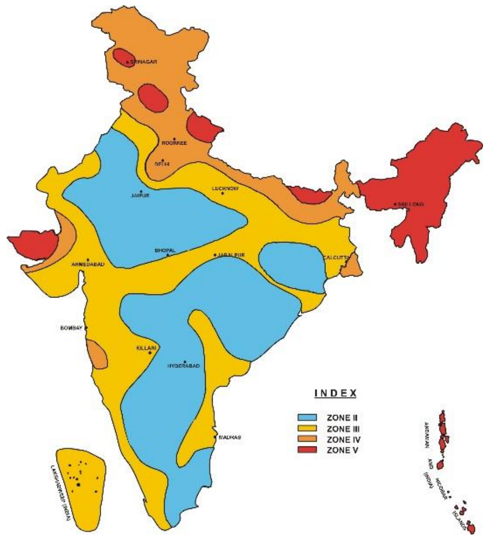


Figure 6.6 *Indian Seismic zone maps 2002 edition*

Table 6.1. *Seismic zones in each revision of Indian Code – increased perception of seismic threat*

<table>
<tr><th colspan="4">Year of Release of Zone Maps</th></tr>
<tr><th>1962</th><th>1966</th><th>1984</th><th>2002</th></tr>
<tr><td>0</td><td>0</td><td rowspan="2">I</td><td rowspan="3">II</td></tr>
<tr><td>I</td><td>I</td></tr>
<tr><td>II</td><td>II</td><td>II</td></tr>
<tr><td>III</td><td>III</td><td>III</td><td>III</td></tr>
<tr><td>IV</td><td>IV</td><td>VI</td><td>IV</td></tr>
<tr><td>V</td><td>V</td><td rowspan="2">V</td><td rowspan="2">V</td></tr>
<tr><td>VI</td><td>VI</td></tr>
</table>

at risk increases more gradually and does so at a higher level of risk compared to RC MRF buildings. The higher inflection point in the equation for the underestimation of hazard suggests that such underestimation may lead to a higher risk. The comparison highlights the risk of complacency induced by underestimating hazards, emphasizing the need for rigorous, data-driven approaches to hazard assessment and risk management to safeguard buildings and lives against earthquake risks.

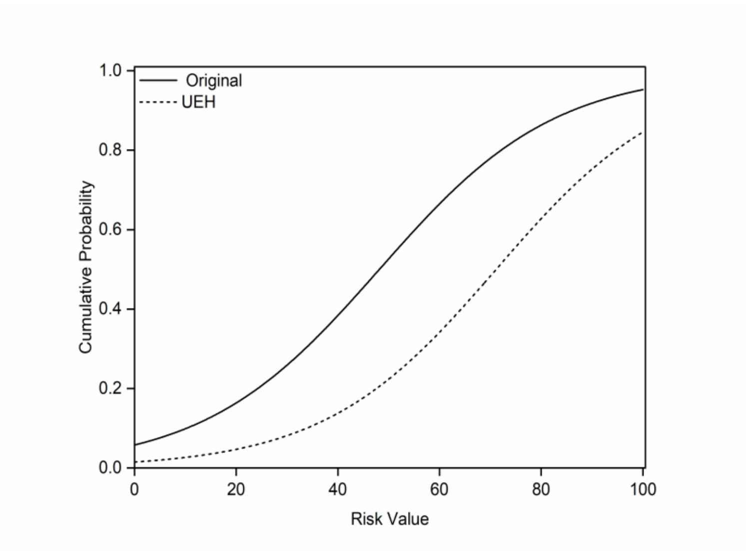


Figure 6.7 *Sigmoidal Curve of RC MRF building typology with Under Estimation of Hazard*

6.5 RETROFIT OF BUILDINGS

Earthquake retrofitting is an essential process aimed at enhancing the seismic capacity of existing buildings to reduce the risk and impact of earthquakes. This process is particularly crucial for buildings that were constructed without adhering to the modern seismic design codes or those that complied with the codes existing at the time of construction but are now outdated due to advancements in seismic understanding and changes in code requirements. Over time, the structural integrity of buildings can deteriorate, further increasing their vulnerability to seismic events. Retrofitting plays an important role in addressing these risks, especially for critical and special buildings.

In reinforced concrete (RC) buildings, one common retrofitting technique addresses the issue of open ground storeys, which are especially vulnerable during earthquakes. Open ground storeys, often used for parking or commercial spaces, have fewer walls, leading to a lack of stiffness and strength in the structure. This condition can cause a soft-story collapse during an earthquake, where the ground floor fails, leading to the potential collapse of the entire building. Retrofitting solutions for this issue include adding new structural elements such as shear walls or steel bracings to increase stiffness and strength, thus enhancing the building's seismic performance.

For masonry buildings, which are typically constructed using brick or stone, the introduction of lintel bands is a common retrofitting measure. Lintel bands are reinforced concrete beams placed at the level of windows and doors (lintel level) around the perimeter of the building. These bands help to tie the walls together, distributing seismic forces more evenly and preventing the out-of-plane failure of walls. This method effectively increases the building's overall ductility, making it more resistant to earthquake-induced stresses.

By implementing retrofitting strategies, the earthquake disaster risk in a region is significantly mitigated, not only safeguards lives but also significantly reduces the economic losses, enhancing the safety of its built environment.

$$P[R] = \frac{1}{1 + e^{(-0.063(R-41.86))}} \tag{6.6}$$

The k-value in the post-retrofitting equation is -0.063, compared to -0.058 in the pre-retrofitting equation for RC MRF buildings. This increase in the k-value indicates a steeper curve for the post-retrofitting scenario. A steeper curve signifies that the probability of reaching a certain damage state increases more rapidly with each incremental increase in risk value. In practical terms, this suggests that after retrofitting, the building's response to increasing seismic risk is more pronounced, highlighting the effectiveness of retrofitting in enhancing the building's seismic resilience. The inflection point for the post-retrofitting equation is at R = 41.86, lower than the pre-retrofitting inflection point of R = 48.17. The inflection point shifts to the left, indicating that the probability of damage becomes significant at a lower risk value after retrofitting. This leftward shift may seem counterintuitive but reflects the recalibration of the risk scale due to improved building strength and resilience. The comparison suggests that retrofitting effectively reduces the vulnerability of buildings to seismic events. By improving the building's structural capacity to withstand seismic forces, retrofitting lowers the risk value at which significant damage is likely to occur. This shift is crucial for enhancing the overall safety and resilience of buildings in seismic zones, reducing the potential for catastrophic damage and loss of life during an earthquake. The comparison between the pre- and post-retrofitting equations highlights the significant impact of retrofitting on the seismic risk profile of buildings. Retrofitting not only enhances the structural integrity of buildings but also shifts the

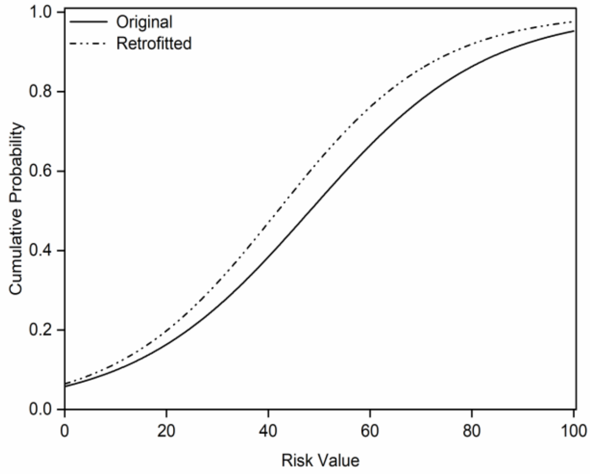


Figure 6.8 *Sigmoidal Curve of RC MRF building typology after implementing retrofit*

paradigm of risk assessment by imposing stricter standards of resilience. This analysis underscores the value of retrofitting as a proactive measure in earthquake risk management, advocating for its widespread adoption in vulnerable buildings to mitigate the impact of future seismic events.

6.6 INCREASING FAR

A higher FAR typically signifies a denser population due to more built-up area per unit of land area, leading to taller or more compact buildings within a given plot. This densification often results in higher occupancy levels, which can escalate the potential human and economic losses in the event of an earthquake.

To specifically assess how variations in FAR influence the city's earthquake disaster risk, an increment of 1.5 in the FAR is considered. This increment represents a substantial increase in the allowable built-up area, potentially exacerbating the risk profile of buildings and the city as a whole. The rationale behind this examination lies in understanding the correlation between increased building density and the amplified risk it poses during seismic events.

An increase in FAR leads to more intensive land use, which, without corresponding enhancements in building design, construction practices, and enforcement of seismic codes, could elevate the vulnerability of structures to earthquake damage. This situation is further complicated in urban settings where the infrastructure may already be under strain from existing demands. Higher densities can strain emergency response capabilities and evacuation efforts, complicate rescue and recovery operations, and increase the likelihood of cascading failures within utility and transportation networks.

Therefore, while higher FAR can contribute to addressing urban space limitations and housing demands, it also necessitates rigorous adherence to updated seismic design standards, enhanced building materials, and construction techniques to mitigate the heightened risk of earthquake disasters. This ensures that urban development does not compromise the safety of the built environment.

$$P[R]=\frac{1}{1+e^{(-0.05(R-62.90))}} \tag{6.7}$$

The k-value in the FAR-related equation is -0.05, which is less than the -0.058 in the RC MRF equation. A lower k-value indicates a gentler slope of the curve, implying that changes in the risk value (R) lead to a more gradual change in the probability of reaching a certain damage state. This suggests that the impact of increasing FAR on seismic risk introduces a more extended transition in risk levels, possibly due to a wider range of building responses to seismic events as FAR increases. The inflection point for the FAR effect is at R = 62.90, significantly higher than the R = 48.17 for the RC MRF buildings. This higher inflection point indicates that the critical risk level, at which the probability of damage notably increases, is reached at a higher risk value when considering the effect of FAR. This shift could imply that buildings in areas with higher FAR are assessed as having a higher baseline risk before significant damage probabilities increase, reflecting the compounded risk factors associated with higher densities, such as increased population and potentially more complex structural interactions.

The comparison indicates that increasing FAR contributes to an overall increase in seismic risk, as evidenced by the higher inflection point. This suggests that densely packed urban environments, where FAR values are higher, could be more susceptible to seismic damage due to factors like increased mass, potential for soil-structure interaction complexities, and challenges in implementing effective seismic design and retrofitting strategies across a diverse array of building types and conditions.

The higher inflection point (R_0) in the FAR equation underscores the need for careful consideration of urban planning and construction practices in densely populated areas. It highlights the importance of integrating seismic risk mitigation strategies in the early stages of urban development planning, especially in areas prone to high seismic activity.

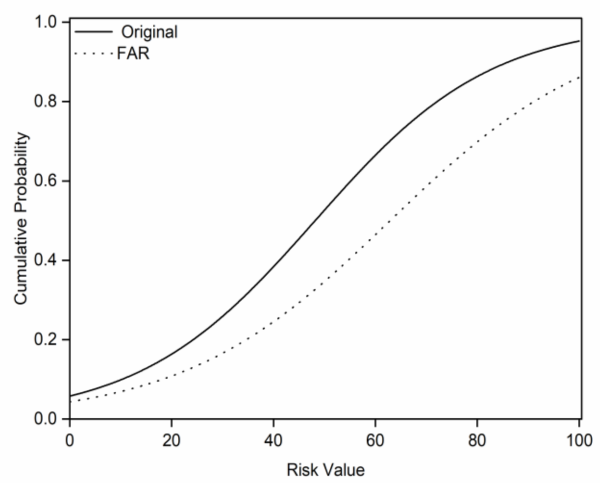


Figure 6.9 *Sigmoidal Curve of RC MRF building typology increasing Floor Area Ratio*

6.7 CONCLUSIONS

The method utilizing a sigmoid function model for estimating the expected number of buildings falling into specific damage categories offers a comprehensive approach to understanding and managing earthquake disaster risk in urban environments. This model, grounded in the analysis of building damage data and their cumulative probabilities, throws light on the construction trends and key risk factors within a city. The importance of retrofitting of buildings is visible through the graphs, with significant number of the building having less risk values which will reduce the overall index of the city. The effect of higher FAR values increases the risk of the buildings and the index. The municipal bodies of cities should be careful in revising upwards the allowable FAR. Also, they should establish mechanisms to monitor violations of municipal bye-laws. Enhancing the dataset on which this model operates could refine its accuracy, suggesting that future research should aim to establish a universal formula for risk estimation applicable across various regions. This would significantly advance the ability to safeguard built environments against the seismic threats they face.

7
Summary and Conclusions

7.0 INTRODUCTION

The qualitative assessment of a region's buildings for earthquake safety provides a comprehensive view of the building's structural weaknesses and is a key prerequisite for quantitative assessments. To achieve earthquake safety in a region, a concise overview of risk is indispensable, i.e., in addition to understanding the building's seismic performance, the factors of urbanisation and urban planning must be comprehended. This method stablishes procedure to evaluate the risk of the individual buildings of any region with focus on the probable seismic performance of the building. Understanding the building design and the influence of soil and foundation conditions. It helps individual building owner to commission an engineering assessment. The present formulation proposed, and the criteria defined are intended to be specifically applied to the buildings of all typologies. The focus spans several critical aspects, including an assessment of Reinforced Concrete Moment Resisting Frames (RC MRF), Brick Masonry Concrete Roof (BMCR), and Brick Masonry with Other Roof(BMOR) buildings in the urban centres. The analysis leverages a sigmoid function model to evaluate the probability of buildings falling into specific damage categories, offering insights into the impacts of Underestimation of Earthquake Hazard (UEH), retrofitting measures, and the implications of Floor Area Ratio (FAR) adjustments on the seismic risk profile of the urban fabric.

7.1 SUMMARY

The study methodically examines the earthquake disaster risk for different building typologies and the region. This approach also provides a nuanced understanding of how buildings respond to seismic risks, highlighting the importance of seismic codes and retrofitting in enhancing structural safety, utilizing a sigmoid function, for the prediction of damage state probabilities are evaluated. . The analysis underscores the significant role of FAR in urban planning, demonstrating how increased building density can exacerbate earthquake disaster risk. Through a comprehensive evaluation, the study reveals the dynamic interplay between construction practices, urban development strategies, and seismic risk mitigation efforts. The findings emphasize the critical need for updated seismic zone mapping, adherence to modern seismic design codes, and the implementation of targeted retrofitting strategies to safeguard the urban built environment against earthquake hazards.

7.2 CONCLUSIONS

Overview of the earthquake disaster risk of the city/region, for identifying hotspots related to risk and the construction practices, and to identify potential weak buildings. The methods should be comprehensible to be re-evaluated periodically, and hence enables to identify deficiencies that may emerge with the fast-changing paradigms of city/regions. The conceptual framework for the assessment methodologies and the assumptions should be thoroughly defined. To present the results, IT and GIS tools should be leveraged to monitor continually the prevalent risk at the different towns and cities of any country.

List of Publications

Journal

- Prakke, B., Pradeep Kumar, R. Earthquake forecasting in the Himalayan region using neural networks models. Sādhanā 49, 58 (2024).

  DOI : https://doi.org/10.1007/s12046-023-02398-4

References

Arnold, C., & Reitherman, R. (1982). Building Configuration and Seismic Design. John Wiley & Sons, New York.

Bureau of Indian Standards (BIS). (2023). Draft Indian Standard Criteria for Earthquake Resistant Design of Structures Part 1 General Provisions, Seventh Revision of IS 1893 (Part 1), New Delhi. Available at: https://www.services.bis.gov.in/tmp/WCCED21022343_26042023_2.pdf (Accessed: 21 October 2023).

Coburn, A.W., & Spence, R.J.S. (2002). Earthquake Protection, 2e. Chichester: Wiley.

Cred, C. (2020). Human Cost of Disasters (2000-2019). United Nations Office of the Disarmament Affairs, No. 61.

Daniell, J.E., Vervaeck, A., Khazai, B., & Wenzel, F. (2012). Worldwide CATDAT damaging earthquakes database in conjunction with Earthquake-report.com – presenting past and present socio-economic earthquake data. Proceedings of the 15th World Conference of Earthquake Engineering (24–28 September 2012), Lisbon, Portugal.

Demartinos, K., & Dristos, S. (2006). First-level pre-earthquake assessment of buildings using fuzzy logic. Earthquake Spectra, 22, 865–885.

DesRoches, R., Comerio, M., Eberhard, M., Mooney, W., & Rix, G.J. (2011). Overview of the 2010 Haiti Earthquake. Earthquake Spectra, 27(1_suppl1), 1-21. doi:10.1193/1.3630129

FEMA 154 (1988). Rapid visual screening of buildings for potential seismic hazards—a handbook. Federal Emergency Management Agency, Washington.

FEMA 154 (2002). Rapid visual screening of buildings for potential seismic hazards—a handbook. Federal Emergency Management Agency, Washington.

FEMA 178 (1989). NEHRP handbook for the seismic evaluation of existing buildings—a handbook. Federal Emergency Management Agency, Washington.

FEMA 178 (1992). NEHRP handbook for the seismic evaluation of existing buildings—a handbook. Federal Emergency Management Agency, Washington.

FEMA 310 (1998). Handbook for the seismic evaluation of buildings: a pre-standard—a handbook. Federal Emergency Management Agency, Washington.

GHI, (2001): Global Earthquake Safety Initiative Project (GESI), Geohazards International United Nations Centre for Regional Development.

Gurme, P. (2017). Latur-Killari Earthquake: An Overview Study.

Jain, S.K. (2016). Earthquake safety in India: achievements, challenges and opportunities. Bulletin of Earthquake Engineering, 14, 1337-1436.

Jain, S.K., Mitra, K., Manish, K., & Mehul, S. (2010). A proposed rapid visual screening procedure for seismic evaluation of RC-frame buildings in India. Earthquake Spectra, 26(3), 709–729.

Marano, K.D., Wald, D.J., & Allen, T.I. (2010). Global earthquake casualties due to secondary effects: a quantitative analysis for improving rapid loss analyses. Natural Hazards, 52, 319–328. https://doi.org/10.1007/s11069-009-9372-5.

Murty, C.V.R., Goswami, R., Vijaynarayanan, A.R., & Vipul, V.M. (2012). Some Concepts in Earthquake Behaviour of Buildings. Gujarat State Disaster Management Authority, Gandhinagar, India.

Murty, C.V.R., Rai, D.C., Kumar, H., et al. (2012). A Methodology for documenting Housing Typologies in the Moderate-Severe Seismic Zones. 15th World Conference on Earthquake Engineering.

NITI Aayog report, Reforms in Urban Planning Capacity in India. September 2021.

NRCC (1993). Manual for screening of buildings for seismic investigation by institute for research in construction. National Research Council Canada, Ottawa.

Ozcebe, G., Sucuoglu, H., Yucemen, M.S., Yakut, A., & Kubin, J. (2006). Seismic risk assessment of existing building stock in Istanbul, a pilot application in Zeytinburnu District. In Proceedings of 8th US national conference on earthquake engineering, San Francisco.

Patel, S.B. (2013). Life between Buildings: The Use and Abuse of FSI. Economic and Political Weekly, 48(6), 68–74. http://www.jstor.org/stable/23391397

Pradeep Kumar, R., & Murty, C.V.R. (2020). Earthquake Disaster Risk Index – A Simple Method for Assessing Relative Risk in a Country. 17th World Conference on Earthquake Engineering, 17WCEE, Sendai, Japan.

Pradeep Kumar, R., & Murty, C.V.R. (2021). Protecting the Built Environment from Earthquakes. The Journal of Governance, 22.

Pradeep Ramancharla, Aniket Bhalkikar, Pulkit Velani, Pammi Vyas, Bharat Prakke, Neelima Patnala, & Niharika Talyan. (2020). A primer on rapid visual screening (rvs) consolidating earthquake safety assessment efforts in India.

Sen, Z. (2010). Rapid visual earthquake hazard evaluation of existing buildings by fuzzy logic modeling. Expert Systems with Applications, 37(8), 5653–5660.

SIA-2018 (2004). Assessment of existing buildings with respect to earthquakes (in German). Technical note 2018. Swiss Society of Civil Engineers and Architects, Zurich, Switzerland.

Singh, M.P., Khaleghi, B., Saraf, V.K., Jain, S.K., & Norris, G. (2002). Roads and Bridges. In 2001 Bhuj, India Earthquake Reconnaissance Report (pp. 363-379). Earthquake Spectra, supplement A to volume 18. Oakland, CA: Earthquake Engineering Research Institute.

So, E., Baker, H., & Spence, R. (2018). Estimation of casualties caused by building collapse in earthquakes through assessment of volume loss and external debris spread. Proceedings of 16th European Conference on Earthquake Engineering-Thessaloniki 2018 (18–21 June 2018), Thessaloniki, Greece.

Sucuoglu, H., Yazgan, U., & Yakut, A. (2007). A screening procedure for seismic risk assessment in urban building stocks. Earthquake Spectra, 23(2), 441–458.

Thangavel Palanivel. (2017). Rapid urbanisation: opportunities and challenges to improve the well-being of societies. Human Development Reports. UNDP.

https://hdr.undp.org/en/content/rapid-urbanisation-opportunities-and-challenges-improve-well-being-societies.

Tucker, B., Trumbull, G., & Wyss, S. (1994): Some Remarks Concerning Worldwide Urban, Dordrecht, Netherlands: Kluwer Academic Publishers.

United Nations. (2022). World Population Prospects 2022: Summary of Results. UN DESA/POP/2022/TR/NO. 3. Available at https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf (Accessed on 21 October 2023).

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ANNEXURE A

Vulnerability Forms

1. Reinforced Concrete Buildings

Sr. No			
Latitude			
Longitude			
Number of Buildings			
Life Threatening Factors	**Sitting Issues**	(a) The building is built on hill slopes that can slide, OR	
		(b) The building is built on river terraces that can slide/creep, OR	
		(c) The building is built on hill slopes /adjacent to hill slopes (even though on flat ground), but vulnerable to falling debris from the hilltop.	
	Soil & Foundation Condition	(a) The soil underneath the building is liquefiable, OR	
		(b) The soil in the area adjoining the site is liquefiable and can flow laterally to move the soil from underneath the building.	
	Architecture Features	(a) The building has an open ground storey that is not designed to resist lateral loads, with/without structural walls in the ground storey, OR	
		(b) The building is almost touching or located close to an adjacent seemingly unsafe building/construction, whose collapse can damage it.	
	Structural Aspects	(a) The minimum transverse dimension of columns is 200mm, AND	
		(b) The ties in columns have 90° hooks, AND	
		(c) The structural design of the building has not been performed by a competent engineer.	

	Construction Details		(a) Concrete used in columns is of grade M15 or lesser, OR	
			(b) Concrete used in columns is hand-mixed, OR	
			(c) Concrete placed in columns is not vibrated by any mechanical device	
Economic Loss Factor	**Sitting Issues (-5%)**		The building is built on sloped ground with access at two or more levels, i.e., at ground, intermediate floor & roof **(-5)**	
	Soil & Foundation Condition (-5%)	**Suitability of soil type**	Soft soil	
			Weak soil	
			High water table	
			Soil with moisture	
		Foundation	Footings on non-uniform soil with no tie beams	
			Footings on non-uniform soil with tie beams	
			Footings on soft soil with no tie beams	
			Footings on soft soil with tie beams	
			Mat foundation on nonuniform soil	
	SUM **(Maximum Sub Total)**			
	Architecture Features (-50%)	**Plan Shape**	Large room sizes	
			Irregular orientation of rooms	
			Complex overall shape with re-entrant corners	
		Elevation profile	Wider top, narrower bottom	
			Heavier top	
			Large projections or overhangs	
			Split roof	
			Large storey heights	
			Differences in storey heights	
			Unsymmetrical staircase location with respect to plan	
			Open ground storey not designed to resist earthquake shaking	
		Door and window openings in walls	Rare single window close to corners	
			About half of openings close to corners	
			Almost all openings close to corners	
			Large area window openings	
			Large area door openings	
		Distance from adjacent building	Houses touch each other	
			Houses have insufficient gap between them	
			Not secured to the structural system	

		Parapets, objects on roof or projections	Large and heavy projections and overhangs	
		Staircases	Narrow	
			Too few in number	
			Too far to reach	
	SUM **(Maximum Sub Total -50)**			
	Structural Aspects (-20%)	**Frame Grid**	Grid of parallel planar frames only along one plan direction	
			No grid of parallel planar frames along both plan directions	
			Frames have symmetric lateral stiffness along one plan direction	
			Frames don't have symmetric lateral stiffness along any plan direction	
			Frames have symmetric lateral strength along one plan direction	
			Frames don't have symmetric lateral strength along any plan direction	
		Roof/Floor slab design	Heavy roof/floor slab	
			Pitched roof/floor slab	
			Split roof/floor slab	
			Roof/floor slab with large size openings, especially located along the edge of the slab	
		Roof/floor – column connection	No/insufficient anchorage of horizontal reinforcement from beams to columns at roof/floor levels	
		Member proportioning	Column weaker (in moment capacity) than beams framing into it at each joint	
		Column and column – foundation connection	No/insufficient anchorage of reinforcement from columns to foundation	
			All longitudinal bars in column lapped at same location	
		Staircase	Unsymmetrical location	
			Both top and bottom integrally built into the building frame	
			Staircase not adequately separated from the house	
		Large water tanks on roof	Not anchored to the structural system	
	SUM **(Maximum Sub Total -20)**			
	Construction Details (-20%)	**Type of materials**	Poor quality of sand	
			Poor quality aggregates	
			Poor quality cement	
			Poor quality bricks	
		Workmanship	Poor geometries of masonry and roof	

			Insufficient curing	
		Concrete mix	Concrete prepared using nominal mix	
			Concrete ingredients measured by volume batching	
	SUM **(Maximum Sub Total -20)**			

2. Brick Masonry Concrete Roof

Sr. No			
Latitude			
Longitude			
Number of Buildings			
Life Threatening Factors	**Sitting Issues**	(a) The building is built on hill slopes that can slide, OR	
		(b) The building is built on river terraces that can slide/creep, OR	
		(c) The building is built on hill slopes /adjacent to hill slopes (even though on flat ground), but vulnerable to falling debris from the hill top.	
	Soil & Foundation Condition	(a) The soil underneath the building is liquefiable, OR	
		(b) The soil in the area adjoining the site is liquefiable and can flow laterally to move the soil from underneath the building.	
	Architecture Features	(a) The outer dimensions of the house at plinth level are less than those at the top in either of the two horizontal plan direction or	
		(b) The house has large unanchored projections and overhangs or	
		(c) The door and window openings in walls are at the corner, or	
		(d) The building is almost touching or located close to an adjacent seemingly unsafe building/construction, whose collapse/pounding can damage it	
	Structural Aspects	(a) The roof is constructed such that it is not integral wihtin itself (i.e., it does not act as a single unit and breaks open during earthquake shaking) and is not anchored into the walls or	
		(b) The walls are thick and made in two wythes or	
		(c) The walls are not integrated into each other at the corners or	
		(d) the staircases are not anchored into the walls of the house	

	Construction Details		(a) The walls are made with mud mortar and are exposed to the vagaries of the outside weather (especially rain water beating)	
			(b) The walls are made with no mortar	
Economic Loss Factor	**Siting Issues (-5%)**		1. The house is on sloped ground with access to house at two/three levels i.e., ground middle floor and roof	5
			2. The house is connected to the sloped ground and there is no gap between the building and the natural slope of the site	5
			3. The house is built on an elevated mound to prevent flooding during monsoon, which can slide/liquefy	5
	Sub Total			
	SUM (Maximum Sub Total -5)			
	Soil & Foundation Condition 5%	Suitability of soil type	1. Soft soil	2
			2. Weak soil	2
			3. High water table	1
			4. Soil with moisture	2
		Foundation	1. Strip foundation on non uniform base	2
			2. Strip foundation with no formal courses of masonry in plinth masonry	2
			3. RC Strip foundation on soft soil	1
			4. Discontinuous RC foundation beam system	4
			5. Continuous RC foundation beam system on soft soil	2
	Sub Total			
	SUM Maximum Sub Total -5			
	Architecture Features 20%	Plan Shape	1. Large room sizes	5
			2. Irregular orientation of rooms	3
			3. Complex overall shape including those with reentrant corners	5
		Elevation profile	1. Wider top, narrower bottom 5	5
			2. Heavier top 5	5
			3. Large projections/overhangs	3
			4. Split roof	5
			5. Large storey heights	5
			6. Differences in storey heights	5
			7. Unsymmetrical staircase location with respect to plan	5
		Openings	1. Rare single window close to corners	1
			2. About half of openings close to corners	2
			3. Almost all openings close to corners	4
			1. Large window openings	4
			2. Large door openings	6

<table>
<tr><td rowspan="30"></td><td rowspan="14">Architecture Features 20%</td><td rowspan="2">Distance from adjacent building</td><td>1. Houses touch each other</td><td>3</td></tr>
<tr><td>2. Houses have small gap between them</td><td>3</td></tr>
<tr><td rowspan="2">Parapets, objects on roof or projections</td><td>1. Unsecrured to structural system</td><td>4</td></tr>
<tr><td>2. Large and heavy projections and overhangs</td><td>0</td></tr>
<tr><td rowspan="4">Staircases</td><td>1. Narrow</td><td>1</td></tr>
<tr><td>2. Too few</td><td>1</td></tr>
<tr><td>3. Too far to reach</td><td>1</td></tr>
<tr><td>4. Poorly constructed</td><td>1</td></tr>
<tr><td rowspan="3">Water tanks on flat roof</td><td>1. Large in size</td><td>1</td></tr>
<tr><td>2. Provided in the middle of the rooms</td><td>1</td></tr>
<tr><td>3. Not anchored to the wall system</td><td>1</td></tr>
<tr><td rowspan="2">Number of storeys</td><td>1. 3 storeys</td><td>2</td></tr>
<tr><td>2. 4 Storey or more</td><td>5</td></tr>
<tr><td colspan="3">Sub Total</td></tr>
<tr><td colspan="3">SUM (Maximum Sub Total -20</td><td></td></tr>
<tr><td rowspan="9">Structural Aspects 40%</td><td rowspan="4">Walls</td><td>1. indirect or limited load paths</td><td>4</td></tr>
<tr><td>2. Large openings in walls that</td><td>4</td></tr>
<tr><td>3. Walls unsymmetrical in one direction</td><td>3</td></tr>
<tr><td>4. Walls symmetric in both directions</td><td>4</td></tr>
<tr><td rowspan="5">Roof design</td><td>1. Heavy roof</td><td>4</td></tr>
<tr><td>2. Pitched roof</td><td>4</td></tr>
<tr><td>3. Split roof</td><td>4</td></tr>
<tr><td>4. Weak diaphragm action tiled roof or separate planks</td><td>4</td></tr>
<tr><td>5. Large cut outs in diaphragm</td><td>4</td></tr>
<tr><td rowspan="13">Structural Aspects 40%</td><td>Foundation wall connection</td><td>1. No anchorage of wall reinforcement to foundation</td><td>5</td></tr>
<tr><td rowspan="6">Wall-wall connection</td><td>1. No roof band with pitched roof</td><td>4</td></tr>
<tr><td>2. No roof band with flat roof</td><td>4</td></tr>
<tr><td>3. No lintel band</td><td>5</td></tr>
<tr><td>4. No sill band</td><td>2</td></tr>
<tr><td>5. No plinth band</td><td>5</td></tr>
<tr><td>6. Arches/vaults without tie rods</td><td>5</td></tr>
<tr><td>Wall to roof/floor connection</td><td>1. No/insufficient anchorage of vertical reinforcement from walls to roof/floor</td><td>3</td></tr>
<tr><td rowspan="3">Staircase</td><td>1. Unsymmetrical location</td><td>5</td></tr>
<tr><td>2. Both top and bottom integrally built into the building frame</td><td>5</td></tr>
<tr><td></td><td>0</td></tr>
<tr><td>Large water tanks on roof</td><td>1. Unsymmetrically located and integrally built staircase</td><td>3</td></tr>
</table>

			2. Staircase not adequately separated from the house	3
	Sub Total			
	SUM Maximum Sub Total -40			
	Construction Details 30%	Type of materials	1. Poor quality of materials	15
		Workmanship	1. Poor geometries of masonry and roof	3
			2. Insufficient curing	10
			3. Adhoc procedures of construction	10
		Concrete mix	1. Concrete prepared using nominal mix	0
			2. Concrete ingredients measured by volume batching	0
	SUM Maximum Sub Total -30			

3. Brick Masonry Other Roofs

Sr. No			
Latitude			
Longitude			
Number of Buildings			
Life Threatening Factors	**Sitting Issues**	(a The building is built on hill slopes that can slide, OR	
		(b The building is built on river terraces that can slide/creep, OR	
		(c The building is built on hill slopes /adjacent to hill slopes (even though on flat ground, but vulnerable to falling debris from the hill top.	
	Soil & Foundation Condition	(a The soil underneath the building is liquefiable, OR	
		(b The soil in the area adjoining the site is liquefiable and can flow laterally to move the soil from underneath the building.	
	Architecture Features	(a The outer dimensions of the house at plinth level are less than those at the top in either of the two horizontal plan direction or	
		(b The house has large unanchored projections and overhangs or	
		(c The door and window openings in walls are at the corner, or	
		(d The building is almost touching or located close to an adjacent seemingly unsafe building/construction, whose collapse/pounding can damage it	
	Structural Aspects	(a The roof is constructed such that it is not integral within itself (i.e., it does not act as a single unit and breaks open during earthquake shaking and is not anchored into the walls or	
		(b The walls are thick and made in two wythes or	
		(c The walls are not integrated into each other at the corners or	
		(d the staircases are not anchored into the walls of the house	
	Construction Details	(a The walls are made with mud mortar and are exposed to the vagaries of the	

			outside weather (especially rain water beating	
			(b The walls are made with no mortar	
Economic Loass Factor	**Sitting Issues 5%**		1. The house is on sloped ground with access to house at two/three levels i.e., ground middle floor and roof **5**	5
			2. The house is connected to the sloped ground and there is no gap between the building and the natural slope of the site **5**	5
			3. The house is built on an elevated mound to prevent flooding during monsoon, which can slide/liquefy **5**	5
	Sub Total			
	SUM **Maximum Sub Total -5**			
	Soil & Foundation Condition 5%	**Suitability of soil type**	1. Soft soil	2
			2. Weak soil	2
			3. High water table	1
			4. Soil with moisture	2
		Foundation	1. Strip foundation on non uniform base	2
			2. Strip foundation with no formal courses of masonry in plinth masonry	2
			3. RC Strip foundation on soft soil	1
			4. Discontinuous RC foundation beam system	4
			5. Continuous RC foundation beam system on soft soil	2
	Sub Total			
	SUM **Maximum Sub Total -5**			
	Architecture Features 20%	**Plan Shape**	1. Large room sizes	5
			2. Irregular orientation of rooms	3
			3. Complex overall shape including those with reentrant corners	5
		Elevation profile	1. Wider top, narrower bottom	5
			2. Heavier top	5
			3. Large projections/overhangs	3
			4. Split roof	5
			5. Large storey heights	5
			6. Differences in storey heights	5
			7. Unsymmetrical staircase location with respect to plan	5
		Openings	1. Rare single window close to corners	1
			2. About half of openings close to corners	2
			3. Almost all openings close to corners	4
			1. Large window openings	4
			2. Large door openings	6
			1. Houses touch each other	3

	Architecture Features 20%	**Distance from adjacent building**	2. Houses have small gap between them	3
		Parapets, objects on roof or projections	1. Unsecured to structural system	4
			2. Large and heavy projections and overhangs Not available in book	0
		Staircases	1. Narrow down	1
			2. Too few in number	1
			3. Too far to reach	1
			4. Poorly constructed	1
		Water tanks on flat roof	1. Large in size	1
			2. Provided in the middle of the rooms	1
			3. Not anchored to the wall system	1
		Number of storeys	1. 3 storeys	2
			2. 4 Storey or more	5
	Sub Total			
	SUM **Maximum Sub Total -20**			
	Structural Aspects 40%	**Walls**	1. indirect or limited load paths	4
			2. Large openings in walls	4
			3. Walls unsymmetrical in one direction	3
			4. Walls symmetric in both directions	4
		Roof design	1. Heavy roof	4
			2. Pitched roof	4
			3. Split roof	4
			4. Weak diaphragm action tiled roof or separate planks	4
			5. Large cut outs in diaphragm	4
	Structural Aspects 40%	**Foundation wall connection**	1. No anchorage of wall reinforcement to foundation	5
		Wall-wall connection	1. No roof band with pitched roof	4
			2. No roof band with flat roof	4
			3. No lintel band	5
			4. No sill band	2
			5. No plinth band	5
			6. Arches/vaults without tie rods	5
		Wall to roof/floor connection	1. No/insufficient anchorage of vertical reinforcement from walls to roof/floor	3
		Staircase	1. Unsymmetrical location	5
			2. Both top and bottom integrally built into the building frame	5
				0
		Large water tanks on roof	1. Unsymmetrically located and integrally built staircase	3

			2. Staircase not adequately separated from the house	3
	Sub Total			
	SUM **Maximum Sub Total -40**			
	Construction Details 30%	**Type of materials**	1. Poor quality of materials	15
		Workmanship	1. Poor geometries of masonry and roof	3
			2. Insufficient curing	10
			3. Adhoc procedures of construction	10
		Concrete mix	1. Concrete prepared using nominal mix	0
			2. Concrete ingredients measured by volume batching	0
	SUM **Maximum Sub Total -30**			