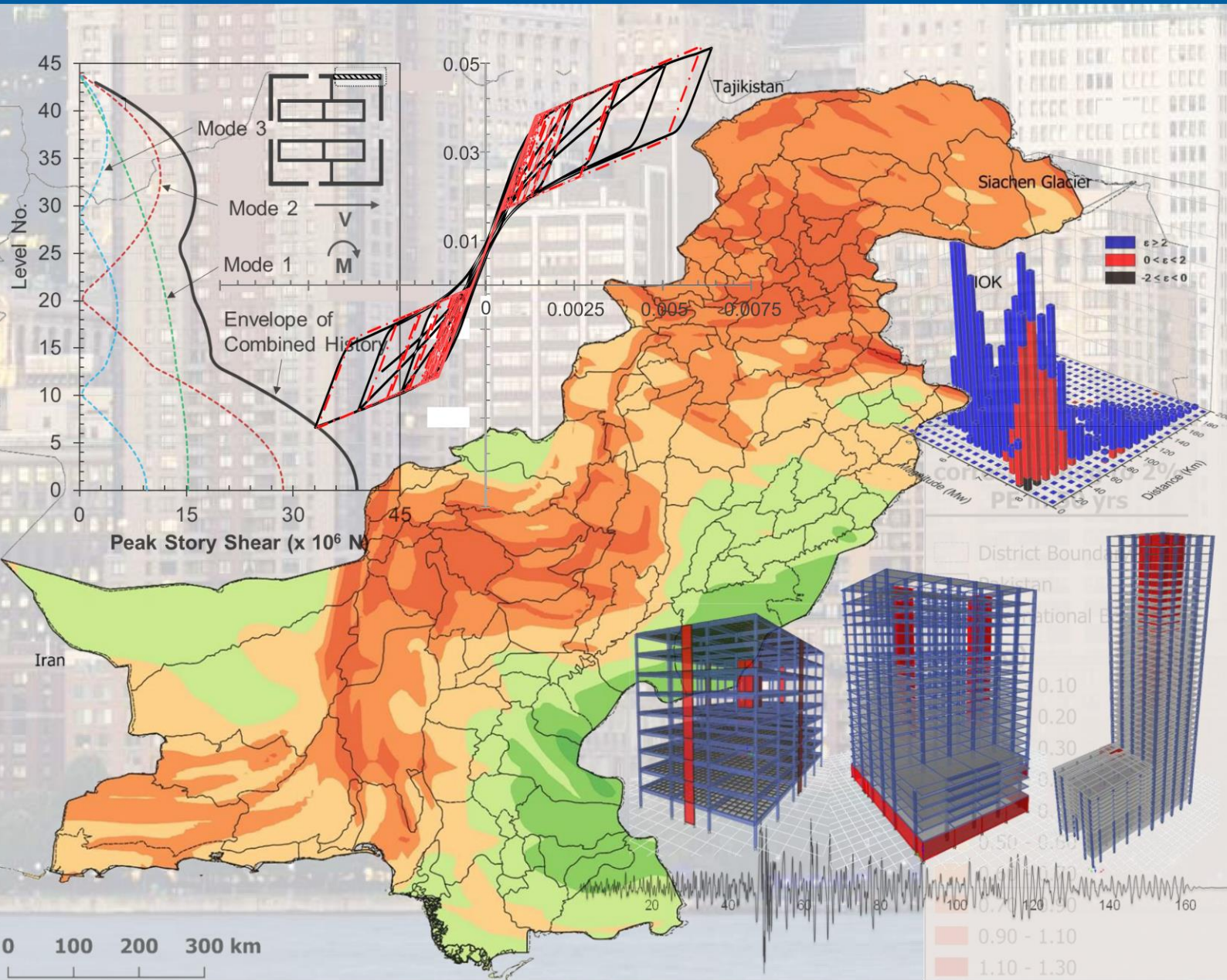# RECOMMENDATIONS AND FOCUS AREAS FOR THE IMPROVEMENT OF
BUILDING CODE OF PAKISTAN
[BCP-2007 WITH SEISMIC PROVISIONS]

This document presents few recommendations from Dr. Fawad A. Najam and Dr. Rao Arslan Khushnood of NUST Institute of Civil Engineering (NICE, NUST) for the improvement of Building Code of Pakistan (BCP-2007). These recommendations are prepared in the light of several recent studies conducted at NICE (NUST) in the areas of probabilistic seismic hazard assessment and performance-based seismic design of structures.

Recommendations and Focus Areas for the Improvement of Building Code of Pakistan (BCP-2007 with Seismic Provisions)

This document presents few recommendations and discussion on focus areas identified for the improvement of Building Code of Pakistan (BCP-2007). The recommendations are prepared in the light of several recent studies conducted at NUST Institute of Civil Engineering (NICE), National University of Sciences and Technology (NUST), Islamabad, in the areas of probabilistic seismic hazard assessment and performance-based seismic design of structures.

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Acronyms and Abbreviations

ASCE	American Society of Civil Engineers
BCP	Building Code of Pakistan
CUVI	Visual Cumulative method
DBE	Design-basis Earthquake
GCMT	Global Centroid-moment-Tensor
GEM	Global Earthquake Model
GMPEs	Ground Motion Prediction Equations
HC	Hazard Curve
IBC	International Building Code
ISC	International Seismological Centre
mb	Short-Period P-Wave Magnitude
MBT	Main Boundary Thrust
MCE	Maximum Considered Earthquake
ML	Local Magnitude
MS	20-s Surface-Wave Magnitude
MW	Moment Magnitude
NEIC	National Earthquake Information Center
NGA	Next Generation Attenuation
PEER	Pacific Earthquake Engineering Research Center
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Analysis
SA	Spectral Acceleration
UBC	Uniform Building Code
UHS	Uniform Hazard Spectrum
USGS	U.S. Geological Survey

Executive Summary

This publication identifies some important focus areas and presents few recommendations for the improvement of Building Code of Pakistan (BCP-2007 with seismic provisions). These recommendations are prepared in the light of several recent studies conducted at NUST Institute of Civil Engineering (NICE), National University of Sciences and Technology (NUST), Islamabad, in the areas of probabilistic seismic hazard assessment and performance-based seismic design of structures. One of the primary purposes of a building code is to establish the minimum requirements to safeguard the public health, safety and general welfare through structural strength and stability against several hazards experienced during the intended design life. Around the world, several national and international building codes reflect the collective wisdom of individuals and organizations associated with industry, academia, practice and governments. These codes are regularly updated to incorporate state-of-the-art research findings and recommendations from constituent committees to prescribe well-structured procedures to ensure public safety and construction of resilient infrastructure. Unfortunately, this has not been the case for Pakistan. A high level of country's seismic hazard, growing population, rapid urbanization and a large number of existing non-engineered buildings are some of the serious challenges faced by us today. Any negligence from the responsible stakeholders in foreseeing the severity of these challenges will directly affect the long-term objective of achieving earthquake resilience in Pakistan. Therefore, a dire need to improve local construction laws, safety provisions and seismic design practice is obvious. The discussion and recommendations presented in this publication are limited only to the provisions and procedures related to seismic safety of structures. These include the need for an updated seismic hazard assessment of Pakistan, the provisions related to structural modeling, the need for an updated seismic design philosophy and seismic analysis procedures, and the use of advanced cement-based materials in local scenario. The implementation aspects of BCP-2007 and the role of construction bye laws from the local development authorities is not included in this publication. These aspects are also equally important and require a diligent focus by the relevant stakeholders.

Chapter 1

Introduction

1.1. Evolution of and Traditional Building Codes

The purpose of building codes and standards is to establish the minimum requirements to ensure public safety and general welfare through structural strength and stability against several natural and man-made hazards. For engineering design purposes, these documents often hold a legal status in particular areas of their jurisdiction when officially enacted by the relevant authorities. They also prescribe requirements for adequate sanitation, light and ventilation, energy conservation, and safety to life and property from fire and other hazards associated to the built environment. A well-researched and comprehensive building code can greatly contribute towards the development and construction of durable and resilient infrastructural facilities in a country.

The development of traditional design and safety codes have a long history dated back to centuries. Figure 1-1 identifies some of the early milestones which led to the development of modern building codes. The undesirable consequences of natural disasters and catastrophes have resulted in a strong realization that certain minimum safety requirements and standards must be met to construct infrastructural facilities. Over the years, these realizations have resulted in the development of several national and international building codes. Figures 1-2 and 1-3 classifies the existing building codes into some important families.

1666 CE - "Rebuilding of London Act" after "Great Fire of London"	1908 CE – The formal building code was drafted and adopted	1988 CE – ASCE 7 by the American Society of Civil Engineers (ASCE)
1680 CE - "The Laws of the Indies" Spanish Crown	1904 CE - A Handbook of the Baltimore City	1927 CE - Uniform Building Code (UBC) [updated every 3 years]
1844 CE - London Building Act	1859 CE - In USA, the City of Baltimore first building code	1997 CE - International Building Code (IBC) by ICC

Figure 1-1: Some of the early milestones which led to the development of modern building codes

Buildings codes also reflect the evolution of structural design philosophies and approaches over last several decades (Figure 1-4). The earlier approaches were mainly based on simple static loadings and elastic analysis procedures. However, with increasing developments in computational methods, experimental techniques and supporting fields, the current structural design practice have now evolved into an explicit consideration of future design loading and inelastic behavior. This publication is mainly focused on the role of building codes in ensuring the seismic safety and adequate design of structures. However, first a quick overview of the history of building codes in Pakistan will be presented.

Figure 1-2: Some families of modern building codes

Figure 1-3: Some families of modern building codes

Risk integrated based design, and a more holistic approach towards consequence based engineering

The introduction of capacity based design approach

The recognition of the difference between brittle and ductile failure modes

Performance based design and more explicit linkage between demand and performance

Formulation of ultimate strength design approach

Formulation of limit state design principles

Explicit consideration of partial factor of safety (FOS)

Limits on the allowable stresses to achieve in-direct factor of safety (FOS)

Figure 1-4: The evolution of structural design philosophies and approaches over last several decades

1.2. A Quick History of Building Codes in Pakistan

Pakistan is located on a highly earthquake-prone and seismically active part of the world. The country lies on a tectonically active Himalayan orogenic belt developed as a result of slow collision (extended over last 30-40 million years) among the Indian, Arabian, and Eurasian tectonic plates. This geological setting has resulted in a number of active seismic sources and faults in the region which are capable of producing moderate- to large-magnitude earthquakes. Besides having a high level of seismic hazard, the country is also confronted over the years with high rate of population increase and rapid growth of urbanization. With all these challenges and high seismic risk, there is an urgent need of equipping the practicing engineers, designers, structural engineering students with state-of-the-art information about the latest structural design philosophies.

The engineering practice in Pakistan has historically remained influenced and governed by the American family of building codes. Over last few decades, the conventional design practice was conducted following the provisions of Uniform Building Code (UBC). A very valuable overview of the status of building codes and bylaws is presented by Bonowitz (2015) in a report titled, "*Seismic Design in Pakistan: The Building Code, Bylaws, and Recommendations for Earthquake Risk Reduction*". This report is published by the Crisis Prevention and Recovery Unit of United Nations Development Programme (UNDP) and presents a detailed review of BCP 2007 provisions. This report classifies the historical developments related to the development and implementation of building codes into several broad phases as shown in Figure 1-5 below.

Pre-partition	1947 through the 1975	1970s to 1986	1986 to 2007	2007 to Date
• Seismic design provisions were added to the building code of the municipality of Quetta after a damaging earthquake there in 1935	• British building codes remained in use after partition. • Some government agencies continue to use British codes even today, though not necessarily for earthquake design of building structures	• Trained engineers began applying American codes, especially the Uniform Building Code (UBC). • Until the international Building Code (IBC) replaced it in 2000, the UBC was the leading model code throughout California and the U.S. west coast. • It was updated on a three-year cycle through its final edition in 1997.	• Pakistan's first national building code was published in 1986 as "an advisory document" with seismic provisions modeled on contemporary editions of the UBC. • Though perhaps intended for adoption by local bylaw, the 1986 code was not officially adopted or enforced. • While sometimes used as a reference, trained engineers continued to use the UBC.	• After the 2005 Kashmir earthquake, Ministry of Housing & Works hired National Engineering Services Pakistan (NESPAK) to develop seismic hazard maps and earthquake design provisions for a thorough update of the 1986 code. • NESPAK collaborated with a committee of experts convened by the Pakistan Engineering Council (PEC), mostly academics, to produce a consensus document that became the 2007 Building Code of Pakistan. • The provisions of BCP-2007 in conjunction with its model codes are used for the structural design of buildings in Pakistan.

Figure 1-5: The historical phases based on the development and implementation of building codes in Pakistan (based on UNDP, 2015)

Figure 1-5 shows that the "Building Code of Pakistan — Seismic Provisions, 2007" (referred onwards as BCP-2007) is the country's first earthquake design code to be referenced in national policy. The preface of the BCP-2007 explains the primary motivation and its development in the following words.

> *"The devastating earthquake of October 08, 2005 made it abundantly clear that earthquake provisions of the Pakistan Building Code 1986 need to be comprehensively bolstered so that public health and safety for all communities are ensured. This has been encapsulated in these "Seismic Provisions". The thrust of these provisions is to establish minimum regulations for earthquake considerations in building systems. (BCP-2007)"*

> *"Like the Pakistan Building Code 1986, the Ministry of Housing & Works (MOHW) Government of Pakistan (GOP) assigned the task of developing the Seismic Provisions to the National Engineering Services Pakistan (Pvt.) Limited (NESPAK). NESPAK submitted different drafts for scrutiny to an Experts Committee formed by the MOHW. The final draft was sent to the Pakistan Engineering Council (PEC) for vetting. NESPAK worked in close collaboration with International Code Council (ICC), USA. PEC formed a "Core Group" of individuals drawn from across the country, representing various stakeholders. It was this Core Group that held intimate deliberations with experts from NESPAK and gave final shape to the document. (BCP-2007)"*

In 2008, the Scientific and Technological Research Division of Ministry of Science and Technology enforced the use of BCP-2007 through a statuary notification for the purpose of structural design of buildings and building-like structures in the country. This was considered a major step in towards nationwide efforts for earthquake risk reduction in the country.

1.3. *"The Earthquake Problem"* and the Role of Building Codes

Figure 1-6 presents the big picture of several processes involved in the seismic analysis and design of built facilities. With each process, the role of building codes is also highlighted. For simplicity, here we divide the complete story into four aspects as follows.

- **Aspect 1:** *An accurate characterization of seismic hazard at construction site*

This involves the detailed probabilistic seismic hazard assessment, seismic deaggregation analysis and site response analysis. Based on detailed studies, the traditional building codes prescribe the necessary details and guidelines for structural engineers directly. These detailed procedures are generally not performed for the design of ordinary engineering facilities and their results are readily available for structural designers to use in the design of structures.

- **Aspect 2:** *Structural Idealization and Numerical Modeling*
  This involves the development of a reasonably accurate computer model of the structure. A structural model is a compromise between the real structure and its mathematical representation. A good structural model should be able to capture all important aspects of structural behavior. Building codes also provide necessary guidelines for the development of mathematical models of structures.

- **Aspect 3:** *Ground Motion Parameters and Design Spectra*
  The involves an accurate characterization of seismic loading to be applied to the structural models. For linear static or pseudo-dynamic analysis, the seismic loading is generally the function of ground motion parameters (representing the seismic hazard of the site) and the design response spectra at adequate levels of structural damping. Traditional building codes also provide these parameters directly for engineers to use for the purpose of structural design.

- **Aspect 4:** *Linear/Nonlinear Static/Dynamic Seismic Analysis Procedures*
  This involves performing the numerical analysis of computer models against the loading prescribed by building codes (aspect 3). Several seismic analysis procedures have been developed over last several decades and building codes prescribe and guide for the use of these methods for different types of structures.

- **Aspect 5:** *Structural Design, Detailing and Construction*
  This involves converting the seismic demands obtained from analysis procedures (aspect 4) into the required amount of materials (reinforcements, steel, concrete etc.) and cross-sectional sizes. This aspect also deals with the use of design equations, factors of safety, member capacities, rebar layouts and other practical aspects of seismic design. This is one of the most important aspect where the building codes provide guidance, design checks, design aids in the form of tables and charts, and other relevant provisions.

In US codes, Eurocodes and some other families of codes, there may exist different standard documents covering different aspects of the seismic analysis and design. On the other hand, national building codes of several other countries also consist of one unified document covering all or many of these aspects.
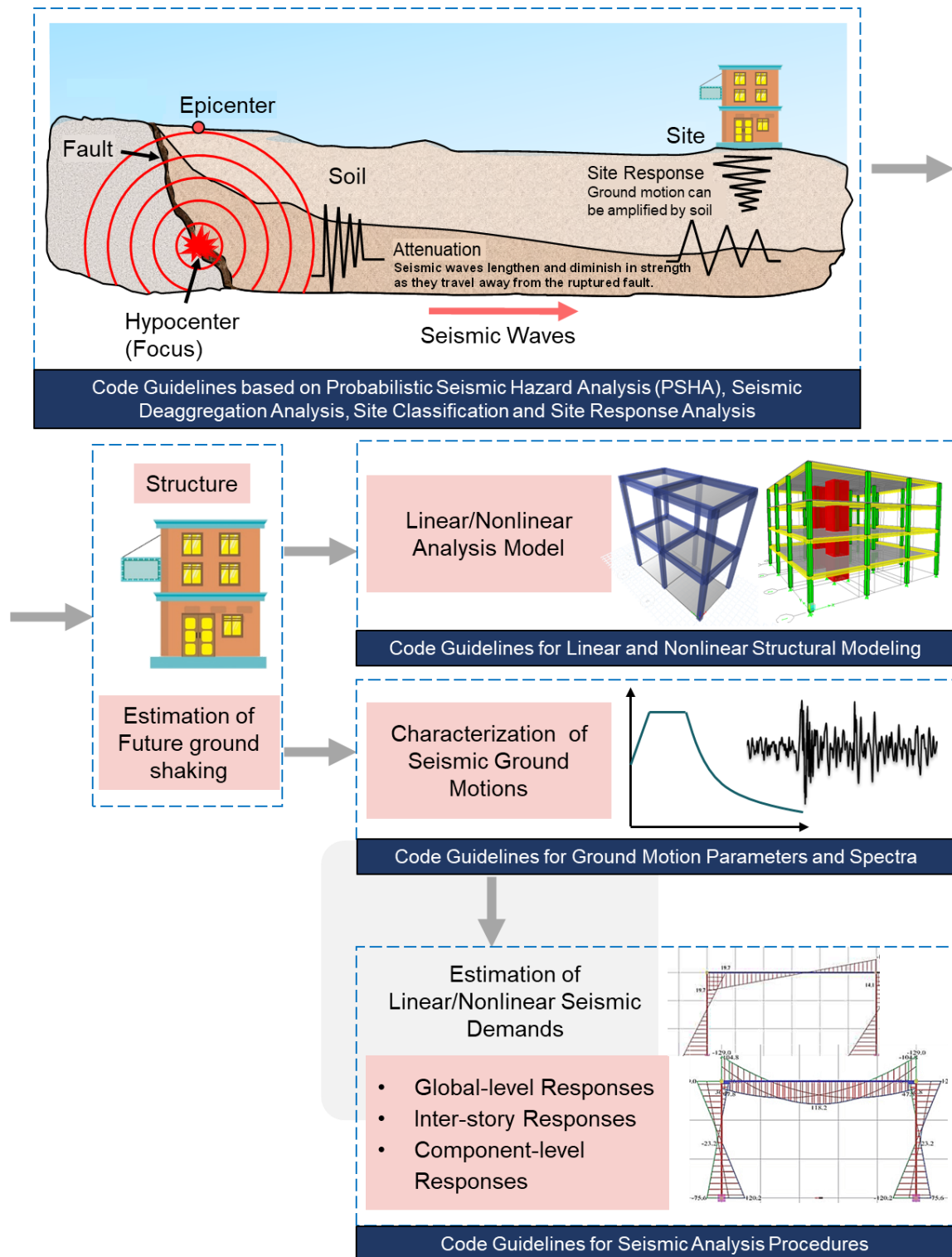
Figure 1-6: Components of "the Earthquake Problem" and the role of building codes

1.4.   About this Report

This publication presents few recommendations for the improvement of Building Code of Pakistan (BCP-2007). These recommendations are prepared in the light of several recent studies conducted at NUST

Institute of Civil Engineering (NICE), National University of Sciences and Technology (NUST), Islamabad, in the areas of probabilistic seismic hazard assessment and performance-based seismic design of structures.

The first chapter provides an introduction of traditional building codes, their evolution in Pakistan and their role in seismic analysis and design of structures. The second chapter presents an overall review of the Building Code of Pakistan (BCP-2007 with Seismic Provisions). The third chapter summarizes some recommendations related to the updated seismic hazard assessment of Pakistan. It also presents an example study in this regard. The fourth and fifth chapters summarize some recommendations related to structural modeling and seismic design philosophy and seismic analysis procedures. Some elements from performance-based seismic design are also discussed with their possible integration with some of the provisions in BCP-2007. The chapter six concludes this document with some closing remarks.

1.5. Scope and Limitations of Proposed Recommendations

The traditional building codes generally address a wide range of issues related to public safety. However, the recommendations presented in this document are only limited to structural analysis, seismic hazard assessment, and structural model for seismic design (Figure 1-7). Other areas, for example energy conservation, light and ventilation requirements, sanitation, and safety to life and property from fire and other hazards etc., are not included in the scope of this document. Moreover, the issues related to code enforcement and its mechanism are also not included in the discussion presented in this document. A complete technical review of the BCP-2007 is also not included in the scope of this publication. The discussion is intended only to give a general overview of some areas which need to be focused. This report highlights the need for an improved version of the BCP-2007, and therefore, should not be considered an official proposal for changing any existing provisions.
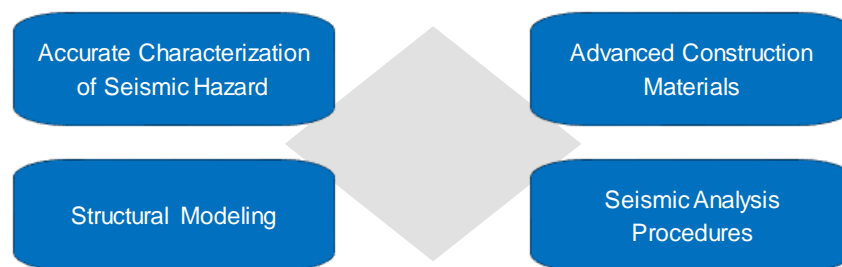
Figure 1-7: The areas covered under the scope of this publication. Several challenges associated with these areas are discussed in the context of engineering practice in Pakistan.

Chapter 2

A Review of the Building Code of Pakistan (BCP-2007 with Seismic Provisions)

2.1.   Introduction and Development

This chapter presents a quick review of some of the important provisions in the Building Code of Pakistan (BCP-2007). The purpose is to familiarize the reader with its scope and preliminary details about seismic hazard assessment, seismic analysis and design procedures prescribed in this document.

The development timeline of BCP-2007 (based on Shabbir and Ilyas, 2007) can be summarized as shown in Table 2-1 below.

Table 2-1: The timeline of the events for the development of BCP-2007 (Shabbir and Ilyas, 2007)

Date	Event
October 8, 2005	Kashmir Earthquake (Mw 7.6)
October 13, 2005	A cabinet meeting held and desired to undertake, review of the Building Code and Regulations at national level to ensure safety and security of the residents.
January 31, 2006	The Prime Minister decided on the finalization of seismic zoning for entire country. The Pakistan Engineering Council (PEC) was tasked to enforce and publicize the revised building parameters. The Ministry of Housing and Works tasked NESPAK Consultants for revision updating of the Pakistan Building Code (PBC 1986) with respect to seismic provisions in coordination with all concerned.
February 2006 Onwards	NESPAK planned to undertake this task in three stages. *Stage-1* studies comprised development of preliminary seismic parameters and the criteria for earthquake resistant design of buildings in Islamabad/Rawalpindi area. The scope of was required to be extended in the *Stage-II* and detailed recommendations for seismic design parameter and earthquake resistant design was to be taken up for entire country. This was to be followed by preparation of a comprehensive Building Code of Pakistan in *Stage-III*.
June 10, 2006	Ministry of Housing and Works reviewed the progress on NESPAK work on State-II (Recommendations for detailed seismic design parameters and criteria for seismic resist design of buildings for the whole of country).
July 6, 2006	PEC Core Group held its 1st meeting at HQ PEC under the Chairmanship of its Convener (Syed Imtiaz Hussain Gilani) and it was decided that four additional experts will be invited to the next meeting.
July 20, 2006	The second meeting of the Core Group was held on 20 July 2006 and two sub-committees, one for Seismic Hazard Analysis and second for Seismic Analysis & Design were formulated to make recommendations to Core Group on 25 July 2006.
August 2006 Onwards	Several combined meetings of the PEC Core Group and NESPAK experts were held at HQ PEC Islamabad and NESPAK House Lahore
March 14-16, 2007	The last meeting of Core Group Subgroup (to finalize the document), and NESPAK experts, was held at NESPAK House Lahore.
End of March 2007	Final draft along with recommendations of the Core Group was sent to HQ PEC.
March 29, 2007	Final draft was forwarded to the Ministry of Housing and Works for approval.
August 09, 2007	The then Prime Minister (Shaukat Aziz) issued letters to the provincial governments asking them to devise by-laws, rules and regulations in accordance with the new code.
August 26, 2007	The new Building Code approved by the cabinet became effective forthwith throughout the country, including Azad Jammu and Kashmir.

The BCP-2007 consists of 11 chapters covering various aspects of structural analysis, design and detailing. There were several source documents used to develop relevant provisions and set minimum requirements. A list of these source documents is presented in Table 2-2.

Table 2-2: The source documents used for the development of BCP-2007

Chapter No.	Topic	Source Documents
1	Scope	-
2	Seismic Hazard	The PSHA study performed by NESPAK (2007)
3	Site Considerations	-
4	Soils and Foundations	Uniform Building Code (UBC) 1997, International Code Council.
5	Structural Design Requirements	- Uniform Building Code (UBC) 1997, International Code Council. - For Wind Design, ASCE 7-05, Chapter 6, Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers
6	Structural Tests and Inspections	Uniform Building Code (UBC) 1997, International Code Council.
7	Reinforced Concrete	ACI (2005), Building Code Requirements for Structural Concrete, ACI 318-05, American Concrete Institute, Farmington Hills, MI.
8	Structural Steel	ANSI/AISC 341-05, Seismic Provisions for Structural Steel Buildings, American Institute of Steel Construction, Inc., Chicago, IL.
9	Masonry	Uniform Building Code (UBC) 1997, International Code Council.
10	Architectural Elements	- ASCE (1993), Minimum Design Loads for Building and Other Structures, ANSI/ASCE 7-93, American Society of Civil Engineers, Reston, VA. - ASCE (2005), Minimum Design Loads for Building and Other Structures, ASCE/SEI 7-05, American Society of Civil Engineers, Reston, VA.
11	Mechanical and Electrical Systems	- ASCE (1993), Minimum Design Loads for Building and Other Structures, ANSI/ASCE 7-93, American Society of Civil Engineers, Reston, VA. - ASCE (2005), Minimum Design Loads for Building and Other Structures, ASCE/SEI 7-05, American Society of Civil Engineers, Reston, VA.

The primary source document for the seismic analysis and design of structures is the last version of Uniform Building Code (UBC 1997). At the time of the development of BCP-2007, the seismic analysis and design philosophy was radically improved compared to what was prescribed in UBC 1997. Between 1997 and 2007, the International Code Council (ICC) published three International Building Codes (IBC) (IBC 2000, IBC 2003 and IBC 2006). Some of the major improvements introduces in these documents include the following.

   a) The basis for the definition of seismic hazard was changed from peak ground acceleration (PGA) to spectral acceleration (SA). In UBC 97, the PGA values corresponding to 10% probability of exceedance in 50 years exposure were used as the basis for seismic zonation. However, from IBC 2000 onwards, the maximum considered earthquake (MCE) level spectral acceleration values

corresponding to time periods of 0.2-sec (denoted as S_s) and 1-sec (denoted as S_1) were used to represent seismic hazard. The design values for these spectral accelerations were prescribed as 2/3 of the MCE (defined as an earthquake with 2% probability of exceedance in 50 years exposure) level values. The hazard maps for S_s and S_1 for US were developed using the up-to-date probabilistic seismic hazard assessment (PSHA) methodology and were included in the IBC 2000 onwards. With this change, the concept of seismic zones (with constant hazard within a zone) was ceased. The seismic hazard parameters (S_s and S_1) can vary from site-to-site depending upon the results obtained from the PSHA.

b) The concept of seismic design categories was introduced. In IBC 2000 onwards, the minimum analysis requirements, design checks and other limitations were made dependent on the level of seismic risk associated with a building. This is done by assigning a seismic design category (SDC) to the building which is function of the seismic hazard level of site and risk category of the building. Six seismic design categories (SDC A to F) were defined. While seismic analysis and design of buildings, relatively strict requirements were set for the SDCs D, E and F compared to SDCs A, B and C.

These major improvements marked an extraordinary shift in seismic design philosophy and also set the direction for future research in this subject. However, for reasons unknown to authors, the code committee for BCP-2007 decided to use UBC 97 as the template for prescribing seismic analysis procedures. It was assumed that a PGA-based seismic zonation of Pakistan developed in line with US seismic zones would establish a direct compatibility with seismic analysis procedures prescribed in UBC 97.

As mentioned in Table 2-1, the seismic zonation prescribed in BCP-2007 is the result of a probabilistic seismic hazard assessment carried out by National Engineering Services Pakistan (NESPAK). A quick overview of this study is presented in next section for reader's interest.

2.2. Probabilistic Seismic Hazard Analysis (PSHA) – NESPAK (2007)

The exact prediction of future earthquakes in a region is not yet possible due to lack of required geo-tectonic information and significant amount of uncertainties involved in the phenomenon. It is therefore assumed that the historical occurrence of major earthquakes (excluding the foreshocks and aftershocks) in any region is random and statistically independent of each other. Such a process is mathematically described as a Poissonian stochastic process or a process with Poissonian probability distribution. In short "*earthquakes have no memory*". Therefore, the best we can do is to estimate the likelihood of future earthquake occurrences in any area by statistical evaluation of the historical data of earthquakes in that area. The science of seismic hazard assessment therefore deals with such an estimation by considering the historical activity of known and unknown seismic sources as well as the geological and seismo-tectonic environment of any region.

Earlier attempts of seismic hazard assessment involved the use of a single critical earthquake scenario (the magnitude and source-to-site distance) for assessing the level of hazard at a site. This process is known as Deterministic Seismic Hazard Assessment (DSHA). This approach directly provides the worst case scenario of hazard instead of the likelihood of occurrence of ground shaking parameter (e.g. peak ground acceleration) for different return periods. The conventional DSHA also do not account for the uncertainties in seismic sources, magnitude and location of earthquake events. However, a later approach known as the Probabilistic Seismic Hazard Analysis (PSHA) is more widely accepted after the establishment of seismic networks and availability of seismicity data. The PSHA is an effective method of integrating all possible earthquake occurrences in a probabilistic framework to calculate a combined probability of exceedence that incorporates the relative frequencies of occurrence of expected ground motions from all contributing sources. This process accounts for all inherent uncertainties associated with seismic hazard, and therefore, is considered better compared to the DHSA.

Nowadays, the PSHA is a fundamental component of earthquake risk assessment, mitigation and management. The methodology for this assessment can be summarized in three steps, (a) modeling of earthquake sources, (b) identification of models that can reasonably represent the attenuation characteristics

of earthquake ground motions, and (c) evaluation of the hazard level at the site. The three basic steps can be briefly described as follows:

Step 1 is the modeling of earthquake sources. In this work, the earthquake sources in the study region are modeled by a combination of smooth gridded seismicity, crustal fault and subduction source models. The seismic activity of each of these sources is characterized by a magnitude-recurrence relationship, which shows the average occurrence rate of earthquakes of a given magnitude occurring inside the source. This step is the most important and most time consuming step in the assessment work.

Step 2 is the identification of models that can reasonably represent the attenuation characteristics of earthquake ground motions within the study region. By using these attenuation models (or 'ground motion prediction equations'), ground motion parameters such as peak ground acceleration (PGA) and spectral acceleration (SA) at the site produced by an earthquake of a given magnitude occurring at a given location are estimated.

Step 3 is the evaluation of the hazard level at the site. The effects of all earthquakes of different magnitudes, occurring at different locations in different seismic sources at different probabilities of occurrence are integrated into hazard curves. Each hazard curve shows the probability of exceeding different PGA or SA levels at the site during a specified period of time. From the obtained hazard curves, uniform hazard response spectra for various return periods for the project site are derived.

For developing an indigenous seismic analysis framework for BCP-2007, the PSHA of Pakistan was conducted by NESPAK in 2006-07. Salient features of this study are reproduced here (BCP-2007).

a) ***Geo-tectonics of the Region:*** The seismo-tectonic environment of the country is divided into several broad seismotectonic zones including
- Himalayan seismotectonic zone in the north,
- Suleiman-Kirthar thrust-fold belt
- Chaman-Ornach Nal Transform Fault Zone
- Makran Subduction Zone in the west
- Rann of Kutch Seismotectonic Zone in the southeast.

b) ***Development of Earthquake Catalogue:*** The historical seismicity data is obtained from two types of sources. The first one is based upon earthquake data from regional data catalogues compiled by International Seismological Centre (ISC) and National Earthquake Information Centre (NEIC) of USGS, and the other from earthquakes recorded by local networks of Pakistan Meteorological Department, Pakistan Atomic Energy Commission (PAEC) and Water & Power Development Authority (WAPDA). A composite list of earthquakes recorded in and around Pakistan was prepared from the data collected from regional as well as local networks mentioned above. Several empirical magnitude conversion relationships were used to homogenize the developed earthquake catalogue in moment magnitude scale. The duplicate earthquakes appearing in different catalogues were removed based on reported time and where time is not available based on the epicentral data. In preparation of this composite list, the first preference was given to ISC catalogue. The fault plane solutions available in the literature and provided by PAEC and Quaid-e-Azam University were also used to assess the source characteristics.

c) ***Delineation of Seismic Sources:*** Two types of seismic sources (line sources i.e. faults and area sources) were modeled with their magnitude-recurrence relationships developed using the collected historical data. It was assumed that the area source zones alone cannot completely account for the long term seismicity associated with major active faults. In order to account for seismicity with large return period, the major active faults of Pakistan were also modeled as characteristic fault sources for PSHA. The whole area of Pakistan was divided into seventeen area source zones (area sources) based on their homogeneous tectonic and seismic characteristics, keeping in view the geology, tectonics and seismicity of each area source zone. The eight area seismic source zones in the northern part of Pakistan are named Hindukush, Pamir, Kohistan, Hazara, Himalayas, Salt Range-

Potwar, Bannu and Punjab seismic source zones. The nine area source zones in southern part of Pakistan are named Suleiman, Sibbi, Kirthar, Kurram-Chaman, Indus plateform, Rann of Kutch, Cholistan-Thar desert, Chagai and Makran.

d) *Modeling of Area Sources:* The well-known Gutenberg-Richter model is used as the magnitude-recurrence relationship of the area sources. This relationship is developed based on the earthquake catalogue and the seismicity parameters are extracted for all area sources.

e) *Modeling of Crustal Faults:* Several shallow crustal faults of Pakistan and surrounding areas were included in the analysis which may influence the seismic hazard in the country. These faults include Main Karakoram Thrust, Main Mantle Thrust, Raikot Fault, Main Boundary Thrust, Panjal-Khairabad Thrust, Himalayan Frontal Thrust, Riasi Thrust, Jhelum Fault, Salt Range Thrust, Kalabagh Fault, Bannu Fault, Kurram Fault, Chaman Transform Fault, Ornach-Nal Transform Fault, Quetta-Chiltan Fault, Kirthar Fault, Pab Fault, Kutch Mainland Fault, Allah Bund Fault, Nagar Parkar Fault, Hoshab Fault, Nai Rud Fault and Makran Coastal Fault. Figure 2-1 shows the fault map of Pakistan as considered in seismic hazard assessment for BCP-2007 (NESPAK, 2007). For the fault characteristic model, the maximum magnitude of the fault was calculated using well known fault rupture-magnitude relationship developed by Well and Coppersmith (1994), taking half-length rupture. The maximum potential magnitude for Himalayan Frontal Thrust was selected equal to the magnitude of recent Kashmir earthquake which is considered the characteristic (maximum) for that fault.
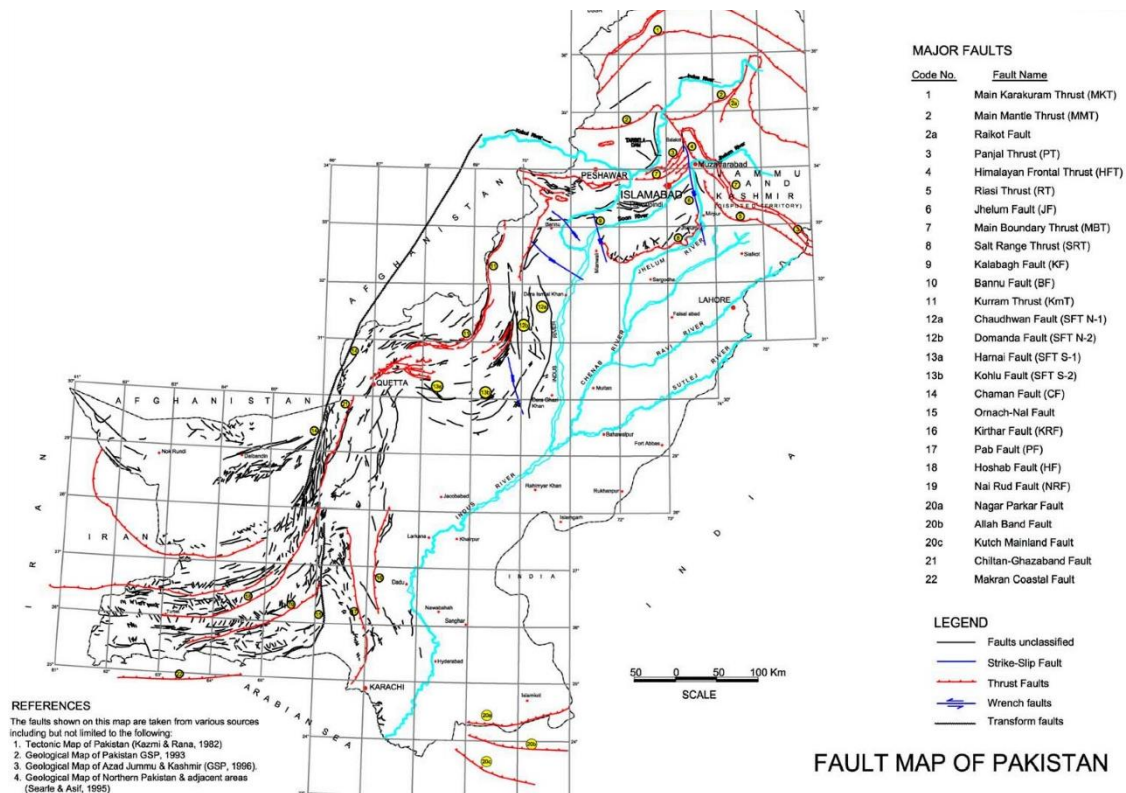
Figure 0-1: The fault map of Pakistan as considered in seismic hazard assessment for BCP-2007 (NESPAK, 2007)

f) *Seismogenic Depths:* Each of the area sources was assigned a maximum magnitude based on maximum recorded seismicity and a minimum magnitude based on threshold magnitude observed in the magnitude-frequency curve for the zone. As the shallow earthquakes are of more concern to seismic hazard, the minimum depth of the earthquakes is taken as 5-10 km for all sources except for

Punjab seismic source zone where the minimum depth of earthquakes is taken as 20 km and for Hindukush zone where minimum depth was taken as 70 km.

g) **Ground Motion Prediction Equations (GMPEs):** The GMPE (also known as the attenuation relationship) developed by Boore et al. (1997) was used. Using this equation, the ground motions were calculated for rock site condition having a shear wave velocity (Vs) of 760 m/sec. Three other equations developed during 1996 to 2004 along with Boore et al (1997) equation were also used in PSHA by giving equal weightage (25%) to each equation. Ground motion amplitudes obtained by these equations are generally same as obtained by using Boore et al. (1997) equation only.

h) **Analysis and Results:** The probabilistic hazard analysis was carried out by using EZ-FRISK software developed by Risk Engineering Inc. of Colorado, USA. As the purpose of the PSHA was to develop seismic hazard contour map, Gridded- Multisite module of EZ-FRISK software was used. In this module a probabilistic hazard analysis is performed for each point on a rectangular grid within the boundary of the region to be mapped. For ease of analysis, the hazard calculations were performed by dividing the study area (covering Pakistan and one degree outside Pakistan) into six parts and ground motion was obtained at each 0.1 degree interval of the rectangular grid (total about 13,000 grid points). The required parameters for all the seventeen area seismic source zones and twenty eight fault seismic sources (characteristic model) were fed to the software. The results of the hazard analysis obtained at each grid point are presented in the form of total hazard from all the seismic sources modeled (areas as well as faults) around 300 km radius of the grid point. The ground motion associated with 10% probability of exceedance in 50 years (475 years return period) was calculated at each grid point. From the results obtained at 0.1 degree interval, contours of Peak Ground Acceleration (PGA) values were plotted through GIS software to present the results in the form of seismic hazard map for 10% probability of exceedance in 50 years (i.e. 475 years return period). This PGA contour map is shown in Figure 2-2 below.

Figure 2-2: The contours of Peak Ground Acceleration (PGA) with 10% probability of exceedance in 50 years exposure period
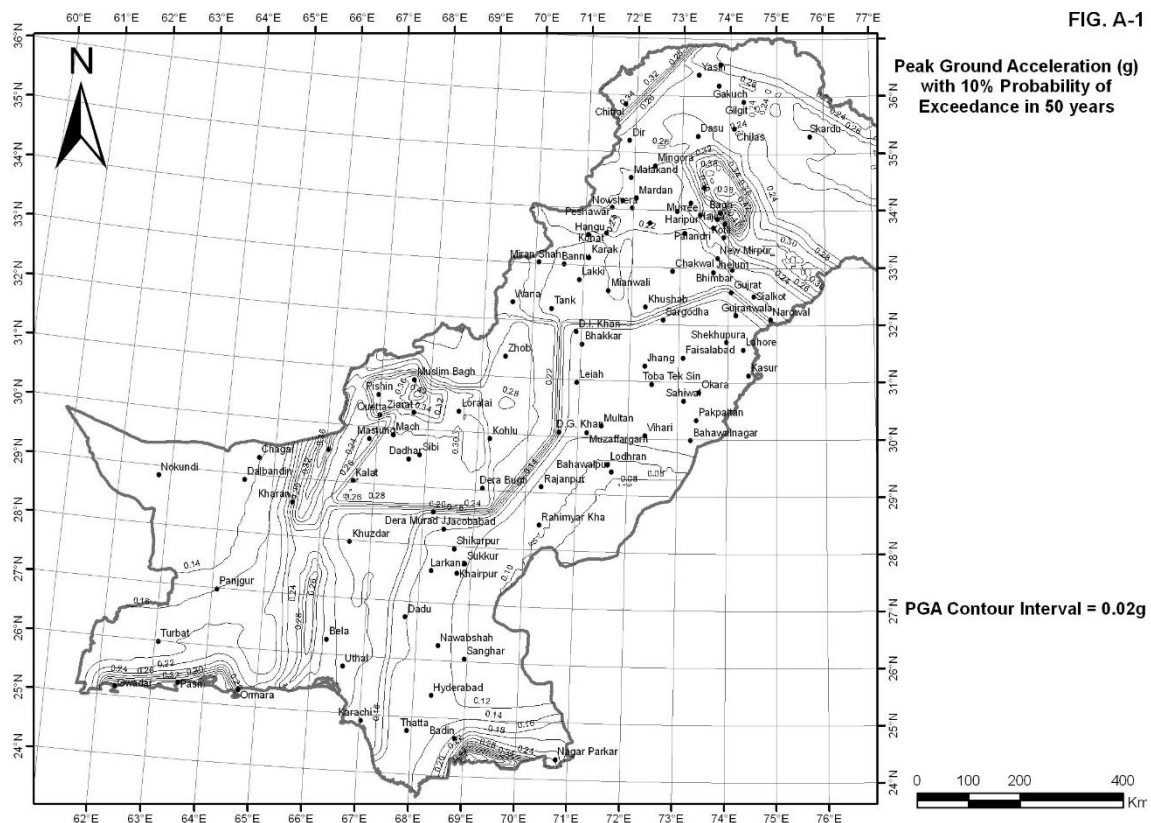
i) ***Seismic Zonation of Pakistan:*** On the basis of PGA values obtained through PSHA, Pakistan was divided into five seismic zones in line with UBC (1997). The boundaries of these zones are defined on the following basis:

Zone 1	0.05 to 0.08 g
Zone 2A	0.08 to 0.16 g
Zone 2B	0.16 to 0.24 g
Zone 3	0.24 to 0.32 g
Zone 4	> 0.32 g

The seismic zoning map of Pakistan developed on this basis is shown in Figure 2-3. Each site in the country is assigned a seismic zone in accordance with Table 2-3. It is recommended that for the equivalent lateral static analysis, each structure shall be assigned a seismic zone factor Z in accordance with Table 2-2 below.

Table 2-3: Seismic Zone Factor Z

Zone	1	2A	2B	3	4
Z	0.075	0.15	0.2	0.3	0.4
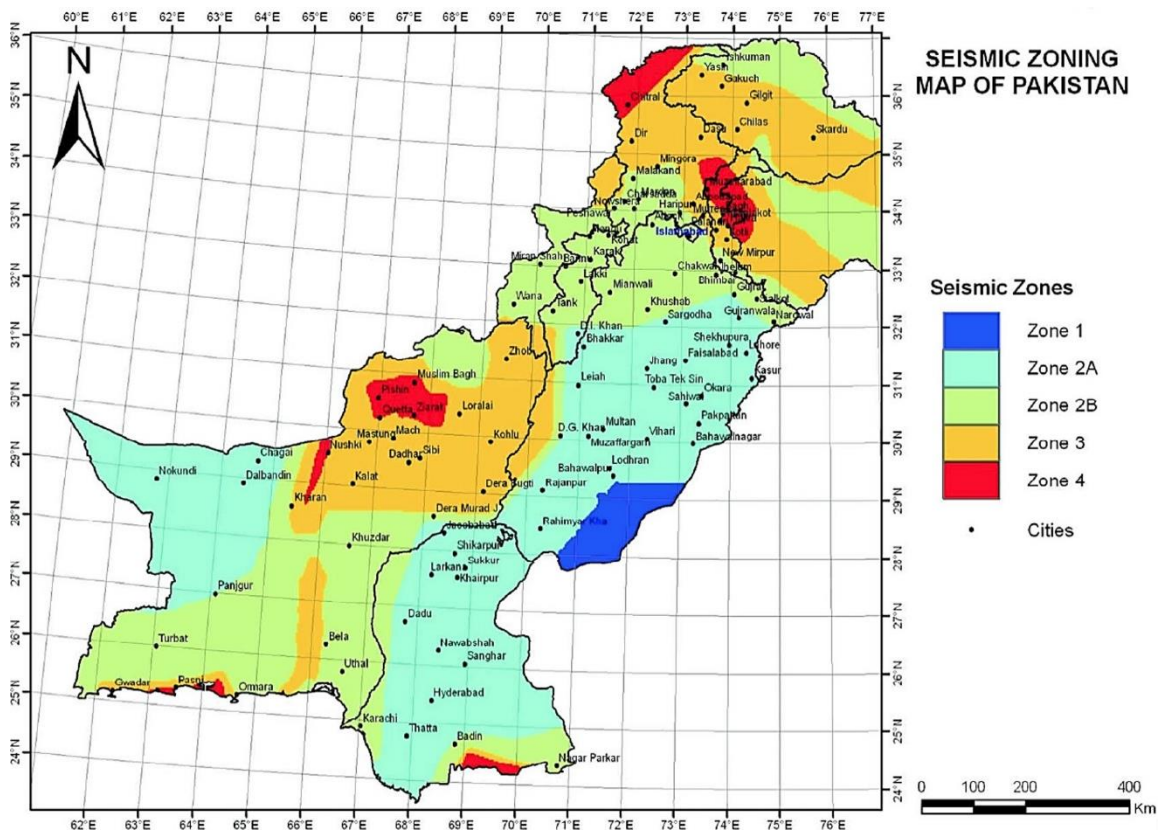
Figure 2-3: The seismic zonation of Pakistan developed based on the Peak Ground Acceleration (PGA) with 10% probability of exceedance in 50 years exposure period (return period of 475 years) (BCP-2005)

2.3. Site and Soil Classification as per BCP-2007

In BCP-2007, the following classification of soils is adopted.

S_A Hard rock with measured shear wave velocity, V_s > 1500 m/s (4920 ft/sec)

S_B Medium hard rock with 750 m/s < V_s < 1500 m/s (2460 ft/sec < V_s < 4920 ft/sec)

S_C Very dense soil and soft rock with 350 m/s < V_s < 750 m/s (1150 ft/sec < V_s < 2460 ft/sec) or with either N > 50 or s_u > 100 kPa (2,088 psf)

S_D Stiff soil with 175 m/s < V_s < 350 m/s (575 ft/sec < V_s < 1150 ft/sec) or with 15 < N < 50 or 50 kPa < s_u < 100 kPa (1044 psf < s_u < 2088 psf)

S_E A soil profile with V_s < 175 m/s (575 ft/sec) or with N < 15 or with Ss_u < 50 kPa (1044 psf) or any profile with more than 3 m (10 ft) of soft clay defined as soil with PI > 20, w_{mc} > 40 percent and s_u < 25 kPa (522 psf)

S_F Soils requiring site-specific evaluation:

         a) Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils

         b) Peats and/or highly organic clays [H > 3 m (10 ft.) of peat and/or highly organic clay where (H = thickness of soil]

         c) Very high plasticity clays [H > 7.5 m (25 ft.) with PI > 75]

         d) Very thick soft/medium stiff clays [H > 37 m (120 ft)]

Where V_s is the shear wave velocity in m/s (ft/sec), s_u is the undrained shear strength in kPa (psf), N is the standard penetration test value, PI is the plasticity index and w_{mc} is the moisture content.

This classification criteria is also summarized in the Table 4.1 of BCP-2007 reproduced below.

Table 4.1-Soil Profile Types

Soil Profile Type	Soil Profile Name/ Generic Description	Average Properties for Top 30 M (100 ft) of Soil Profile		
		Shear Wave Velocity, v_s m/sec (ft/sec)	Standard Penetration Tests, N [or N_{CH} for cohesionless soil layers] (blows/foot)	Undrained Shear Strength, s_u kPa (psf)
S_A	Hard Rock	>1,500 (>4,920)		
S_B	Rock	750 to 1,500 (2,460 to 4,920)	–	–
S_C	Very Dense Soil and Soft Rock	350 to 750 (1,150 to 2,460)	>50	>100 (>2,088)
S_D	Stiff Soil Profile	175 to 350 (575 to 1,150)	15 to 50	50 to 100 (1,044 to 2,088)
S_E[1]	Soft Soil Profile	<175 (<575)	<15	<50 (<1,044)
S_F	Soil requiring Site-specific Evaluation. See 4.4.2			

1   Soil Profile Type S_E also includes any soil profile with more than 3 m (10 ft) of soft clay defined as a soil with a plasticity index, PI > 20, w_{mc} ≥ 40 percent and s_u < 25 kPa (522 psf). The Plasticity Index, PI, and the moisture content, w_{mc}, shall be determined in accordance with the latest ASTM procedures.

2.4. Seismic Analysis Procedures prescribed in BCP-2007

Similar to other conventional seismic design codes, the BCP-2007 also prescribes three seismic analysis procedures for the purpose of seismic design. These include the equivalent static analysis procedure (also

referred as the static force procedure), the response spectrum analysis procedure and the time history analysis procedure. However, for the purpose of structural design, only first two are mostly used. The nonlinear time history analysis is also discussed with its intended use for design review of the lateral force resisting system.

The static lateral force procedure is recommended for the following structures:

a) All structures, regular or irregular, in Seismic Zone 1 and in Occupancy Categories 4 and 5 in Seismic Zone 2. (Note: Each structure is required to assign an occupancy category from 1 to 5 based on intended function of the structure)

b) Regular structures under 73 meters (240 feet) in height with lateral force resistance provided by systems listed in Table 5.13 of BCP-2007, except where the structure is located on Soil Profile Type S_F and has a period greater than 0.7 second.

c) Irregular structures not more than five storeys or 20 meters (65 feet) in height.

d) Structures having a flexible upper portion supported on a rigid lower portion where both portions of the structure considered separately can be classified as being regular, the average storey stiffness of the lower portion is at least 10 times the average storey stiffness of the upper portion and the period of the entire structure is not greater than 1.1 times the period of the upper portion considered as a separate structure fixed at the base.

The dynamic lateral-force procedure (response spectrum analysis or time history analysis) is recommended for other structures including the following:

a) Structures 73 meters (240 feet) or more in height, except if a structure lies in Seismic Zone 1 and in Occupancy Categories 4 and 5 in Seismic Zone 2.

b) Structures having a stiffness, weight or geometric vertical irregularity of Type 1, 2 or 3 as defined in Table 5.11 of BCP-2007, or structures having irregular features not described in Table 5.11 or 5.12 of BCP-2007, except as permitted by Section 5.30.4.2 of BCP-2007.

c) Structures over five storeys or 20 meters (65 feet) in height in Seismic Zones 3 and 4 not having the same structural system throughout their height except as permitted by Section 5.30.4.2 of BCP-2007.

d) Structures, regular or irregular, located on Soil Profile Type S_F that has a period greater than 0.7 second. The analysis shall include the effects of the soils at the site and the site-specific spectrum or ground motions should be used for their seismic analysis. Moreover, the possible amplification of building response due to the effects of soil-structure interaction and lengthening of building period caused by inelastic behavior should also be considered.

a) Equivalent Static Force Procedure as prescribed in BCP-2007

In BCP-2007, the equivalent static force procedure from UBC-97 is adopted with seismic zonation developed by NESPAK (2007). In this procedure, the seismic loading is assumed as equivalent static forces applied at each story in lateral direction. These equivalent static forces are determined using an empirical expression developed over last several decades. Generally, the total design base shear is determined first and is distributed along the height of the building as equivalent lateral forces.

The expression for determining the design value of base shear have a long history spanning over last 100 years. The story started with the use of a simple percentage (e.g. 5 - 10%) of the seismic weight applied as equivalent static forces to represent the effects of future earthquake. Those forces were supposed to resist by the elastic action produced by structure against the anticipated earthquakes. However, over the years, the expression to calculate the design base shear significantly improved. Now, although the general form of expression is still the same (i.e. base shear is expressed as some percentage of seismic weight), the coefficient or multiplier for the seismic weight is significantly improved. In UBC-97, this base shear coefficient is a function of seismic zone (i.e. the level of seismic hazard), soil type, and structure's ductility, time period

and occupancy category (importance). With the advent of performance-based seismic design philosophy and nonlinear modeling and analysis, the widespread use of equivalent static force procedure often receives some criticism especially for mid- to high-rise RC buildings. The story which started from a simple mass-proportional lateral load resisted by the elastic action has now evolved into an explicit consideration of design earthquakes applied to the detailed nonlinear finite-element models.

In UBC-97 and BCP-2007, the total design base shear in a given direction is determined from the following expression:

$$V = \frac{C_v I}{R T} W$$

The total design base shear need not exceed the following:

$$V = \frac{2.5 C_a I}{R T} W$$

The total design base shear shall not be less than the following:

$$V = 0.11 C_a I W$$

In addition, for Seismic Zone 4, the total base shear shall also not be less than the following:

$$V = \frac{0.8 Z N_v I}{R} W$$

Where

V = Design base shear

W = Seismic weight (the expected weight of the building at the time of anticipated ground motion)

C_a and C_v = Seismic coefficients, dependent on hazard level and soil class

R = Over-strength factor representative of the inherent over-strength and global ductility capacity of the lateral force-resisting system [From ASCE 7-05 onwards, this coefficient is refereed to as the "response modification factor". It is also referred to as the "behavior factor" in Eurocodes]

I = Importance factor, dependent on the structural occupancy type

T = Structure's fundamental period of vibration, in seconds, in the direction under consideration. It is empirically calculated using the expressions provided in BCP-2007 or UBC-97. It should be noted that this first-mode time period is not intended to result from the classical modal analysis of the structure.

Z = Seismic zone factor determined in accordance with the seismic zonation developed as a result of PSHA conducted by NESPAK (2007). The values from Table 2-2 are recommended.

N_v = A near-source factor used in the determination of C_v in Seismic Zone 4. It is a function of the proximity of the building or structure to known faults with magnitudes and slip rates as set forth in Tables 5.19 and 5.20 of BCP-2007.

The design base shear is distributed along the height of the structure using a simple linear distribution adopted from UBC-97. The $P - \Delta$ requirements, allowable drift checks, horizontal and vertical irregularity considerations and accidental torsion and its amplification are also adopted from UBC-97.

b) Response Spectrum Analysis (RSA) Procedure as prescribed in BCP-2007

The response spectrum analysis (RSA) procedure is a pseudo-dynamic analysis procedure which is based on the static application of several sets of equivalent lateral loads to the structure. These sets of equivalent lateral loads are separately calculated for each vibration mode of the structure while accounting for the contribution of that mode in total seismic response. Each set of these lateral loads is then separately applied to the structure to determine the elastic structural response corresponding to a particular vibration mode of the

structure. The peak valued of seismic responses of all vibration modes (having a significant contribution to total structural response) calculated in this manner are then combined statistically to determine the total elastic seismic responses of the structure. These elastic responses (forces, moments, displacements and drifts etc.) are reduced with a response modification factor (or behavior factor) accounting for the structure's global over-strength and ductility to determine the design seismic demands. These (reduced) design forces and moments are then used for proportioning the structure and determining the required reinforcement. By doing so (i.e. by reducing the forces and moments used in design from the elastic values), we in fact, allow some acceptable level of inelastic action of structure against the future design earthquake. Due to this limited inelastic action, the actual displacements produced by the future design earthquake will be higher compared to those determined through elastic analysis and reduced by response modification factor. Therefore, the displacements and all related responses (e.g. the inter-storey drifts etc.) are again amplified with a displacement amplification factor to estimate the peak inelastic displacement demands. Moreover, for some critical members whose failure can cause threat to global structural safety and stability (e.g. the transfer girders or critical columns etc.), no inelastic action should be allowed in case of future design earthquake. The design forces of such members (after reduction with response modification factor) are again amplified with an over-strength factor in order to ensure that they remain elastic during the design earthquake. The values of these seismic design factors (response modification factor, displacement amplification factor and structural over-strength factor) depend on the building code being used. From structure's side, the basic inputs in this procedure are the modal properties (natural periods, mode shapes and modal participation factors). From seismic loading's side, the basic input is the response spectrum curve (i.e. a curve relating the peak response acceleration of any simple structure with its natural time period). The modal properties of any structure are determined from the classical modal analysis procedure (either through eigen-value analysis or the Ritz analysis). The elastic response spectrum curve for any building site is either provided by the building codes (through a generic template and piecewise function dependent on the site's hazard parameters and soil type) or by the detailed site-specific PSHA study.

Similarly, the BCP-2007 also provides the following two options for selecting the elastic response spectrum for the RSA procedure. The minimum design level of ground motion is defined by an earthquake with a 10-percent probability of being exceeded in 50 years.

a) A generic code-prescribed elastic design response spectrum constructed in accordance with Figure 2-4. This curve is the function of C_a and C_v values associated with the specific site. The spectral ordinates are in "g" units and therefore, the design acceleration ordinates should be multiplied by the acceleration due to gravity, 9.815 m/sec2 (386.4 in/sec^2). The shape of this prescribed spectrum represents typical short-period design ground motions. It is assumed that the same shape is applicable to all major seismo-tectonic regions in the country.

b) A site-specific elastic design response spectrum based on the geologic, tectonic, seismologic and soil characteristics associated with the specific site. The spectrum should be developed for a damping ratio of 0.05, unless a different value is shown to be consistent with the anticipated structural behavior at the intensity of shaking established for the site.
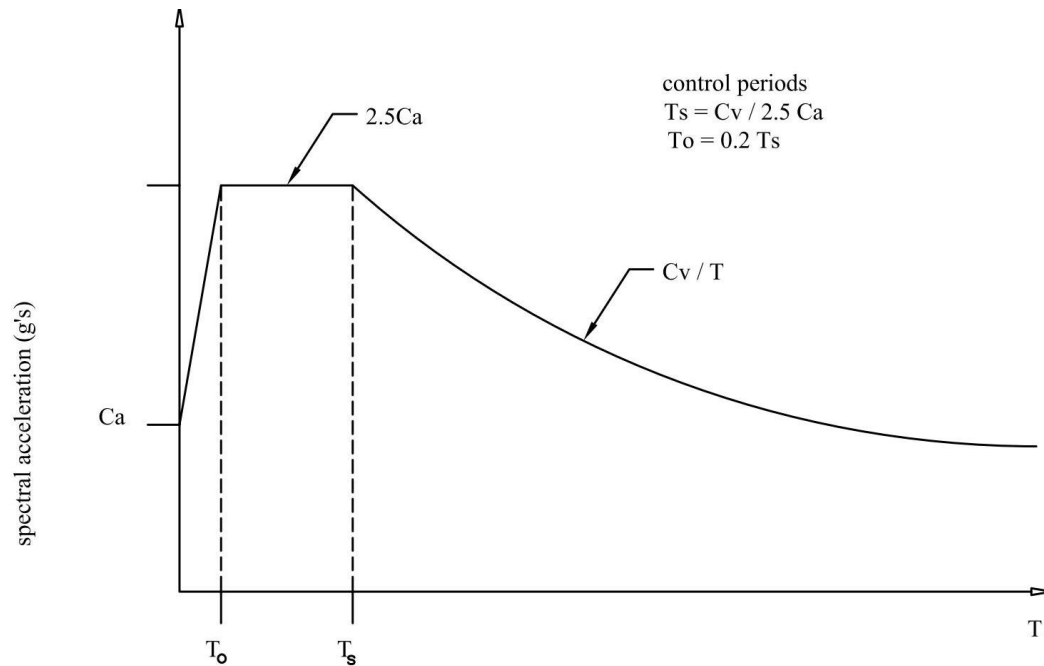
Figure 2-4: The 5% damped elastic response spectrum recommended to be used for the structural design practice in Pakistan. The seismic coefficients C_a and C_v are the functions of site's hazard level (in the form of seismic zone) and the soil typy. The design level of hazard is defined by an earthquake event with 10% probability of exceedance in 50 years exposure period [475 years return period] (BCP-2005)

As mentioned above, the elastic responses determined using the RSA procedure are required to be reduced for the purpose of design. However, the reduced total base shear is also required to be compared with that obtained using the equivalent static force procedure. The conventional building codes (e.g. UBC 97 or ASCE 7) recommend to scale the results of the RSA procedure such that the design base shear should match with (80%, 90% or 100% of the) design base shear obtained from the equivalent static force procedure. Accordingly, the BCP-2007 also prescribes the following three cases of this scaling for the RSA results.

a) For all regular structures where the code-specified response spectrum curve is used, the elastic responses should be reduced such that the corresponding design base shear (determined using the RSA procedure) is not less than 90 percent of the base shear determined using the equivalent static force procedure.

b) For all regular structures where the site-specific response spectrum curve is used, the elastic responses should be reduced such that the corresponding design base shear (determined using the RSA procedure) is not less than 80 percent of the base shear determined using the equivalent static force procedure.

c) For all irregular structures, regardless of whether the code-specified or site-specific response spectrum is used, the elastic responses should be reduced such that the corresponding design base shear (determined using the RSA procedure) is not less than 100 percent of the base shear determined using the equivalent static force procedure.

This requirement of a base shear scaling for the response spectrum analysis (RSA) procedure can be seen from a historic perspective. It was included in the earlier building codes as a means to ensure that the minimum strength of a structure designed using the RSA procedure is similar to the strength that would be required if the structure was designed using the equivalent static force procedure. In earlier version of several building codes, the RSA procedure was included as an optional procedure which the designer could use in

order to capture a more accurate distribution of effective earthquake forces (compared to the default design option i.e. the equivalent static force procedure) along the height of structure. This would result in a better distribution of capacity throughout the structure compared to what is required by static procedure having an empirical foundation. While ensuring that the design base shear should be at least comparable with the equivalent static base shear, the allowance of using a reduced design base shear (i.e. 80% or 90% of the equivalent static base shear) can be seen as a reward for using a more accurate design method (i.e. the RSA procedure). Currently, some building codes allow for the design base shear to be as low as 80% of the equivalent static base shear for some regular structures. This is also the case for the UBC-97 and the BCP-2007. However, for irregular structures (or the structures with high seismic risk), the conventional codes (including the UBC-97 and the BCP-2007) ensure that the design base shear should be at least 100% of the equivalent static base shear. So, the later standards, although acknowledge that the RSA method provides a more realistic distribution of effective earthquake forces, still relate the minimum allowable capacity of the structure to that determined using the equivalent static force procedure.

Similar to other conventional buildings codes, the BCP-2007 also recommends including all significant modes in the RSA procedure such that at least 90 percent of the participating mass of the structure is included in the calculation of response for each principal horizontal direction. The peak member forces, displacements, storey forces, storey shears and base reactions for each mode are recommended to be combined by recognized methods [mostly the square root of the sum of squares (SRSS)]. When three-dimensional models are used for analysis, modal interaction effects should be considered when combining modal maxima. If the building has plan or vertical irregularities, the vibration modes in both directions may be coupled and the translational mode shapes may not be separated into individual horizontal directions. Moreover, in some special cases, the natural time periods of the structure may not be well-separated. The complete quadratic combination (CQC) rule accounts for these effects of modal interaction, and therefore, is recommended in such cases.

The BCP-2007 defines the vertical component of ground motion as two-thirds of the corresponding horizontal accelerations. Therefore, the vertical response spectrum for the RSA in vertical direction can also be constructed accordingly. Alternative factors are also recommended when substantiated by site specific data. Where the Near Source Factor (N_a) is greater than 1, site-specific vertical response spectra is recommended to be used in lieu of the factor of two-thirds.

c) Linear Time History Analysis (LTHA) Procedure as prescribed in BCP-2007

The time history analysis (also referred to as the response history analysis) is the rigorous dynamic analysis procedure. In this procedure, the complete governing dynamic equation of motion is solved for the structure subjected to a ground motion. Beside the restoring lateral stiffness effects, the inertial and damping effects of the structure's mass and energy dissipation respectively, are also included in this analysis procedure. From structure's side, the primary inputs include the definition of detailed geometry, its mass and the amount of energy dissipation (often represented by damping coefficients). From loading's side, the required input includes a ground motion shaking function (often represented by a plot between horizontal ground acceleration and time) which represents the future earthquake shaking. Since the prediction of an actual future earthquake is not possible, we are left with the following three options to develop this ground acceleration function (or time history) for this detailed dynamic analysis procedure.

   a) Select the data of past earthquakes recorded on sites with similar properties (soil type etc.) as the structure's site. These selected past earthquakes should be produced by the similar seismic sources (and in similar seismo-tectonic environment) as the actual site of the structure. The source-to-site distance, faulting mechanism and other hazard governing parameters of the selected ground motions should match with those of the actual site of the structure. The as-recorded hazard level and other characteristics of previously recoded ground motions never exactly match with those of a future earthquake expected at a particular site. Therefore, before using in the time history analysis, these selected ground motions are also modified in accordance with the hazard level (defined by the response spectrum curve) of that site.

b) Use Green's functions and other techniques to develop synthetic time histories. These are the artificial (hypothetical) ground acceleration functions which can be used to perform the dynamic analysis of the structure. This approach, although nowadays available in several structural analysis software, is not popular among the structural engineering community.

c) Physics-based predictions of time histories. This technique includes simulating the actual rupture of the governing seismic source and the propagation of seismic waves to the site. This approach is very rare and is not yet practical for general structural engineering applications.

The structural model required for time history analysis procedure is generally more sophisticated compared to the equivalent static force procedure and the response spectrum analysis (RSA) procedure. Apart from lateral stiffness effects, it should also be able to represent and capture the inertial and damping effects of the structure. Similarly, the selection of seismic loading (time histories) also require more expertise and skills in the areas of engineering seismology and hazard assessment. Moreover, the latest analysis guidelines require to use a large number of ground motions records representing the anticipated seismic hazard at the building site. This process of selecting representative ground motions, performing the detailed dynamic analysis and post-processing of results may cost a significant amount of time. An ordinary design office may not have necessary expertise and resources to undergo this complete process for each project. For most practical cases, the equivalent static force procedure or the RSA procedure may serve the purpose of estimating design demands within their required degree of accuracy. Due to these reasons, until recently, the time history analysis is not commonly used for the purpose of structural design, although several new codes and studies are now emphasizing on its use instead of the RSA procedure.

The BCP-2007 prescribes that the time history analysis should be performed with pairs of appropriate horizontal ground-motion time history components that are selected and scaled from not less than three recorded earthquake events. Appropriate time histories should have magnitudes, fault distances and source mechanisms that are consistent with those that control the design-basis earthquake (or maximum capable earthquake) at building's site. Where three appropriate recorded ground-motion time-history pairs are not available, appropriate simulated ground-motion time-history pairs may be used to make up the total number required. The following guidelines are also prescribed for the modification of selected ground motion records.

a) For each pair of horizontal ground motion components, the square root of the sum of the squares (SRSS) of the 5 percent-damped site-specific spectrum of the scaled horizontal components shall be constructed.

b) The ground motion records shall be scaled such that the average value of their SRSS spectra does not fall below 1.4 times the 5 percent-damped code-prescribed or site-specific spectrum of the design-basis earthquake for periods from 0.2T second to 1.5T seconds (Where T is the fundamental natural period of the structure in the direction under consideration). The code-prescribed or the site-specific spectrum can also be referred to as the "target spectrum" in this case.

The latest strong motion recording stations are capable of simultaneously recording 3 components (two horizontal components 90^0 apart and one vertical component) of each ground motion. The time history analysis is generally performed only in two horizontal directions. In some special cases (e.g. for structures with significant irregularities or with special features e.g. the base isolation mechanism etc.), the vertical time history analysis can also be performed. In equivalent static force procedure and the RSA procedure, the effect of vertical ground motions can simply be added linearly to the gravity loads (using amplification factors dependent on that seismic hazard parameters) in design load combinations.

The BCP-2007 prescribes that the record pair of time histories (representative of the actual future earthquake motions) shall be applied simultaneously to the model considering torsional effects. The parameter of interest shall be calculated for each time history analysis. For the purpose of structural design, all response modifications prescribed for the RSA analysis are also applicable to the linear time history analysis procedure. If three time histories analyses are performed, then the maximum response of the parameter of interest shall be used for design. If seven or more time-history analyses are performed, then the average value of the response parameter of interest may be used for design.

Moreover, for the structures (regular or irregular) located on soil profile type S_F and having a time period greater than 0.7 second, the analysis shall should also the effects of the soils at the site and should also conform to the following requirements.

a)   Either the RSA procedure should be conducted using a site-specific response spectrum, or the linear time history analysis should be conducted using the ground motions developed and modified in accordance with site-specific response spectrum.

b)   The possible amplification of building response due to the effects of soil-structure interaction and lengthening of building period caused by inelastic behavior should be considered in the analysis.

d) Nonlinear Time History Analysis (NLTHA) Procedure as prescribed in BCP-2007

The time history analysis procedure can also be applied to a nonlinear structural model. Nonlinear modeling of structures is a relatively recent and detailed area in structural engineering and requires significant expertise in understanding the true inelastic behavior of individual structural components. The nonlinear time history analysis procedure (NLTHA) is therefore not used in ordinary design offices for conventional structural analysis. With a recent advent of the performance-based seismic design philosophy, the role of nonlinear response history analysis is also included in the structural design practice. Conventionally, this procedure is only used for detailed design review or settlement of design disputes etc.

The BCP-2007 allows the use of alternative lateral-force procedures (instead of those discussed in earlier sections) using rational analyses based on well-established principles of mechanics. The use of nonlinear time history analysis (NLTHA) also falls in this category and therefore should meet the requirements set by the code for the selection of time histories. The results of nonlinear time history analysis are a true measure of the real behavior of the structure and need no modification with the response modification factor, displacement amplification factor or over-strength factor.

When nonlinear time-history analysis is used to justify a structural design, a design review of the lateral force resisting system should be performed by an independent engineering team, including persons licensed in the appropriate disciplines and experienced in seismic analysis methods. The lateral-force-resisting system design review shall include, but not be limited to, the following:

a)   Reviewing the development of site-specific spectra and ground-motion time histories.

b)   Reviewing the preliminary design of the lateral-force-resisting system.

c)   Reviewing the final design of the lateral-force-resisting system and all supporting analyses.

Along with the plans and calculations, the engineer of record is also required to submit a confirmatory statement by all members of the engineering team involved in the review process.

2.5.   Structural Modeling Requirements prescribed in BCP-2007

In BCP-2007, there is no separate chapter dedicated to the structural modeling requirements for new and existing building and non-building structures. However, based on the UBC-97, several provisions implicitly guiding about this important aspect of seismic analysis are included. These guidelines are compiled and reproduced here for reader's interest.

a)   ***The Linear Static Analysis:*** A mathematical model of the physical structure shall include all elements of the lateral-force-resisting system. The model shall also include the stiffness and strength of elements, which are significant to the distribution of forces, and shall represent the spatial distribution of the mass and stiffness of the structure. In addition, the model shall comply with the following:

   i) Stiffness properties of reinforced concrete and masonry elements shall consider the effects of cracked sections.

ii) For steel moment frame systems, the contribution of panel zone deformations to overall storey drift shall be included.

b) ***The Linear Dynamic Analysis:*** A mathematical model of the physical structure shall represent the spatial distribution of the mass and stiffness of the structure to an extent that is adequate for the calculation of the significant features of its dynamic response. A three-dimensional model shall be used for the dynamic analysis of structures with highly irregular plan configurations such as those having a plan irregularity and having a rigid or semi-rigid diaphragm. The stiffness properties used in the analysis and general mathematical modeling shall be in accordance with those mentioned above in (a).

c) ***The Nonlinear Dynamic Analysis:*** The capacities and characteristics of nonlinear elements shall be modeled consistent with test data or substantiated analysis, considering the Importance Factor.

2.6. General Observations and Concluding Remarks

The scope of this publication includes to identify some of the important areas which should be focused while improving the BCP-2007. A detailed review for each provision may not be possible to cover under this scope. However, as mentioned in Chapter 1, a detailed review of some of the provisions of BCP-2007 is already conducted under a UNDP project and is published in a report titled, "Seismic Design in Pakistan: The Building Code, Bylaws, and Recommendations for Earthquake Risk Reduction" (Bonowitz, 2015). This report also highlights several shortcomings, inconsistencies and limitations in BCP-2007. Without further comments, an excerpt from this report is reproduced here for readers' information.

"The nature of the 2007 BCP as an amalgam of American standards reflects the speed with which the document was compiled. Specific shortcomings and opportunities for improvement are discussed below. Here, with respect to the code's overall development, the essential point is that the BCP remains, six years after its publication, limited to structural design and devoted almost entirely to earthquake design of new buildings. Key participants from NESPAK and the PEC committee agree that the sense of urgency after the 2005 earthquake led to decisions that might have been made differently had more time been available (Gilani, 2013; Lodi et al., 2013; Qadeer, 2013). The 2007 BCP is not the comprehensive building code — with provisions for fire safety, exiting, mechanical and electrical design, etc. — that some NESPAK staff had hoped and even planned to produce (Shabbir and Ilyas, 2007; Qadeer, 2013).

But even with respect to the seismic provisions, some experts and agencies, including the National Housing Authority, have expressed regret that the development schedule required wholesale incorporation of American source documents and prevented the creation of a truly Pakistani code, one suited specifically to the country's established practices and particular needs (NHA). In this regard, the 2007 BCP is unlike the building codes of India, Japan, or New Zealand (or, for that matter, the U.S.), each of which is unique and reflective of its own history and society.

One unfortunate result of a "borrowed" code is that it might not give due attention to conditions endemic to Pakistan, such as the ubiquitous use of masonry partitions and infill. More important, the American codes presume certain materials and practices that might be missing in Pakistan. Borrowing source documents therefore calls for careful customization to local conditions. But that effort would have been needed to produce a uniquely Pakistani code in any case. Meanwhile, the use of borrowed American codes and standards might actually have some benefits: They provide a now familiar model, or framework, for future code development in Pakistan to follow. They reference new material standards and structural systems that can help advance Pakistani practice. The latest American codes, published by the International Code Council, are themselves built from dependent standards that each address a specific topic, giving them a modular structure that can be developed or customized piece by piece. Finally, even as country-specific codes in India, New Zealand, etc. continue to develop, they are coming closer to each other in concept. After all, the fundamentals of earthquake science and engineering are the same everywhere" (Bonowitz, 2015).

<div align="center">

Chapter 3

Recommendations related to updated Seismic Hazard Assessment of Pakistan

</div>

3.1   Introduction

This chapter presents some discussion and recommendations related to the need of an updated seismic hazard zonation and mapping of Pakistan. Some key features of the probabilistic seismic hazard assessment conducted by NESPAK (2007) is already presented in Chapter 2. In conjunction with this study, the seismic zone factors and other related provisions in BCP-2007 are adopted from the UBC-97 for proposing the seismic analysis and design procedures. The seismic zone of each administrative unit (tehsil) in the country is provided in BCP-2007 in a tabular form. The Chapter 16 Appendix of UBC-97 also provides the list of compatible seismic zones for major regions and cities of the world. In this list, the seismic zones of four major cities of Pakistan (Lahore 2A, Islamabad 4, Peshawar 4, and Karachi 4) are also included. However, the NESPAK PSHA resulted in lower PGA values for Islamabad, Peshawar and Karachi and therefore these cities were included in zone 2B. Bonowitz (2015) suggests that this lower zonation of the BCP-2007 reflects the engineering criteria used by leading Pakistani firms over the previous two decades.

Beside NESPAK (2007), several other studies have also presented the PSHA of Pakistan and surrounding region. A comparative analysis of these studies can also help us in understanding a more clear picture of the seismic hazard of the country. However, we start the discussion with an overview of the seimso-tectonic environment of Pakistan.

3.2   Seimso-tectonic Environment of Pakistan – A Quick Overview

Pakistan lies in a seismically active and earthquake-prone region of the world. The country and its surrounding region possess a complex seismo-tectonic environment where Arabian, Indian, and Eurasian tectonic plates are interacting with different rates of movement (Kazmi and Rana 1982). In the northern part of Pakistan, the Indian plate is in a state of a slow head-on collision (spanning over 50-55 million years) with the Eurasian plate at a rate of 3.7-4.2 cm/year (Chen et al. 2000). The country is located on the north-west edge of the Indian plate as shown in Figure 3-1 (Khan et al. 2008). The convergent boundary between two continental plates, also referred to as North Collision Boundary, NCB (indicated as Mark-1 in Figure 3-1) has resulted in the development of Himalayan orogenic belt and Hazara Arc (Kazmi and Rana 1982; Molnar and Tapponnier 1977; Perry et al. 2019; Seeber et al. 1981). The north-west Himalayan folds and thrust belt stretches from the eastern Kashmir basin to the western Afghan border near Parachinar. The major thrust faults in the northern Pakistan include the Main Boundary Thrust (MBT), Punjal Thrust (PT), Salt Range Thrust (SRT), the Himalayan Frontal Thrust (HFT), Hazara arc, and Himalaya arc. The NCB has also resulted in the development of two complex subduction zones with deep brittle seismological structures; the Hindukush and the Pamir ranges (Negredo et al. 2007). The Pamir range extends from Hindukush ranges in the west through the Wakhan (Afghanistan), Chitral (Pakistan) to Kongur Tagh (China) in the east (Arnaud et al. 1993). Most part of the Pamir range is located in Tajikistan (Central Asia). The Hindukush range is the extension of Karakorum, Himalaya and Pamir mountain range (Searle and Mike 2013) and stretches from Afghanistan to northern Pakistan and China with a length of 800km. Both of Pamir and Hindukush ranges are situated in the north-west of the country and are the center of deep earthquakes.

In the west, the convergence of Indian and Eurasian plates forms an oblique collision zone. This West Collision Boundary (WCB) is indicated by Mark-2 in Figure 3-1. The well-known sinistral strike-slip faults such as Chaman, Ghazaband, and Ornach-Nal faults, and Sulaiman-Kirthar mountain ranges are the results of this inclined collision. The rate of left lateral shear between these two plates is approximately 3.0 cm/year (Khan et al. 2008). The western thrust belt includes Sulaiman and Kirther belt, extends 600km from Khuzdar in the south towards the north, which then bends in the Quetta Syntaxes towards the southeast (Bannert and Raza

1992). The thrust faults such as Kohlu, Mekhtar and Ziarat are also located in the northern part of this fold and thrust range (Bannert and Raza 1992; Kazmi and Jan 1997). At the end of the Sulaiman range (SR), the mountain range turn towards the west for approximately 300 km, which again take a sharp turn towards the south near Quetta (Rafi et al. 2012). This complex tectonic structure is called the Quetta Transverse Zone (QTZ) and is located in the east of WCB as depicted in Figure 3-1. The QTZ is comprised of several thrust faults (e.g. Ghazaband fault) and folds that are associated with the Indian-Eurasian plate boundary (Quittmeyer et al. 1979).

In the south of Pakistan, the Arabian plate (the oceanic floor of Oman) is subducting under the Eurasian plate with a dip angle of 10 degrees extending 400-500 km towards the north (Byrne et al. 1992) resulting in the development of Makran Subduction Zone (MSZ) (Apel et al. 2006). The annual subduction rate of the Makran Subduction Zone (MSZ) is between 32 to 35 mm/year (McClusky et al. 2003) on the eastern side. While at the western side between Oman and Iran, the convergence rate is 19.5 mm/years (Musson 2009). The MSZ is indicated by Mark-3 in Figure 3-1 (Farhoudi and Karig 1977; Shearman et al. 1976; Stoneley 1974). It is located in the southeast of Iran and southern Pakistan that extends for almost 900 km along the Eurasian-Arabian plate boundary (Zarifi and Raeesi 2010). The eastern margin of the Makran subduction zone is the left-lateral (sinistral) transform fault called the Ornach-Nal fault which is the southward extension of the Chaman fault (junction between the Eurasian and Indian plates). The Minab fault system (Zagros fold and thrust belt) in Iran forms the western margin of the Makran subduction zone (Regard et al. 2010).

This complex geo-tectonic environment has posed a high level of seismic hazard to Pakistan and its surrounding regions. In the past, the country has been hit by some major and devastating earthquakes resulting in a huge number of fatalities as shown in the Table 1.
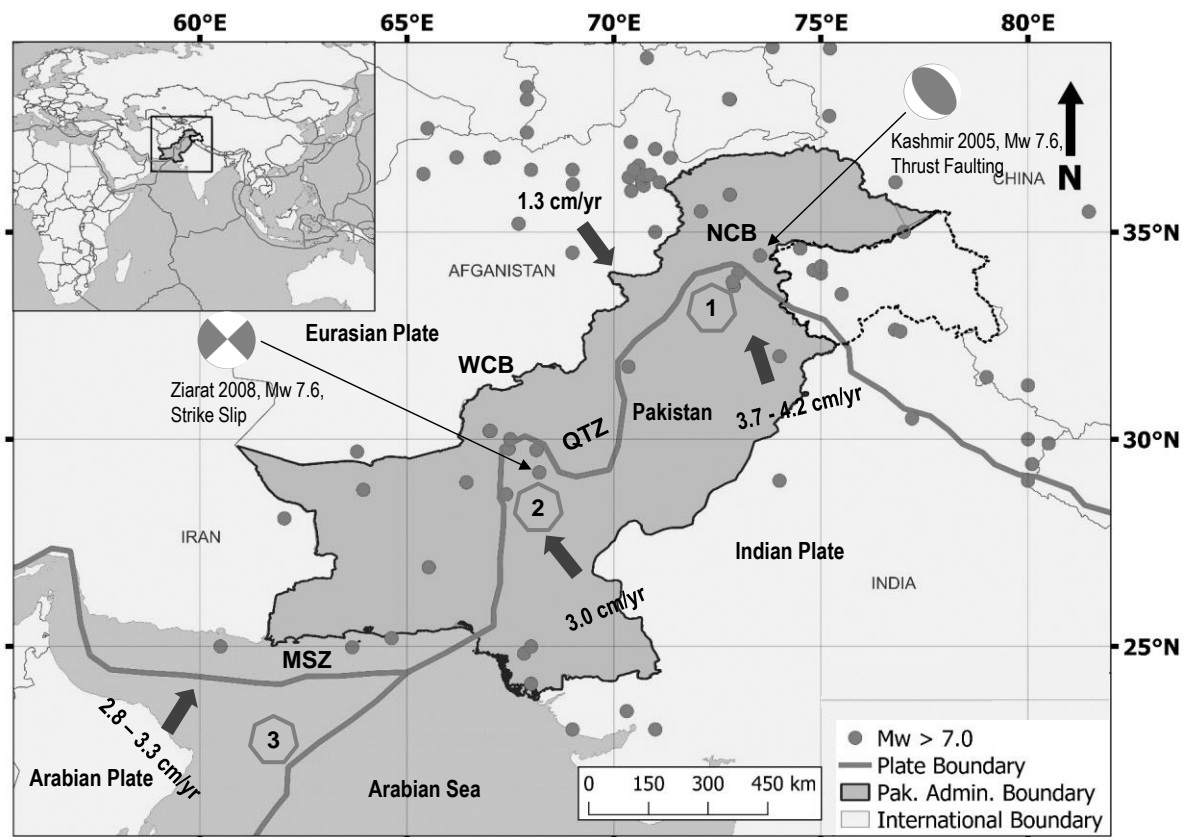
Figure 3-1: The seismo-tectonic environment of Pakistan. Arrows depict relative plate motions and velocities among the three tectonic plates i.e. Indian, Eurasian, and Arabian. The velocities of plates are extracted from Bird (2003); Jade (2004); Sella et al. (2002); Vernant et al. (2004).

Table 3-1: Some major earthquake events and the number of fatalities occurred in Pakistan and adjoining regions

Date	M_w	Location	Deaths	Source
24/09/2019	5.6	Mirpur, Azad Kashmir	38	(USGS 2019)
25/12/2015	6.3	Gilgith-Balthistan	4	-do-
26/10/2015	7.5	Badakhshan, Afghanistan	399	-do-
28/09/2013	6.8	Awaran, Balochistan	400	-do-
24/09/2013	7.4	Awaran, Balochistan	825	-do-
18/01/2011	7.2	Dalbandin, Balochistan	3	-do-
29/10/2008	6.4	Ziarat, Balochistan	215	-do-
08/09/2005	7.6	Balakot , Azad Kashmir	73000	(Durrani 2005)
27/02/1997	7	Balochistan region	57	(ISC 2019)
28/12/1974	6.2	Khyber Pukhtunkhwa	5300	(Utsu 2002)
28/11/1945	8.2	Makran, Balochistan	300-600	-do-
31/05/1935	7.7	Ali jaan, Balochistan	30000 - 60000	(Bangash 2011)
21/10/1909	7	Sibi, Balochistan	100	(Quittmeyer and Jacob 1979)
24/09/1827	7.8	Lahore, Punjab	1000	-do-
16/06/1819	7.7-8.2	Allahbund, Sindh	>1543	-do-
02/05/1668	7.6	Sindh region	50000	-do-

3.3 Challenges and Frontiers in Accurate Characterization of Seismic Hazard in Pakistan

Before we review some of the existing studies to assess the seismic hazard of Pakistan, let's first identify some major areas which should be focused in near future in order to achieve a long-term goal of developing earthquake resilient infrastructural facilities in Pakistan. Figure 3-2 presents a list of all such areas. Some of these areas (e.g. the characterization of local seismic sources, development of updated earthquake catalogue for Pakistan, the development of ground motion prediction equations or attenuation models and ground motion parameters) are related to the probabilistic seismic hazard assessment. These will be discussed in succeeding section. Besides, several equally important and related issues also need to be addressed on priority. Some of them (e.g. the detailed site response analysis, investigation of the basin effect at local soft soil deposits etc.) will be emphasized here using the following three examples.

Accurate Characterization of Seismic Hazard for Pakistan

- Characterization of Seismic Sources
- Updation of Existing Local Earthquake Catalogues
- Site/Soil Characterization
- Ground Motion Prediction Equations (GMPEs) or Attenuation Models
- Ground Motion Characteristics
- Ground Motion Parameters
- Hazard Mapping for Adequate Levels of Resolution
- Probabilistic Seismic Hazard Analysis (PSHA)
- Seismic Deaggregation Analysis
- Site Response Analysis
- Site Amplification Effects
- Liquefaction Potential of Local Soils

Figure 3-2: Some key areas to be focussed in order to completely characterize the seismic hazard in Pakistan.

Example 1 – Shear wave velocity (V_s^{30}) profile of the country: The velocity of shear waves in first thirty meters of soil (referred as V_s^{30}) is an important property of soil stiffness. The site and soil classification in almost all conventional building codes is based on V_s^{30} values. The site class (along with the seismic zone factor) is then used as an input in Uniform Building Code (UBC-97) to determine the site coefficients C_a and C_v. Similarly, the site class is also used to determine the site modification factors F_a and F_v in IBC-2000 onwards. Currently for Pakistan, there exists no comprehensive and experimentally-backed study focused on the determination of shear wave velocity at different depths. In conventional design practice, the site soil investigation is mainly focused on the determination of bearing capacity of the soil. The standard penetration test (SPT) is also sometimes conducted and the N value is reported. The SPT-N can also be used to determine the site class using the classification guidelines prescribed in different building codes. However, the site classification is not the only input required for any detailed seismic evaluation of structures. In order to quantify the local soil amplification effects, it is also important to determine the dynamic characteristics of soil deposits. Similarly, the determination of damping and energy dissipation properties of local sites is also an important area which requires attention. As an example of what is required, an approximate (slope-derived) V_s^{30} map for Pakistan is shown in Figure 3-3.

Example 2 – An accurate characterization of tectonic setting of the country: The complex tectonic environment of Pakistan requires diligent efforts to characterize the seismic sources contributing towards the hazard in the country. Several studies have recently focused this issue. A summary of such studies will be presented in succeeding section. Here, an example of a comprehensive study is shown in Figure 3-4. In this study, conducted by Zaman (2016) and Zaman & Warnitchai (2016), several major tectonic features are identified and studied to produce a reliable seismic source model for hazard analysis of the country. Several other studies have also aimed to accurately model the shallow crustal fault sources in Pakistan and a summary will be presented in next sections.
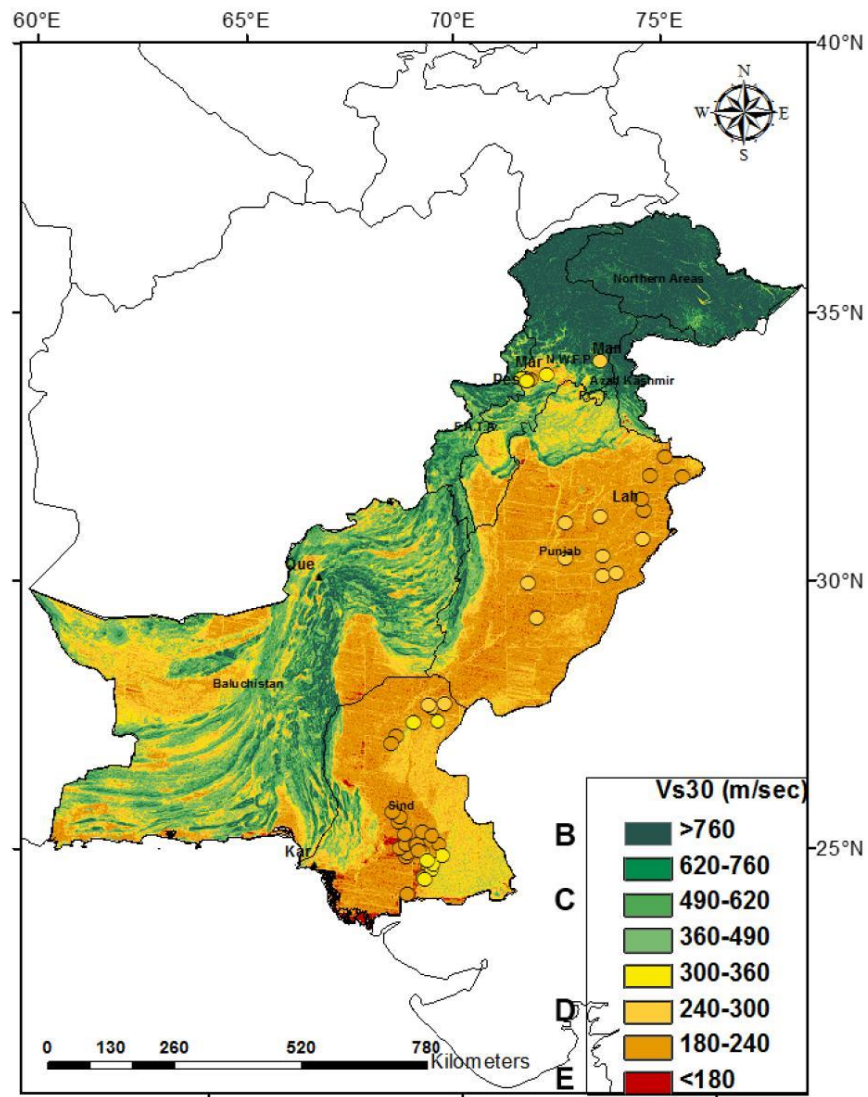
Figure 3-3: The slope-derived V_s^{30} map for Pakistan

Color-coded circles by V_s^{30} (m/sec) indicate the location of compared V_s^{30} measurements. Man (Mansehra), Mar (Mardan) Pes (Peshawar), Lah (Lahore), Que (Quetta), Kar (Karachi). Source: Zaman and Warnitchai (2016).
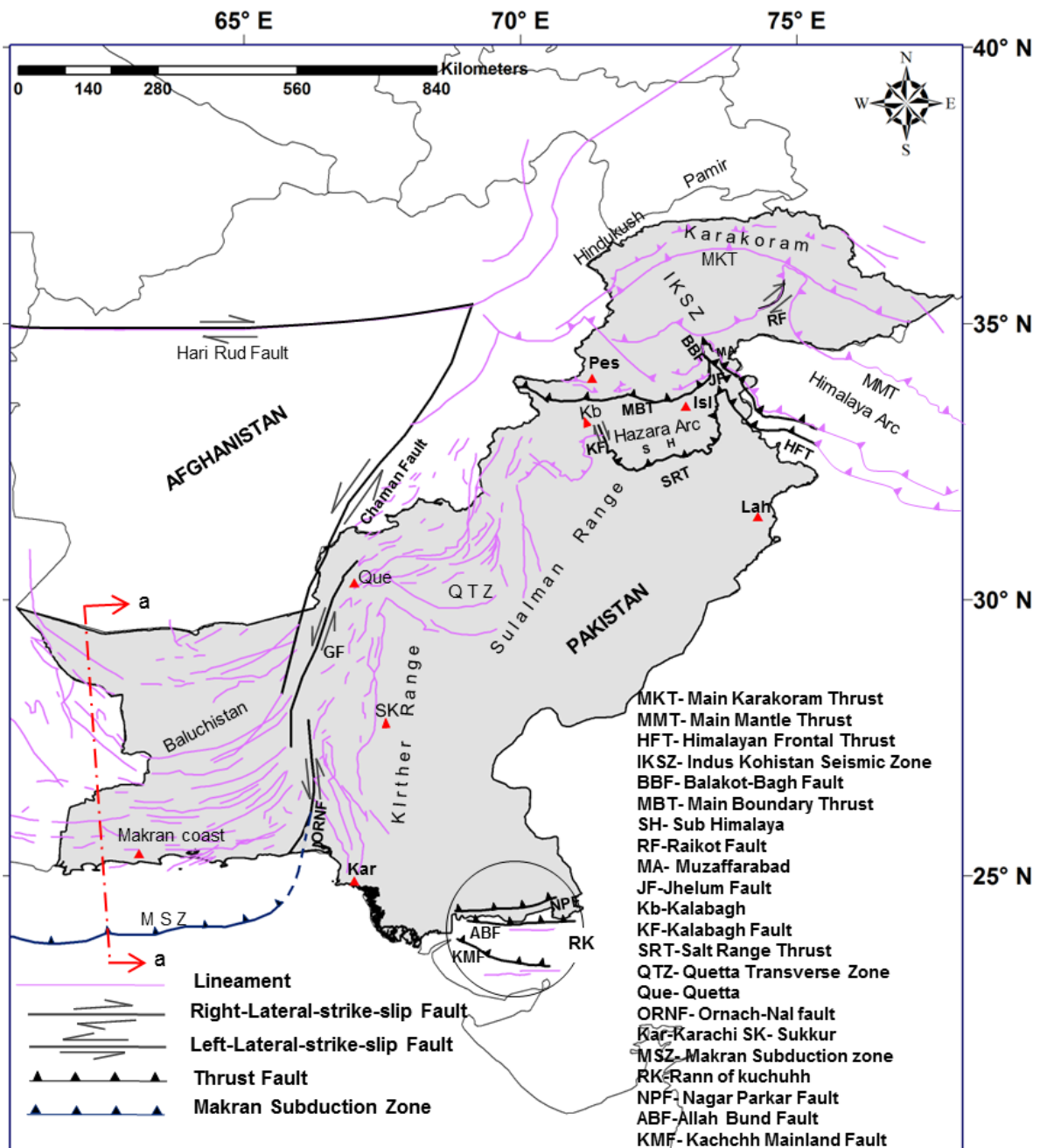
Figure 3-4: The regional tectonic setting of Pakistan (Modified from Sarwar et al., 1979). Source: Zaman (2016)

Example 3 – Site response analysis and basin effects: The third example is related to the site response analysis and potential basic effects at several local sites in Pakistan. The need to focus these areas can be emphasized using the following example. The only significant recorded acceleration time history (available in literature) during the 8th October 2005 Kashmir earthquake (M_w 7.6) is reported by Durrani et al., (2005). It is recorded at Abbottabad and is possibly obtained from the Directorate of Structural Design at the Pakistan Atomic Energy Commission. The three components of this acceleration time history are shown in Figure 3-5 while the 5%-damped elastic response spectrum of EW component of this ground motion is shown in Figure 3-6. The comparison with standard design spectrum prescribed in BCP-2007 is also shown in this Figure.

A significant mismatch between the spectra of actual recorded ground motion and the code-prescribed design spectra for various site classes can be observed in the time period range between 1 and 2 sec. The spectral

shape for this ground motion doesn't match with the typical short-period ground motions (with peak spectral accelerations lying in the time period range of 0.2 sec to 0.5 sec). Instead, a higher spectral acceleration in an unusual range of 1 sec to 2 sec is observed. This can potentially be the result of site amplification and basic effects. In the conventional response spectrum analysis (RSA) procedure for the seismic design, the equivalent static force vectors for each significant vibration modes are directly proportional to the spectral acceleration. Since the RSA procedure is applied to a linear elastic computer model, the resulting seismic demands (displacements, drifts, shear forces and bending moments etc.) are also proportional to the spectral acceleration. This means that the buildings with first-mode natural time periods lying in the range of 1 sec to 2 sec have experienced almost twice the seismic demands compared to those used for the purpose of their seismic design according to BCP-2007. Moreover, the code design provisions recommend to reduce the seismic demands by a response modification factor (or behavior factor) with a value ranging between 1.5 to as much as 8. This factor would have further increased the mismatch between design seismic demands and the actual demands experienced by the structures during the 8th October 2005 Kashmir earthquake (M_w 7.6). Our structural analysis and design can be significantly inaccurate if we ignore the site amplification effects. While discussing the unusual spectral shape for this recorded ground motion at Abbottabad, Durrani et al., (2005) writes;

The 5% elastic spectrum shows a relatively broad range of high amplification, from 0.4 to 2.0 seconds. The highest amplification is about 4.0. This is compared to the value of 2.6, which is the 84 percentile amplification factor given by Newmark and Hall (1982), thus indicating the relative severity of the Abbottabad record. The range of periods corresponding to high amplifications is also unusual, extending to 2.0 seconds. Such a feature would result in relatively high demand imposed on both short and intermediate-long period structures Durrani et al., (2005).
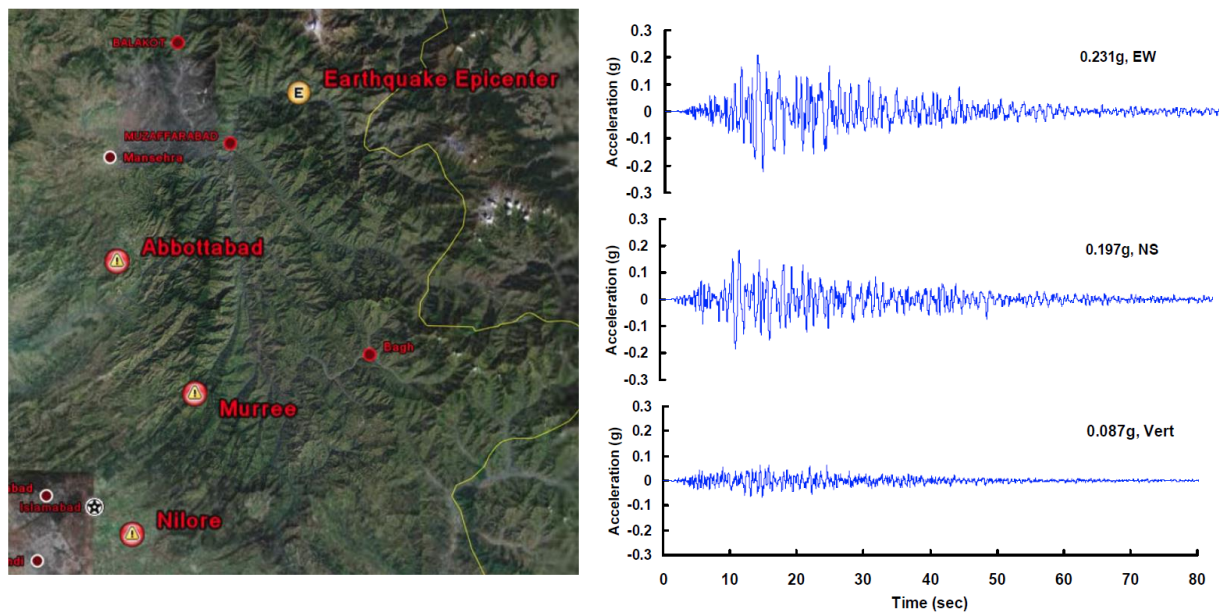
Figure 3-5: The recorded acceleration time histories at Abbottabad during the 8th October 2005 Kashmir earthquake (M_w 7.6). Source: Durrani et al., (2005)
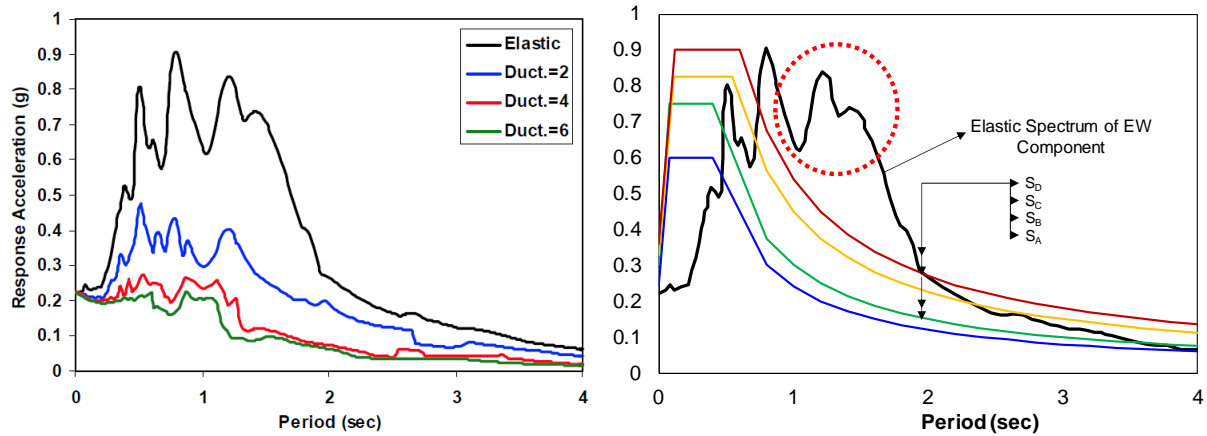
Figure 3-6: The 5%-damped elastic response spectrum of EW component of recorded acceleration time history at Abbottabad during the 8th October 2005 Kashmir earthquake (M_w 7.6). The comparison with standard design spectrum prescribed in BCP-2007 is also shown. Source: Durrani et al., (2005)

3.4   The PSHA of Pakistan – An Overview of Existing Studies

As part of the attempts to mitigate the seismic risk, various efforts have been made in the past to estimate the likelihood of seismic ground shaking in the region. The first seismic hazard assessment for Pakistan was carried out in 1986 to develop a consistent seismic design criteria for inclusion in the Pakistan Building code (BCP 1986). This study was based on a catalogue developed using instrumentally recorded earthquakes from 1905 to 1979 CE (Rossetto and Peiris 2009). Based on the hazard defined by the ranges of Modified Mercalli Intensity (MMI) scale, the country was divided into four seismic zones (BCP 1986). Later, a more comprehensive probabilistic seismic hazard analysis (PSHA) was carried out as part of the Global Seismic Hazard Assessment Program (GSHAP) (Giardini and Basham 1993; Giardini et al. 1999; Zhang et al. 1999). Under this program, the PSHA of Pakistan and surrounding region was carried out using the classical methodology developed by Cornell (1968) and McGuire (1978). This methodology is based on the area source delineations and assumes a uniform rate of seismicity in each separated source zone. An intrinsic limitation of this method is that the seismic hazard assessment results can be significantly affected by the delineation of these source zones which are mainly dependent on the subjective judgment of the hazard analyst. In GSHAP (Giardini and Basham 1993; Giardini et al. 1999; Zhang et al. 1999), more than twenty seismic area sources were delineated for Pakistan and surrounded areas. The results were presented in the form of a map showing the peak ground acceleration (PGA) with a 10% probability of exceedance in 50 years.

After the devastating M_w 7.6 Kashmir earthquake in 2005, the government of Pakistan took an initiative to develop the seismic provisions for the revision of the Pakistan Building Code (BCP 1986). The Ministry of Housing & Works (MOHW) assigned this task to National Engineering Services Pakistan (NESPAK), a leading consulting organization in the country. An updated PSHA (Shabbir and Ilyas 2007) of the country was performed using the methodology developed by Cornell (1968) and McGuire (1978). The updated PGA map was developed as a result of this study. Following the code framework from the Uniform Building Code (UBC 1997), the country was divided into 5 zones (zone 1, 2A, 2B, 3 and 4) based on the PGA values. In 2007, this zonation map, along with several seismic provisions, were included in an updated version of the Building Code of Pakistan (BCP 2007). Meanwhile, another detailed PSHA was conducted by the Pakistan Meteorological Department (PMD) in collaboration with the Norwegian Seismic Array (NORSAR) (PMD and NORSAR 2007). Based on the conventional methodology (Cornell 1968; McGuire 1978), 19 seismic area sources were delineated in this study. Moreover, the seismicity of Hindukush region was also classified into shallow, intermediate and deep layers (0-30 km, 30-120 km and 120-300 km). The values of PGA and spectral acceleration (SA) at the natural periods of 0.2, 0.5, 1.0 and 2.0 sec were reported for the return periods of 50, 100, 200, 500 and 1000 years.

In last decade, several improved PSHA studies were conducted to assess the seismic hazard of Pakistan and surrounding areas. Ali (2011) used the conventional Cornel-McGuire methodology (Cornell 1968; McGuire 1978) to develop the updated seismic hazard maps of Pakistan. Later, Zaman et al. (2012) also conducted a detailed PSHA study to develop a comprehensive set of hazard maps, hazard curves and uniform hazard spectra for various regions of Pakistan. In this study, the procedure used to develop the US national seismic hazard maps (NSHMP) (Petersen et al. 2008) was adopted. This procedure includes the spatially-smoothed gridded seismicity approach (Frankel 1995) which has been successfully applied in many countries (Frankel 1995; Lapajne et al. 2003; Lapajne et al. 1997; Ornthammarath et al. 2011). Using an earthquake catalogue, this approach represents the hazard with spatially-smoothed seismicity parameters in areas where the historical fault surface ruptures are absent or the causative seismic sources are largely unknown. However, the historical seismicity alone may not satisfactorily reflect the hazard at low probabilities of exceedance (e.g., 0.0004/year corresponding to 2,475 years return periods). Therefore, in this study, some crustal faults having enough geological and paleoseismic evidence and slip rates were also modeled beside the smoothed seismicity. Moreover, the subduction source model for the Makran Subduction Zone (MSZ) was also included. More recently, the PSHA of Pakistan is also conducted as part of the Earthquake Model of Middle East (EMME) (Şeşetyan et al. 2018). In this study, a combination of spatially-smoothed seismicity approach (Frankel 1995) and the conventional area sources approach was used to develop the hazard maps of the country.

3.5 Why an Updated and Comprehensive PSHA Study is Required?

With all of these studies mentioned above, *why we still need an updated PSHA study for Pakistan? Is the seismic hazard of the country increasing with time?* To answer these questions, we may need to go into the actual process of estimating the hazard at a particular site.

Firstly, we don't have any scientific evidence that the earthquake phenomenon *per se* is increasing globally with time. We have around 100 years of historical seismicity data for the magnitude and location of earthquakes. If we group the historical earthquake data in a series of a smaller time window, say 5 years, it may mislead us in believing that the total number of earthquakes are increasing with time. This may also match with our observation that the social and economic loss caused by earthquakes is also globally increasing with time. However, this observation would be wrong. If we analyze the data by dividing it in a series of larger time window, it can be easily observed that the earthquake events are distributed randomly in the history. The number of earthquakes in a particular larger window of time would be almost same as other windows in the history and they are not following any increasing trend. Therefore, the actual level of seismic hazard is not increasing with time. In fact, what is increasing is the "seismic risk". The risk is often characterized as a product of site's seismic hazard and the vulnerability of the structure. A rapid growth in population and unsustainable urbanization in Pakistan is resulting in increased seismic vulnerability of structures. The need for more and versatile infrastructural facilities is exponentially increasing in the country. The engineering design practice, on the other hand, is still based on conventional and sometimes almost obsolete procedures. A rapid increase in non-engineered construction (especially low-rise brick masonry buildings) have also rendered our cities vulnerable to earthquake damage. Over the years, these challenges are resulting in an increase in seismic vulnerability of structures. Resultantly, we are facing an increasing seismic risk in the region.

As mentioned in preceding section, several PSHA studies have been conducted for Pakistan and surrounding regions. Each of these studies portray a different picture of the seismic hazard of the country. Sometimes, the difference in PGA or SA values for a particular site is even different by a factor of 2-3. If the actual level of seismic hazard almost remains the same in a particular region (as discussed earlier), why these studies have resulted in a different predictions? The answer lies in the uncertainties associated with the process of this prediction. In fact, the work "prediction" should not be used for seismic hazard analysis. A right word would be "forecasting". The PSHA process forecasts the likelihood and level of the future earthquakes in a study region. In this process, all the uncertainties (aleatory and epistemic) are accounted using different techniques. The basis for this forecasting is the historical seismicity data and geological features of the region. Moreover, this

forecasting is done in a probabilistic framework (similar to the weather forecasting). The earthquake occurrence rates determined for each contributing seismic source is integrated to obtain the total hazard of a particular site. Following are some important factors which may affect the results of a PSHA study.

a) **Comprehensiveness of Earthquake Catalogue:** Nowadays, there are several well-established international seismic monitoring networks which can record the strong motion data in real-time. With time, the number of recorded events are increasing and therefore, the earthquake catalogues being used in the PSHA process are getting more and more detailed. Recently, several studies have also focused on compilation of updated earthquake catalogues. For any PSHA study, this process of catalogue compilation is performed using different national and international databases and the final number of events may be different in each case. For example, the NESPAK (2007) catalogue developed for the BCP (2007) included the earthquake events from 1668 CE to 2006 CE. Similarly, Zare et al. (2014) developed an earthquake catalogue for the Earthquake Model of Middle East (EMME) project which included the whole region of Pakistan. The earthquake events in this catalogue were reported up to 2014 CE. More recently, Khan et al. (2018) have also developed an earthquake catalogue which contains seismic events up to 2016 CE. Table 3-2 presents a comparison among these three catalogues.

Table 3-2: The earthquake catalogues compiled by different studies for Pakistan and surrounding region.

Study	NESPAK (2007)	Khan et al. (2018)	Zare et al. (2014)
Time Span	1668 CE – 2006CE	25 AD – 2016CE	1250 BC – 2014 CE
No. of Events	5428	7579	7272

Since the developed catalogue is the basis for future forecasting of seismic hazard, the results of PSHA from different studies may be different depending upon the quality of catalogue.

b) **Magnitude and Location Uncertainties:** The accuracy of magnitude and locations for recorded events in different international databases is different. There may exist significant errors in these parameters especially for historical events. The process of converting the information from historical records and literature into the modern day magnitude scale and epicentral locations can induce a significant uncertainty in the PSHA process. The results of different studies may be affected differently by these uncertainties.

c) **Seismic Source Delineation and Modeling – Background Seismicity:** The historical seismicity data and geo-tectonic features of an area are used to delineate and model the seismic sources for the PSHA process. These seismic sources can be point sources, line sources or area sources. The conventional PSHA is based on the consideration of area sources only, while the seismicity is assumed to remain uniform within an area source. However, a latest approach recommends to model the background seismicity using the smoothed gridded seismicity approach. This approach can better capture the variation of background seismicity in a region. Different studies can opt for different source modeling techniques which may affect their results.

d) **Seismic Source Delineation Modeling – Crustal Faults:** The conventional PSHA procedure forecasts the hazards using only the area sources. However, the crustal faults can also be explicitly modeled with their magnitude-recurrence relationships. A significant amount of research has been conducted in last 3 decades related to the modeling of crustal faults. However, the accurate fault parameters (slip rates, fault geometry etc.) are not available for some existing faults in Pakistan. Therefore, their accurate modeling and resulting contribution towards total seismic hazard at a site cannot be accurately captured. Different PSHA studies have addressed this issue differently ranging from no consideration of crustal faults on one side, to explicit modeling of more than 100 faults on

the other side. Resultantly, their forecast vary significantly especially for areas in close vicinity of active crustal faults.

e) ***Ground Motion Prediction Equations (GMPEs):*** The GMPEs (or attenuation models) are a set of equations which relate the rate of decrease in a ground motion parameters (e.g. PGA or SA etc.) with an increase in source-to-site distance. Based on the statistical analysis of huge datasets, several GMPEs are proposed in last few decades for stable continental regions, active tectonic regions and subduction zones. The most commonly used GMPEs are developed by an initiative known as the "Next Generation Attenuation (NGA)" by the Pacific Earthquake Engineering Research (PEER) Center of UC Berkeley. Due to very limited availability of recorded strong motion data in Pakistan, no GMPEs are yet developed for the ground motion parameters produced by earthquakes in this region. Therefore, different PSHA studies have opted to use the well-known GMPEs developed for datasets with similar tectonic environment as of Pakistan and surrounding regions. With time, the GMPEs available in literature are being updated as the new recorded data is available. Therefore, the results of PSHA may also get affected by the selection and update of available attenuation models.

f) ***Epistemic Uncertainties:*** With a range of uncertainties in the selection of seismic source modeling, magnitude-recurrence relationships, GMPEs and other factors, the epistemic uncertainties are often handled using different techniques. One commonly used technique is the logic tree approach in which a weighted average of all available options is determined. The weights for each option (e.g. source models, recurrence relationships or GMPEs) are selected based on the confidence we have on the adequacy of that option for the region of interest. Since, different studies may use different ways to handle these uncertainties, the resulting hazard forecast may also be different.

Considering the factors mentioned above, all the PSHA studies have limitations and as our understanding of the earthquake phenomenon increase, there is always a room for improved studies. The difference among the hazard forecasts of different studies can be understood if the adequacy of inherent assumptions made by these studies as well as their implications are known. Bonowitz (2015) also indicates the inconsistencies among the seismic hazard forecasted for Pakistan by different studies. While discussing possible future improvements in the BCP-2007, he writes

The UBC allows for seismicity reductions based on "consideration of regional tectonics and up-to—date geologic and seismologic information" (ICBO, 1997, p2-404). Bilham et al. (2007) describe two more recent efforts to map the country's seismicity: one by the Global Seismic Hazard Assessment Program (GSHAP, 1999) and one that resulted in the 2007 BCP seismic zone map. Both are necessarily imperfect, but the two together show differences that should be resolved at least for policy purposes in the next BCP update. in particular:

- *The GSHAP map suggests higher seismicity than the BCP map along and south of the corridor between Peshawar and Islamabad.*
- *The GSHAP map and Bilham et al. (2007) both suggest that the BCP map underestimates seismicity along the coast south of Karachi. The latter note that the codified seismicity for Karachi and environs should almost certainly be higher than Zone 2B, despite the lack of recent large events there.*
- *In southwest Pakistan, where Balochistan province borders Iran, the GSHAP map shows significantly higher seismicity than would be indicated by the BCP map, which zones this area as 2A or 2B. The April 16, 2013 M7.7 earthquake in this area shook buildings enough to prompt evacuations in Karachi almost 400 miles away. This event produced peak ground accelerations of about 0.24g along the Iran border (USGS, 2013), yet the closest parts of Pakistan are all mapped as Zone 2A, where the 500-year peak ground acceleration is expected to be only about half as high (Bonowitz, 2015).*

3.6   Recent Example of an Improved PSHA Study for Pakistan

A recently conducted PSHA study for Pakistan is briefly explained here as an example. It is conducted at the National University of Sciences and Technology (NUST), Islamabad. Several improvements have been made over existing studies at each step of the PSHA methodology to develop a relatively reliable set of hazard maps, hazard curves and uniform hazard spectra for the region. In contrast to earlier hazard maps of Pakistan, which are mostly computed using the conventional seismic area source zone delineations, this study is based on the combination of spatially-smoothed gridded seismicity, explicit modeling of crustal faults and subduction zone source models. The intrinsic drawback of the earlier method is that the seismic hazard assessment results can be significantly affected by the delineation of these zones, which could be heavily dependent on the subjective judgment of the hazard analysts. The gridded seismicity source model accounts for the expectation that future large and damaging earthquakes will occur close to previous small and moderate-size earthquakes. This approach is also used for the development of the latest US National Seismic Hazard Maps (Petersen et al., 2008). In this section a brief overview of this study is given. The specific details can be seen in Rasheed (2019), and Rahman et al. (2020).

An updated earthquake catalogue of pre-historically reported (AD 10 to 1900 CE), historical (1900 CE to 1964 CE) and instrumentally recorded (1900 CE to December 2018 CE) earthquake events are compiled using multiple international and national databases. The catalogue is then homogenized for the same magnitude scale and declustered to remove the foreshocks and aftershocks. The completeness of catalogue for different magnitude ranges is also checked. The temporal and spatial distribution of final declustered earthquake events is presented in Figure 3-7.
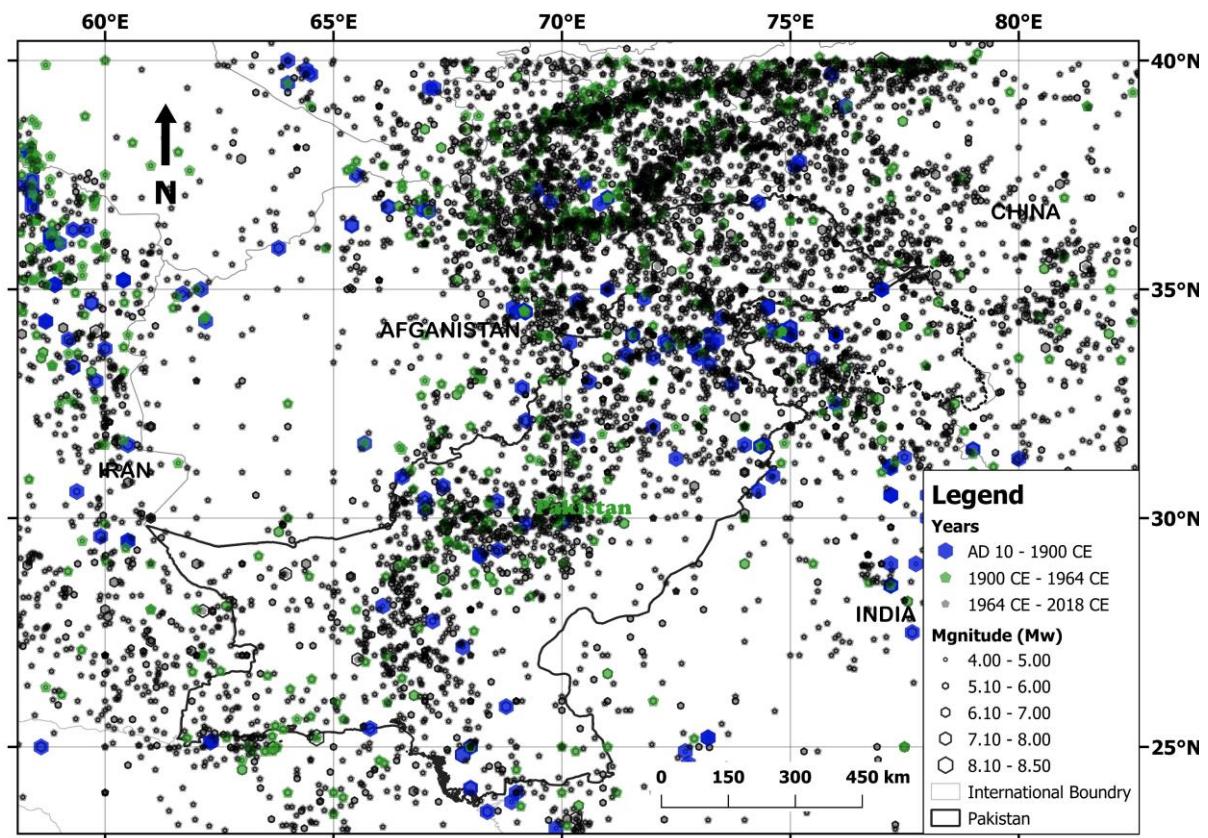
Figure 3-7: The temporal and spatial distribution of final declustered earthquake catalogue consisting of 7845 earthquake events.

Figure 3-8 is depicting that the classification of Pakistan's historical seismicity based on seismogenic depth. The shallow events are mostly concentrated along the main plate boundary. The deep earthquakes, on the

other hand, are mostly concentrated in Hindukush region (mostly outside the administrative boundary of the country). Figures 3-9 and 3-10 further divides the declustered catalogue into shallow ($depth < 50\ km$) and deep earthquakes ($depth > 50\ km$). Around 83% of the total earthquake events are shallow events with focal depth < 50 km.
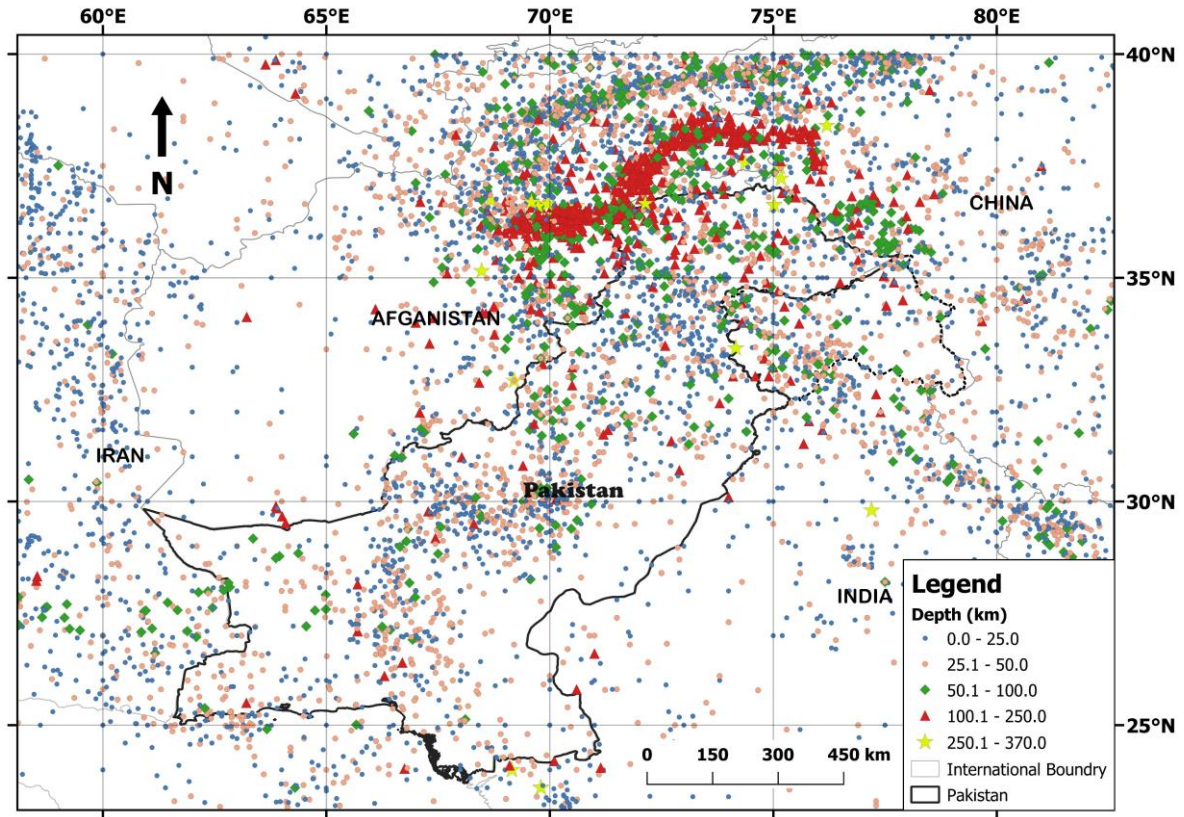
Figure 3-8: The earthquake events in the catalogue classified based on focal depths.
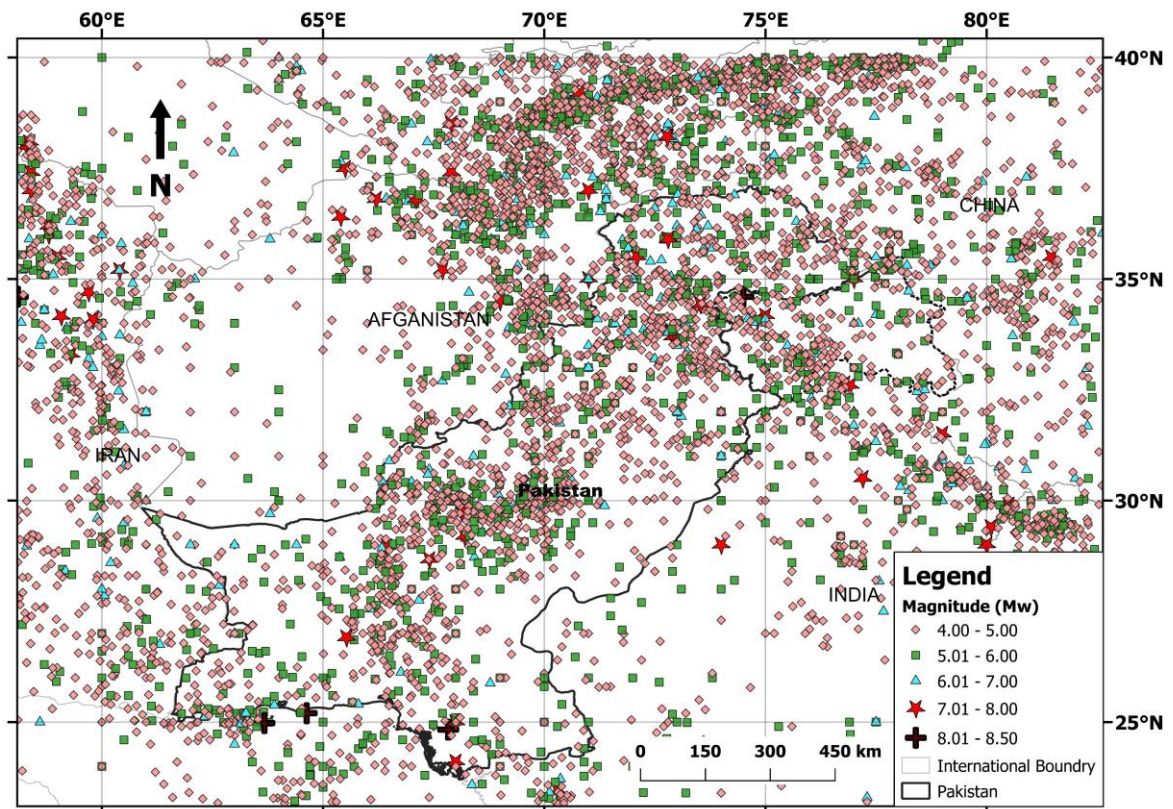
Figure 3-9: The spatial distribution of shallow earthquakes (depth < 50km).
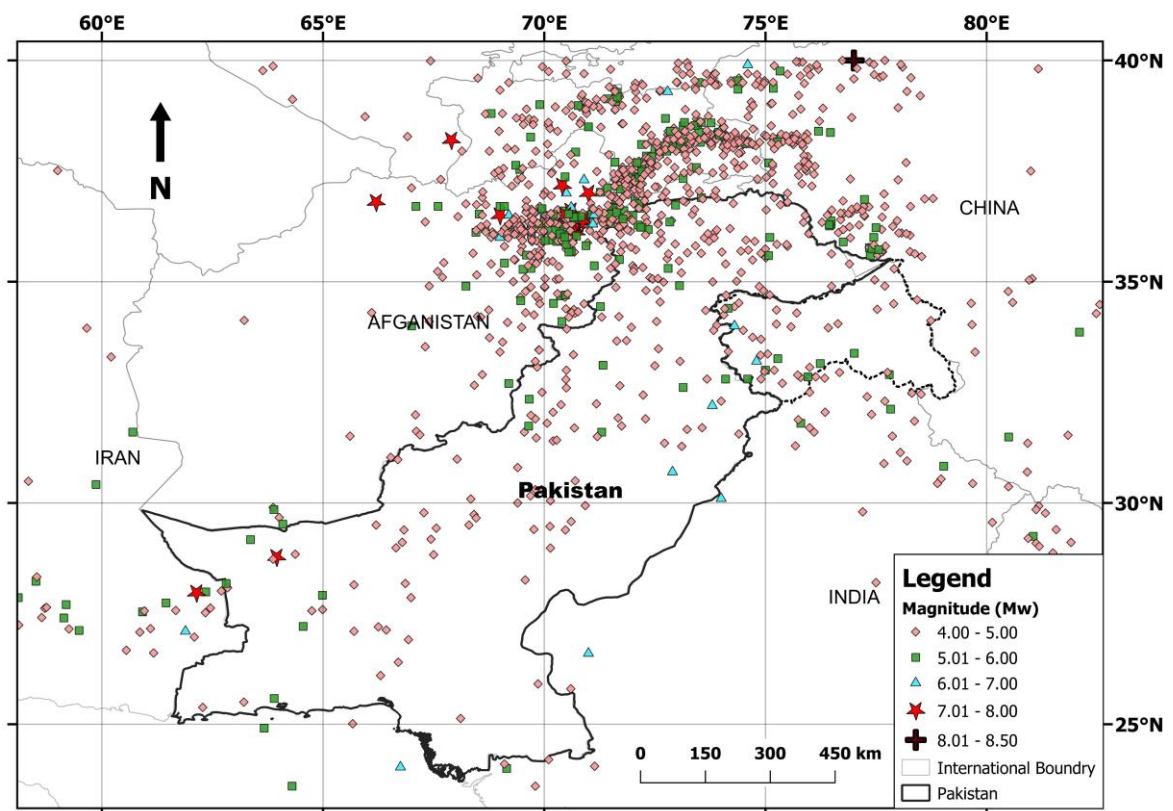
Figure 3-10: The spatial distribution of deep earthquakes (50km < depth < 250km).

The background seismicity of Pakistan is modeled using both the area source zones and the spatially smoothed gridded seismicity approach. The results from both source models are averaged in a logic tree with 50% probability weights assigned to each model. The country and the surrounding areas are divided into 23 shallow crustal source zones (0-50 km) and 5 deep source zones (50-250 km), as shown in the **Error! eference source not found.** 3-11. The delineation of area sources is performed by considering the seismicity pattern and active crustal faults of the region. The principles for delineation of area sources proposed by GSHAP (Giardini 1999) and EMME (Danciu et al. 2018) are also taken into consideration. The magnitude frequency distribution (MFD) for the seismic area source zones is characterized by the truncated Gutenberg-Richter (GR) model (Gutenberg and Richter 1944).
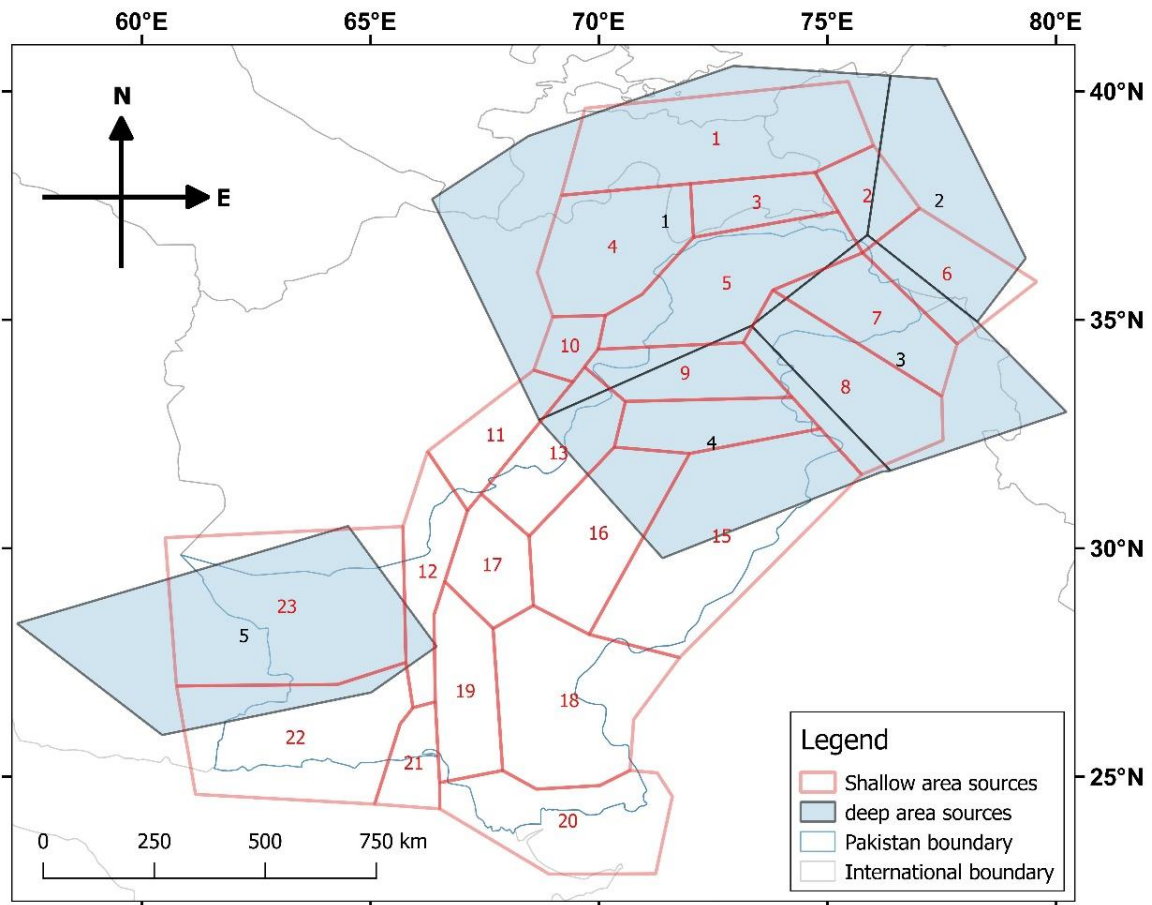
Figure 3-11: The shallow and deep area seismic source zones delineated based on historical seismicity

To avoid the subjectivity introduced due to area source model, Frankel (1995) used the zone free spatially smoothing approach for modelling the background seismicity. In the Frankel (1995) spatially smoothed seismicity approach, the rate of seismicity is estimated by overlaying a grid of specified spacing (in this case $0.1° \times 0.1°$). The number of events having magnitude greater than M_{ref} (reference magnitude) are then counted in each cell for different magnitude intervals. The count represents the maximum likelihood estimate of 10^a for that particular cell. The grid of numbers is then spatially smoothened with a 2-dimensional Gaussian function with a correlation distance (Frankel 1995). For Pakistan region, the activity rate for the background seismicity is computed using the truncated Gutenberg Richter model (GR). The smoothed activity rates i.e. 10^a values derived for the seismogenic depth ranges of 0-50 km and 50-250 km are shown in Figures 3-12 and 3-13 respectively.
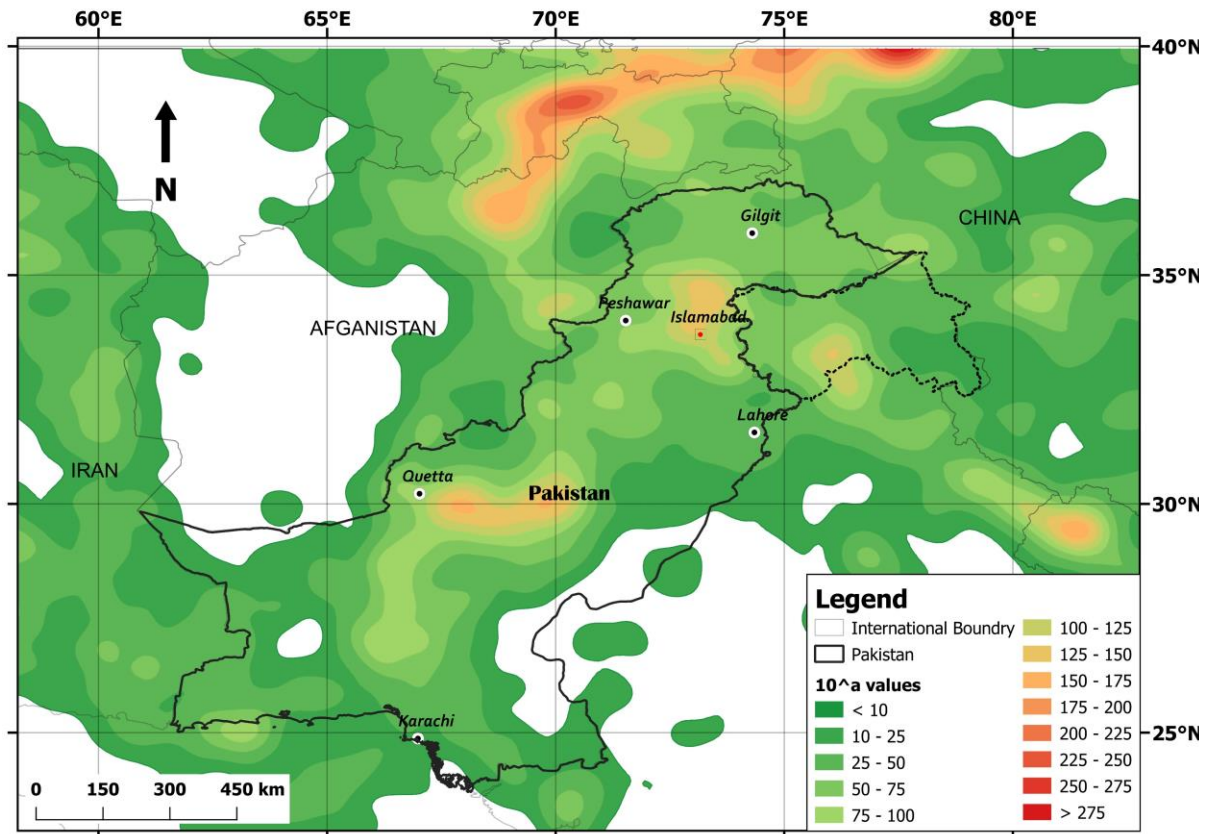
Figure 3-12: Smoothed activity rate 10^a value derived for seismicity from 0-50 km depth.
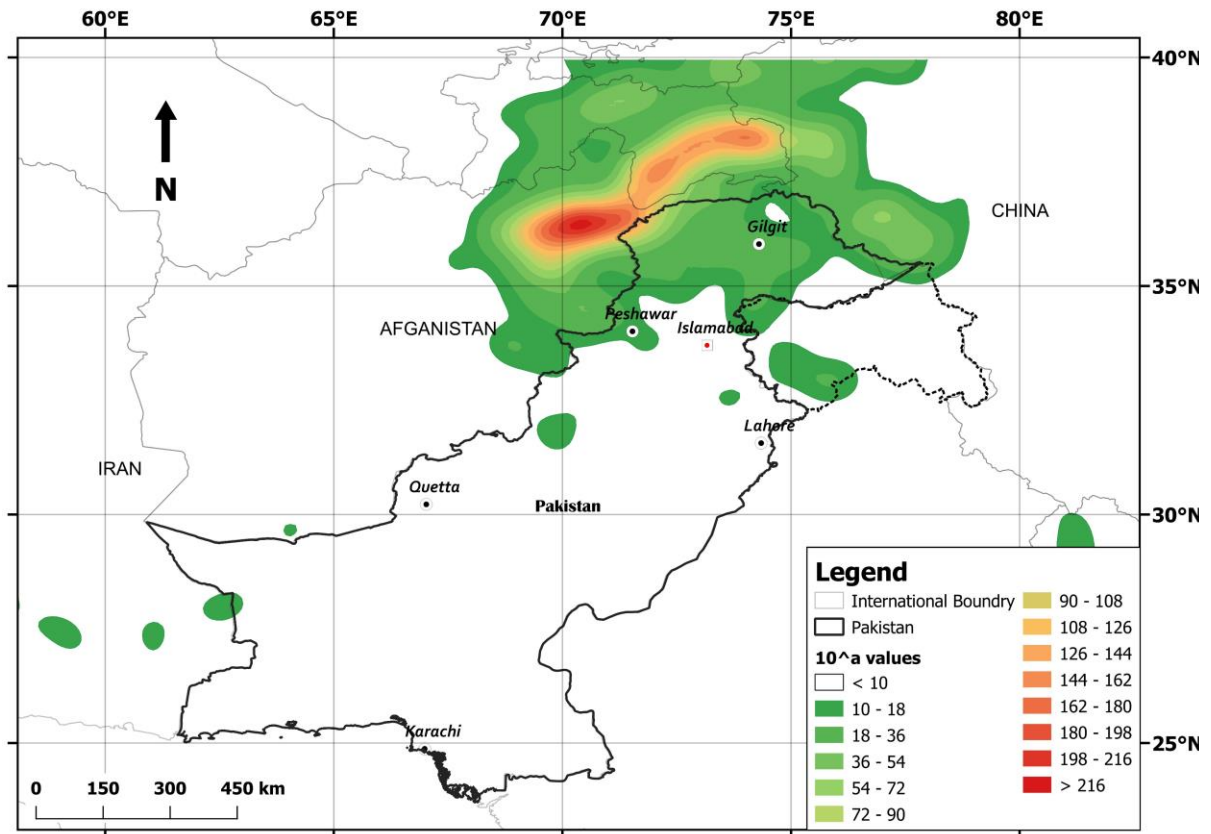
Figure 3-13: Smoothed activity rate 10^a value derived for seismicity from $50 - 250$ km depth.

The crustal fault sources are modeled using their geological slip rates obtained from the updated global active faults database of Global Earthquake Model (GEM 2019) and from the data reported by Kazmi and Jan (1997). A total of 110 active crustal faults in the administrative boundary of Pakistan and surrpunding areas (within 300 km) are incorporated and explicitly modeled as shown in the **Error! Reference source not ound.**3-14. The earthquake recurrence rate for higher magnitude earthquakes on crustal faults is determined by using the geometric parameters, faulting mechanism and geological slip rates of the crustal faults. A number of stochastic recurrence models e.g. (Anderson 1979; Anderson and Luco 1983; Stirling et al. 1996; Youngs and Coppersmith 1985) are available to estimate the fault seismic activity from geological slip rates. To deal with the double-counting of the seismicity from background and active faults, a threshold magnitude of M_w 6.5 (used by ESHM13 and Petersen et al. (2008)) is selected to separate the earthquakes associated to the background from that of the active faults. A symmetric buffer zone (15km) is created on both sides of the active crustal faults. Events having magnitudes smaller than M_w 6.5 are assumed to have occurred in the background buffer zone, whereas events larger than M_w 6.5 are assumed to be fault specific.

The Makran Subduction Zone (MSZ) is also modeled using a combination of inclined area source zone and the spatially smoothened seismicity approach. The 1945 M_w 8.2 earthquake event is the maximum earthquake observed in this region which also generated a tsunami. To characterize the seismicity of this complex area source, the Gutenberg-Richter magnitude recurrence model (Gutenberg and Richter 1944) is used.

Several Ground Motion Prediction Equations (GMPEs) developed by the PEER Next Generation Attenuation (NGA) initiative are employed to estimate the hazard at bedrock level. The logic tree procedure is used to deal with the epistemic uncertainties associated with the source models and GMPEs. The probability weight of 50% is assigned to each model (i.e. the smoothed seismicity with crustal faults, and the conventional area sources) in a logic tree frame. The analysis is performed using the-state-of-art OPENQUAKE engine developed by Global Earthquake Model (GEM) Foundation.
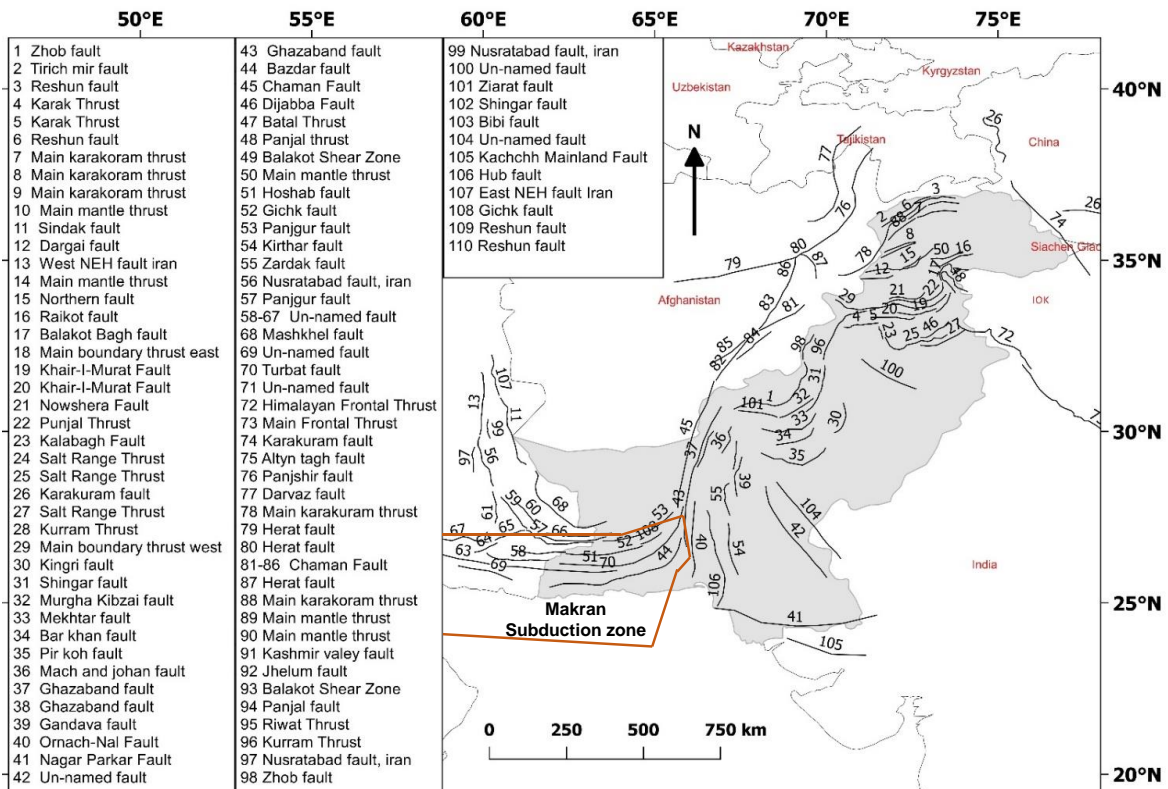
Figure 3-14: The active crustal faults of Pakistan obtained from the GEM (2019) active crustal faults database and Kazmi and Jan (1997)

As mentioned above, several improvements have been made over existing studies at each step of the PSHA methodology to develop a relatively reliable set of hazard maps, hazard curves and uniform hazard spectra for the region. A detailed comparison of the presented study with the previous studies is presented in the Table 3-3.

The maps for the Peak Ground Acceleration (PGA) and Spectral Accelerations (SA) at natural periods of 0.2 sec, 1 sec and 2 sec are developed for the 10% and 2% probability of exceedance in 50 years (DBE and MCE levels, respectively). The DBE and MCE levels correspond to the return periods of 475 and 2475 years respectively. These hazard maps are presented in Figure 3-15. The hazard curves and Uniform Hazard Spectra (UHS) for several major cities of Pakistan are also developed and Presented in Figures 3-16 and 3-17 respectively. The hazard maps show that the pattern of hazard variation in the country is similar to several previous studies (BCP 2007; Rafi et al. 2012; Şeşetyan et al. 2018; Zaman et al. 2012; Zhang et al. 1999), however, the PGA values are higher in varying degrees (except PMD and NORSAR 2007). The computed hazard is significantly higher in northern and southwestern regions of the country which are closer to the main plate boundary, major active faults and the Makran Subduction Zone (MSZ).

These results provide an improved the understanding of seismic hazard in Pakistan. The presented hazard maps, curves and spectra can be effectively used for the purpose of structural design and performance assessment of new and existing structures in the country. They may also be used as the basis for developing the improved strategies for the disaster risk reduction in the country.
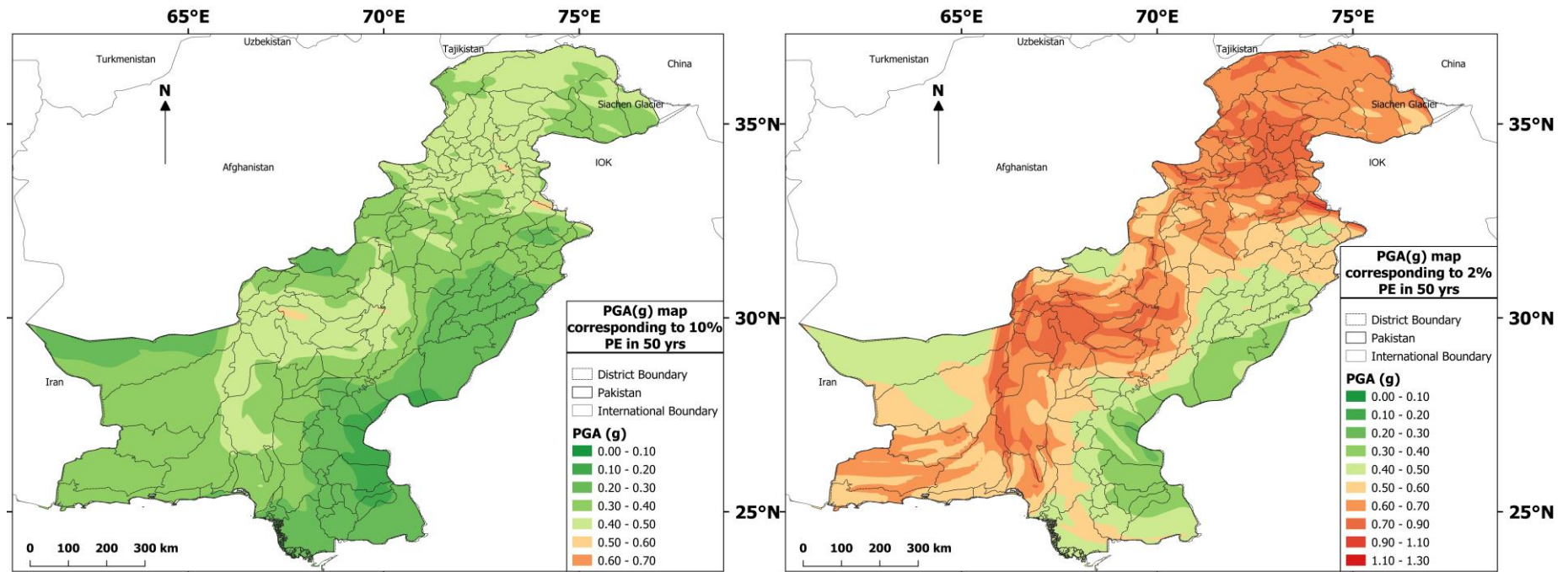
(a) The hazard map of Pakistan for peak ground acceleration corresponding to 10% (left) and 2% (right) probability of exceedance in 50 years [DBE level with 475 years (left) and MCE level with 2475 years (right) return period]
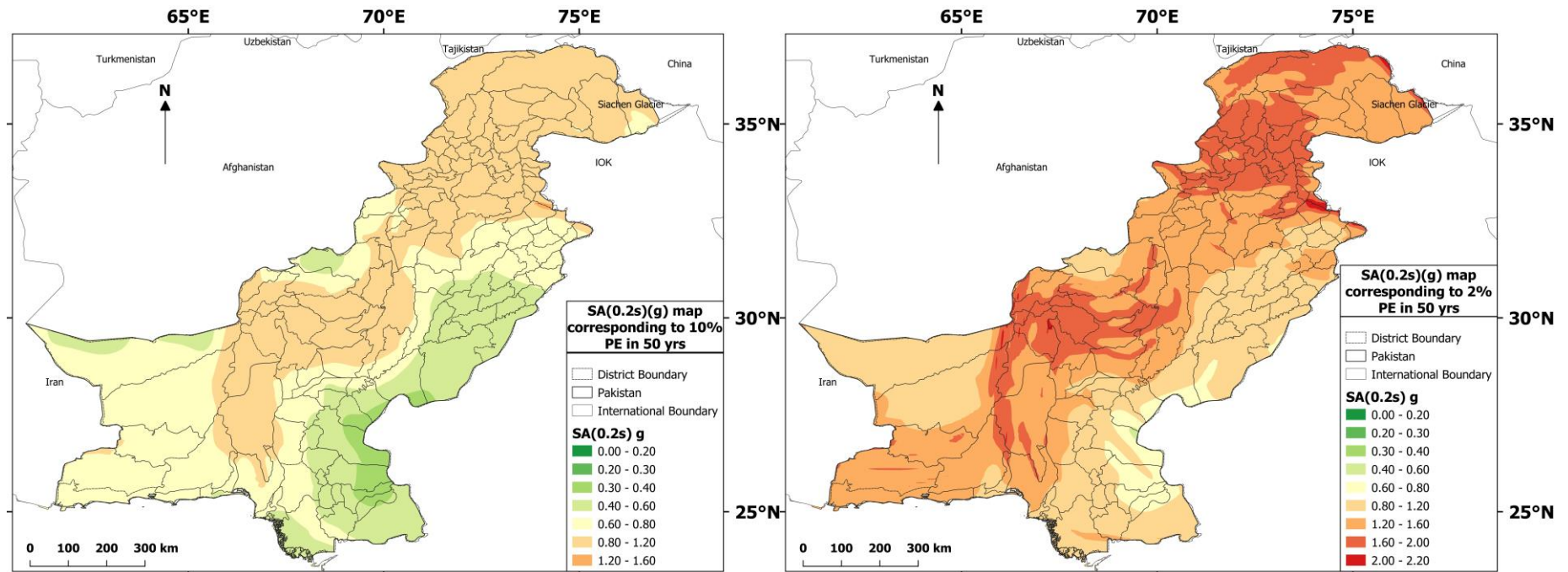
(b) The hazard map of Pakistan for spectral acceleration at 0.2 sec corresponding to 10% (left) and 2% (right) probability of exceedance in 50 years [DBE level with 475 years (left) and MCE level with 2475 years (right) return period]
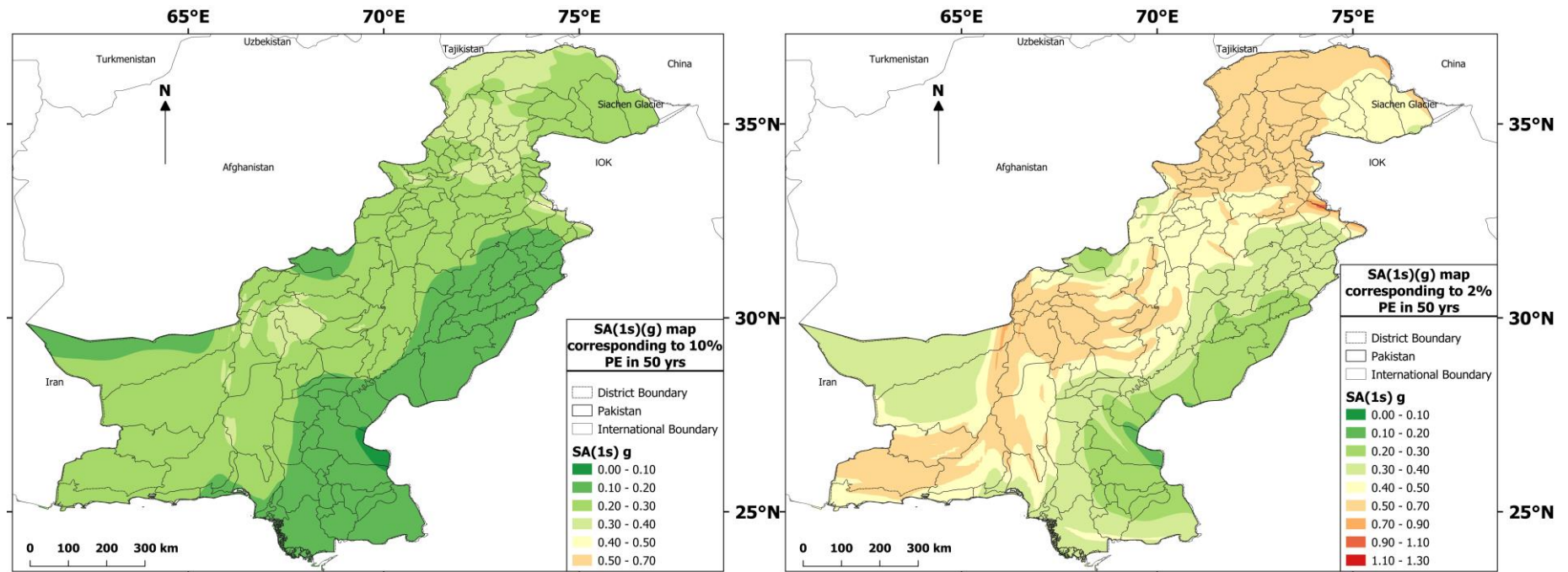
(c) The hazard map of Pakistan for spectral acceleration at 1 sec corresponding to 10% (left) and 2% (right) probability of exceedance in 50 years [DBE level with 475 years (left) and MCE level with 2475 years (right) return period]
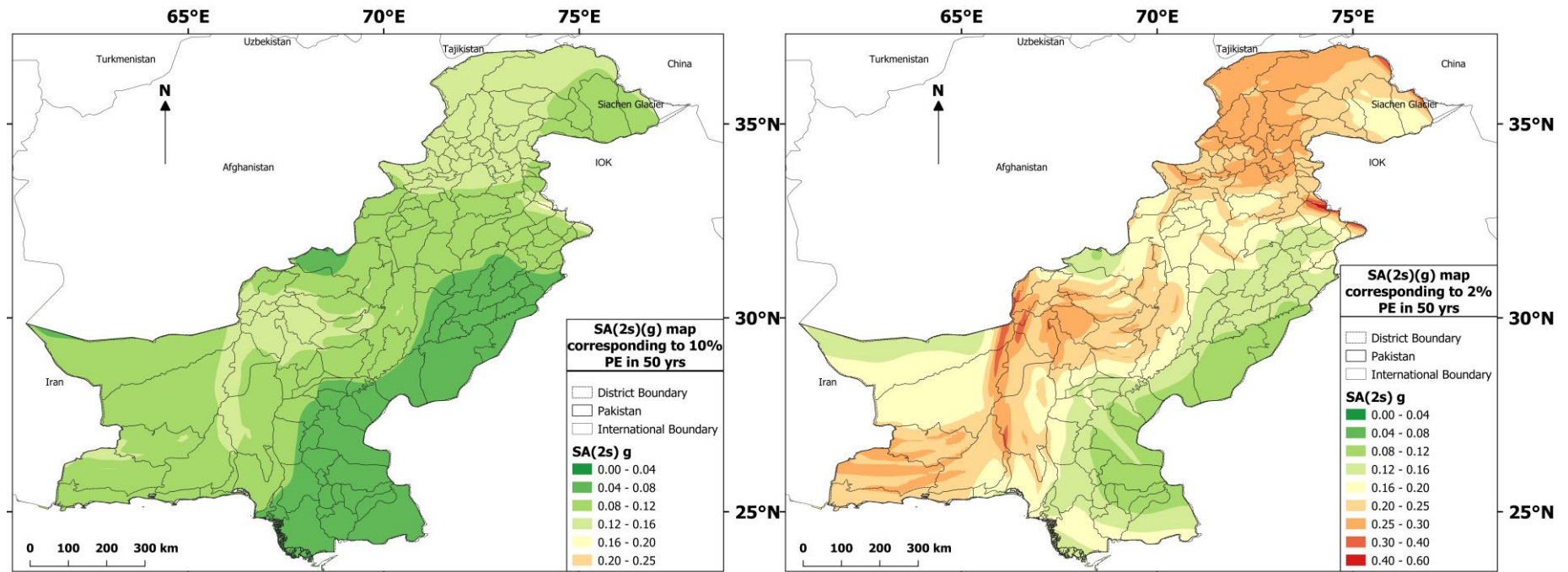
(b) The hazard map of Pakistan for spectral acceleration at 2 sec corresponding to 10% (left) and 2% (right) probability of exceedance in 50 years [DBE level with 475 years (left) and MCE level with 2475 years (right) return period]

Figure 3-15: The hazard maps of Pakistan computed in the presented study.

Table 3-3: A comparison of the PSHA study conducted at NUST (Asad et al., 2020) with the past studies carried out for Pakistan and surrounding regions

Study	GSHAP (Zhang et al. 1999)	PMD and NORSAR (2007)	NESPAK (2007)	Zaman et al. (2012)	GEM EMME (2014)	NUST (Rahman et al., 2020)
Year	1992-1999	2007	2007	2012	2014	2019
Methodology	PSHA (Cornell 1968; McGuire 1976) approach using FRISK88M Software.	PSHA (Cornell 1968; McGuire 1976) approach using FRISK88M Software.	PSHA (Cornell 1968; McGuire 1976) approach using FRISK88M Software.	National Seismic Hazard Maps (NSHM) using USGS Software for PSHA.	Both (Cornell 1968; McGuire 1976) and NSHM methods with 60% and 40% probabilistic weights.	Both (Cornell 1968; McGuire 1976) and NSHM methods with 50% probabilistic weights assigned to each.
Source models characterization	More than 20 seismic area sources with uniform seismicity.	19 seismic area sources with uniform seismicity.	17 seismic area sources with uniform seismicity.	Background spatially smoothed-gridded seismicity.	More than 18 seismic area sources with background spatially smoothed-gridded seismicity in two different source models.	23 seismic area sources with background spatially smoothed-gridded seismicity in two different source models.
Active crustal faults	Nil	Nil	28 active crustal faults modeled using characteristic fault model. Slip rates are not used to estimate the earthquake recurrence rate.	13 active crustal faults modeled, using both the characteristic and Gutenberg-Richter (GR) models with equal weightage to estimate the earthquake recurrence rate.	More than 100 active faults are modeled, using GR model by (Anderson and Luco 1983) to estimate the earthquake recurrence rate.	110 active crustal faults modeled using the GEM (2019) active faults catalogue. Both the characteristic and GR models by (Youngs and Coppersmith 1985) with equal probabilistic weightage are used to estimate the earthquake recurrence rate.
Makran Subduction zone	Modeled as simple area source	Modeled as simple area source	Modeled as simple area source	The interface between two tectonic plates is modeled as sloping area source.	The inter slab seismicity (0-50 km) is modeled as complex inclined area source, whereas the in slab seismicity (50-150 km) is modeled as simple area source.	The seismicity associated to the interface between two tectonic plates (5-55 km) is modeled as a complex sloping area source. Whereas the shallow (0-5 km) and deep in slab (55-250 km) seismicity is modeled as background seismicity.
Earthquake	Pre-historic (before	102 years (1905-	102 years (1904-	107 years (1902-2009)	Pre-historic (before	Pre-historic (before 1900) and

Study	GSHAP (Zhang et al. 1999)	PMD and NORSAR (2007)	NESPAK (2007)	Zaman et al. (2012)	GEM EMME (2014)	NUST (Rahman et al., 2020)
catalogue	1900) and historic (1900-1997) earthquake catalogue with $M_w > 5$.	2007) earthquake catalogue with $M_w > 4.8$.	2006) earthquake catalogue with $M_w > 4.5$.	earthquake catalogue with $M_w > 4.5$.	1900) and historic (1900- 2006) earthquake catalogue with $M_w > 4$.	historic (1900- 2018) earthquake catalogue with $M_w > 4$.
Classification of Earthquake depth	Nil	Classify the seismicity of Hindukush region into shallow, intermediate and deep layers (0-30 km, 30-120 km and 120-300 km)	Nil	Classify the background seismicity into very shallow, shallow, intermediate and deep layer (0-25 km, 25-50 km, 50-100 km and 100-250 km) throughout the study area.	Classify the background seismicity into shallow, in slab and deep layer (0-40 km, 40-100 km and >100 km). Deep seismicity is considered only in Hindukush region. The in slab seismicity in subduction zone, whereas the remaining background seismicity is modeled using only shallow source.	Classify the background seismicity into very shallow, shallow, intermediate and deep layer (0-25 km, 25-50 km, 50-100 km and 100-250 km) for faults seismic source model, whereas for Area source model the BG seismicity is divided into shallow (0-50 km) and deep (50- 250) layers throughout the study area.
GMPEs	Only single GMPE of (Huo and Hu 1992) was used for ground motion estimation. No multiple GMPEs were used to account for the epistemic uncertainty.	GMPE of (Ambraseys et al. 2005) was used. No multiple GMPEs were not used to account for the epistemic uncertainty.	GMPE of (Boore et al. 1997) was used. No multiple GMPEs were not used to account for the epistemic uncertainty.	Multiple GMPEs for different earthquake environments were used. **For crustal faults, very shallow and shallow**: three NGA west 1 GMPEs CB08(0.33), BA08(0.33), CY08(0.33) **Intermediate:** Y97(0.5), AB03(0.5) **Deep:** Y97(1.0) **Subduction zone:**	Multiple GMPEs for different earthquake environments were used. **Active shallow crustal region:** AK14(0.35), CY08(0.35), AC10(0.2), Z06(0.1) **Stable shallow crustal region:** AB06(0.4), C03(0.25), T97(0.35) **Deep Seismicity:**	Multiple GMPEs for different earthquake environments were used. **For crustal faults, very shallow and shallow**: three NGA west 2 GMPEs CB14(0.33), BA11(0.33), CY14(0.33) **Intermediate:** Y97(0.5), AB03(0.5) **Deep:** Y97(1.0) **Subduction zone:** Y97(0.25), AB03(0.25),

Study	GSHAP (Zhang et al. 1999)	PMD and NORSAR (2007)	NESPAK (2007)	Zaman et al. (2012)	GEM EMME (2014)	NUST (Rahman et al., 2020)
				Y97(0.25), AB03(0.25), Z06(0.5)	Y97(0.5), LL08(0.5) **Subduction zone:** Z06(0.4), Y97(0.2), AB03(0.2), LL08(0.2)	Z06(0.5)
Results	A PGA map for 10% PE in 50 years (475 years return period).	PGA and SA (0.2, 0.5, 1.0 and 2.0s) values for return periods of 50, 100, 200, 500 and 1000 years. Hazard curves and UHSs for major cities were developed.	PGA map for 475 years return period. PGA values for major cities are also given.	Mean PGA and SA (0.2, 1.0s and 2.0s) maps for return period of 475 and 2475 years. Hazard curves were developed for major cities of Pakistan.	Hazard results are reported in mean 5, 16, 50, 84 and 95% quartile ground motions. The PGA and SA (0.1, 0.15, 0.2, 0.25, 0.30, 0.50, 0.75, 1.0 and 2 s) maps are developed for return periods of 72, 475, 975, 2475 and 4975 years.	The PGA and SA (0.2, 1.0s and 2.0s) maps are developed for return period of 475 and 2475 years. Hazard curves and UHSs were developed for five major cities of Pakistan.

CB08: (Campbell and Bozorgnia 2008) **, BA08:** (Boore and Atkinson 2008) **, CY08:** (Chiou and Youngs 2008) **, CB14:** (Campbell and Bozorgnia 2014) **, BA11:** (Atkinson and Boore 2011) **, CY14:** (Chiou and Youngs 2014) **, Y97:** (Youngs et al. 1997) **, AB03:** (Atkinson and Boore 2003) **, Z06:** (Zhao et al. 2006) **, AK14:** (Akkar et al. 2014) **, AC10:** (Akkar and Çağnan 2010) **, AB06:** (Atkinson and Boore 2006) **, C03:** (Campbell 2003) **, T97:** (Toro 2002) **, LL08:** (Lin and Lee 2008)
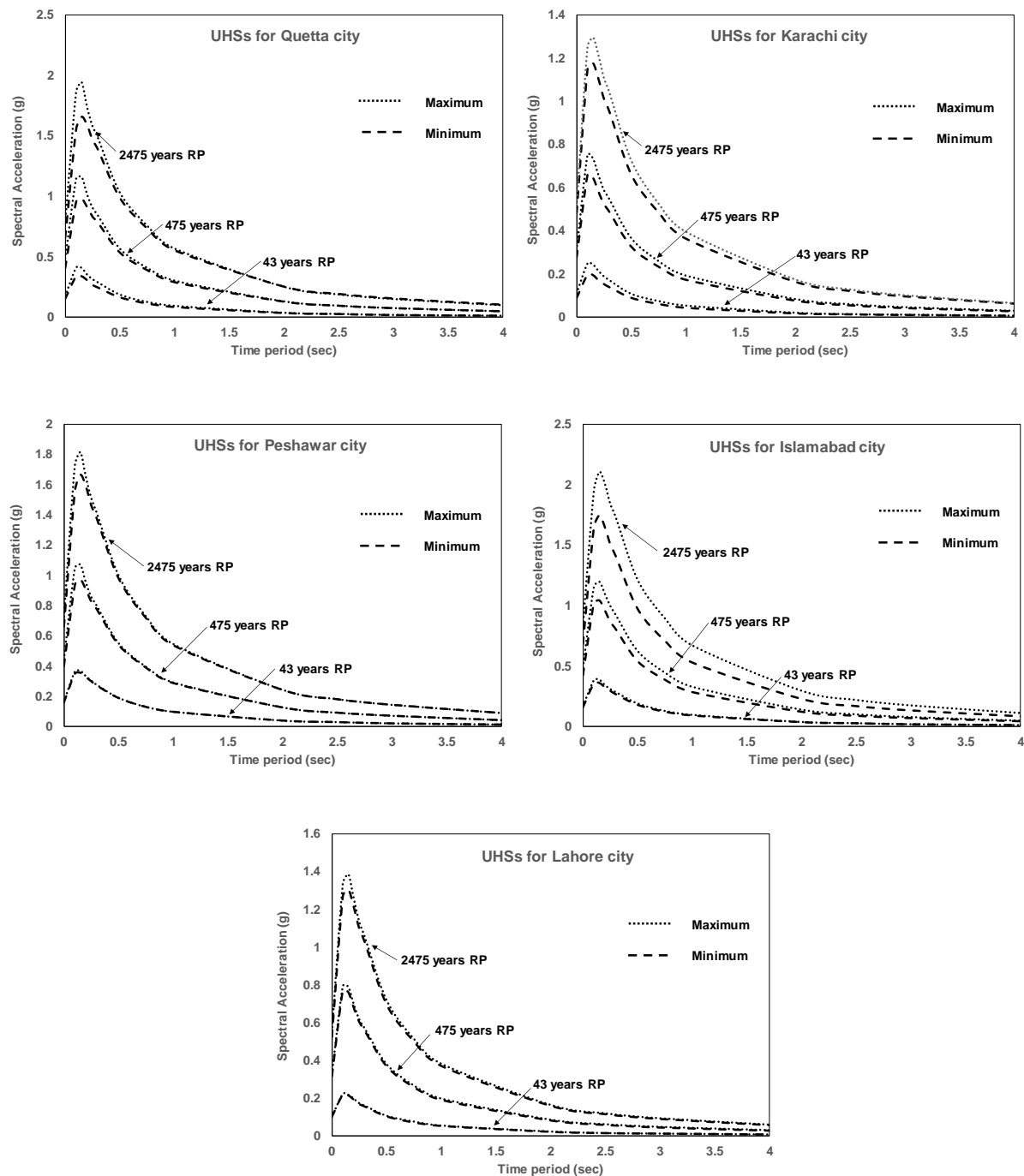
Figure 3-16: The Uniform Hazard Spectra (UHS) for 43 years (SLE), 475 years (DBE) and 2475 years (MCE) return periods for major cities (Peshawar, Islamabad, Lahore, Quetta and Karachi). The variation of uniform hazard spectra with in the city is shown by the maximum and minimum limits of the spectra.
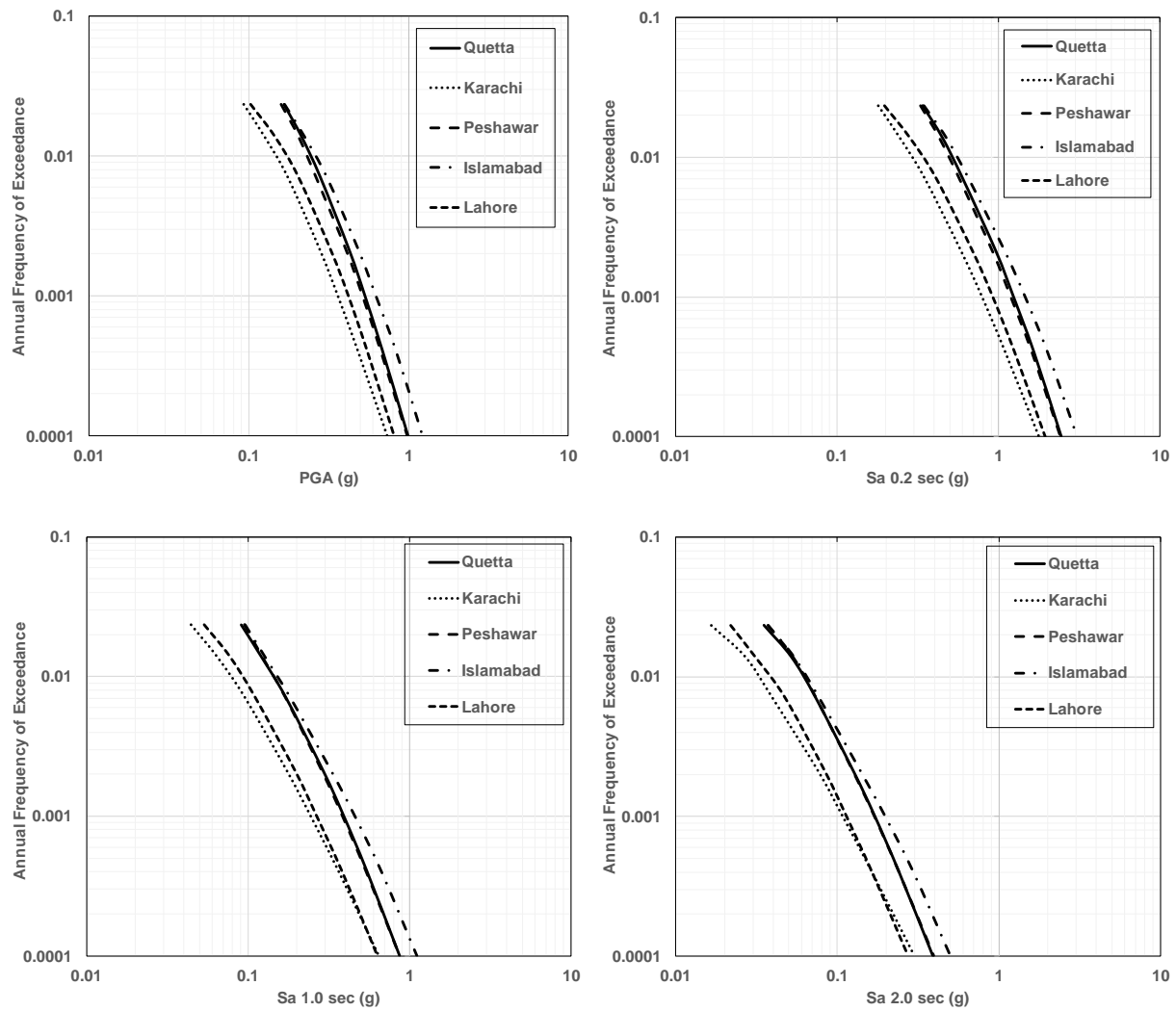
Figure 3-17: The seismic hazard curves for PGA, SA (0.2 s), SA (1 s) and SA (2 s) for five major cities (Quetta, Karachi, Peshawar, Islamabad and Karachi) of Pakistan

Chapter 4

Recommendations related to Structural Modeling

4.1 Introduction

A computer model of a structure is a compromise between the real structure and its mathematical representation. With recent advances in computing and modeling tools, and with growing challenges in terms of increase in population, urbanization, complexities in structural forms and innovative systems, the practicing structural engineers and designers nowadays need to equip themselves with various advanced skills. The demand and complexity is rapidly increasing for built environment including accommodation, offices, and commercial areas to accommodate rapidly growing urban population. Resultantly, the cities and infrastructure of future will need to be denser, complex and taller. These challenges require great expertise and computational capabilities in terms of using state-of-the-art nonlinear analysis procedures, latest computer modeling software and developing insight into the complex dynamic behavior of structures. This chapter identifies some focus areas in structural modeling which need attention in local context and practice in Pakistan.

4.2 Nonlinear Modeling of Structures – The Need of the Hour

Over last few decades, the structural design against earthquakes has passed through a continuous process of evolution. The story which started from a simple mass-proportional lateral load resisted by elastic action has now evolved into an explicit consideration of design earthquakes applied to the detailed nonlinear finite-element models. The exponential growth in computational power in recent years is continuously narrowing the industry-academia gap by providing the cutting-edge research and technology to practicing engineers at their doorstep. As a result, the structural designers nowadays are equipped with far more aids and tools compared to a couple of decades ago. Moreover, recent advancements in nonlinear modeling techniques have also opened a whole new research area dealing with constructing computer models with close-to-real behaviors. With such a range of options available, the choice of modeling scheme and the analysis procedure for design decision-making often becomes a matter of "*the more the sweat; the more the reward*" for designer.

From design point-of-view, the real purpose of structural analysis is not merely to simulate the detailed 3D models and compute design demands, but also to understand the complex structural behavior. This understanding may not always be obtained by simplified linear analysis. In some cases, it can be more effectively developed using nonlinear modeling and analysis procedures. This insight should then help in devising the most efficient design scheme in terms of reduction in cost, time, effort and other resources. On the other hand, there are some limitations which generally hinders the use and role of nonlinear modeling and analysis in structural design practice. For example, for a high-rise building project, setting up a full nonlinear structural model— sophisticated enough to capture all important aspects of material and component nonlinearity—may be an onerous task compared to a linear elastic model. Nonlinear modeling not only requires great expertise and detailed insight of various complex interactions and phenomena (associated with individual inelastic components), but also demands significant computational effort and resources. Moreover, the latest analysis guidelines require to use a large number of ground motions records representing the anticipated seismic hazard at the building site. This process of selecting representative ground motions, performing the detailed nonlinear response history analysis (NLRHA) and post-processing of results may cost a significant amount of time. Also, an ordinary design office may not have necessary expertise and resources to undergo this complete process for each project. For most practical cases, the linear elastic analysis may serve the purpose of estimating design demands within their required degree of accuracy.

These limitations, however, are reducing with the advent of latest seismic analysis solvers, software tools and guidelines (e.g. ASCE/SEI 41-06/13) which provide a significant help in understanding and implementing the

nonlinear modeling of structural components. The nonlinear model of a structure is capable of clearly identifying the structural damage and performance in terms of deformation demand-to-capacity ratios. The seismic simulation is more realistic and meaningful compared to a linear elastic model. It is therefore, need of the hour to equip the next generation of structural engineers with this valuable tool so as to make them understand the complex inelastic structural behavior.

In local context of Pakistan, the Figure 4-1 identifies some key areas where the linear and nonlinear modeling issues may be addressed in upcoming version of the BCP-2007. Currently, the BCP-2007 provides almost no modeling guidelines and the practice is mostly based on earlier versions of ASCE 7, UBC 97 and reference manuals of commercial software packages. There is a need to develop a comprehensive modeling criteria associated with each seismic analysis procedure. Apart from some of the areas mentioned in Figure 4-1, the updated version of guidelines may focus on basic modeling assumptions, consideration of geometric nonlinearity, and the modeling of connections.

Structural Modeling

- Modeling tools and requirements
- Nonlinear modeling of structures
- Modeling of Masonry Infill Walls
- Modeling of local structural systems (bamboo/cribbage/dhajji deewari, etc.)
- Modeling of soil-structure interaction
- Modeling of historical buildings
- Modeling of poorly executed structures
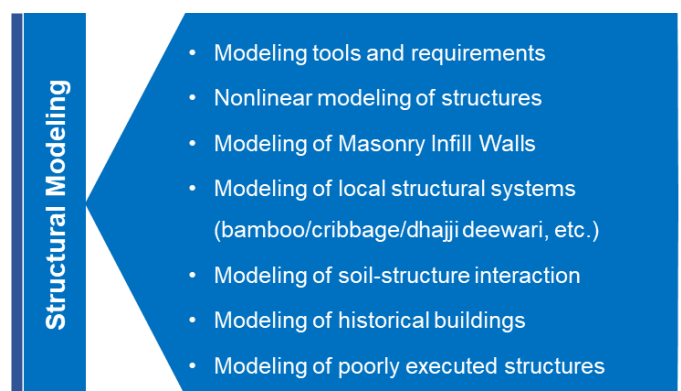
Figure 4-1: Some focus areas in the linear and nonlinear modeling of structures

As an example of how clearly the structural performance can be understood from the results of nonlinear analysis, Figure 4-2 presents an example of structural damage as obtained from the nonlinear response history analysis procedure. The damage in masonry infill walls and RC shear walls under an example ground motion is shown. The damage is characterized and color coded by the strain demand-to-capacity ratios in individual elements. This visual representation of material cracking or yielding or any other damage can provide a clear idea about the expected structural performance and condition at a certain earthquake level. These damage figures can be shown and made understandable even to clients and other stakeholders. Using such representations, architects, clients, designers, consultants and all related professionals can have a meaningful discussion in case of any conflict and can easily arrive at a compromise. The designers can answer "what will happen, if…?" type questions from the building owners. It is also possible to understand the progression of structural damage using a nonlinear analysis of building. As an example, Figure 4-3 presents the results obtained from the monotonic and reversed-cyclic pushover analysis of an example building (in its string direction). The limit states achieved at different roof drift levels can be marked on pushover curves to conveniently understand the damage progression at the global structure level. These two examples indicate how effective are the results of nonlinear static or dynamic analysis in clearly understanding the complex inelastic response of building structures.

Damage in Masonry Infill Walls and RC Shear Walls under a Ground Motion (Nonlinear Response History Analysis)
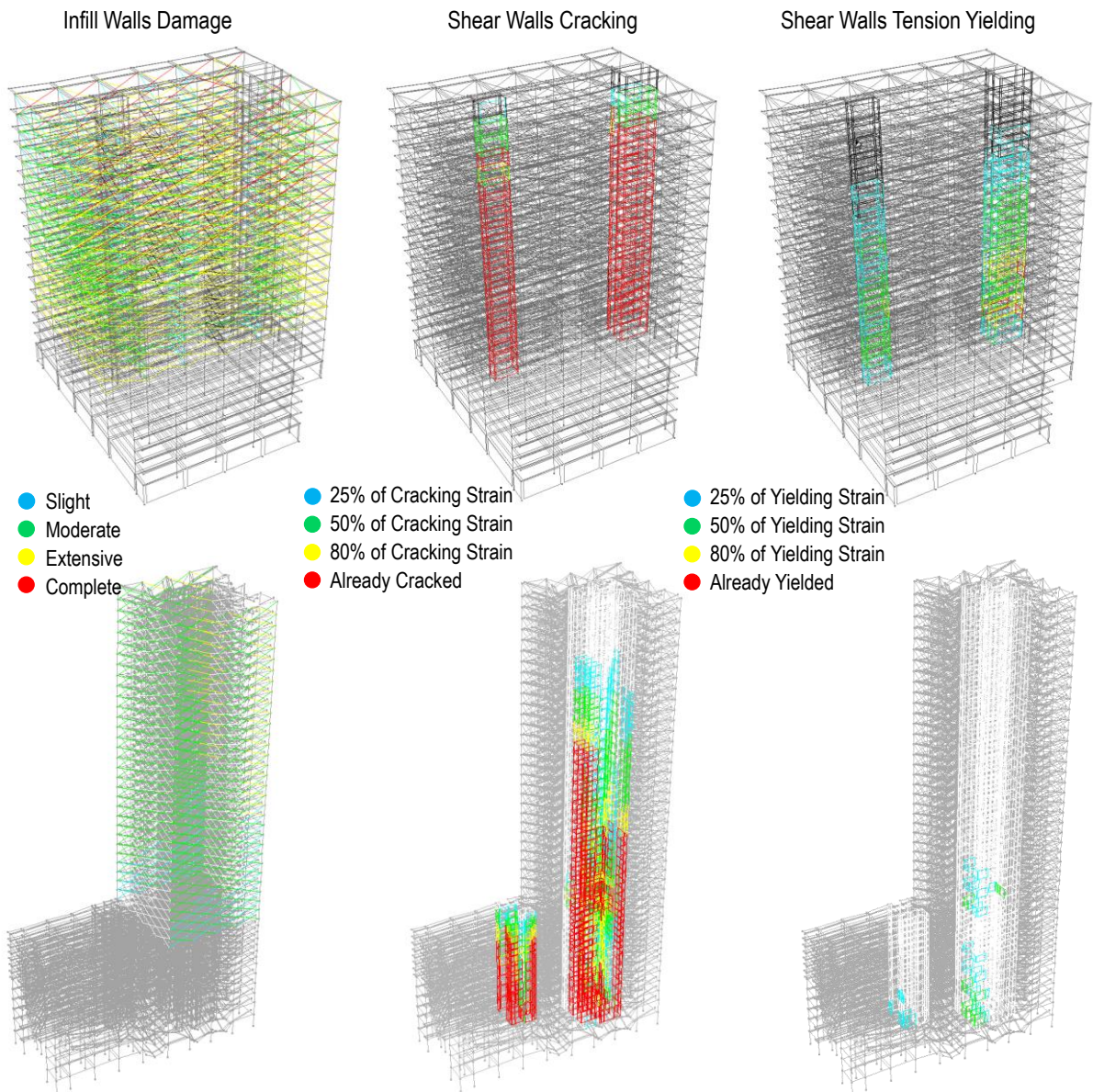
Figure 4-2: An example of structural damage characterized by the strain demand-to-capacity ratios as obtained from the nonlinear response history analysis procedure. The damage in masonry infill walls and RC shear walls under an example ground motion is shown.
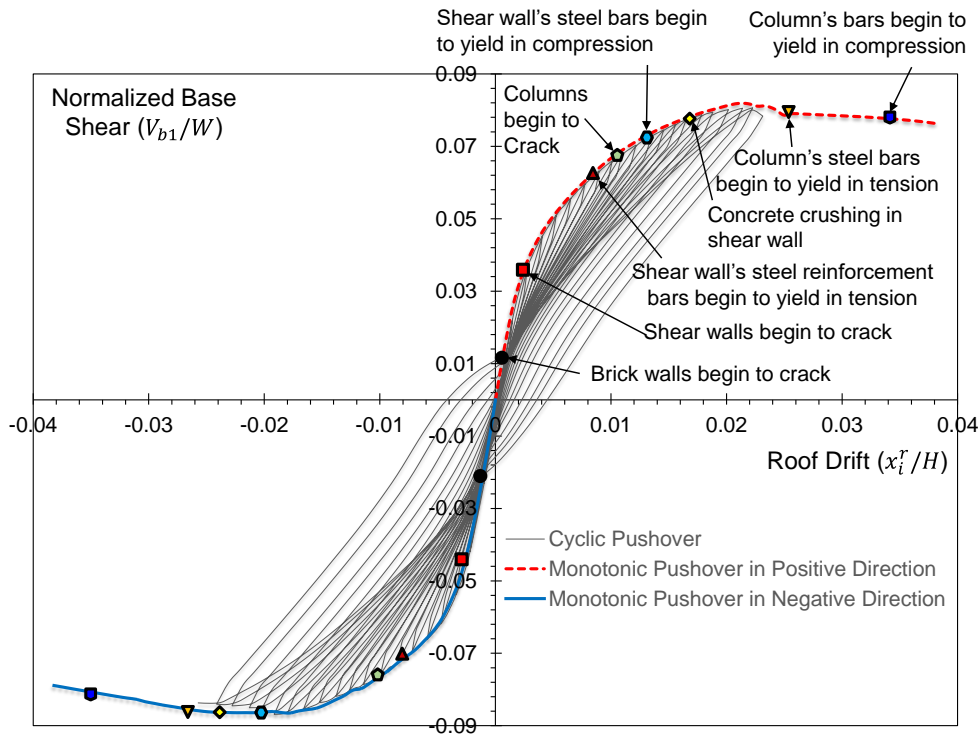
Figure 4-3: An example of the progression of structural damage as obtained from the monotonic and reversed-cyclic pushover analysis procedures.

4.3 Modeling and Analysis Guidelines for Masonry In-filled RC Frame Structures in Pakistan

The infilled RC frame buildings are a common form of structure for low to mid-rise construction in many countries. One of the major issues, especially in the context of Pakistan, is the accurate modeling and analysis of masonry wall structures. A huge number of existing buildings use masonry walls made of burnet clay bricks laid using lean mortar. The surface is then plastered in most cases for a smooth finish. These walls are used either as load bearing components in low-rise buildings or as the infill walls in frame and shear wall structures. The modeling and analysis for both cases should be a focus area in the development of updated modeling guidelines. The clay brick masonry infill walls are brittle under in-plane lateral forces. When used in infilled frames, they impart an initial stiffness to the frame but can develop diagonal cracks under very low level of lateral drifts. Soon after the tensile cracking in diagonal direction, the stiffness contribution of walls drops to negligible. Moreover, the weak out-of-plane strength of these walls is one of the primary reason for both the social and economic losses. This tricky behavior of masonry infill walls can only be captured using a nonlinear model. It is very difficult to mimic their behavior in a conventional linear elastic model which is widely used in practice for the purpose of structural analysis and design.

In conventional design practice, the masonry infill walls are generally considered as nonstructural components and their influence on overall structural response is not included during the conventional code-based design process. However, several studies have shown that the masonry infill walls can impart an early strength and stiffness to the RC frame and therefore, may influence the overall seismic performance of the building. These walls generally have low deformability and high initial lateral stiffness. During a strong earthquake shaking, the masonry infill walls in first or second story may crack prior to any other structural failure. This may result in the development of soft story mechanism in the buildings. In such cases, the traditional design practice based on ignoring the effect of infill walls may result in significantly inaccurate prediction of seismic performance. In fact, for an accurate consideration of infill wall effects, a nonlinear force-deformation behavior-sophisticated enough to

capture the typical failure mode of infill walls-should be used to model the behavior of these walls. Currently, with the use of linear elastic modeling, there is no practical scheme to account for the effects of these infill walls in the design of RC components of such buildings.

With a huge masonry building stock in Pakistan, this issue should be addressed on urgent basis. Apart from the modeling of masonry itself, there are other related issues which may need a focus. Here we summarize these issues using following questions.

a) What response modification values and other seismic design factors are suitable for structures with such brick masonry infill walls (contributing to the frame stiffness)?

b) In case of irregular distribution of these masonry walls (both in plan and along the height), a significant torsional effects may be induced in the structure subjected to lateral inertial forces. Are there any guidelines available to avoid this undesirable response?

c) The inclusion of initial stiffness imparted by masonry infill walls results in shortening of natural vibration periods and other modal properties of buildings. This may ultimately result in affecting the dynamic response of such buildings. Does the approximate fundamental period used in the equivalent linear period or the natural periods of all significant modes used in the response spectrum analysis comply with the real natural periods of the buildings?

d) If a designer decides to model the masonry infill walls as a structural component, how would he model the interaction between concrete frame and masonry infill wall?

e) Is there any unified guideline for quantifying different limit states, vulnerability curves or failure modes of masonry walls constructed as part of local construction practice in Pakistan?

After the Kashmir 2005 earthquake, the Earthquake Reconstruction & Rehabilitation Authority (ERRA) developed a set of safety guidelines under the slogan "Build Back Better". These guidelines were mostly focused on placing techniques for confined masonry (ERRA, 2007). Although this topic requires a detailed investigation and discussion, we keep it to minimum and end the discussion on the following note from Bonowitz (2015) reproduced here for readers' information.

> *"Concrete moment frames with unreinforced (or nominally reinforced) brick or block infill are ubiquitous in Pakistan. Because these are not common structure types in the United States, however, the U.S. codes cover them only in general. The most applicable provisions from the 1997 UBC appear in the 2007 BCP as well, but again only in general terms in Chapters 5 and 10, not with material-specific guidance in either Chapter 7: Structural Concrete or Chapter 9: Masonry. The key provisions are:*
>
> *Section 5.33.2.4.1 allows the relatively flexible concrete moment frame to be "enclosed by or adjoined by" (or, presumably, infilled by) more rigid elements such as masonry panels, as long as "failure" of the masonry does not impair the performance of the frame.*
>
> *Section 10.2.3 requires that the effect of adjoining architectural components on the structural system be considered in the design of both elements.*
>
> *Aside from these general rules, the BCP gives no quantitative provisions about how to analyze or design these potentially complex interactions, and conventional practice even among leading engineers in Pakistan has been to (improperly) ignore any effects of the masonry on lateral response (Lodi et al., 2013; Sharif et al., 2011)."* (Bonowitz 2015).

4.4 The Need of Modeling Guidelines for Indigenous Structural Systems of Pakistan

Another related challenge in the domain of structural modeling is the local structural systems and their load resisting mechanisms. Often, the historical buildings, landmarks and monuments are characterized by such systems and their preservation and limited interventions require very sophisticated modeling techniques. The region of Pakistan has remained the home of several historical cultures and civilizations. With such a rich and diverse historical background, there exist several historical structures with cultural or archeological importance. In

almost all major cities of the country, one may find several historical mosques, castles and other landmarks. This rich cultural heritage need to be preserved and maintained with minimum structural interventions. This requires a detailed evaluation both in terms of material degradation and global structural stability. A very limited amount of investigation has been conducted to understand the structural behavior of such buildings.
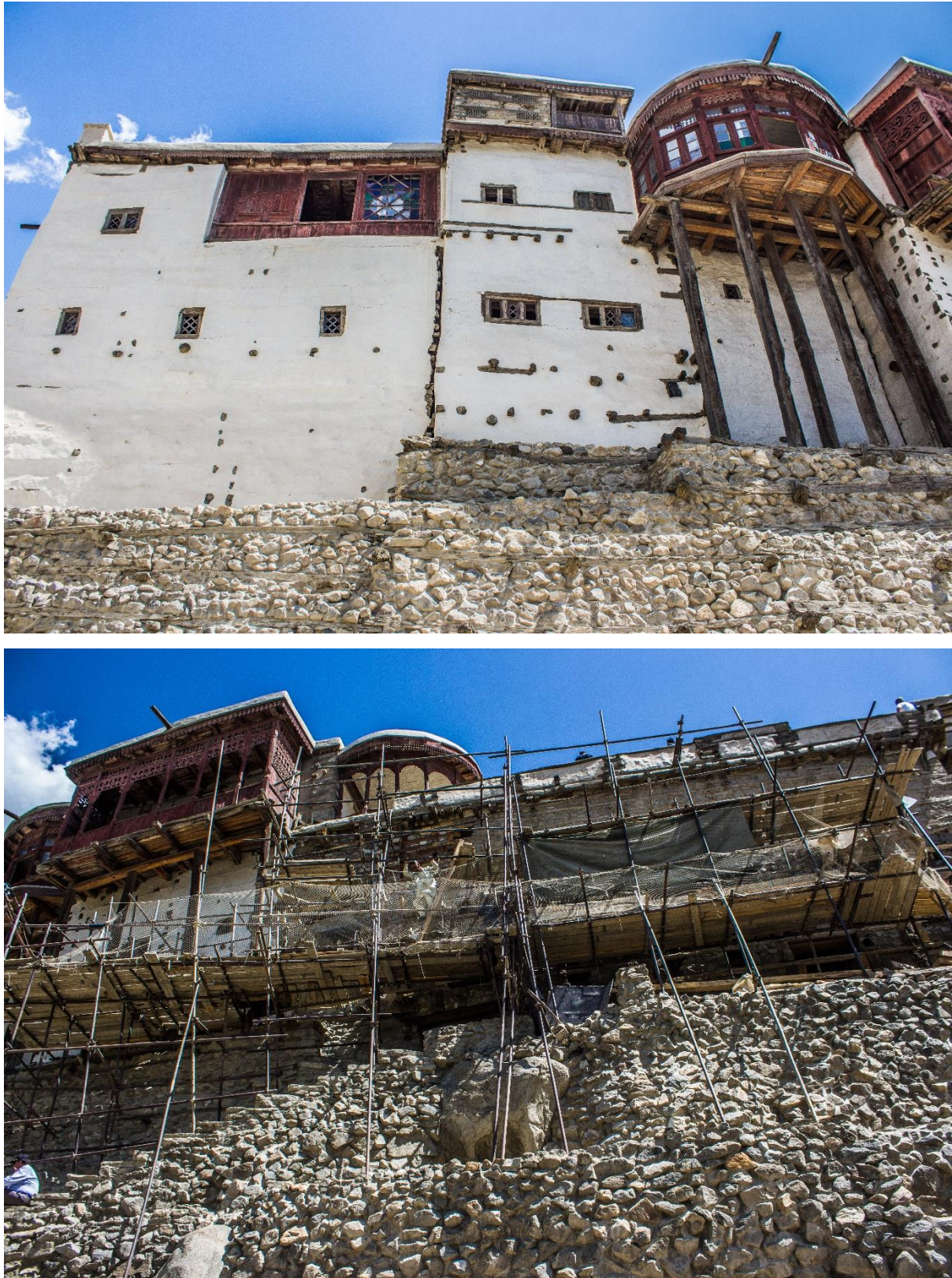
Figure 4-4: Some views of the Baltit Fort and current rehabilitation work.

Figure 4-5: The curtain wall of Baltit Fort
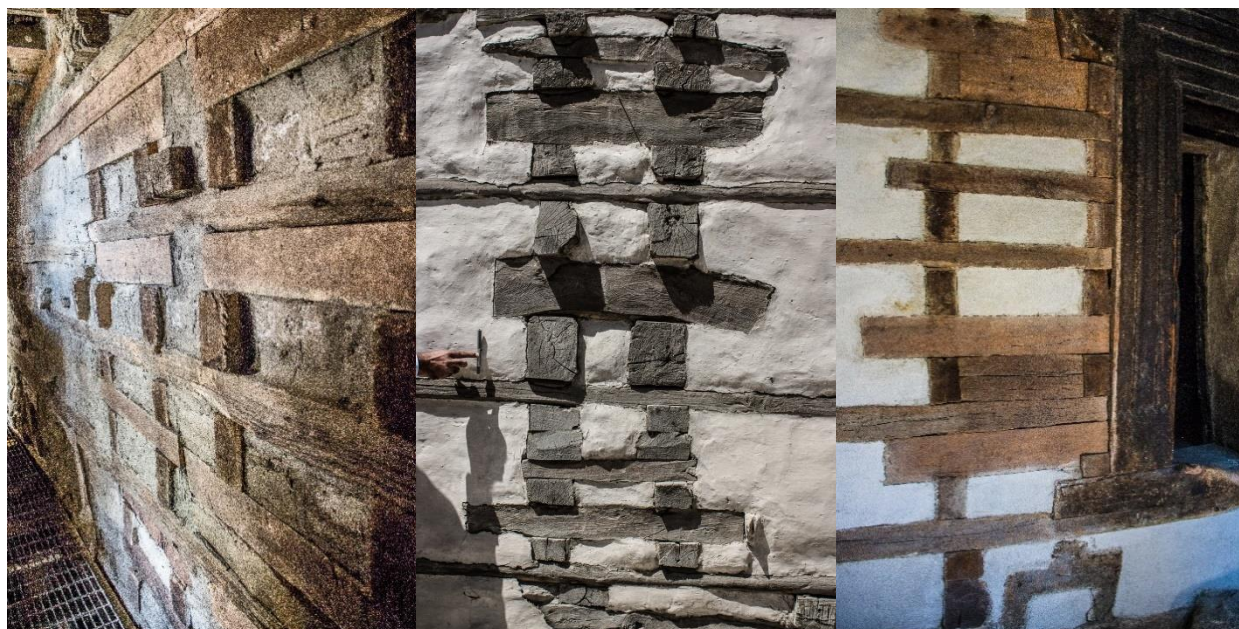
Figure 4-6: Some views of the cator and cribbage construction system at Baltit Fort

Figure 4-7: Some views of the carved wooden frames with cator and cribbage construction system

Here we highlight the importance of structural preservation of historical and cultural heritage using the example of Baltit Fort. The Baltit Fort is a well-known historical landmark in northern part of Pakistan. It is located at a very scenic location of Karimabad at Hunza and is surrounded by world's famous mountainous peaks of Karakorum range. The fort is believed to be originally built over moraine which is glacially formed accumulation of unconsolidated glacial debris and rocks. This type of accumulation occurs in both currently and formerly glaciated regions through geomorphological processes. Due to this reason, the fort building has experienced severe settlement issues in the recent past. Towards the eastern side of the fort, there is a curtain wall, which is not the part of main fort structure but was later constructed to enhance the facade and to provide additional strength to building structure (Figure 4-4). Due to an uneven settlement of moraine, the curtain wall has leaned significantly, thus posing a risk of collapse under a moderate- to large-magnitude earthquake event.

The structural modeling and analysis of such structures is a challenge. It requires a detailed understanding of the material level response and the old load-bearing mechanisms employed in the construction of such structures. It also requires an expertise in terms of latest computing tools and modeling software. If we were to preserve these assets of national and cultural importance and overcome these challenges, we need to move forward and embrace the computational advancements in versatile technological fields. The role of a well-researched building code will be vital in this journey.

Chapter 5

Recommendations related to Seismic Design Philosophy and Seismic Analysis Procedures

This chapter identifies some focus areas and presents some discussion related to the seismic design philosophy and seismic analysis of structures in the local context of Pakistan. We start this discussion with a quick overview of how the seismic analysis and design procedures are evolved over last several decades.

5.1 The Evolution of Seismic Design Philosophy over Past Few Decades

The analysis procedures in early 20th century were essentially based on the use of simplified structural models subjected to simplified loading types. For example, for the purpose of structural design, the seismic load was historically idealized as a simple mass-proportional lateral static loading. Later, with the increasing applications of modal analysis and the formulation of the response spectrum analysis (RSA) procedure, the role of vibration modes and natural periods in understanding and controlling the seismic demands was recognized. With the advent of computer programs and dynamic analysis solvers in mid-1960s and 1970s, and with the increasing availability of more ground motion records, the use of detailed dynamic analysis procedures based on the direct integration solution of the governing dynamic equations of motion was established. This also started the use of nonlinear modeling for a relatively better structural idealization as compared to the linear elastic models.

In late 1980s and 1990s, the importance of nonlinear modeling and analysis increased significantly with the emergence of performance-based seismic engineering (PBSE) as a well-accepted methodology for the seismic evaluation and design of building structures (ATC 40, 1996). This methodology uses the predicted structural performance to equip the decision-makers with the key information regarding structural safety and risk. The performance is primarily characterized in terms of expected damage to various structural and nonstructural components and building contents. Since the structural damage implies an inelastic behavior, the traditional design and analysis procedures that are based on linear elastic behavior can only implicitly predict the performance. By contrast, the objective of nonlinear seismic analysis procedures is to directly estimate the magnitude of inelastic seismic demands.

The performance-based design (PBD) approach is a recent shift in our understanding of structural design. It provides a systematic and flexible methodology for assessing the structural performance of a building, system or any component, as opposed to the cookbook type design methods prescribed in building codes. The building code design procedures are intended to result in buildings capable of providing certain levels of performance, however, the actual performance of individual building design cannot be assessed as part of the traditional code design process. The performance-based evaluation explicitly evaluates how a building is likely to perform; given the potential hazard it is likely to experience, considering uncertainties inherent in the quantification of potential hazard and uncertainties in assessment of the actual building response. This methodology explicitly evaluates the response of the buildings under the potential seismic hazard while considering different probable site-specific seismic demand levels (Service Level Earthquake (SLE) and Maximum Considered Earthquake (MCE)). For this purpose, various state-of-the-art nonlinear analysis procedures and latest computer modeling tools are used to accurately determine the nonlinear seismic demands of whole structure and its individual components.

The generic procedure for the determination of nonlinear seismic demands involves a number of key steps. The engineer is first required to set up a computer model which is expected to mimic the behavior of the actual structure. The anticipated seismic shaking is characterized after a seismic hazard analysis while accounting for various site-specific phenomenon. A suitable analysis procedure is then applied to the structural model considering all important loading scenarios. This results in the predictions of engineering demand parameters (EDPs) which can be subsequently compared with an acceptance criteria (generally prescribed by the seismic evaluation guidelines) to determine the seismic performance of the building. The EDPs normally comprise of

global displacements (e.g. at roof or at any other reference point), inter-story drifts, story forces, component distortions, and component forces (FEMA 440, 2005). The level of complexity in this overall process may vary widely depending upon the choice of modeling scheme and analysis procedure, as well as the required degree of accuracy.

Although the seismic evaluation guidelines allow the use of approximate analysis procedures for conventional low- to mid-rise structures, the detailed NLRHA procedure is still recommended as a final check especially for the structures having extraordinary importance or those with special features.
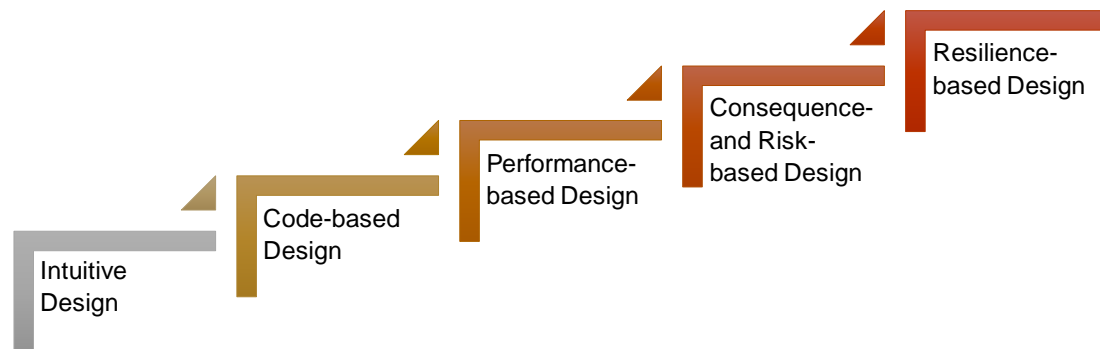
Figure 5-1: The evolution of seismic design philosophy over past few decades and future trends

5.2 The Four Levels of Seismic Design Guidelines – An Example from India and Nepal

A relevant example of how the seismic provisions and design guidelines evolve over last several decades in developing countries is discussed briefly in this section. The framework used in developing and improving the seismic design guidelines in India is briefly introduced here. The primary reference for this discussion is Prof. C. V. R. Murty of the Indian Institute of Technology (IIT) Kanpur. He has several key contributions towards the significant revisions of the Indian seismic codes for buildings and bridges. This framework, as shown in Figure 5-2, divides the evolution of building codes into four generations as explained below.

A. Pre-code → Stiffness based design (pre 1962)

2A. 1962 onwards → First Indian Standard for Earthquake Resistant Design. Concept of seismic force, configuration, and strength is recognized. The key elements include.

      a) Estimation of seismic design forces (corrected later in 2016)
          i) The country was divided into 4 seismic zones
          ii) The seismic design criteria, analysis/design procedures were fully specified. The roles of damping, spectral acceleration, and approximate time period were recognized.
          iii) Rationalized R factors
          iv) Design vertical acceleration coefficient (A_v)
          v) Minimum base shear provisions
          vi) Cracked Section Properties I_{eff}
      b) Level of design force was still incorrect because the earthquake hazard was not represented accurately through seismic zone factor Z
      c) The key challenges include;
          i) The classical MMI scale says that at level 9, the RC structures should collapse. But in India, they are collapsing at 7. So, the design level is not reconciled with the classical understanding of the MMI scale.
          ii) First-mode torsion issue.
          iii) Masonry infill walls issue. They behave as structural elements and therefore, need to be included in the structural analysis. However, if we model them using a single

equivalent diagonal strut, then the structural model becomes biased in one direction and the torsion is induced.

iv) Open ground stories due to parking. So RC walls are introduced (2% of building footprint) with an idea that they will reduce forces in columns and compensate for vertical stiffness irregularity.

2B. Concept of ductility (2B)

a) In most existing buildings, the beams are stronger than columns.

b) The deformation capacity of the structure is also important to know at this level 2B. So, if we do seismic hazard assessment, we also need to determine the deformation demand.

3. Deformability

a) In the end, all it matters is whether the deformation capacity is more or less than the demand. Even if the structure has much strength or it is designed properly, if deformation demand is more than capacity, it is going to fail. So the MMI scale says that for 9 up, the structures will collapse even if they are engineered.

b) With the current design practice, the plastic hinges only form at base (1/3). The beams at higher levels do not contribute in collapse mechanism. So we can have undesirable collapse mechanisms. So, we want to develop a method for a mechanism in which all beams contribute to the mechanism.

c) If we can make a structure with most mass participating in first mode, we can have the same confidence which people 70 – 80 years ago had with manual calculations.

d) A methodology is being developed in which you proportion and design a building to have 80% of its mass participating in first mode.

e) A closed loop method of design is needed. Forward loop is insufficient. For example, the role of beam-column connection flexibility is not accounted in traditional forward loop of force-based design. Structure → Member → Cross-section → Material

f) So, the deformation-based design is the next target where maximum deformation capacity of structure is also the primary design input.

4. Energy-based Design

a) We have to quieten the structure quickly i.e. to dissipate the input energy imparted by the shaking. The challenge is to add adequate hysteretic energy dissipation in the structure.

b) This consideration may lead to an energy focused design once the first three levels are satisfied.

The progress in the development of seismic analysis and design guidelines in a country can be viewed in the light of these four levels. In India, the documents covering the Level 1 and 2 are already developed. The development of design documents for Level 3 is under progress. In authors' opinion, Pakistan can also adopt this model or its derivative for the level-wise development of seismic design codes and guidelines. The idea of one comprehensive code covering all aspects of materials, analysis, design and construction of all structures (regardless of their height, structural system, and occupancy and risk category) may not be practical.

Seismic Design

Stiffness-Based Design	Strength-Based Design	Deformation-Based Design	Energy-Based Design
Design for K_i only	K_i and V_{Bd}	K_i, V_{Bd} and Δ_{max}	K_i, V_{Bd}(??), Δ_{max} and E

INSUFFICIENT for Earthquake-Resistant Design

Currently IN PRACTICE

Force Design
(1) No hierarchy of relative strengths of members
(2) Design of members for shear **independent** of P-M interaction

Capacity Design
(1) Strong-Column Weak-Beam Philosophy
(2) Design of members for shear **dependent** of P-M interaction

Currently under DEVELOPMENT
Collapse Mechanism Deformability

Currently under RESEARCH
Collapse Mechanism Deformability Energy Absorbed

Levels of EQRD	1	2	3
Mandatory for	Normal buildings in **low seismic zones**	Normal buildings in **moderate & high seismic zones**	Critical and Lifeline buildings
Optional for	-	Normal buildings in **low seismic zones**	Normal buildings in **moderate/high seismic zones**

Figure 5-2: The four generations of seismic design guidelines and codes (taken from C. V. R. Murty, 2019)

In the light of above discussion, Figure 5-3 presents some technical focus areas related to the seismic design philosophy and seismic analysis of structures in Pakistan. These areas enlist the seismic analysis procedures in the order of their complexity. Figure 5-4 graphically presents the relative modeling complexities and uncertainties of both the major linear and nonlinear seismic analysis procedures. A brief discussion on some of these focus areas will be presented in subsequent sections.

Seismic Analysis Procedures

- Updated Linear Static Procedure for Seismic Analysis and Design of Simple and Regular Buildings
- Updated Linear Dynamic Procedures for Seismic Analysis and Design of Relatively Complex Buildings
- Nonlinear Static Procedures (Pushover Analysis)
- Nonlinear Dynamic Procedures (Nonlinear Response History Analysis) for Performance-based Assessment of Structures

Figure 5-3: Some focus areas related to the seismic design philosophy and seismic analysis of structures
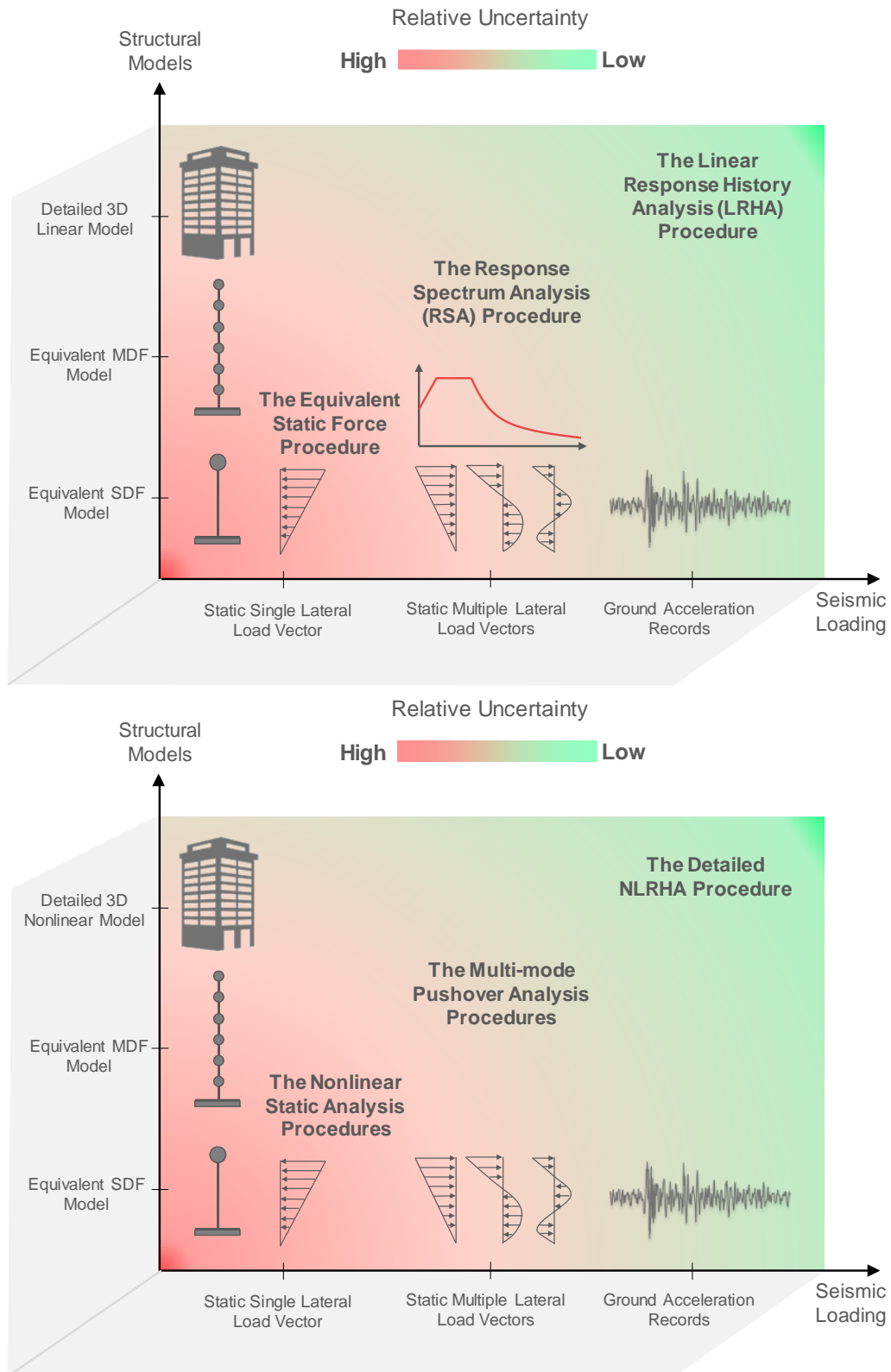
Figure 5-4: The relative modeling complexities and uncertainties of major linear and nonlinear seismic analysis procedures.

5.3 The Need of an Updated Equivalent Static Procedure for Seismic Design of Structures in Pakistan

Practicing engineers are always interested in simple procedures which can provide reasonably accurate response estimates in lesser time and computational effort. For most practical cases, the linear elastic analysis may serve the purpose of estimating design demands within their required degree of accuracy. However, in linear analysis based seismic design procedures, several improvements have been proposed in recent years based on new research findings. Various international building codes adopt these findings to develop improved procedures and provisions. In the updated version of BCP, needless to say, that there is an urgent need to incorporate an updated version of the equivalent static force procedure for seismic design. For the ASCE 7-05 and IBC 2000 frameworks of the ELF procedures, the short-period and long-period spectral accelerations can be prescribed for various sites in Pakistan based on the updated PSHA as discussed in the Chapter 3.

An important point to consider here is that after ASCE 7-05, IBC 2000, IBC 2003 and IBC 2009, the hazard definitions were revised again in ASCE 7-10 onwards. The conventional definitions for the short-period and long-period spectral accelerations (S_s and S_1) were based on the MCE level (i.e. an event with 2% probability of exceedance in 50 years expos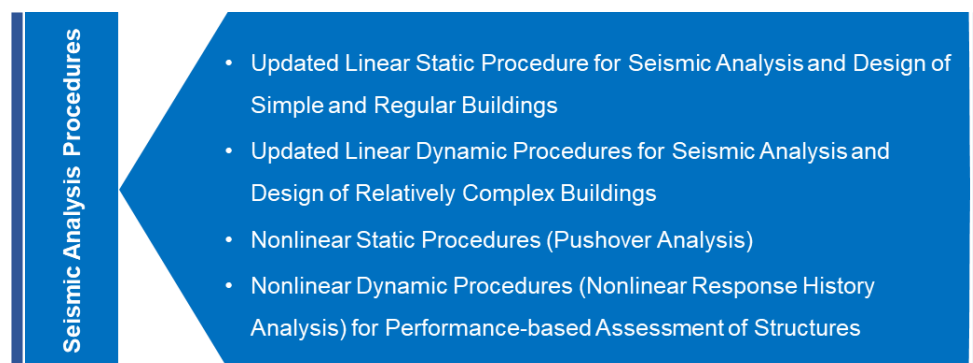ure). However, from ASCE 7-10 onwards these definitions are based on the risk-targeted maximum considered earthquake (MCE$_R$). The MCE$_R$ is defined as an earthquake event which have a collapse risk of 1% in 50 years. The new MCE$_R$ maps for US were developed for the revised S_s and S_1 and were included in ASCE 7-10 and later versions. As opposed to the previous MCE maps, which required that buildings throughout the US to be designed to resist uniform-hazard ground shaking levels, the new MCE$_R$ maps require that buildings be designed to provide the same level of seismic performance, meaning that they will be equally (un)likely to collapse in earthquakes. These new maps are referred to as risk-targeted because the likelihood of collapse is known as the seismic risk level. This new requirement acknowledges that, even when similar buildings located in different regions are designed for uniform-hazard ground motion, or spectral acceleration (adjusted for differences in soil characteristics), regional differences in other attributes of the seismic hazard will likely result in differing probabilities of collapse. A uniform-hazard ground motion map does not fully encapsulate regional differences in how often earthquakes occur and how their seismic waves travel, which are both fundamental contributors to collapse risk. The ground motions displayed in the new maps have been adjusted so that at most locations, when engineers design buildings to resist these accelerations, buildings will have about a 1 percent chance of collapsing due to an earthquake during their assumed lifespan of 50 years (NEHRP 2012).

Soon after its formal implementation, the BCP 2007 was recognized as a major step forward for achieving earthquake resilience and improving the structural engineering practice in Pakistan. However, the conventional practice mostly remained a mix of varying, disconnected and seemingly arbitrary choices of standards for seismic provisions. In this regard, the following note from Bonowitz (2015) is interesting.

> *"… the current code is an amalgam mostly of recent (but not current) American codes and standards. While reflective of leading practices in place in Pakistan in 2007, it does not focus on specific characteristics of Pakistani construction, it might be un-conservative with respect to the presumed seismic hazard, and it lacks provisions for mitigating risks posed by existing buildings. But all these issues can be addressed through continuing research and regular revision cycles. Certainly Pakistan's academics and practicing engineers, including several interviewed for this report, are motivated to update and enhance the code (TCDPAP, 2007; Gilani, 2013)." (Bonowitz 2015).*

While discussing the possible improvements in the next version of BCP 2007, Bonowitz (2015) further writes.

> *"This issue will become more acute if, as expected, the next version of the BCP drops its reference to the obsolete UBC and switches to the IBC, whose structural criteria rely almost entirely on separate reference standards. One reason the IBC does this is that it became impossible to do what the 2007 BCP tries to do: include everything in a single volume. Pakistan's stakeholders will have to decide how best to balance the use of current standards with the convenience of an all-in-one volume. One approach worth considering would be to use the American model as a general code (that is, the BCP would adopt and amend the IBC and refer to separate references standards as it does) but produce a more convenient standalone version to address only concrete structures, which continue to dominate construction in Pakistan." (Bonowitz 2015).*

5.4 The Need of an Improved Design Spectrum and Dynamic Analysis Provisions

The BCP 2007 prescribes the typical short-period shaped design spectrum (with peak values ranging between 0.2 sec and 0.5 sec) for the response spectrum analysis procedure of buildings. The empirical evidence from spectra of several recorded events in the country may not comply with this short-period shape. One such example for the Kashmir 2005 earthquake recorded in Abbotabad is already discussed in Chapter 3. There is a huge need to conducted detailed site-specific PSHA for developing a more rational design spectrum. The default assumption may work well for predicting the uniform hazard from typical shallow crustal earthquakes. However, it may not be able to represent other types of ground motions and may not be able to accurately capture the local site effects.

Similarly, the guidelines for the selection and modification of ground motions can be improved in later versions of the BCP 2007. With the advent of latest computational platforms and automation, the linear dynamic analysis is slowly replacing the conventional RSA as part of the primary design procedure. Although the current version of BCP 2007 allows the use of the linear response history analysis procedure, it doesn't provide sufficient information on the modeling requirements and ground motion selection for the dynamic analysis. Similarly, very few studies on the seismic deaggregation analysis are available for the sites in Pakistan. The information of relative contributions from different seismic sources is the key for the selection of representative ground motions form various international databases.

In the updated seismic analysis provisions, the use of dynamic analysis should be encouraged both during the design of new buildings as well as for the detailed performance evaluation of existing buildings. For using the site-specific response spectrum, an example for such an encouragement can also be seen in the UBC 97 and the current version of BCP 2007. For the design of regular buildings, if the site-specific response spectrum is used, the RSA results are required to be scaled up to 80% of the base shear obtained from the ELF procedure (compared to 90% if the code spectrum is used).

5.5 The Need of a Framework for Seismic Assessment of Existing Buildings in Pakistan

In several developing countries like Pakistan, a large number of non-engineered or non-seismically designed buildings are constructed over last several decades. These existing buildings pose a high risk to the lives and economies of their residents. Recent studies around the globe have also shown that nowadays a significant percentage of building cost is of the non-structural components and contents. The need for a detailed seismic performance evaluation of existing building stock becomes very important in such a scenario.

Several international organizations have provided frameworks for the seismic assessment of existing building stock. The frameworks proposed by Federal Emergency Management Agency (FEMA) of the US can be simplified to develop an effective and practical assessment methodology in our local scenario. The example mentioned in section 5.2 can also be adopted in this regard. The framework for the seismic assessment of existing building stock can be categorized under the following 4 levels.

1) Rapid Visual Screening (Post-Earthquake Occupancy): Screening methodology to identify the potentially deficient structures.
2) Conceptual Visual Survey (Relative Degree of Damage): A visual survey of selected structures before the earthquake event for identifying the technical deficiencies.
3) Simplified Quantitative Assessment: A simplified analysis to assess the overall safety margin.
4) Detailed Quantitative Assessment (Building & Component Deficiency): A detailed analysis applied to the RC buildings and structures.

5.6 Prescriptive vs. Performance-based Seismic Design – A New Front

The performance-based seismic design and assessment methodology is a relatively recent shift in our understanding of structures. It is an approach in which structural design criteria are expressed in terms of achieving a set of performance objectives or levels (and not in terms of passing some code-prescribed checks). This approach explicitly links the structural performance with earthquake hazard and ensures that the structure reaches specified demand level in both service and strength design levels.

> **The Essence of PBD**
>
> *A "decision-maker" states a desire that a building be able to "perform" in a certain way, e.g. protect life safety, minimize potential repair costs, minimize disruption of use, etc.*
>
> *The "engineer" uses his or her skill to provide a design that will be capable of achieving these objectives.*

The primary motivation for performance-based seismic design originates from the non-suitability of traditional building codes to design high-rise buildings with new structural systems and innovative shapes and materials. The design codes doesn't specify any explicit verification of the building performance. They can't answer about what level of structural damage is expected in case of future ground shakings of different levels. On the other hand, the building owners, residents and public at large see the process of structural design and construction with a different view. In 1980s and 1990s (in the prevailing era of building codes), the building owners in US began to question how their buildings would perform in future earthquakes and demand that engineers should design (or upgrade) their buildings to perform better. The building owners and public does not care about the code, or theories or procedures. All they care about is "building safety" and "structural performance". They usually express their desires in terms of a series of performance objectives. These objectives can be certain levels of safety and damage, operational discontinuity, repair cost or any other indicators. The performance-based design and assessment methodology emerged as a response to all these needs. This methodology requires the designer to assess how a building is likely to perform under extreme events. A correct application of this methodology helps to identify unsafe designs. It enables arbitrary restrictions to be lifted and provides scope for the development of innovative, safer and more cost-effective solutions.

Are All Buildings Codes Correct ?

- Building codes differ in seismic analysis and design philosophies.
- If they differ, can all of them be correct ?
- Did we inform the structures to follow which code when an earthquake or thunderstorm strikes?
- Codes change every 3 or 5 years, should we upgrade our structures every 3 or 5 years to conform?
- Codes intend for "Life Safety", not damage limits or cost implications.

Prescriptive Building Codes – A Shelter

Public: Will the building be safe?

Owner: Will the building collapse/ will it be damaged ?

    Can I use the building after a given earthquake?

    How much will repair cost?

    How long will it take to repair?

    Can I make building that will not be damaged and will not collapse?

Structural Engineer: Not sure, but I did follow the "Code"

- As long as engineers follow the code, they can be sheltered by its provisions.
- The building codes "implicitly" ensures that the performance of structure will be acceptable if its rules are followed.
- The performance may not be acceptable in certain cases.

So, we end up in changing the rules every three years, or invent new rules.

The performance-based seismic design and assessment methodology is developed in response to the cook book-type prescriptive building codes. This methodology encourages the designer to go beyond the code to determine the actual inelastic response of the structure under several levels of anticipated ground motions. Therefore, this methodology cannot be simply coded under a traditional prescriptive framework of building codes. However, the code provisions can be systematically made more "performance-oriented" by employing some of the concepts considered in this methodology. Several attempts are being made to bring some elements of performance-based design (e.g. the probabilistic framework to define different levels of seismic hazard etc.) in the traditional codes. This can be identified as another important front in the updation and improvement of BCP-2007.

Chapter 6

Concluding Remarks

The discussion is concluded with an emphasis on the update cycle mentioned in preface of the BCP-2007. The code provisions were proposed to be revised every three years. So, several rounds of revisions are already due. It is proposed that the updated version can focus on some of the areas mentioned in this report. The issues highlighted in this document are real and have long-term implications. The new provisions should directly be relevant to the seismic performance of new and existing building stock in Pakistan. These provisions should be based on the state-of-the-art research findings in the light of international best practices.

For reasons unknown to authors, the engineering practice in Pakistan has historically remained influenced by the American family of building codes. The use of UBC-97 as the model code has served its purpose in its time. The new concepts including seismic design categories, risk categories, importance class, updated seismic design factors (R, C_d, Ω etc.) should be incorporated in updated BCP. The new and updated seismic hazard assessment should be conducted to get an updated picture of the country's hazard. The updated seismic hazard maps for different return periods and for spectral acceleration at different periods should be developed and made part of the updated seismic analysis philosophy. The improved provisions about the structural modeling of different structures and the use of dynamic analysis should be included. The provisions about the design of wood structures, light gage steel structures and flood-resistant structures can also be included. The code provisions can be made more performance-oriented so that the designer is encouraged to see what will happen to the structure in case of an event higher that what is considered in design.

Achieving the earthquake resilience in a country is not the work of one organization or sector of a society. It is a collective effort in which the researchers, practitioners and public work together towards this common goal (Figure 6-1). This document is mainly focused on the role of research and academic. However, the roles of other components of this equation are also equally important. While discussing the issues and possibilities of the role of young graduates in bridging the gap between industry and academia, Bonowitz (2015) comments;

> "As a new document, the BCP provisions might be unfamiliar to some engineers, builders, and regulators, leading to ineffective or inconsistent application. But this is merely a learning curve issue; the situation will improve with time. Indeed, the universities have been teaching the codes referenced by the BCP for years already, and their graduates have been applying its concepts on real projects (Lodi et al., 2013). Professional development among motivated practitioners, facilitated by communications tools far newer than the code itself, can bridge any anticipated education gap." (Bonowitz 2015).
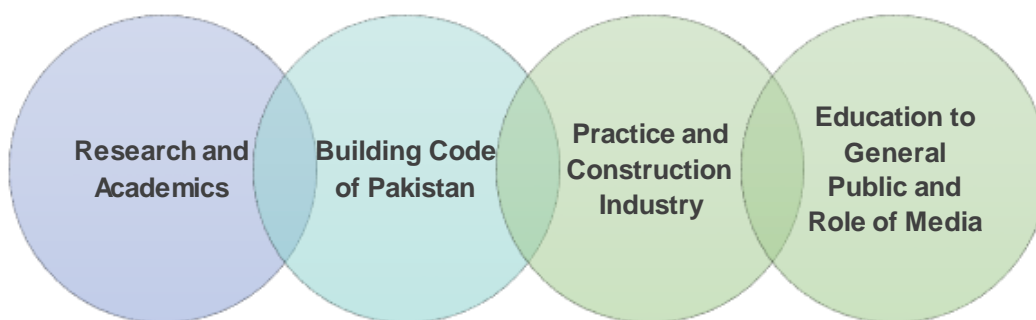
Figure 6-1: Some of the key elements required to achieve earthquake resilience in Pakistan

Figure 6-2 identifies the "five elements of change" in achieving a long-tern earthquake resilience in a society according to Prof. C. V. R Murty. These elements are typology, education, safety, practice and policy. This framework can be good role model for any developing country. The first two (typology, education) are related to educational reforms in the related engineering disciplines. The next two (safety, practice) are related to the development of skills and availability of technical resources. The last element (policy) is an attitudinal measure related to the implementation of standards and policies. While accepting the importance of all these elements and their components, this document only focusses on some of the issues related to education, safety and practice. It is also important to keep the complete picture in mind. A combined effort in all aspects will be the key to achieve the goal.
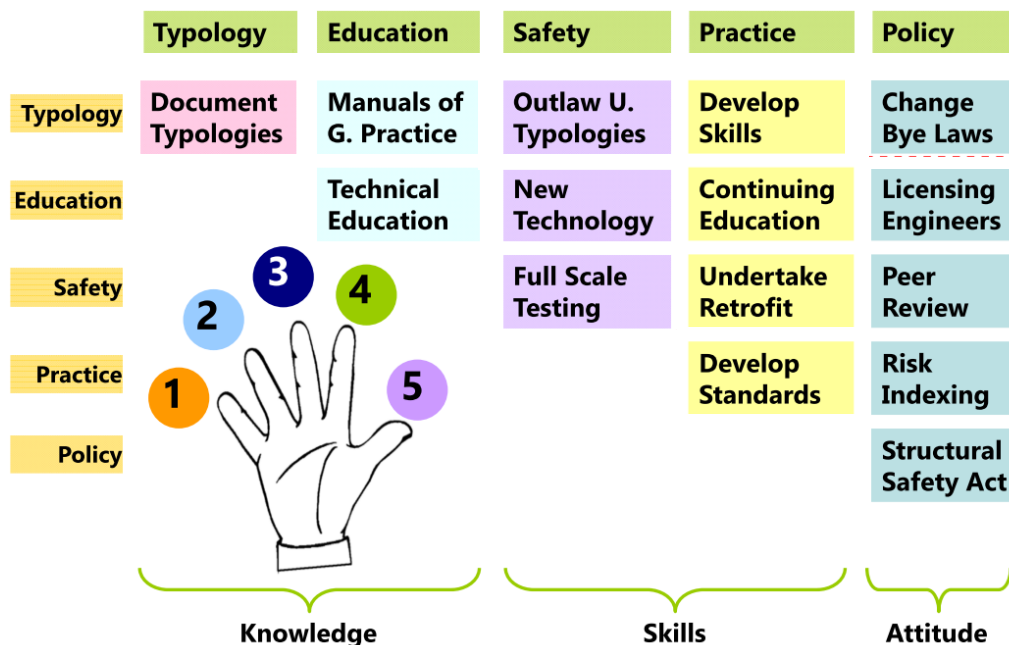
Figure 6-2: The five elements of change according to Prof. C. V. R Murty.

The role of a well-researched building code is pivotal in bringing a seismic shift in our engineering practice and achieving the earthquake resilience in Pakistan (Figure 6-3). The roles of practicing engineers, government authorities, academics and general public are also equally important in this regard. With a combined effort on all fronts, the country is looking forward for achieving a sustainable and long-term resilience against the earthquake induced damages and losses. Let's be part of it.

Figure 6-3: The role of a well-researched building code is pivotal in bringing a seismic shift in our engineering practice and achieving the earthquake resilience in Pakistan
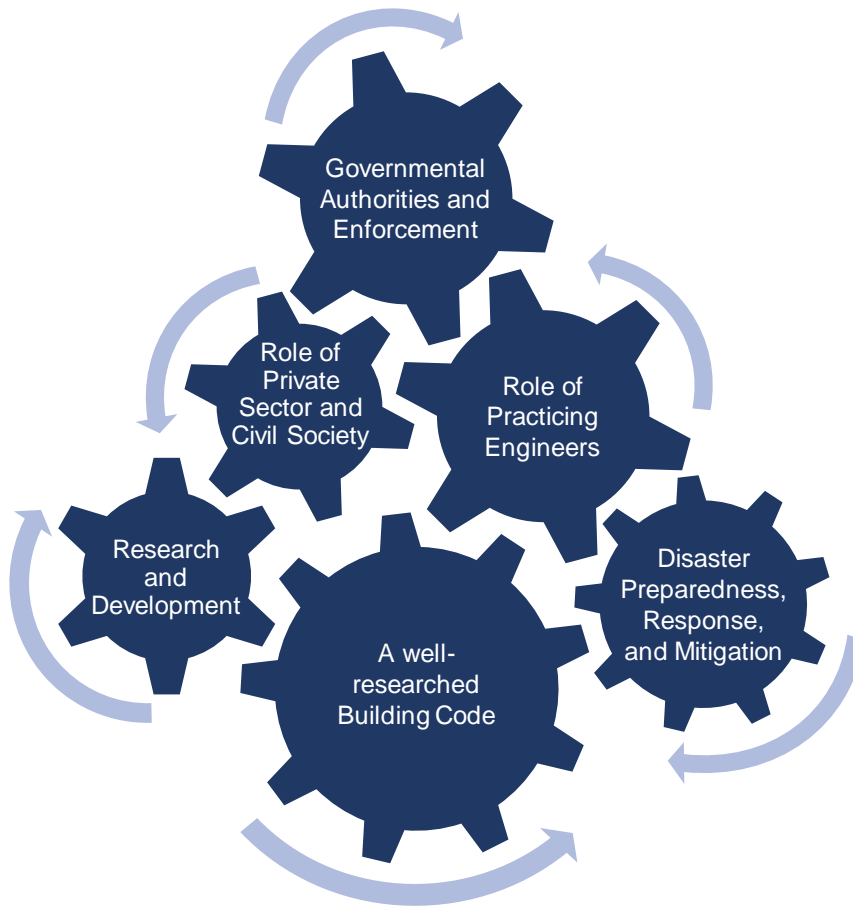
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Appendix A: A Quick Profile of 2019 M_w 5.2 Azad Kashmir Event (September 24th 2019):

The M_w 5.2 Kashmir earthquake struck northern Pakistan on 24 September 2019 at 16:01:55 local time (11:01:55 UTC). It was a shallow earthquake with located near the city of Mirpur located in Azad Kashmir region. It had a magnitude of 5.1 according to moment magnitude scale (M_w) and a maximum felt intensity of VII (very strong) on the Modified Mercalli scale. There was severe damage in Mirpur District, causing the deaths of 40 people and injuring a further 850. The tremors were felt in the Kashmir region, Punjab (Pakistan), Punjab (India), Uttarakhand and northern parts of India including New Delhi. The key information of this event is shown below.

Date/Time	2019-09-24, 11:01:55 UTC
Location	Northern Pakistan, Kashmir
Magnitude	M_{wb} 5.6 (IRIS), M_{ww} 5.2 (USGS)
Location	Latitude 33.1062° N, Longitude 73.7655° E
Depth	10.0 km
Casualties	40 deaths, over 850 injuries

The Mangla Dam is located at a distance of 10.74 Km from the epicenter. The dam structure is reported to remain safe during the earthquake event. The authors are unable to get the recoded time history data from seismometer installed at Mangla dam. However, the closest IRIS seismic monitoring station is installed at Nilore, Islamabad (75.25 Km from the epicenter). The data is available from the IRIS earthquake data management center through the online repository. The acceleration time histories recorded at Nilore are shown in Figures A-1 to A-3.
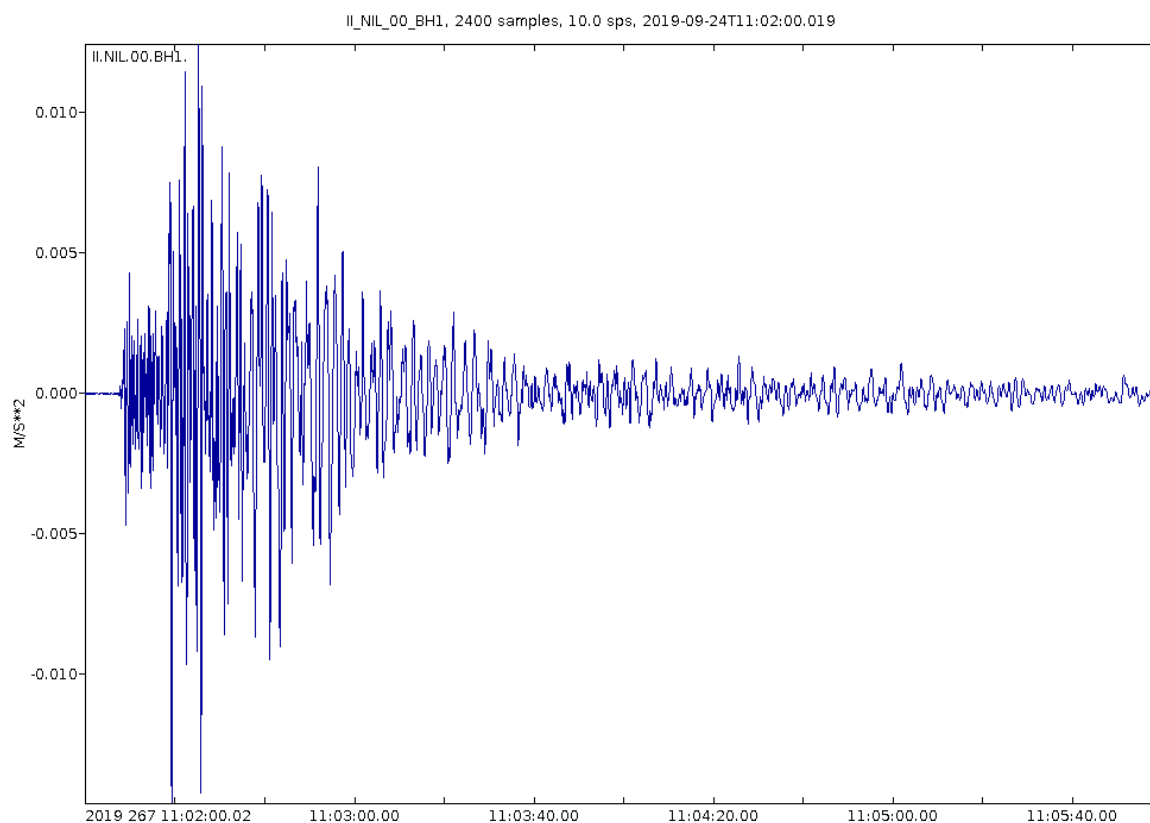
Figure A-1: The horizontal acceleration time history (in units of m/sec/sec) recorded by Channel BH1 at Nilore (closest IRIS station located at 75.25 Km from the epicenter).

II_NIL_00_BH2, 2400 samples, 10.0 sps, 2019-09-24T11:02:00.019
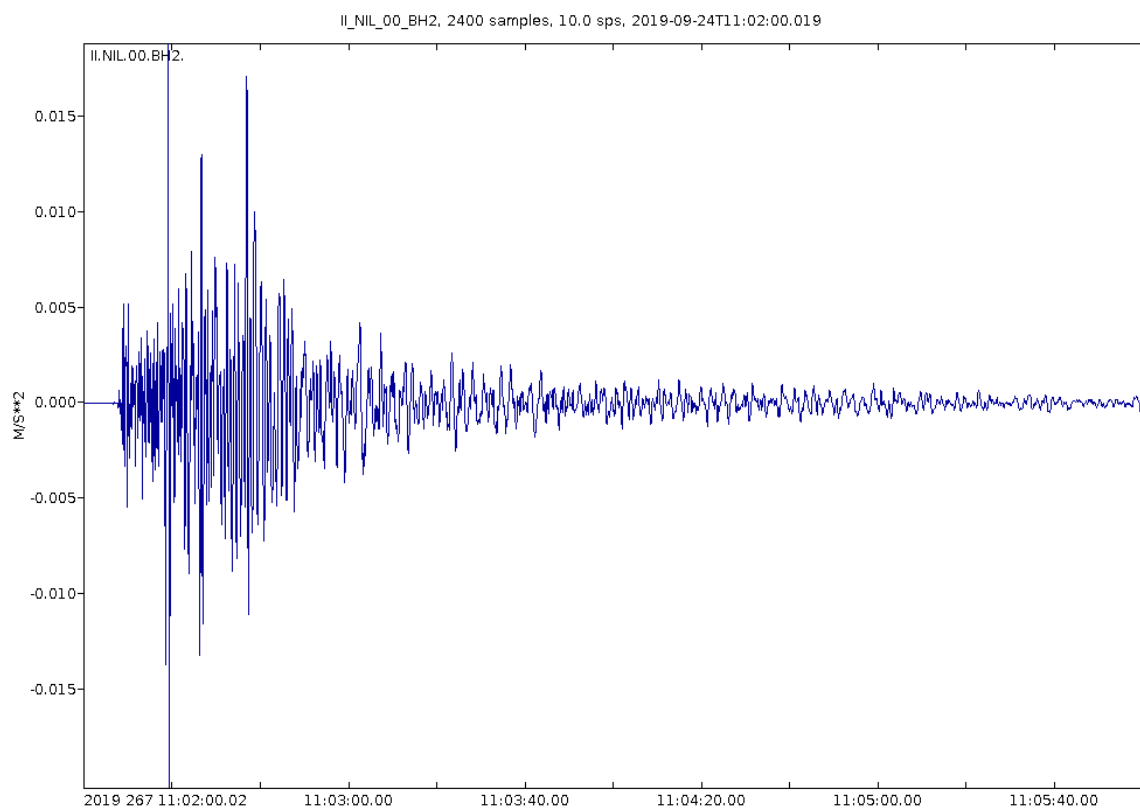
Figure A-2: The horizontal acceleration time history (in units of m/sec/sec) recorded by Channel BH2 at Nilore (closest IRIS station located at 75.25 Km from the epicenter).

II_NIL_00_BHZ, 2400 samples, 10.0 sps, 2019-09-24T11:02:00.019
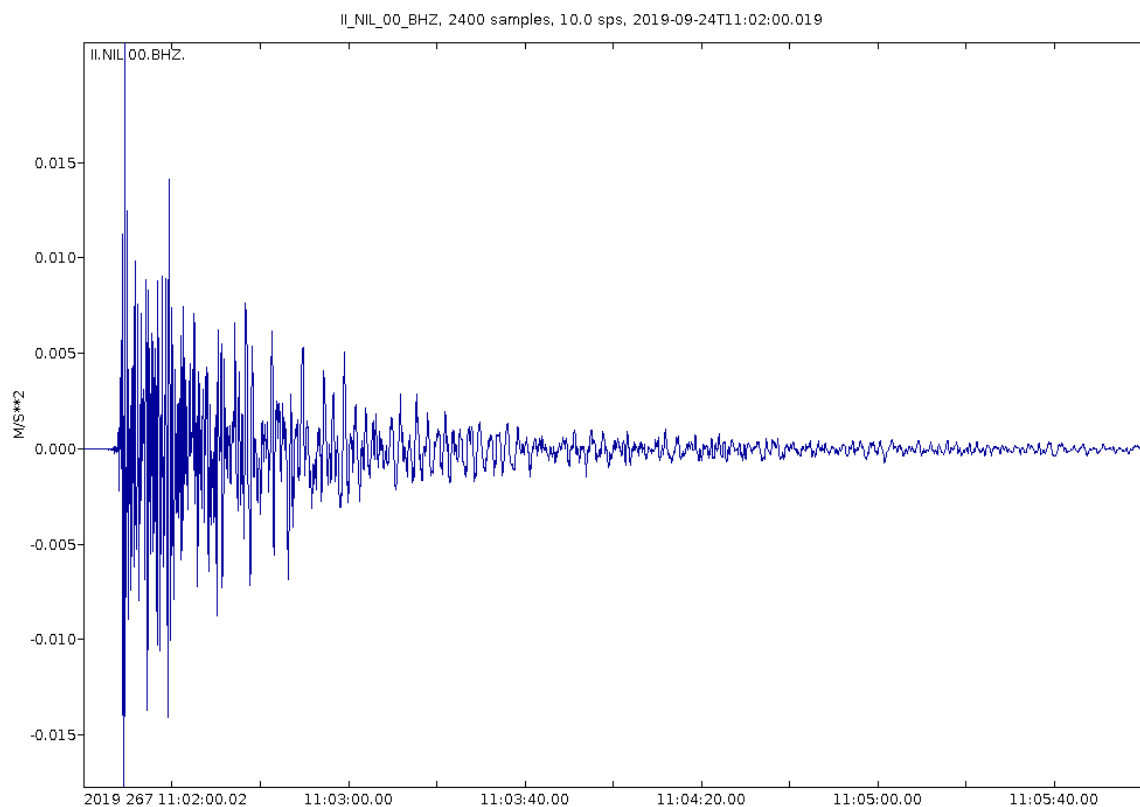
Figure A-3: The vertical acceleration time history (in units of m/sec/sec) recorded by Channel BHZ at Nilore (closest IRIS station located at 75.25 Km from the epicenter).

A pictorial overview of structural and nonstructural damage caused by this earthquake event are shown in Figures below. These images are collected from residents, students and local media. All sources are duly acknowledged. The content is used here for the educational purposes only.

(a)

(b)

<div align="center">(c)   (d)</div>

Figure A-4: The damage to road infrastructure and lifelines. Sliding of loose soil deposits resulted in severe damage to existing facilities.

Figure A-5: The severe damage to non-engineered construction built on slopes.

(a)

(b)

(c)

(d)

(e)

(g)
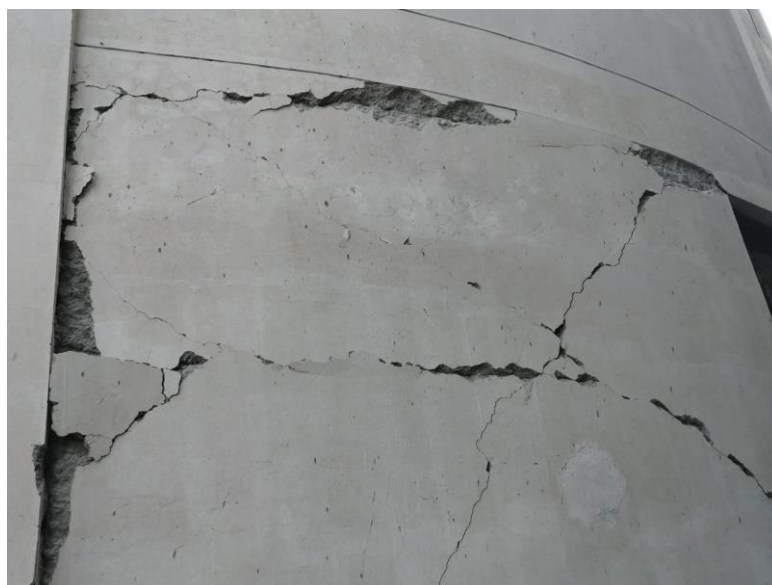
(g)

Figure A-6: The damage to masonry infill walls at the Mirpur University of Sciences and Technology.

(a) The spalling of brick tiles

(b) The collapse of block/brick masonry

(c) The collapse of improperly supported overhangs
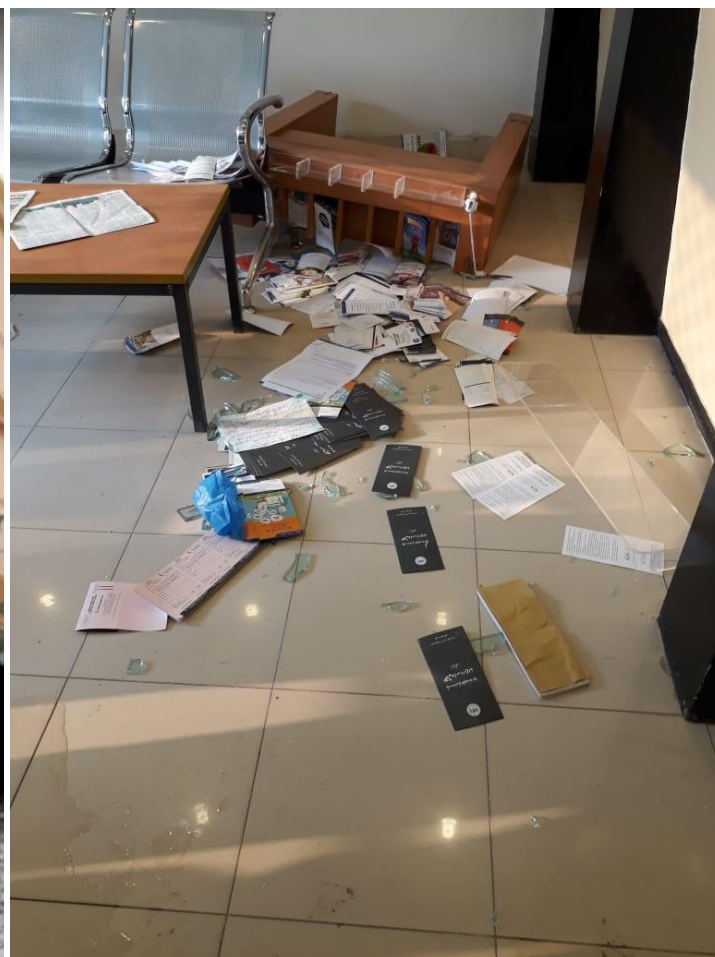
(d) An example of the nonstructural damage to building contents

Figure A-7: Examples of the damage to structural and nonstructural components caused by 24th September Kashmir earthquake event.

Appendix B: Media and Disasters: An Example Set of Infographics for Local Mass Media and School Curricula

The role of mass media is vital in creating awareness about disasters. Educating the massess about what causes earthquakes and what measures should be taken during and after an earthquake, is a key component of disaster management cycle. Also, the information about disasters and safety measures should be included at appropriate levels in the school curricula. An example set of urdu infographics for local media and school curricula are shown in Figures B-1 to B-5 below.
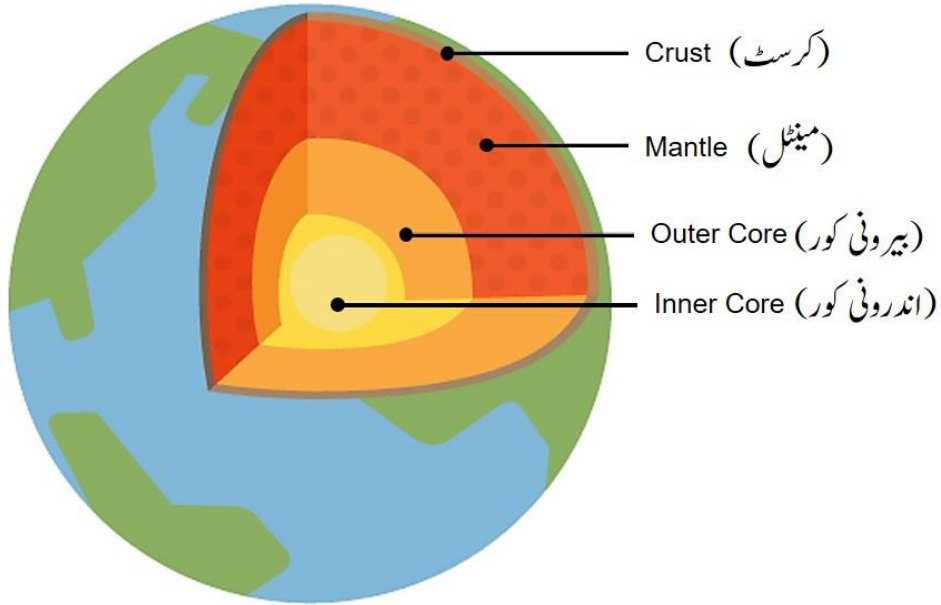
Figure B-1: The internal structure of earth. The three layers (crust, mantle and core) are shown (not to scale). The core is further divided into outer and inner core. The crust is composed of a relatively thin solid rocky layer while the mantle is composed of highly-pressurized molten rocks.

Figure B-2: The seismotectonic setting of Pakistan. The country lies on the boundary between Indian and Eurasian plates. Both the plates are in a state of slow collision since millions of years. The interaction at plate boundaries have resulted in several large-magnitude earthquakes in the past. In south, the Arabian plate is subducting under the Eurasian plate resulting in the formation of Makran Subduction Zone (MSZ).
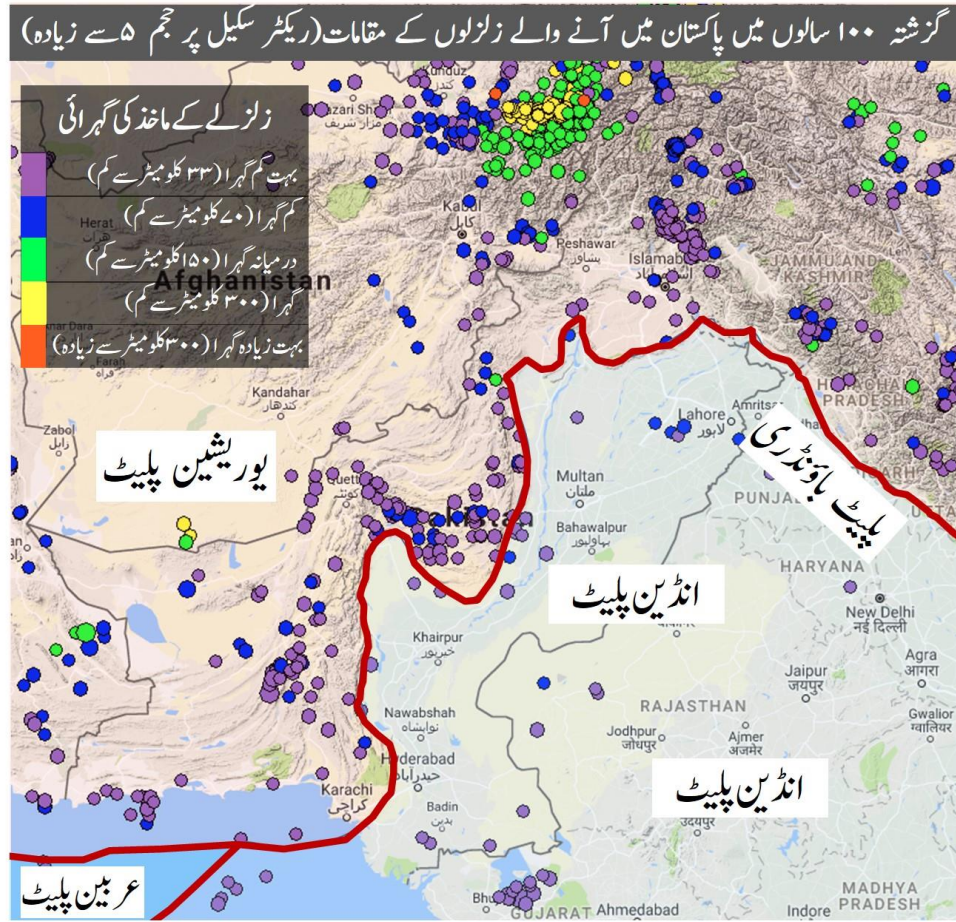
Figure B-3: The historical seismicity of Pakistan ($M_w > 5$). Note that the shallow crustal earthquakes are spread along the main plate boundary while the intermediate and deep events are mostly concentrated in the Hindukush region.

Figure B-4: The attenuation of seismic waves as the source-to-site distance increase.

پاکستان میں زلزلے کا خطرہ

زون ۱

بہت کم شدت
عمارتوں کو کسی نقصان کا خطرہ نہیں

کیا محسوس ہوگا؟: زیادہ تر لوگ محسوس نہیں کر سکتیں گے۔

زلزلے کے دوران کیا کرنا چاہیے؟: الماری، شیلف یا فرنیچر سے دور رہیں جو آپ پر گر سکتا ہے۔

اہم مقامات: فورٹ عباس

زون ۲۔ الف

کم شدت
عمارتوں کو ہلکے نقصان کا خطرہ

کیا محسوس ہوگا؟: زیادہ تر لوگوں کو محسوس ہو گا۔ میز، کرسیاں، فرنیچر اور دیگر اشیاء گر سکتی ہیں۔

زلزلے کے دوران کیا کرنا چاہیے؟: کھڑکیوں، فرنیچر اور کمزور دیواروں سے دور رہیں۔

اہم مقامات: سر گودھا، بھکر، فیصل آباد، جھنگ، گوجرانوالا، حافظ آباد، لاہور، قصور، اوکاڑہ، شیخوپورہ، وہاڑی، ملتان، لودھراں، خانیوال، ڈیرہ غازی خان، راجن پور، لیہ، مظفر گڑھ، بہاولپور، بہاولنگر، رحیم یار خان، جاتی، جیکب آباد، شکارپور، لاڑکانہ، سکھر، گھوٹکی، خیرپور، ڈیرہ اسماعیل خان، نوشہرو فیروز، نواب شاہ، دادو، حیدرآباد، ٹھٹھہ، سانگھڑ، میرپور خاص، عمر کوٹ، تھرپارکر۔

زون ۲۔ ب

درمیانی شدت
عمارتوں کو درمیانے نقصان کا خطرہ
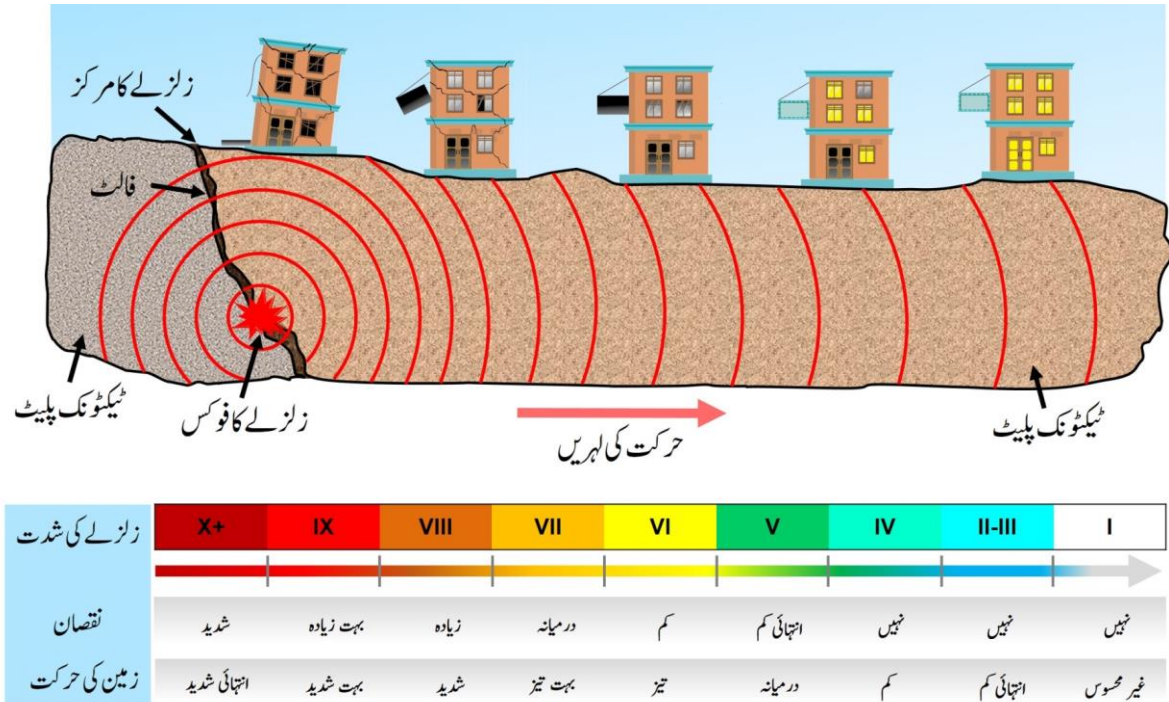
کیا محسوس ہوگا؟: اینٹوں کی دیواریں مکمل طور پر گر سکتی ہیں۔

زلزلے کے دوران کیا کرنا چاہیے؟: فوری طور پر کسی میز کے نیچے پناہ لیں۔

اہم مقامات: اٹک، اسلام آباد، راولپنڈی، جہلم، چکوال، خوشاب، میانوالی، گجرات، منڈی بہاءالدین، سیالکوٹ، نارووال، جعفر آباد، کچی، خضدار، آواران، بیلا، کیچ، پنجگور، بولان، ہری پور، مردان، صوابی، چارسدہ، پشاور، نوشہرہ، کوہاٹ، بنوں، لکی مروت، ٹانک، کرم اور کزئی، جنوبی وزیرستان، شمالی وزیرستان، بدین، کراچی، ملیر، جھمبر، نیو میرپور، اشکومن۔

زون ۳

زیادہ شدت
عمارتوں کو شدید نقصان کا خطرہ

کیا محسوس ہوگا؟: اینٹوں کی دیواریں مکمل طور پر گر سکتی ہیں۔ پتھر سے چنی ہوئی دیواریں گر سکتی ہیں۔ کمزور ستون گر سکتے ہیں۔ عمارت جزوی طور پر گر سکتی ہے۔

زلزلے کے دوران کیا کرنا چاہیے؟: اپنے سر کی حفاظت کریں۔ کسی میز یا پلنگ کے نیچے پناہ لیں۔

اہم مقامات: کوئٹہ، قلعہ عبداللہ، لورالائی، برحان، موسیٰ خیل، قلعہ سیف اللہ، ژوب، سبی، کوہلی، ڈیرہ بگٹی، نصیر آباد، بولان، قلات، مستونگ، خاران، گوادر، دیر، سوات، شانگلا، مالاکنڈ، دسو، مانسہرہ، بگکرام، ایبٹ آباد، باجوڑ، مہمند، خیبر، کوٹلی، پلندری، راولاکوٹ، چلاس، داسو، کوچ، گلگت، سکردو، سیلین۔

زون ۴

انتہائی زیادہ شدت
عمارتوں کو انتہائی شدید نقصان کا خطرہ

کیا محسوس ہوگا؟: عمارت جزوی طور پر یا مکمل طور پر گر سکتی ہے۔ آپ کا کھڑا رہنا ناممکن ہو سکتا ہے۔ چھت جزوی طور پر یا مکمل طور پر گر سکتی ہے۔

زلزلے کے دوران کیا کرنا چاہیے؟: اپنے سر کی حفاظت کریں۔ فوری طور پر کسی میز یا پلنگ کے نیچے پناہ لیں۔

اہم مقامات: پشین، زیارت، چترال، باغ، تھجرہ، مظفر آباد

Figure B-5: The seismic zonation of Pakistan (as per BCP-2007) explained with major cities mentioned against each zone.

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