DETERMINATION OF GROUND MOTION PARAMETERS OF URBAN CENTERS OF BALUCHISTAN PROVINCE

BY

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geotechnical Engineering

NUST Institute of Civil Engineering (NICE)

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H-12 Sector, Islamabad, Pakistan

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DEDICATION

The research is wholeheartedly dedicated to the final messenger of Allah, Prophet Muhammad (peace be upon him). His love in my heart and my strong faith helps and motivates me to keep going forward.

“Say: If ye do love Allah, follow me (Muhammad S.A.W), Allah will love you and forgive your sins.” [Qur’aan 3:31]

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Lastly, it is my privilege to thank **my beloved parents** who have always encouraged and motivated me to continue my research and never give up.

ABSTRACT

Ground motion prediction equations is cornerstone of Probabilistic Seismic Hazard Assessment. A big pool of GMPEs is available nowadays for active crustal and subduction zone categories which are derived on dataset of different regions including database of Middle East, Europe (non-NGA) and NGA WEST 2 database. For countries like Pakistan which do not have local GMPEs, selection of GMPE is difficult and is merely based on hit and trial. Comparative analysis of latest set of GMPEs for these respective categories on seismic hazard of Pakistan is unknown. In this study Probabilistic Seismic Hazard analysis conducted on urban centers (Gwadar and Quetta) of Baluchistan province, a sample from Pakistan given their potential to become economic hubs as rapid infrastructure development is expected in the region. The analysis is based on area source approach along with the modelling of major active crustal faults of the region. Three set of GMPEs were selected where first set consists of GMPEs developed by NGA WEST 2, second set consist of non-NGA based GMPEs while third set is a hybrid set in which NGA WEST 2 and non-NGA based GMPEs are used together. Logic tree method is employed in this work to take into consideration the epistemic uncertainty in different GMPEs for each tectonic zone and in the seismic source models as well. For 10% and 2% probability of exceedance in 50 years (return period 475 and 2475 years respectively), updated hazard maps for PGA and spectral acceleration for structural period of 0.1 sec, 0.2 sec, and 1 sec are created. These results can be effectively used to reduce seismic risk, to develop effective disaster mitigation, and management strategies

TABLE OF CONTENTS

DEDICATION VI

ACKNOWLEDGEMENT VII

ABSTRACT VIII

CHAPTER 1 1

1. Introduction 1

1.1 Background 1

1.2 Problem Statement 2

1.3 Aims and Objectives 2

1.4 Tectonic Setting of the region 3

1.5 Areas of Application 4

1.6 Software Used 4

1.7 Thesis Layout 4

CHAPTER 2 6

2. Literature Review 6

2.1 International Research Work 6

2.2 Local Research Work 8

CHAPTER 3 10

3. Methodology 10

3.1 Probabilistic Seismic Hazard Assessment (PSHA) 10

3.2 Selection of Seismic Sources 11

3.2.1 Catalogue of Earthquakes 11

Pakistan Meteorological Department (PMD) 11

International Seismological Centre (ISC) 11

United States Geological Survey (USGS) 11

3.2.2 Seismic Source Definition 12
3.2.1.1 Seismic Area Sources 14
3.2.1.2 Active Crustal Faults 17
3.3 Characterization of Seismicity 19
3.4 Ground Motion Prediction Equation (GMPE) 29
3.4.1 GMPE Selection 29
3.4.2 Spectral ordinates and return period 31
3.5 Probability of Exceedance 31
CHAPTER 4 32
4. Results and Discussion 32
CHAPTER 5 44
5. Conclusions and Recommendations 44
5.1 Conclusion 44
5.2 Recommendations 44
REFERENCES 45

LIST OF ABBREVIATIONS

PSHA	Probabilistic Seismic Hazard Assessment
DSHA	Deterministic Seismic Hazard Assessment
PMD	Pakistan Meteorological Department
USGS	United States of Geological Survey
ISC	International Seismological Center
IBC	International Building Code
BCP	Building Code of Pakistan
PGA	Peak Ground Acceleration
SA	Spectral Acceleration
GMPE’s	Ground Motion Prediction Equations
NGA	Next Generation Attenuation
GSN	Global Seismographic Network
NSF	National Science Foundation
IRIS	Incorporated Research Institutions for Seismology

LIST OF FIGURES

Figure 1.1 The tectonic setting of Pakistan. (a) displays the slip rates plate boundaries of the Eurasian, Indian and Arabian Plates. (b) highlights Pakistan's geological feature (Rahman et al., 2021) 3
Figure 3.1 Flow Chart of Research Methodology 10
Figure 3.2 Logic Tree Used in Analysis. (a) Subset 1. (b) Subset 2 13
Figure 3.3 Area Sources of Study Area 14
Figure 3.4 Active Crustal Fault consider in Study Area 19
Figure 3.5 Zone 1 Regression Analysis 20
Figure 3.6 Zone 2 Regression Analysis 21
Figure 3.7 Zone 3 Regression Analysis 21
Figure 3.8 Zone 4 Regression Analysis 22
Figure 3.9 Zone 5 Regression Analysis 22
Figure 3.10 Zone 6 Regression Analysis 23
Figure 3.11 Zone 7 Regression Analysis 23
Figure 3.12 Zone 8 Regression Analysis 24
Figure 3.13 Zone 9 Regression Analysis 24
Figure 3.14 Zone 10 Regression Analysis 25
Figure 3.15 Zone 11 Regression Analysis 25
Figure 3.16 Zone 12 Regression Analysis 26
Figure 3.17 Zone 13 Regression Analysis 26
Figure 4.1 Seismic Hazard Maps of Peak Ground Acceleration (a & b) and Spectral Acceleration values (c, d, e, f, g & h) for 10 % and 2 % PE in 50 years by using set of Hybrid GMPEs........ 34
Figure 4.2 Seismic Hazard Maps of Peak Ground Acceleration (a & b) and Spectral Acceleration values (c, d, e, f, g & h) for 10 % and 2 % PE in 50 years by using set of GMPEs developed by NGA WEST 2 36
Figure 4.3 Seismic Hazard Maps of Peak Ground Acceleration (a & b) and Spectral Acceleration values (c, d, e, f, g & h) for 10 % and 2 % PE in 50 years by using set of non- NGA GMPEs... 38

LIST OF TABLES

Table 3.1 Seismicity Model of Study Area (Seismic Area Sources) 27
Table 3.2 Seismicity Model of Study Area (Crustal Faults) 28
Table 3.3 Ground Motion Prediction Equation Used 30
Table 4.1 PGA and SA values for 2% Probability of Exceedance (PE) in 50 years 39
Table 4.2 PGA and SA values for 10% Probability of Exceedance (PE) in 50 years 40
Table 4.3 Comparison of 2% PE in 50 years with previous studies 41
Table 4.4 Comparison of 10% PE in 50 years with previous studies 42

CHAPTER 1

1. Introduction

1.1 Background

Pakistan is world's most active and earthquake-prone region. Several major earthquakes have affected Pakistan in the last couple of centuries. In past, various attempts has been made to calculate ground motion parameters and to mitigate seismic risks. Even in this modern age our technical hands i.e., seismologists, geologists, and earthquake engineers, are not able to predict this natural phenomenon. Urban centers of Baluchistan province (Gwadar and Quetta) are also regarded to be earthquake prone. Gwadar and Quetta hold a unique dilemma contrary to rest of the cities of Baluchistan province when it comes to seismic hazard. Gwadar has an important strategic location as it is situated at the intersection of the Middle East, Central Asia, and South Asia, the three most economically valuable continents in the globe (Hussain, 2016). Gwadar city is in a phase of development and has gained more importance due to China Pakistan Economic Corridor (CPEC) and beneficial in terms of connectivity, trade, and infrastructural development. One of the most crucial features, which causes an earthquake and tsunami hazard for the city, is that it is breathing around the Makran subduction zone. The largest recorded earthquake was magnitude 8.1 M_s in 1945, which also resulted in a tsunami that killed 4,000 people. (Rehman et al., 2013). Quetta, largest urban center of Baluchistan is a trade and communication center between Pakistan, Iran, and Afghanistan and considered as one of the Pakistan's highest earthquake activity regions. A strong earthquake with magnitude of M_W=8.1 struck the city in 1935, destroying the city. (Rehman et al., 2012)

Risk and seismic hazard are two crucial topics in engineering design. The goal of seismic hazard assessment is to predict seismic hazard for use in applications such as seismic risk assessment and to estimate seismic hazard and the uncertainty that goes along with it in both time and space. Although seismic hazard assessment is more of a technical topic, because to its enormous social implications, it needs special attention (Wang, 2011). Both deterministic and probabilistic methods have been in use for more than 30 years in actual practice. In the deterministic approach, specific ground motion probability levels are chosen along with distinct earthquake scenarios. The probabilistic approach considers all scenarios for deterministic earthquakes that are feasible and pertinent (including all combinations of magnitude and location) with possible ground motion probability levels (Abrahamson, 2006).

An equation or model known as the "ground motion prediction equation" (GMPE), is used to quantify the amount of shaking or ground motion that occurs during seismic events. A pool of GMPEs is available nowadays. Some GMPEs are developed by using NGA WEST 2 database and some are based on non-NGA or Global database. However, no GMPE has been created for Pakistan, hence we have to utilize GMPEs that are created for other regions. In this study, Latest types of available GMPEs including the database of Middle East, Europe (non-NGA) and NGA WEST 2, are utilized to study their effect on the SA and PGA values and to draw comparative analysis between them. Spectral acceleration values for different return period are calculated and updated seismic hazard maps are prepared for 2% and 10% probability of exceedance.

1.2 Problem Statement

Nowadays, big pool of GMPEs is available for active crustal and subduction zone categories which are derived on dataset of different regions including database of Middle East, Europe (non-NGA) and NGA WEST 2 database. Comparative analysis of latest set of GMPEs for these respective categories on seismic hazard of Pakistan is unknown. Therefore, a dire need to assess the seismic hazard was felt and urban centers (Gwadar and Quetta) of Baluchistan province, a sample from Pakistan were selected for this purpose as they have potential to become economic hubs as rapid infrastructure development is expected in the region. Some attempts were made in the past by Zaman (2012), Waseem (2020) and Rehman (2021). Earthquake catalogue used in previous studies are barely covering earthquake events up to 2009 or 2010 and the crustal faults were not considered in modeling the seismic sources or very negligible number of faults were modeled by some researchers. So, on the basis of improvements in the current stock of knowledge, there was a need to study the effect of latest set of GMPEs on the SA and PGA values and to draw updated seismic hazard maps of these urban centers using latest set of GMPEs.

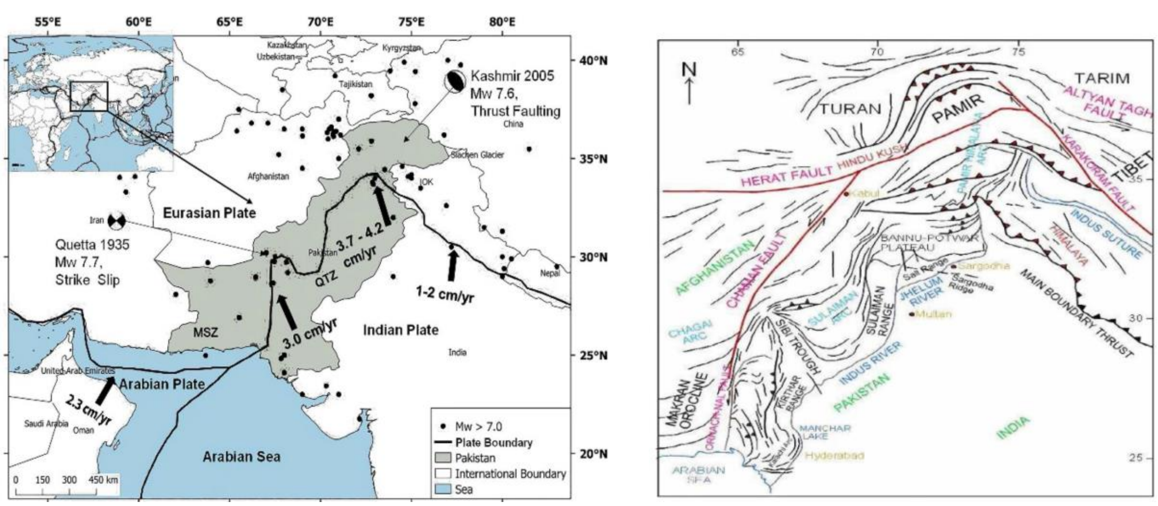
1.3 Aims and Objectives

The aim of this study is to draw seismic hazard maps of Urban Centers of Baluchistan Province using different set of ground motion prediction equations. Main objectives of the study are:

- To conduct probabilistic seismic hazard analysis (PSHA) of urban centers of Baluchistan province using different sets of ground motion prediction equations (GMPEs)
- To draw comparative analysis between latest set of ground motion prediction equations.
- To draw an updated seismic hazard maps using latest set of GMPEs

1.4 Tectonic Setting of the region

The three main tectonic plates of Earth, the Indian-Australian, Arabian and Eurasian, are responsible for seismic activity in Pakistan as shown in Figure 1.1. The Indian-Australian plate has been colliding with the Eurasian plate since millions of years, while the Arabian plate has been subducting beneath the Eurasian in the Arabian Sea in southern Pakistan. The two plates, Indian and Eurasian are slowly converging during a thirty to forty million year span (Aitchison et al., 2007). Makran subduction zone (MSZ) is formed by the subduction of the oceanic floor of Oman under the Eurasian plate, in the South West (Stoneley, 1974).



(a) (b)

Figure 1.1 The tectonic setting of Pakistan. (a) displays the slip rates plate boundaries of the Eurasian, Indian and Arabian Plates. (b) highlights Pakistan's geological feature (Rahman et al., 2021)

The Ornach-Nal fault which is a s extension of the Chaman fault in south direction, makes up the eastern edge of the Makran subduction zone which is actually a junction between the Eurasian and Indian plates. These are the major tectonic elements that are close to Gwadar. In the West, Suleiman and Kirther belts comprises of the fold and thrust belt that stretches over 600 kilometers from Khuzdar from the South to the North, before it bending towards the Southeast in the Quetta Syntaxes (Bannert & Raza, 1992). The Suleiman range is seismically active and was the epicenter of the 1935 Quetta earthquake (Waseem et al., 2020). Before sharply turning south near Quetta, the mountain range, turns west for roughly 300 kilometers towards the Suleiman range (SR) (Rafi et al. 2012). Because of the complicated tectonic environment, urban center of Baluchistan province and its surrounding areas are posed to a higher level of seismic hazard. As a result, an evaluation of the seismic hazard in Baluchistan is desperately required using different set of GMPEs.

1.5 Areas of Application

- Seismic hazard analysis results can be effectively used by professional structural designers to reduce seismic risk by designing earthquake-resistant infrastructure.
- The updated hazard maps can be used by the different organizations and agencies to develop effective disaster preparedness, mitigation, and management strategies.
- Urban planners and policymakers can frame public policies for land use planning and designing to fulfil the sustainable development goals of seismically active areas using the results of seismic hazard research.

1.6 Software Used

MS Excel, ArcGIS v.10.1, ZMAP and CRISIS v. 2020, these three software packages were used in the course of this study for performing the seismic hazard analysis. MS Excel has been used for earthquake data compilation and homogenization. ArcGIS is a well-known mapping and geographical data analysis tool. This study uses the ArcMap application of this software to create a seismicity map of urban centers of Baluchistan province. The map shows different seismic sources identified around the province with the historic catalogue displayed on them. ZMAP is a collection of tools that seismologists can use to evaluate earthquake data. In this study, the seismicity of the chosen area is investigated using this software. CRISIS is a seismic hazard module that enables complete seismic model definition for probabilistic seismic hazard assessment. This software calculates the rate of exceedance of desired ground motion scenarios over a specific time frame provided varied values of structural periods using a ground motion model that has been developed using a set of GMPE.

1.7 Thesis Layout

This thesis comprises of four chapters. The first chapter gives a quick description of the problem. The geology and tectonic setting of the study area. Moreover, all of the software packages used in this investigation are introduced. In second chapter, the literature is explored to obtain a thorough understanding of the subject. The first half of this chapter discusses international research, while the second section discusses the research carried out in Pakistan. The third chapter is the most important part of this research. It begins with an introduction to the PSHA technique, followed by distinct discussions of each of the processes involved in the process. The results are presented in chapter four along with discussions. Chapter five represents the conclusions and suggestions for future researchers are made, as well as the lack of input data in Pakistan.

CHAPTER 2

2. Literature Review

The danger of harm to the structure is of great extent if located in seismically active zone and predicted by degree and nature of ground motions developed during seismic activity. The seismic hazard assessment is used to determine ground motion parameters and the probability of exceedance of seismic activity that occurred in the future by combining the data of the historical earthquakes occurred in the past with geological, seismological, statistical, and other information.

Deterministic seismic hazard analysis and Probabilistic seismic hazard analysis are the two types of techniques commonly used for seismic hazard calculation. PSHA method is advantageous as compared to DSHA as it considered all earthquake sources that may affect the region and it overcomes many uncertainties regarding the magnitude of the earthquake, distance between site and source and probability of occurrence of desired event can also be predicted.

2.1 International Research Work

Ashadi et al. (2015) carried out PSHA to determine PGA and spectral acceleration values for central Java region located in Java Island in Indonesia. This region is considered among seismically active region of Indonesia. Results indicated that northeast Central Java has subjected to the highest seismic hazard with PGA of 0. 45g, whereas the Kendal regency, in central Java has the lowest hazard with a PGA of 0.13g.

Subedi et al. (2016) based on latest knowledge of seismicity, carried out PSHA of Nepal. Earthquake data for 300 km radius around the area enclosed by 26.5-30.5 N latitude and 80-89 E longitude were collected and merged and converted to moment scale using different relations. Dependent events were removed from catalog. And Activity rate based upon size of earthquake is calculated using Kernel estimation method (equations). Result shows that maximum PGA for the return period of 475 years for hard soil is 300 gal, for medium soil is 400 gal and for soft soil is 500 gal.

Ayele (2017) carried out Probabilistic Seismic Hazard Analysis (PSHA) in which he developed a seismic hazard map of Ethiopia and its neighboring region that covers 0^{o} N to 20^{o} N latitude and 30^{o} E to 50^{o} E longitude using PSHA technique. CRISIS and Wizmapll software were used to achieve desired objectives. Result shows that PGA value for 10% and 2% probability of exceedance in 50 years vary between 0-0.18g and 0-0.35 g respectively for 475 and 2475 return periods. Hazard map and 0.2s spectral acceleration were developed.

Ince & Kurnaz (2018) used PSHA method to calculate seismic hazard for the province of Kahramanmaras, Turkey. PGA values for 10% probability of exceedance in 50 years were calculated and PGA zonation maps were created. Due to collision of Arabian and Anatolian plates, the Eastern Anatolian Fault and Dead Sea Fault were created and Kahramanmaras was under the influence of these faults. Analysis was performed using CRISIS software. Results indicated that PGA values for Boore et al. (1997) lies between 0.21 and 0.41 g and between 0.25 and 0.41 g for Kalkan and Gulkan (2004). In both cases maximum PGA value is 0.41 g. Acceleration values were higher in the south-eastern parts as compared with other.

Foytong et al. (2020) using PSHA method construct seismic hazard map in term of PGA and spectral acceleration for Northeast region of Thailand to reduce the damage caused by earthquake in future. To achieve the desired objectives earthquake data from 1912 to 2015 were obtained. Gardner and Knopoff (1974) technique were used to decluster in order to remove foreshocks and aftershocks. No specific GMPE was develop for Thailand. Next Generation Attenuation (NGA) model, and the GMPEs provided by Atikson and Boore (2003,2008) and Youngs et al. (1997) were both employed. According to the findings, the province of Bueng Kan has a high PGA value between 4 and 30 percent of g, which corresponds to a likelihood of exceeding 2 percent in 50 years. The PGA was almost 30% g along the Thakhaek fault line. The maximal ground acceleration in Nong Khai province was around 20 percent g.

Midzi et al. (2020) updated seismic hazard map of South Africa using PSHA method and spectral acceleration at 0, 0.15, and 0.2 s for 10 % probability of exceedance in 50 years were computed. Declustering of catalogue was done according to Reasenberg (1985) cluster-based method, using SEISAN software. Twenty-two seismic zones were generated, and seismicity of each source zone were characterized according to Gutenberg and Richter distribution and earthquake recurrence parameters were calculated using ZMAP and SEISAN software. Two GMPEs, Akkar et al. (2014) and Boore and Atkinson (2008) were used in this study. PSHA was performed using Open-Quake software. Results indicated that higher PGA values were observed in KOSH gold mining region of South Africa and PGA value for Witwatersrand gold mining region was 0.2 g.

2.2 Local Research Work

Bhatti et al. (2011) executed seismic hazard analysis for Islamabad (considering an area of about 100-150 km) using PSHA technique. Ground motion parameters were determined which are helpful in designing earthquake resistant structures. The PMD catalogue was used, which featured historical events from 25 AD to 1905 and instrumental recordings from 1906 to 2009. All the earthquake magnitudes were converted to moment magnitude M_W. CRISIS software is used for seismic hazard analysis. Result shows that the earthquake risk in Islamabad varies from sector to sector and is not constant. The PGA determined in this study for return period of 2500 years ranges from 0.24 g to 0.37 g.

Rehman et al. (2013) carried out probabilistic and deterministic seismic hazard analysis according to Pakistan building codes to determine PGA values for Gwadar city using EZ-FRISK software. To achieve the desired objectives, earthquake data from 1927 to 2010 were collected. Earthquakes were reported in different magnitudes which were converted to moment magnitude M_W using different relations. Next generation attenuation relation by Campbell and Bozorgnia (2008), Boore and Atkinson (2007), and Abrahamson and Silva (2008) were utilized. Deterministic analysis yielded a PGA value of 0.38 g for Gwadar City and Probabilistic analysis yielded horizontal ground acceleration of 0.15 g and 0.34 g for a return period of 100 and 500 years respectively

A Q Bhatti (2013) carried out seismic hazard analysis of Quetta city and to define seismic loading, design parameters were derived according to modern building codes and maps were developed for spectral acceleration values of 0.2 and 1 second with 2% probability of exceedance in next 50 years. Results indicated that an increased in PGA value is 67 % of g for a probability of 2 % exceedance in 50 years and 40 % of g (3.96 m/s^2) for probability of 10 % exceedance in 50 years. These results were then compared with results of PMD, who reported that 10 percent chance of exceedance in 50 years is 39.28 percent g (3.85m/s^2).

Khaliq et al. (2019) carried out seismic hazard analysis for Peshawar district using probabilistic approach, following the Cornell & McGuire approach to obtain PGA values and to draw seismic hazard curves. Surface ground motion maps were proposed in which the local soil effects were incorporated. CRISIS software was used to achieve desired objectives. Results indicate various PGA values along with their respective return periods.

Waseem et al. (2019) reassessed seismic hazard for Karachi according to Pakistan building code using PSHA and DSHA technique. Karachi is seismically active city as triple junction where Arabian, Indian and Eurasian Plates collide is present 110 km to the Southwest of Karachi and the active Chaman transform fault is located 120 NW of Karachi. PSHA were performed using EZ-FRISK software. Result indicated that PGA value for return period of 475 years was 0.23–0.25 g, same as proposed by Sesetyan et al. (2018)

Waseem et al. (2020) used PSHA technique to draw Pakistan's seismic hazard map according to building code of the country. PGA and Spectral acceleration were measured. EZ-FRISK software was then used to perform analysis. Results indicated that seismic hazard have higher value in the region where the active tectonic features like Makran subduction zone and Hindukush-Pamir were located. Higher the PGA value for the Suleiman range, 0.40 g for return period of 475 year.

Rahman et al. (2020) developed Seismic Hazard map, and PGA and Spectral acceleration values were obtained using PSHA technique for Bangladesh based upon history of seismicity, crustal fault, and subduction zone source models. Using Gardner and Knopoff algorithm, declustering was done to remove foreshocks (dependent events). Three different GMPE were used to calculate peak ground acceleration and spectral acceleration. Using EZ-FRISK software analysis were performed. Results indicated that the PGA value for the eastern region has been increased while decreased for northwestern regions of Bangladesh compared with previous studies.

Haider & Rehman (2021) calculated the seismic hazard for Karachi taking in consideration the modern building codes by utilizing the PSHA technique. Peak ground acceleration, spectral acceleration was determined, and risk maps were prepared. Results indicated that with a return period of 2500 years spectral acceleration at 0.2s was 1.37 m/s^2 and spectral acceleration at 1 s was 0.41 m/s^2, respectively and calculated PGA were 0.70–0.77 m/s^2.

In the light of above literature, a dire need to assess the seismic hazard using latest set of ground motion prediction equations was felt and urban centers (Gwadar and Quetta) of Baluchistan province, a sample from Pakistan were selected for this purpose. Latest types of available GMPEs including the database of Middle East, Europe (non-NGA) and NGA WEST 2, are utilized to study their effect on the SA and PGA values and comparative analysis between them were drawn.

CHAPTER 3

3. Methodology

3.1 Probabilistic Seismic Hazard Assessment (PSHA)

Cornell's work (Cornell 1968) is mainly used for the development of Probabilistic seismic hazard analysis or assessment (PSHA). Literature suggests that the "PSHA" term started in the 1970s' decade. Later, (Hanks and Cornell 1994) provided a detailed tutorial to perform PSHA. The PSHA technique has been modified by a number of researchers including Atkinson and Goda (2011) and Petersen et al. (2008) (Haider and Rehman 2021). Using probabilistic technique contour maps can be developed that show the expected amounts of ground and structural shaking in the region for a given return period (in years). Generally, PGA and SA, which stands for peak ground acceleration and structural acceleration respectively, represent the shaking level. Actual information about seismicity of the region can be obtained from PSHA. In PSHA, ground motion parameters can be obtained using all potential sources of earthquakes, their rate of occurrence, and their distances from a site. Uncertainties related to the intensity, location and occurrence of earthquakes existed, which are covered up during PSHA. Historical seismicity, earthquake source geometry identification, the formulation of recurrence law, ground motion parameters, and local site condition, are all significant factors consider during PSHA. (Bhatti et al 2011)

Generally, steps which involved to carry out probabilistic seismic hazard assessment are compilation of reliable earthquake catalogue, identification of seismic sources, selection of ground motion prediction equations (GMPEs) and calculation of probabilities of ground motion exceeding than the desired motion. Figure 3.1 shows the flow chart of the research methodology.

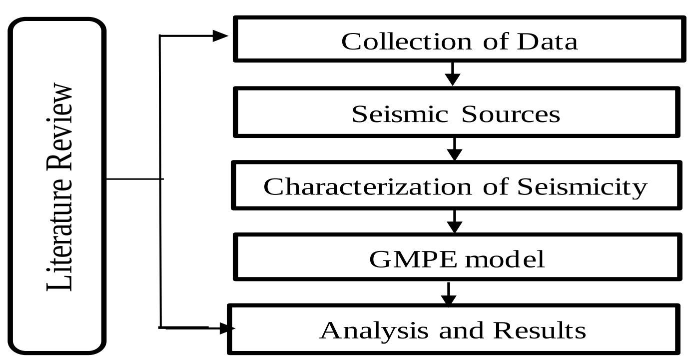


Figure 3.1 Flow Chart of Research Methodology

3.2 Selection of Seismic Sources

3.2.1 Catalogue of Earthquakes

The compilation of an earthquake catalogue is the beginning point and a key element to carry out the seismic hazard analysis. Thus, it is important to assemble a complete record of earthquakes that have occurred previously in the form of a catalogue, which will be used to identify seismic sources and to calculate the seismicity parameters. Many international bodies record earthquakes, such as the United States Geological Survey (USGS), International Seismological Centre (ISC), the European-Mediterranean Seismological Centre (EMSC) and the Global Centroid-Moment-Tensor (CMT). Local agencies that keep track of seismic activity in Pakistan include Pakistan Meteorological Department (PMD), seismological division of Water and Power Development Authority (WAPDA) and National Engineering Services Pakistan (NESPAK). The catalogue was compiled using the following datasets.

Pakistan Meteorological Department (PMD)

PMD possesses Pakistan's leading earthquake recording network, and it is solely responsible for disseminating the most up-to-date seismic activity information to government and non-government groups, as well as the public. Since 1954, the PMD seismic recording network has been in operation. Worldwide Standardized Seismic Network (WWSSN) stations were set up in Quetta, Islamabad, and Peshawar in the 1960s. This network allows PMD to capture tele seismic events, and PMD's data store now contains records of distant earthquakes. (PMD & NORSAR, 2007)

International Seismological Centre (ISC)

ISC is an international seismic recording organization established in the United Kingdom. It has more than 50 member countries that supply data to it. It gathers earthquake data from over 130 government and private organizations throughout the world.

United States Geological Survey (USGS)

The United States Geological Survey (USGS) is a major contributor to global seismic data collection. The Global Seismographic Network (GSN), developed in cooperation between the USGS, the National Science Foundation (NSF), and the Incorporated Research Institutions for Seismology (IRIS), a state-of-the-art network of digital sensors connected by a communications network. It is made up of more than 150 seismic stations located all around the world.

To execute this study and to prepare a catalogue of earthquakes, instrumentally recorded earthquake events with epicenters at 22° to 33° N latitude and 58° to 70° E longitude are studied. Earthquake data utilized is obtained for period of 1920-2020 from a number of agencies including International Seismological Center (ISC), Pakistan Meteorological Department (PMD), and United States of Geological Survey (USGS). The earthquake events of the area of interest were extracted from the PMD master catalogue, which was obtained from the PMD office, Islamabad. The events came out to be 2622. ISC data was obtained from their website and downloaded which comprised of 1360 events. Similarly, data from USGS website was downloaded which contained 1489 events. The downloaded material was in different formats and patterns; thus, the first step was to prepare working MS Excel files. These agencies reported earthquake in different magnitudes including body wave magnitude M_b, surface wave magnitude M_s, local magnitude M_L and moment magnitude M_W. As the size of the earthquake increases these magnitudes get saturated and hence cannot be reported or relied upon (Hanks & Kanamori, 1979) and (Chen et al., 2003)

Hence a more stable type of magnitude was developed based on the energy released during an earthquake called the "Moment Magnitude" (M_W) which is an absolute uniform magnitude scale around the world (Chen et al., 2003) .In this study, all the magnitudes are homogenized to a moment magnitude using the following set of equations (Scordilis, 2006).

$$\mathrm{Mw} = 0.67\ \mathrm{Ms} + 2.07 \qquad \text{For } 3 \leq \mathrm{Ms} \leq 6.1 \tag{1}$$

$$\mathrm{Mw} = 0.99\ \mathrm{Ms} + 0.08 \qquad \text{For } 6.2 \leq \mathrm{Ms} \leq 8.1 \tag{2}$$

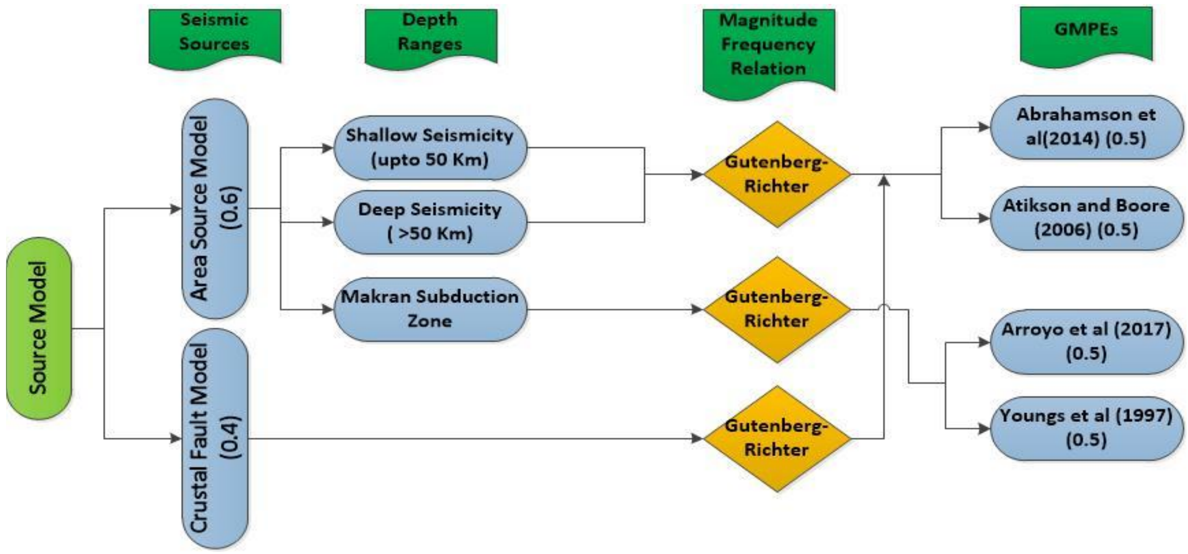
$$\mathrm{Mw} = 0.85\ \mathrm{Mb} + 1.03 \qquad \text{For } 3.5 \leq \mathrm{Mb} \leq 6.2 \tag{3}$$

For conversion of local magnitude, equation proposed by (Heaton et al., 1986) is used.

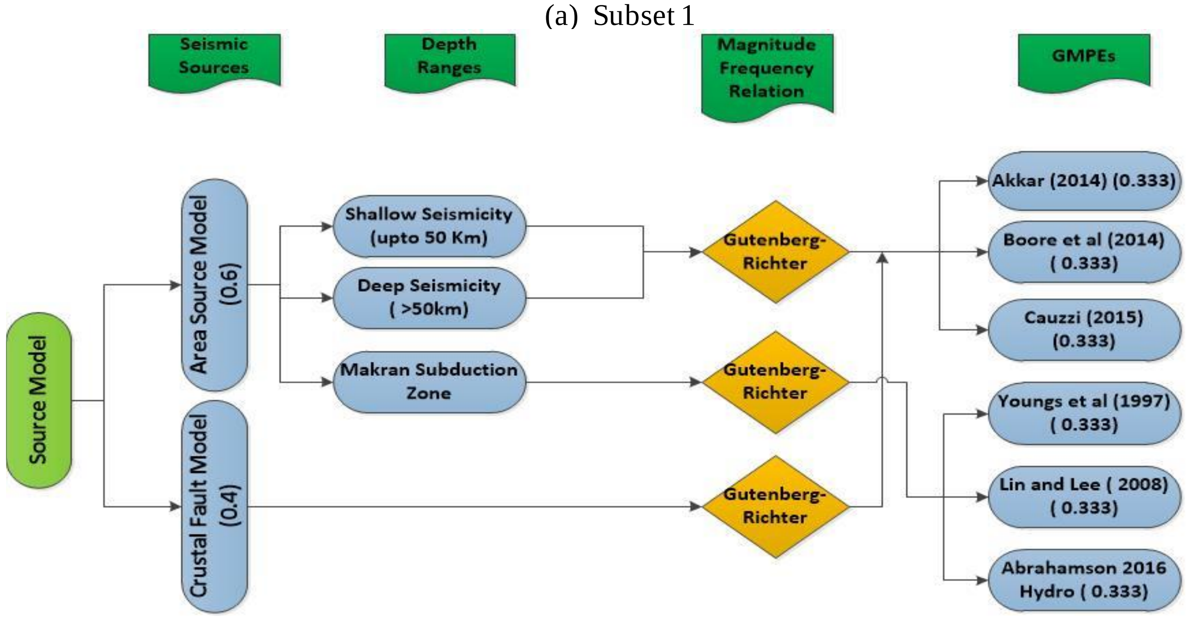
$$\mathrm{Mw} = \mathrm{ML} \qquad \text{For } \mathrm{ML} \leq 6 \tag{4}$$

3.2.2 Seismic Source Definition

The characterization of seismic sources consists of two different approaches for modelling: (1) area source model and (2) the active faults seismic source model. In order to deal the epistemic uncertainty in the modeling both source models are organized in the form of logic tree with 60% weightage to area source model and 40% weightage to crustal faults model as Figure 3.2 . The fact that area sources connect geological information and the tectonic with a pattern of observed seismicity describes why the area model is somewhat preferred over the fault model. (Danciu et al., 2018)



(a) Subset 1



(b) Subset 2

Figure 3.2 Logic Tree Used in Analysis. (a) Subset 1. (b) Subset 2

3.2.1.1 Seismic Area Sources

Two key assumptions are used for the selection of a seismic area source: focal depth of earthquake and pattern of faults (Rahman et al., 2021) . Thirteen seismic area sources are identified as shown in Figure 3.3, out of which zones 7 and 11 are categorized as deep source zones, zone 8 and 9 as subduction zone and remaining as shallow source zones.

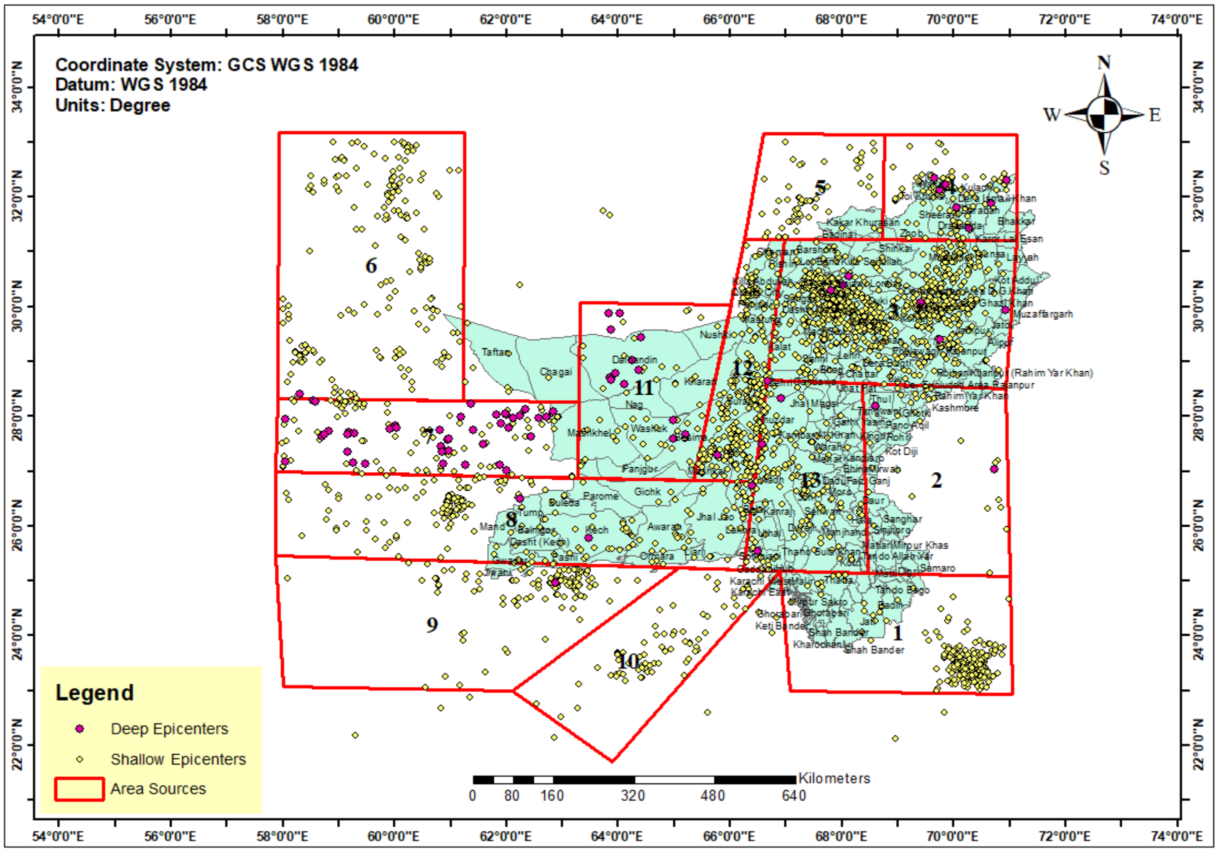


Figure 3.3 Area Sources of Study Area

Zone 1

This zone mostly includes Indian areas and extends to the southern shores of Pakistan's Sindh province. Numerous events have occurred in this region, making it one of the areas with the highest activity in recent years. The worst disaster in this zone happened on January 26, 2001, with a magnitude of M_W 7.7. It is bounded by following coordinates:

67.082, 22.994; 71.044, 22.928; 71.012, 25.087; 66.898, 25.188

Zone 2

Zone 2 mostly consists of Thar desert area. Although earthquake of magnitude 7 M_W on 20th October 1909 rocked certain portions of this zone but there was little damage reported because to the lack of infrastructure in the area. It is bounded by following coordinates:

68.466, 25.149; 71.012, 25.087; 70.943, 28.503; 68.379, 28.599

Zone 3

This zone contains eastern part of Quetta. This zone has been affected by many $M_W \geq 5$ earthquakes in the past. It suffered M_W 7.2 earthquake in 1931. The following coordinates define its boundaries:

66.662, 28.66; 70.943, 28.503; 71.14, 31.203; 66.988, 31.227

Zone 4 and 5

Zones 4 and 5 are in the Northern Punjab region. In the past, these zones have seen a few M_W >5 earthquakes. The following coordinates define their boundaries:

Zone 4=68.736, 31.22; 71.14, 31.203; 71.128, 33.137; 68.772, 33.135

Zone 5= 66.27, 31.229; 68.736, 31.22; 68.772, 33.135; 66.604, 33.143

Zone 6 and 7

Zones 6 and 7 contains the area of Iran. These zones have been affected by many M_W greater than 5 earthquakes in the past. The southern areas of Iran are seismically very active. Iran experienced a M_W 7.7 earthquake recently on 16th April 2013. It is bounded by following coordinates:

Zone 6= 57.908, 28.326; 61.242, 28.291; 61.25, 33.162; 57.927, 33.168

Zone 7= 57.877, 26.982; 63.29, 26.874; 63.308, 28.269; 57.908, 28.326

Zone 8

This zone has Makran Mountain Ranges in its northern part while Arabian Sea in southern part. Most of the events reported within this zone are above magnitude 5.0 (M_W) but the seismic activity isn't much frequent within the zone. This zone is bounded by following coordinates:

57.88, 25.454; 66.247, 25.204; 66.44, 26.812; 57.877, 26.982

Zone 9

This region is present on the coasts of Pakistan. The southern end of this zone is connected to the Arabian Sea. Gwadar is a part of this zone. It is one of the important seaports of Pakistan in terms of trading. On November 27, 1945, a devastating tsunami earthquake with a magnitude of M_W 8.1 struck this area. Tsunami waves had caused significant damage on Karachi seashores. Seismic activity in this region is mainly due to the MSZ. Vertices of this zone have following coordinates:

58.021, 23.077; 62.113, 22.987; 65.089, 25.239; 57.88, 25.454

Zone 10

This zone lies in Arabian Sea near the coast of Karachi. It has the Eurasian Indian-Arabian plate's triple junction near its center which is considered to be threatening to Karachi tough it hasn't showed large earthquakes in past still its significance cannot be over-ruled. Vertices of this zone have following coordinates:

62.113, 22.987; 63.892, 21.693; 67.03, 25.184; 65.089, 25.239

Zone 11

This zone has Makran ranges in its south while Registan Desert in its north. The zone has experienced a M_W 7.2 event on 18th January 2011. Vertices of this zone have following coordinates:

63.29, 26.874; 65.353, 26.833; 66.018, 30.022; 63.33, 30.079

Zone 12

This zone includes the all-important seismically active city of western Quetta. This zone has suffered lots of M_W 6 plus earthquakes in past and the deadliest was in 1935 of M_W 7.7 which killed at least 30,000 people and is known to be one of the deadliest earthquakes ever hit South-Asia. It is bounded by following coordinates:

65.353, 26.833; 66.44, 26.812; 66.988, 31.227; 66.27, 31.229

Zone 13

Zone 13 contain sthe cities of Khuzdar, Larkana and Jacobabad and Hyderabad and southern portion consists of Kirthar Mountains and its geologic formations. Its coordinates are as follows:

66.247, 25.204; 68.466, 25.149; 68.379, 28.597; 66.662, 28.66

3.2.1.2 Active Crustal Faults

Global Earthquake Model (GEM 2020) an updated global active fault database is used to obtain the active crustal fault data for Baluchistan province. Within the targeted area, Figure 3.4 depicts important active crustal faults, out of which some known faults are explained here.

Chaman Fault

The Chaman fault system, extends from Afghanistan into western Pakistan and is situated in the displacement zone between the Indian plate and the Helmand block, is another very noticeable tectonic structure in Pakistan's southern region. This fault is expected to slip between 2 and 20 millimeters every year (Zaman & Warnitchai, 2012)**.**

Hoshab fault zone

The Hoshab fault has an east west trend close to Nasirabad and Hoshab and gradually curves to the northeast in the east. This 300 km-long fault can be traced as a thrust fault with the north block sliding upward (S. A. Khan et al., 2003)

Ornach-nal Fault

Indian plate's western boundary is defined by the Chaman fault system. It includes the Ornach-Nal fault. Geological offsets were used to estimate the slip rate, which is roughly 20 to 40 mm each year for this strike slip fault. Ornach-Nal fault is a continuation of Chaman fault to the south. (Zaman & Warnitchai, 2012)

Panjgur fault zone

The Panjgur fault is situated in Central Baluchistan to the south of Panjgur town and is connected to the Chaman fault. This fault is situated in the east west close to the town of Panjgur and eventually bends northeast, just as the Hoshab fault. It is around 250 kilometers long. (S. A. Khan et al., 2003)

Kirthar Range

The eastern portion of the Kirthar Mountains is known as the Kirthar Range. It is a hill range that is around 400 km long and 30 km wide that runs north to south. The height of the mountain varies from roughly 1,000 meters in the south to 2,400 meters in the north. (Kazmi., A.H and Jan., 1997)

Ghazaband Fault

Within 80 km to the east of the Chaman fault in the axial belt, left-lateral displacement is exhibited by the Ghazaband fault and has a lower slip rate of 1 mm/yr (Zaman & Warnitchai, 2012).

Makran Subduction Zone

Complex tectonic areas make up the MSZ's borders. A 1000-km segment of the Eurasian-Arabian plate border lies in the Makran region of southern Pakistan and southeast Iran. The Ornach-Nal fault system creates the eastern boundary of the Makran as a transition zone between the Zagros continental collision and the Makran Oceanic subduction. (Byrne et al., 1992), and the Minab fault system (Iran) forms the western boundary. (Byrne et al., 1992) and (Heidarzadeh et al., 2008). Located in the Arabian Sea, the main thrust fault is around 225 km long. This fault is present slightly to the south of the coastal regions of Pasni and Ormara. This region has experienced worst earthquakes in Pakistan as it has a very high seismic rate.(S. A. Khan et al., 2003)

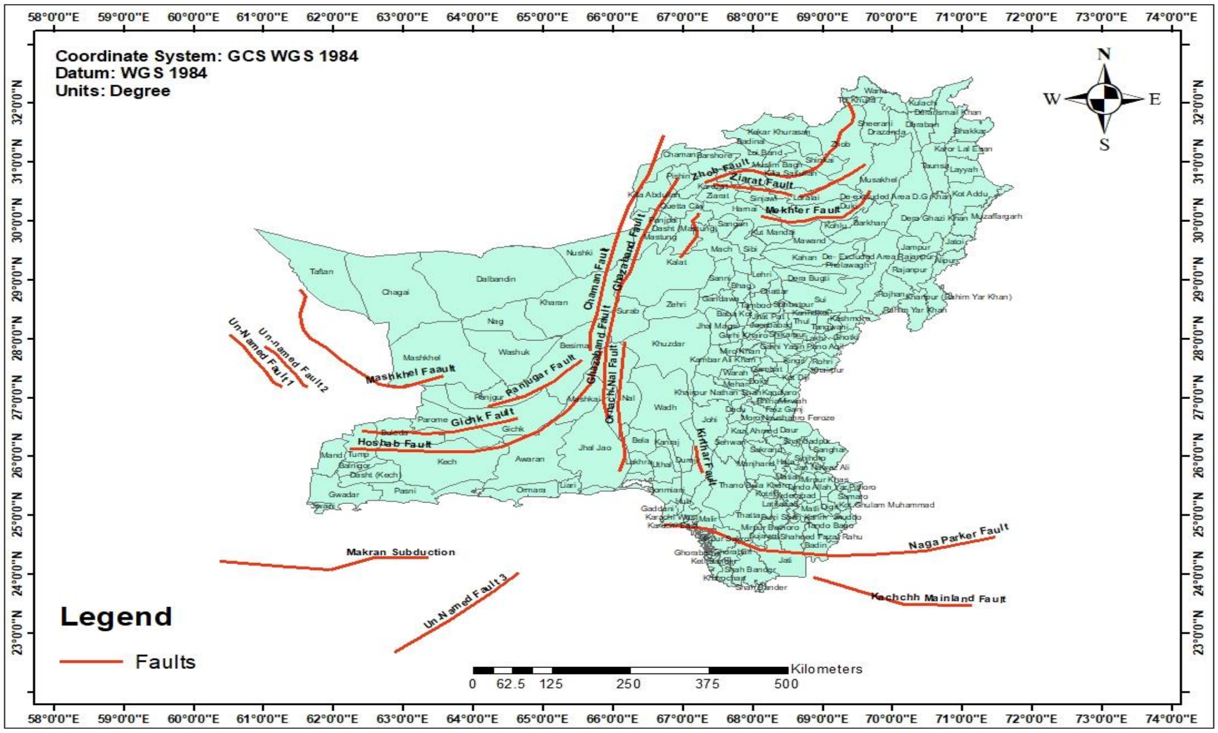


Figure 3.4 Active Crustal Fault consider in Study Area

3.3 Characterization of Seismicity

The seismicity of regions where fault data lack geological evidence of earthquakes is assessed using historical frequency assessment technique. It includes a statistical study of a database of earthquakes that have happened in a specific area. Beno Gutenberg and C.F. Richter have developed a correlation between earthquake magnitude and its frequency. They proposed the following relationship between the two parameters:

$$logN(M) = a - bM \tag{5}$$

$$anorm = a - logN \tag{6}$$

$$\lambda_M = a_{norm} - bM_{thres} \tag{7}$$

Where the left portion of the empirical relation represents the quantity of incidents each year for which an earthquake of magnitude M will be exceeded (recurrence rate). And on right side “a” and “b” are termed as seismic constants. The term "a" refers to a zone's seismicity, which varies by location, and "b" refers to the possibility of small or severe earthquakes. The probability of major earthquakes increases as the value of "b" decreases. (Bhatti et al., 2011). This empirical relation is formulated on the basis of Poisson's principle which states that earthquakes are spatially and temporally independent. The hazard estimation could be affected by the foreshocks and aftershocks associated with major event (Hashash et al., 2012). For analyzing the catalogue completeness it is necessary to remove foreshocks and after-shocks as Poisson model is violated by the existence of aftershocks (Nasir et al., 2013). Therefore, all aftershocks were removed from the earthquake catalogue.

ZMAP software was used to determine the Gutenberg & Richter constant values for seismic sources. Constant "a" and "b" values with regression analysis graphs for all thirteen area source zones are displayed below:

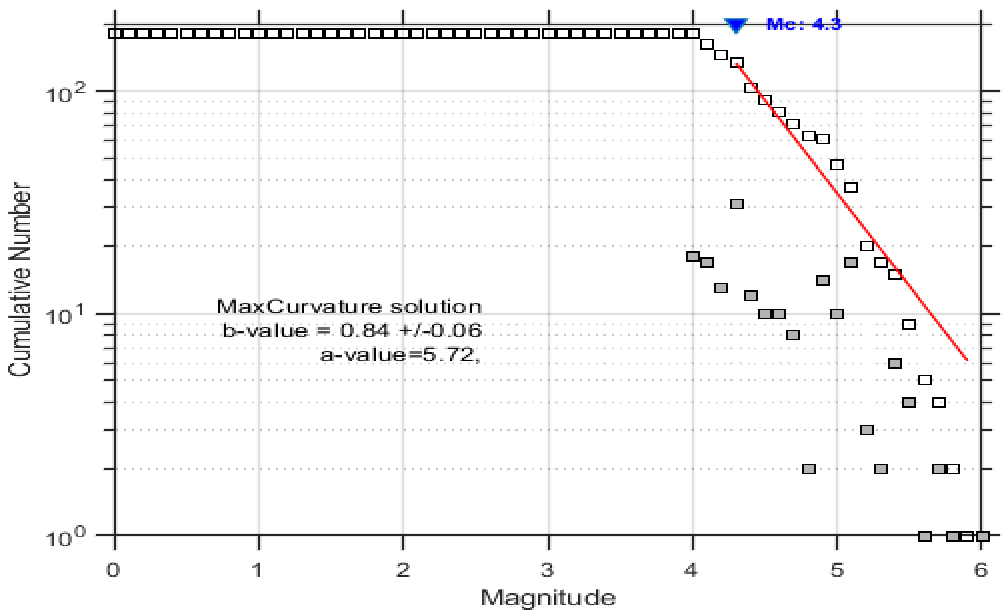


Figure 3.5 Zone 1 Regression Analysis

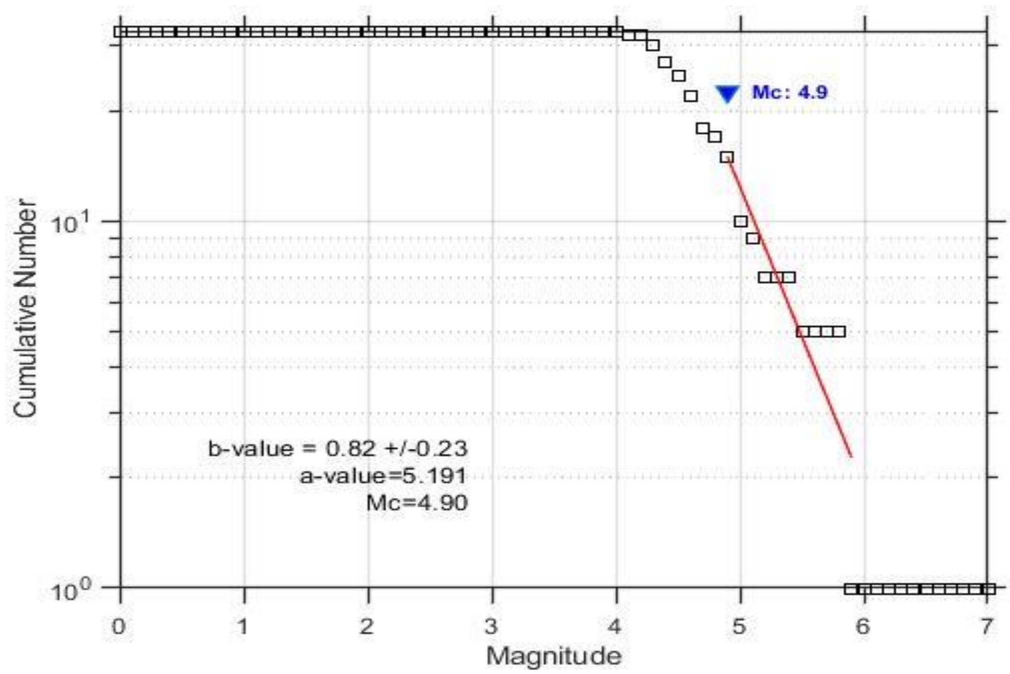


Figure 3.6 Zone 2 Regression Analysis

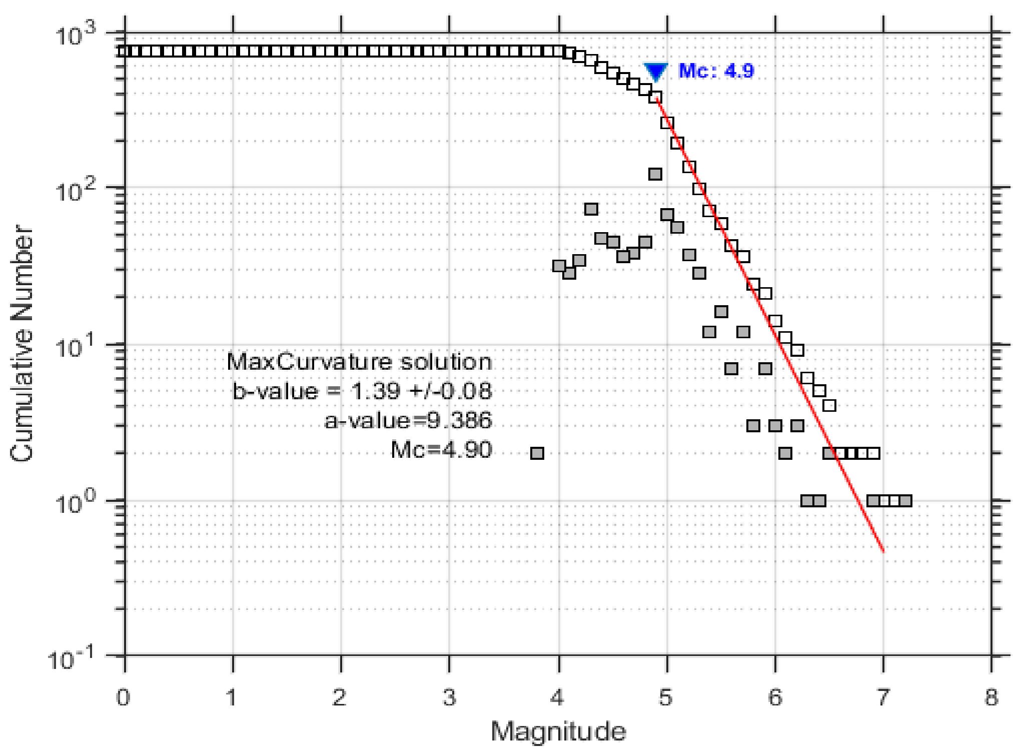


Figure 3.7 Zone 3 Regression Analysis

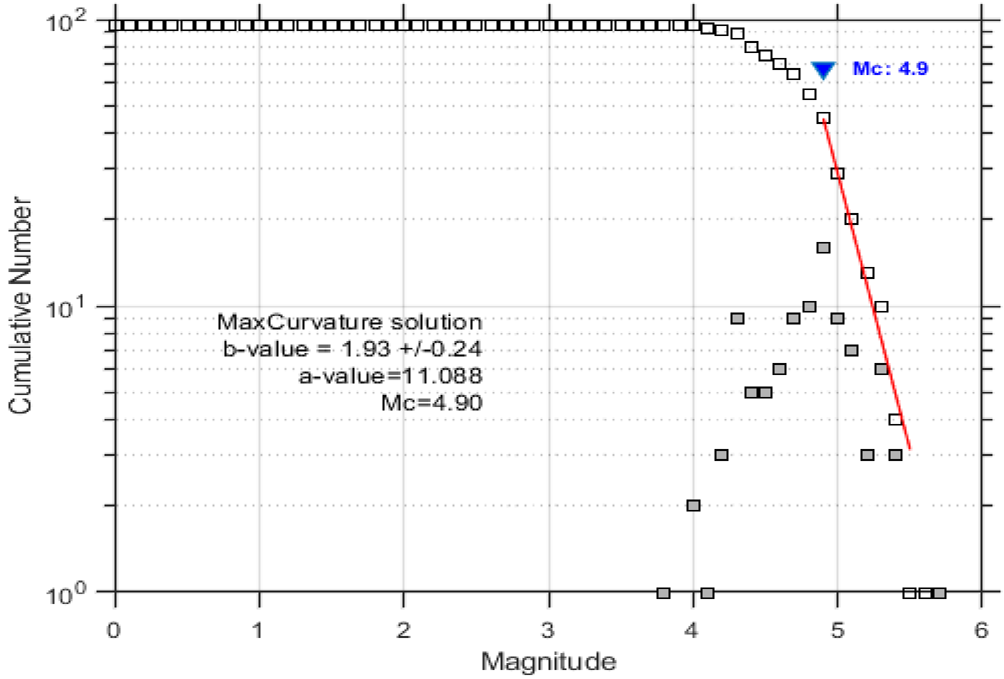


Figure 3.8 Zone 4 Regression Analysis

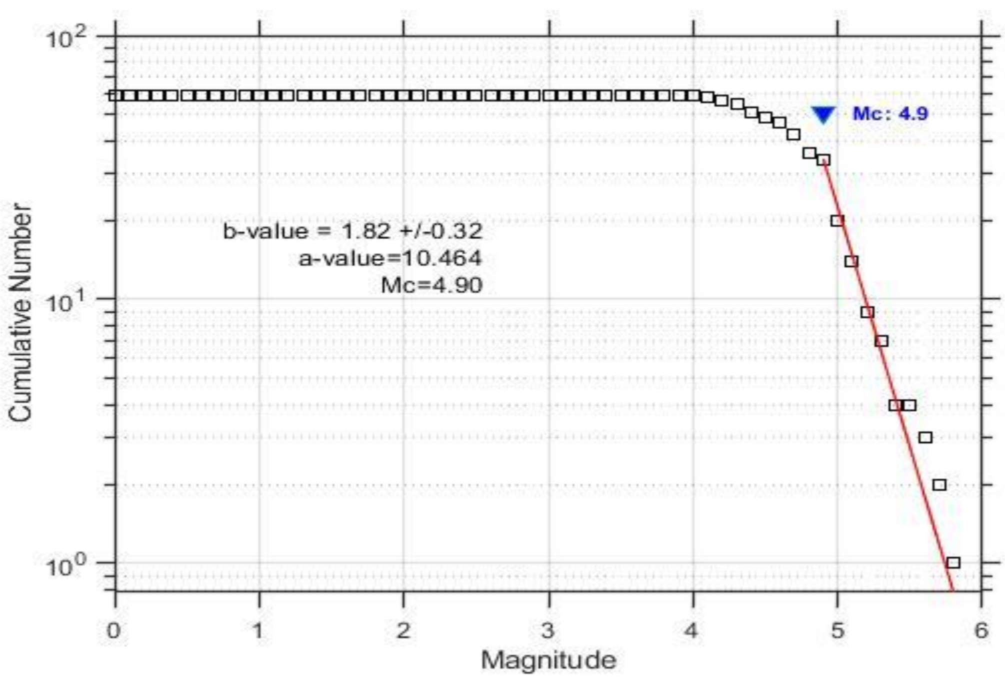


Figure 3.9 Zone 5 Regression Analysis

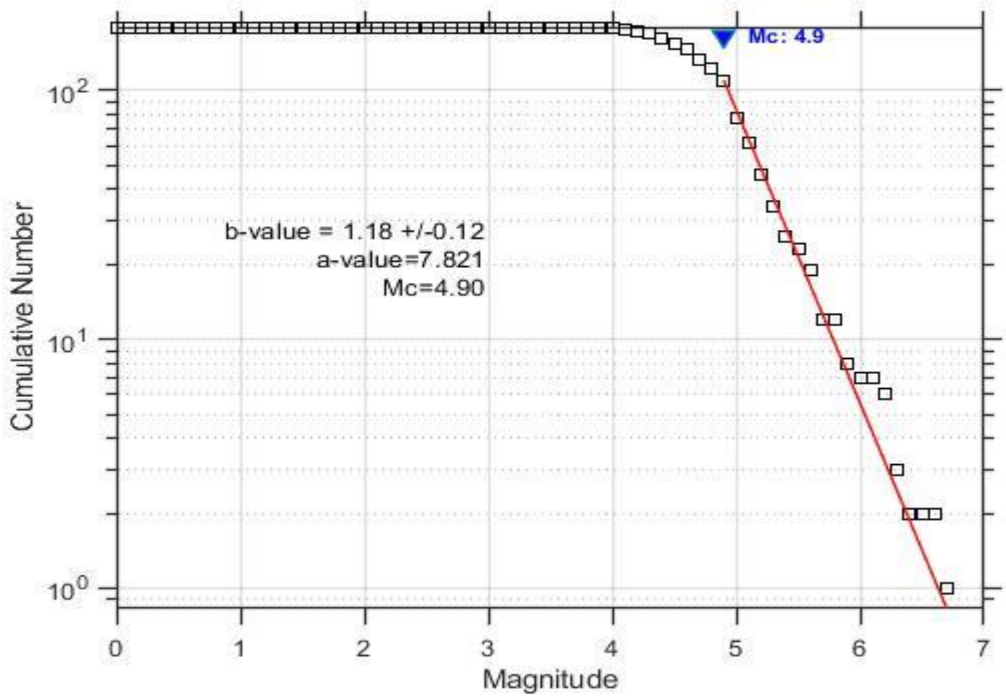


Figure 3.10 Zone 6 Regression Analysis

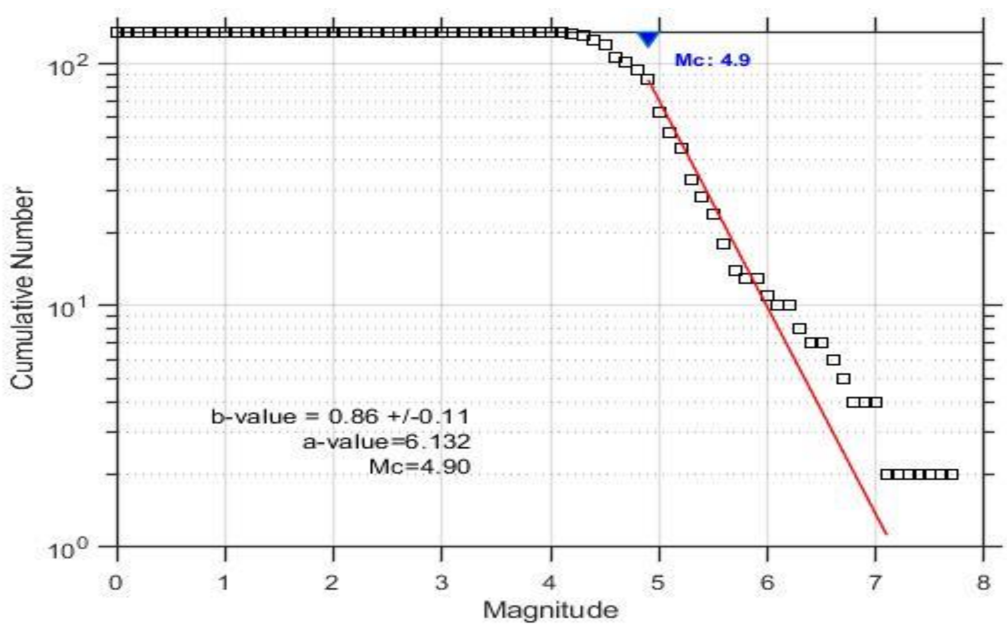


Figure 3.11 Zone 7 Regression Analysis

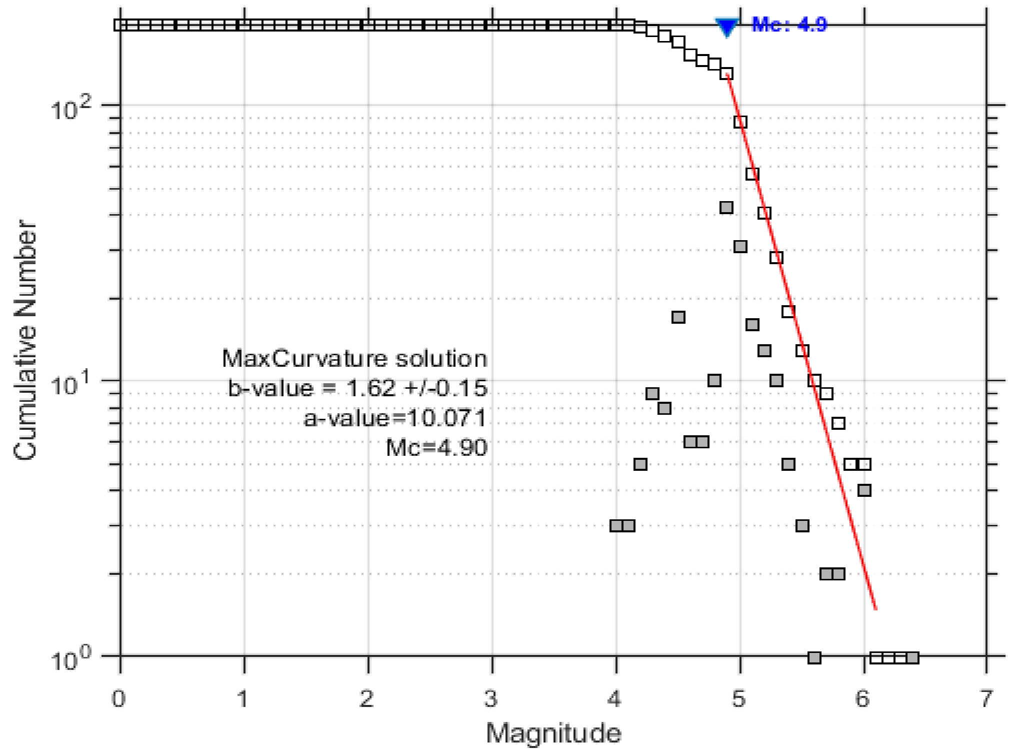


Figure 3.12 Zone 8 Regression Analysis

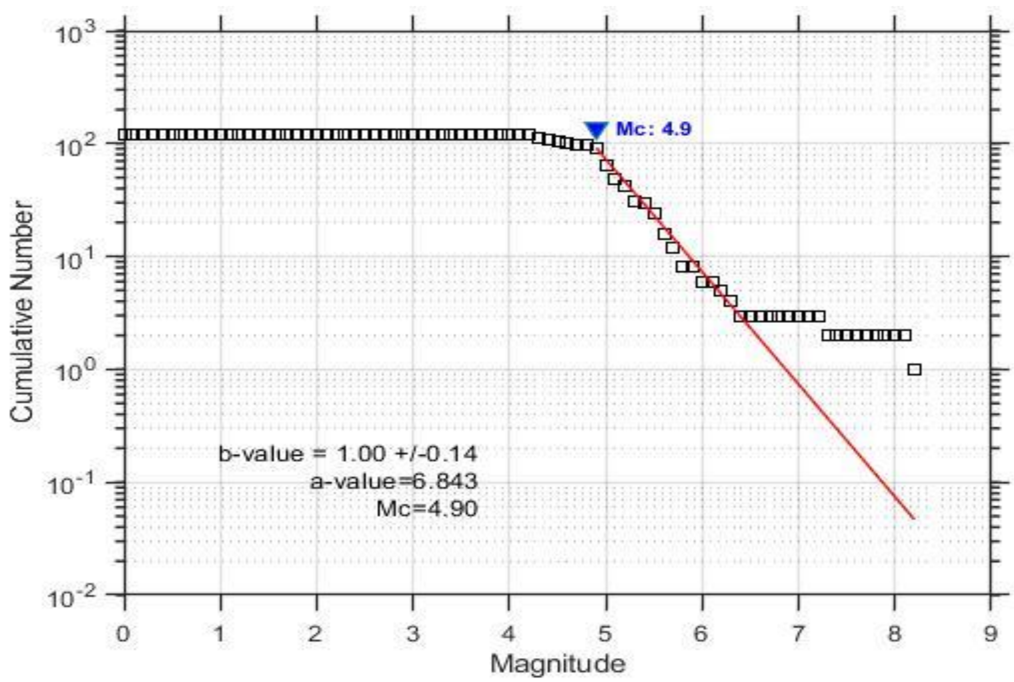


Figure 3.13 Zone 9 Regression Analysis

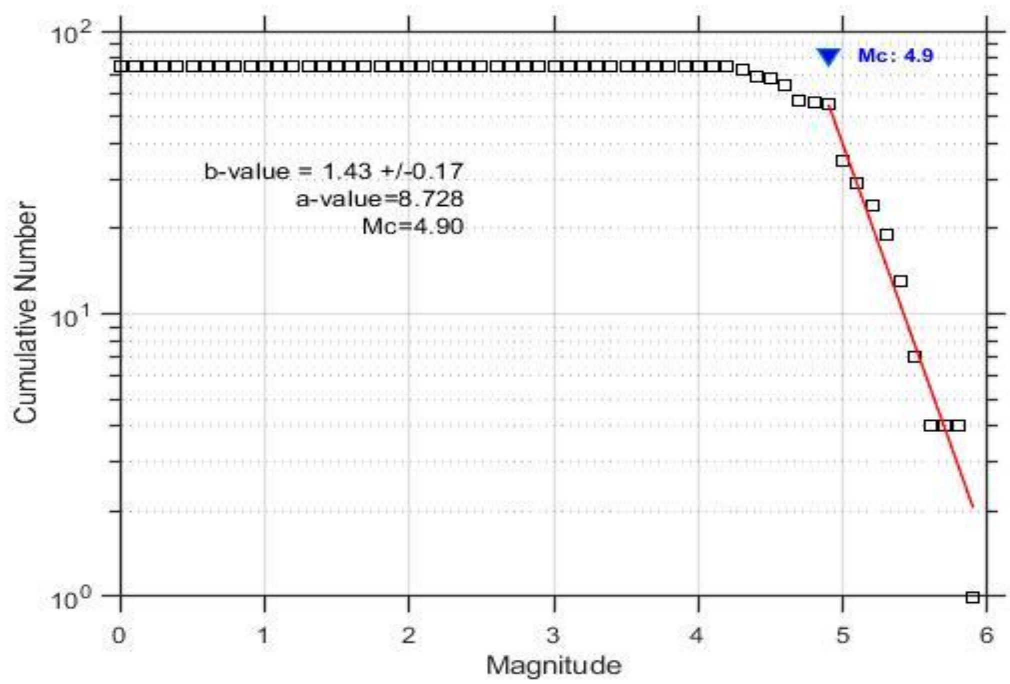


Figure 3.14 Zone 10 Regression Analysis

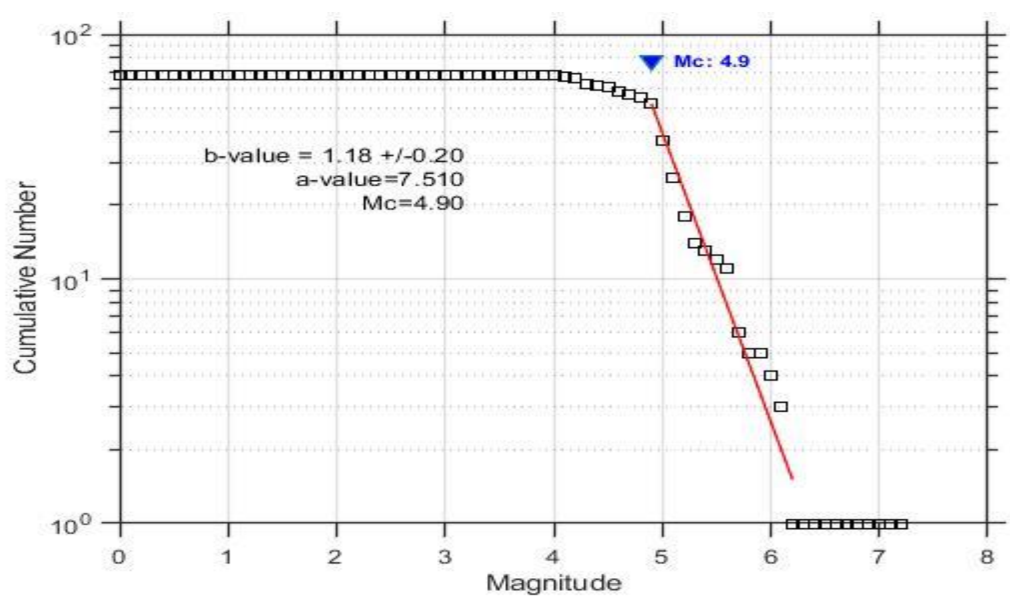


Figure 3.15 Zone 11 Regression Analysis

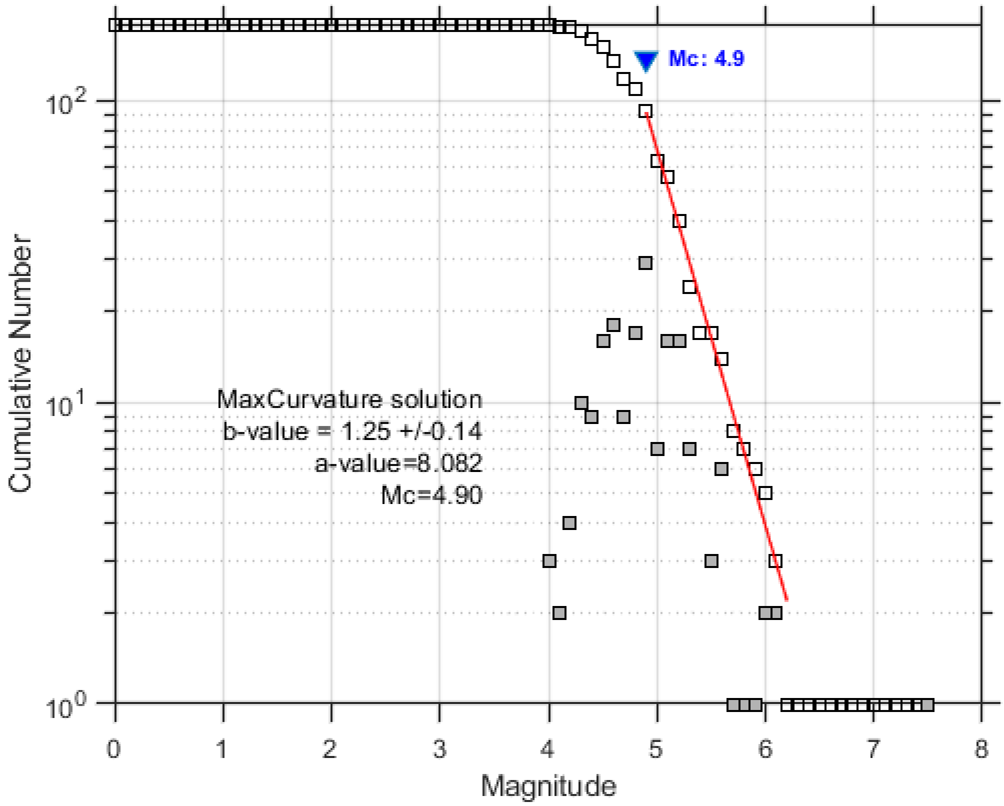


Figure 3.16 Zone 12 Regression Analysis

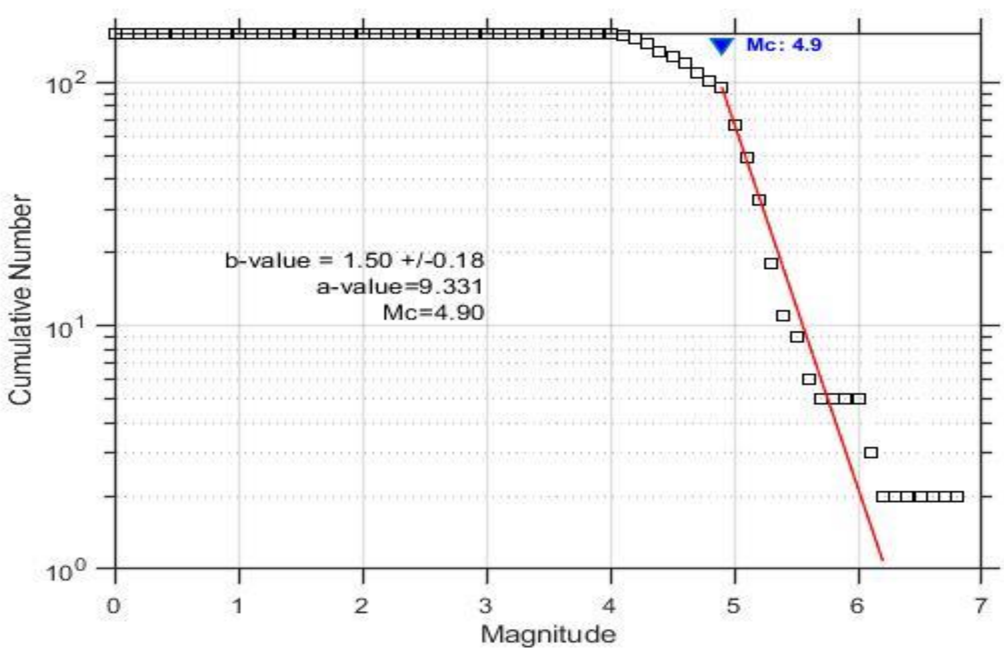


Figure 3.17 Zone 13 Regression Analysis

Table 3.1 Seismicity Model of Study Area (Seismic Area Sources)

Sr.No	Zones	Gutenberg-Richter Constants				M_{max}	M_{thres}	λ	No. of Years (N)
		a	β=b*ln10	b	a(norm)				
1	Zone1	5.72	1.934	0.84	3.928	7.7	4.5	0.148	62
2	Zone2	5.191	1.888	0.82	3.150	7	3.5	0.280	110
3	Zone3	9.386	3.201	1.39	7.395	7.2	4.5	1.140	98
4	Zone4	11.088	4.444	1.93	9.325	5.7	4.5	0.640	58
5	Zone5	10.464	4.191	1.82	8.524	5.8	4.5	0.334	87
6	Zone6	7.821	2.717	1.18	5.881	6.7	4.5	0.571	87
7	Zone7	6.132	1.980	0.86	4.159	7.7	4.5	0.289	94
8	Zone8	10.07	3.730	1.62	8.092	6.4	4.5	0.802	95
9	Zone9	6.843	2.303	1	4.899	8.2	4.5	0.399	88
10	Zone10	8.728	3.293	1.43	6.784	5.9	4.5	0.349	88
11	Zone11	7.51	2.717	1.18	5.704	7.2	4.5	0.394	64
12	Zone12	8.082	2.878	1.25	6.148	7.7	4.5	0.523	86
13	Zone13	9.331	3.454	1.5	7.363	6.8	4.5	0.613	93

Table 3.1 & Table 3.2 represent the seismicity model for area under consideration & Table 3.2. Maximum magnitude determination for seismic source zones has become increasingly important in probabilistic seismic hazard assessment as maximum magnitude earthquakes may dominate ground motion assessments when dealing with low probability hazards (Bommer & Crowley, 2017). In this study, maximum magnitude associated to the seismic area sources is obtained through software directly and recurrence rate is calculated using Gutenberg and Richter relation. M_{thres} is 4.5, the smallest magnitude considered in this study for seismic sources. As earthquakes with a magnitude that is lower than M_w 4.5 are considered to have small engineering significance and they are not considered dangerous for the structures (Baker, 2013). Negative value of λ is not accepted by the software, therefore threshold magnitude is lowered for zone 2.

Table 3.2 Seismicity Model of Study Area (Crustal Faults)

Sr.No	Faults	Gutenberg-Richter Constants				M_{max}	M_{thres}	λ
		a	β=b*ln10	b	a(norm)			
1	Chaman Fault	6.12	2.23	0.97	4.457	7.8	4.5	0.092
2	Ghazaband	6.83	2.53	1.1	5.143	7.9	4.5	0.193
5	Hoshab	5.33	1.89	0.82	3.590	8	4	0.310
6	Kach Mainland	6.05	2.23	0.97	4.771	7.8	4.5	0.406
7	Mekhter	6.27	2.23	0.97	4.437	7.7	4.5	0.072
4	Ornach-nal	7.82	2.95	1.28	6.167	7.8	4.5	0.407
3	Zhob	4.52	1.70	0.74	3.073	7.3	4	0.113
8	Ziarat	6.93	2.74	1.19	5.550	7.9	4.5	0.195
9	Kirthar Fault	6.23	2.31	1	4.648	7.7	4.5	0.220
10	Mach and Joan	6.23	2.31	1	4.648	7.7	4.5	0.220
11	Gichk	6.23	2.31	1	4.648	7.7	4.5	0.220
12	Naga Parkar	6.23	2.31	1	4.648	7.7	4.5	0.220
13	Murgha Gibzai	6.23	2.31	1	4.648	7.7	4.5	0.220
14	Mashkhel	6.23	2.31	1	4.648	7.7	4.5	0.220
15	Un-named Fault 1	6.23	2.31	1	4.648	7.7	4.5	0.220
16	Un-named Fault 2	6.23	2.31	1	4.648	7.7	4.5	0.220
17	Panjugar	6.23	2.31	1	4.648	7.7	4.5	0.220
18	Subduction	6.23	2.31	1	4.648	7.7	4.5	0.220
19	Un-named Fault 3	6.23	2.31	1	4.648	7.7	4.5	0.220

It might be possible to estimate the recurrence rates for small-to-moderate magnitude earthquakes on each fault directly from the earthquake database in well-instrumented, seismically active regions (Youngs & Coppersmith, 1985). For an earthquakes on crustal faults, in Table 3.2 for serial number 1 to 8, Gutenberg-Richter constant values and recurrence rate is calculated using Gutenberg-Richter relation by assuming a symmetrical 15 km buffer zone on either sides of these faults. (Rahman et al., 2021) (Daneshfar & Benn, 2002). The empirical equation presented by Wells and Coppersmith (1994) is used to determine the maximum magnitude of faults whereas, Gutenberg-Richter constant values and recurrence rates for serial number 1 to 8 were averaged and assigned to serial number 9 to 19 because of absence of significant number of earthquakes on these faults. Like zone 2 of area sources, threshold magnitude is lowered for Hoshab and Zhob fault as negative value is not accepted by the software.

It is established that higher b values are a representation of small magnitude. (Chen et al., 2003) studied the reasons behind b-value generation errors. He analyzed three data sets, including a 24-

year set of earthquake data (M_W) from around the world, and found that most seismic source b-values lies near 1.0. However, he noticed certain variations with too small values, which he considers as inappropriate. This is owing to the lack of earthquakes of smaller magnitude in these areas. In this study b-values mostly approach unity, which means these zones are not prone to higher magnitude earthquakes.

3.4 Ground Motion Prediction Equation (GMPE)

It is an equation or a model that is used to calculate the shaking or the ground motion that occurs during seismic activity. The output of ground motion prediction equation is spectral acceleration, peak ground acceleration and peak ground velocity. Literature suggests that GMPE is also known as regression model or attenuation relationships which describe the reduction in amplitude of ground motion with increase in a distance between site and source (PMD & NORSAR, 2007) .During seismic activity, ground motion expected to occur at a site can be affected by different parameters including seismic source, site condition or fault geometry, intensity of earthquake and distance from source.

The generalized equation for ground motion prediction is:

$$lnY = c1 + c2M - c3lnR - c4R + c5 + c6S + \mathcal{E} \qquad (8)$$

Where Y denotes the ground motion, M denotes the earthquake magnitude, R denotes the source to site distance, F denotes the region's faulting mechanism, S represents the condition of site soil, and ε shows random error. Since there is no GMPE established for Pakistan, so we have to rely on GMPEs developed for other countries.

3.4.1 GMPE Selection

Based on the mechanism, tectonic plate boundaries all around the world produce various seismic zones. Active crustal zones, stable continental zones, and subduction zones are the most common types of these zones. Zones which are formed at interaction of plate boundaries called active crustal zones and possess a shallow/deep crustal earthquake. The second one is stable continental zones which are not much common around the world. These zones are not related with any plate boundaries and are mostly characterized by intra-plate earthquakes. The third category is of subduction zones which are the case of subduction of a tectonic plate under another. These zones produce both interface and in-slab earthquakes.

The area under study is associated with two main categories discussed above. Zones 1, 2, 3, 4, 5, 6, 7, 10, 11, 12 and 13 and all faults are of active crustal type. Zones 8 and 9 are subduction zones. In this study, a number of GMPEs are studied for each source in a logic tree to overcome the epistemic uncertainties in the GMPEs selection. Three set of GMPEs are used for analysis. In first set GMPE's which are assigned to each source are developed by NGA WEST 2. In second set non-NGA based GMPE's are used while third set is hybrid set in which NGA WEST 2 and non-NGA based GMPEs are used together. Further each set consists of two subsets. The first subset comprises of a combination of two GMPEs with equal weightage while, the second subset comprises of three GMPEs with equal weightage, as shown in Figure 3.2.

NGA WEST 2 database is created as part of a big multi-disciplinary research initiative that is supervised by The Pacific Earthquake Engineering Research Center (PEER). The database contains one of the most extensive sets of metadata available, including multiple distance measurements, site characterizations, and earthquake source data (Ancheta et al., 2014). In the most recent modification of the Building Seismic Safety Council's NEHRP Recommended Provisions, the database is now listed as a key source of ground motion measurements. GMPEs used in this study is enlisted in the Table 3.3.

Table 3.3 Ground Motion Prediction Equation Used

GMPEs	Tectonic Regime
Abhramson silva and kamai 2014 (NGA WEST2)	Active Deep and Shallow Crustal
Atikson and Boore 2006	Active Deep and Shallow Crustal
Akkar and Bommer (2014)	Active Deep and Shallow Crustal
Boore et al 2014 (NGA WEST 2)	Active Deep and Shallow Crustal
Cauzzi 2015	Active Deep and Shallow Crustal
Derras et al 2016 (NGA WEST 2)	Active Deep and Shallow Crustal
Cambell and Bozorgina 2014 (NGA WEST 2)	Active Deep and Shallow Crustal
Idriss 2014 (NGA WEST 2)	Active Deep and Shallow Crustal
Bindi 2011	Active Deep and Shallow Crustal
Arroyo and singh 2017	Subduction
Youngs et al 1997	Subduction
Lin and Lee 2008	Subduction
Abrahamson 2016 Hydro	Subduction
Parker et al 2020	Subduction
Contreras and boroschek 2012	Subduction

3.4.2 Spectral ordinates and return period

PGA should not be used to estimate the damage potential caused by an earthquake as it unable to denote the dynamic nature of loads. Many earthquakes of the same PGA have varying energy levels, shaking durations, and frequency levels (A. Haider & Rehman, 2021). For 0.2s and 1.0s structural periods, the international building code (IBC) and Building code of Pakistan (BCP, 2021) has defined seismic loading with regard to spectral acceleration values and probability of exceeding in 50 years is limited to 2%. (Return period 2475 years).

Spectral acceleration values along with PGA for 0.1, 0.2, and 1.0 seconds have been calculated in this study. Risk level is frequently stated in modern building codes with regard to percentage of exceedance rate over a structure's lifetime. Seismic loading is often referred to as return period (A. Haider & Rehman, 2021). It's the timeframe (in years) in which an earthquake can repeat itself.

$$\mathrm{Tr} = -T/\ln\,(1-P) \tag{9}$$

where T is the building's life duration, P represents the chance of exceedance whereas, T_r shows the return period. Return periods 475 and 2475 years have been taken in consideration to carry out this study. In this study, the hazard was calculated using RCRISIS. It's a cutting-edge technology for determining ground motion exceedance rates at the target location.

3.5 Probability of Exceedance

The analysis concludes with the generation of exceedance probabilities for various levels of ground motion. Return period and time frame are the parameters on which these probabilities of exceedance depend. The exceedance probabilities are calculated by CRISIS using the following expression:

$$\Pr(A \geq a|Mi, Tj, k) = 1 - \sum_{s=0}^{Ns} Pk(s, Mi, Tj)[1 - \Pr\,(A \geq a|Mi, Tj, k)]^s \tag{10}$$

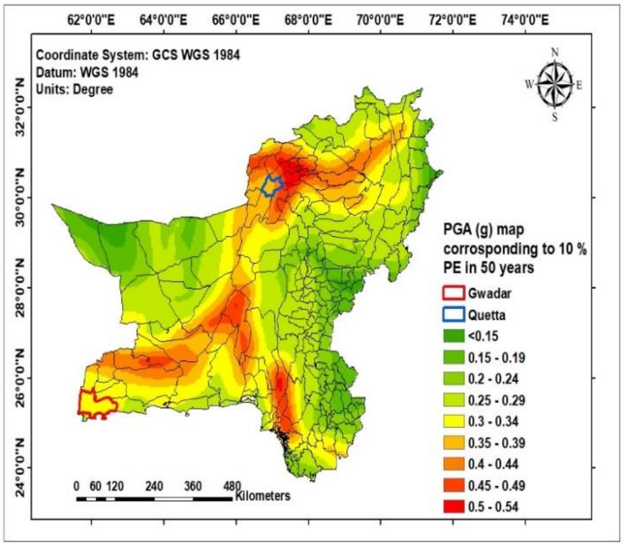
where $\Pr(A \geq a|Mi, Tj, k)$ is the probability that intensity a exceeded given that a seismic event of magnitude Mi occurred at source k, that is at a distance of R_k from the earthquake source. This likelihood is determined by the source-to-site distance as well as the magnitude of earthquake, which are determined using the GMPE's probabilistic interpretation of intensities. Concept of (BCP, 2021) seismic loading for ground shaking or motions with 2% exceedance probability in fifty years is utilized here. This makes a return period of 2475 years.

CHAPTER 4

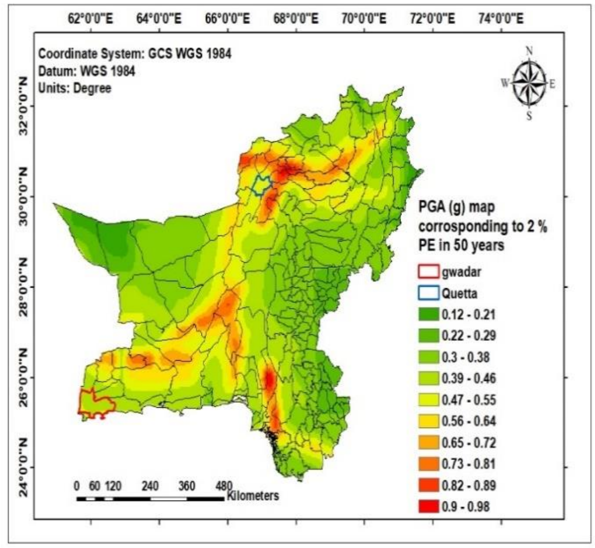
4. Results and Discussion

In this study, the hazard was calculated using R-CRISIS. It's a cutting-edge technology for determining ground motion exceedance rates at the target location. At each phase of the procedure for seismic hazard assessment, there are numerous uncertainties and assumptions. The logic tree procedure is applied to overcome these uncertainties. Epistemic, and aleatory uncertainties are generally considered during estimation of ground motion parameters (Abrahamson, 2006). Aleatory uncertainty refers to the spatial uncertainty in the earthquake events in a given time interval and specific location. The integration process is used to account for this uncertainty in the PSHA computations. Whereas, epistemic uncertainty is generated by a lack of knowledge and awareness of geological processes, such as the lack of ground acceleration for defining a region's attenuation model. To reduce the impact of these uncertainties, various logic tree models having a specified probabilistic weightage applied to each calculation step. This method is employed in this work to take into consideration the epistemic uncertainty in different GMPEs for each tectonic zone and in the seismic source models as well. A grid spacing of 0.2^o x 0.2^o (approximately 22.2 km) is employed in both directions in this analysis. For 10% and 2% probability of exceedance in 50 years (return period 475 and 2475 years respectively), hazard maps for PGA and spectral acceleration for structural period of 0.1 s, 0.2, and 1 s are created under a common reference site condition with 760 m/s mean shear wave velocity in the top 30 m of the crust. The National Earthquake Hazard Reduction Program (NEHRP) defines this reference site class as a boundary between site classes B and C.

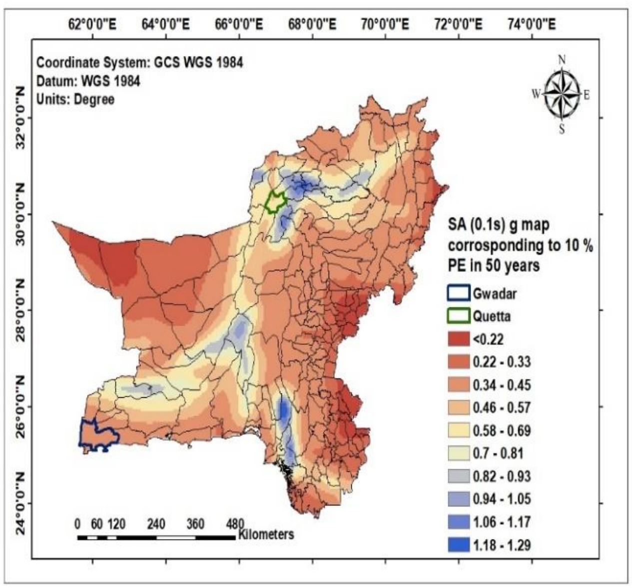
The hazard maps for spectral acceleration (0.1s, 0.2s, and 1s time periods) and PGA are shown in the Figure 4.1, Figure 4.2 and Figure 4.3 at 10 % and 2 % probability of exceedance in 50 years by using a different set of GMPE's.



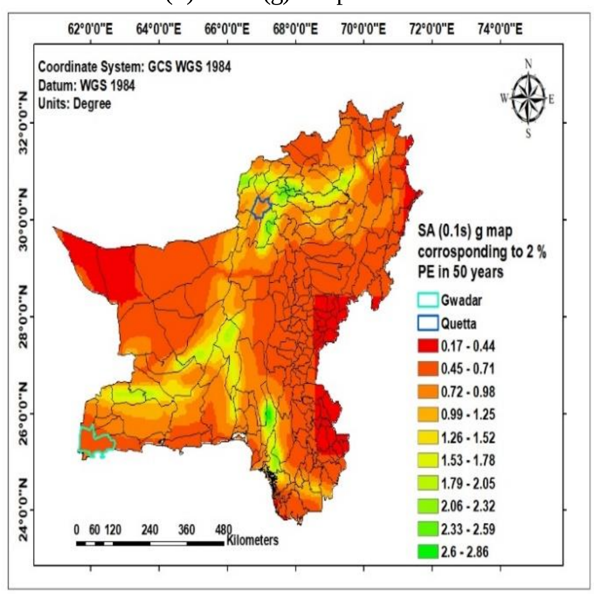
(a) PGA (g) map for 10 % PE



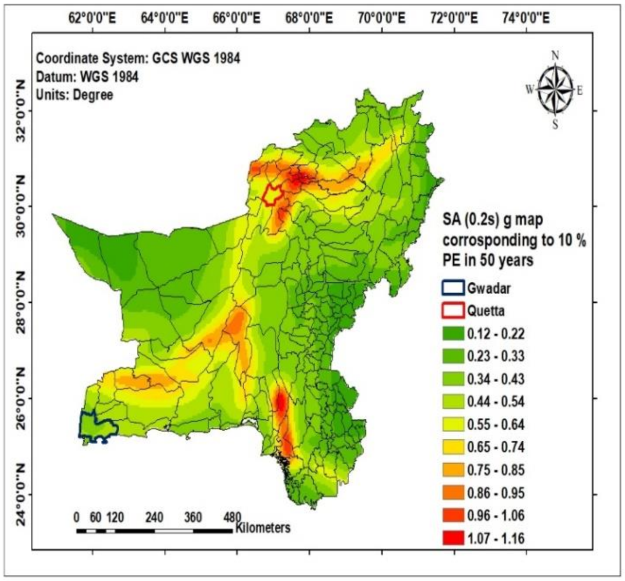
(b) PGA (g) map for 2 % PE



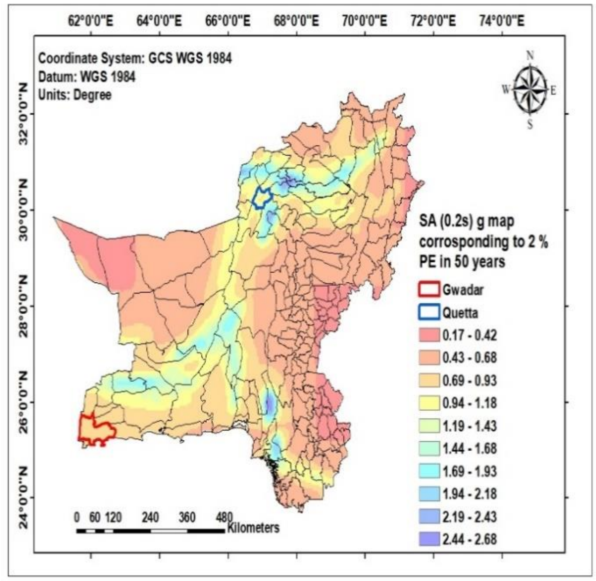
(c) SA (0.1s) g map for 10 % PE



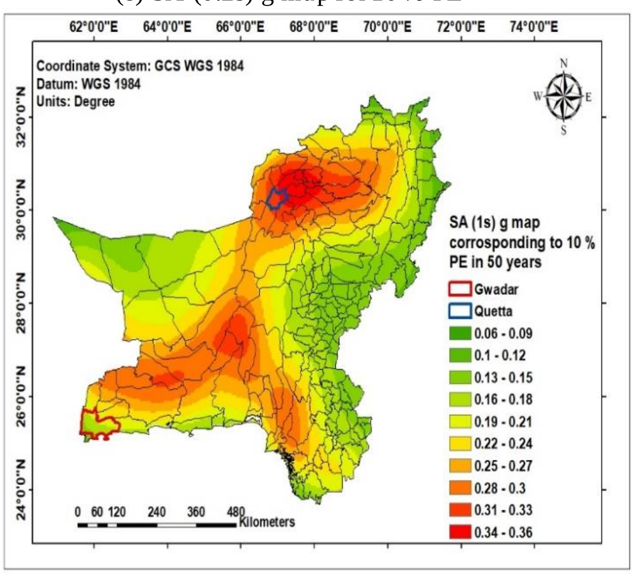
(d) SA (0.1s) g map for 2 % PE



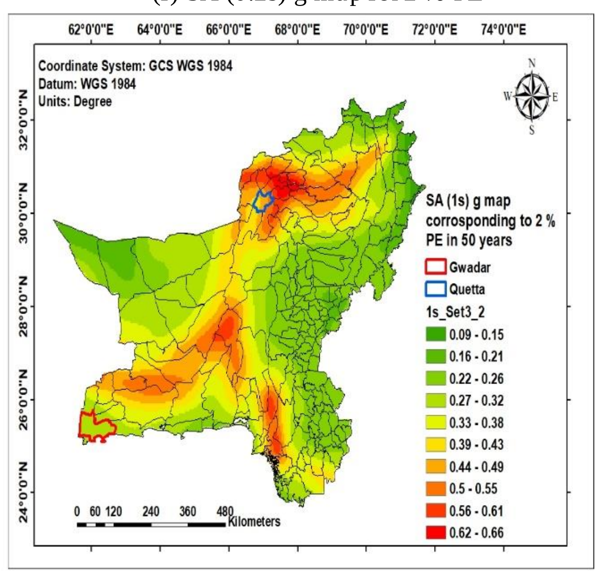
(e) SA (0.2s) g map for 10 % PE



(f) SA (0.2s) g map for 2 % PE

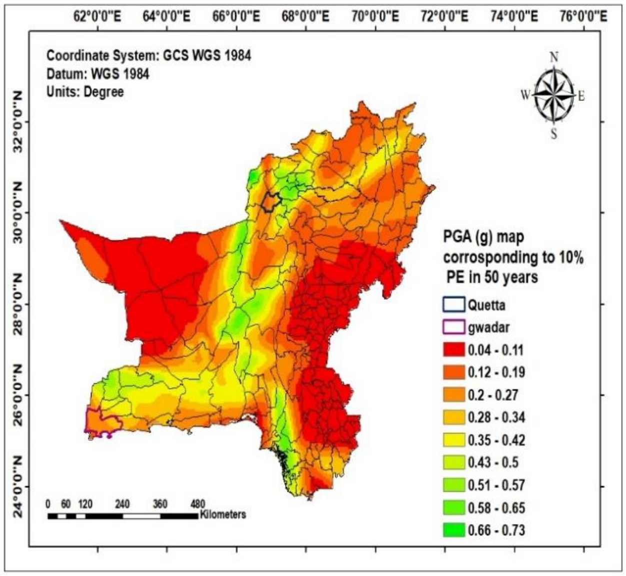


(g) SA (0.1s) g map for 10 % PE

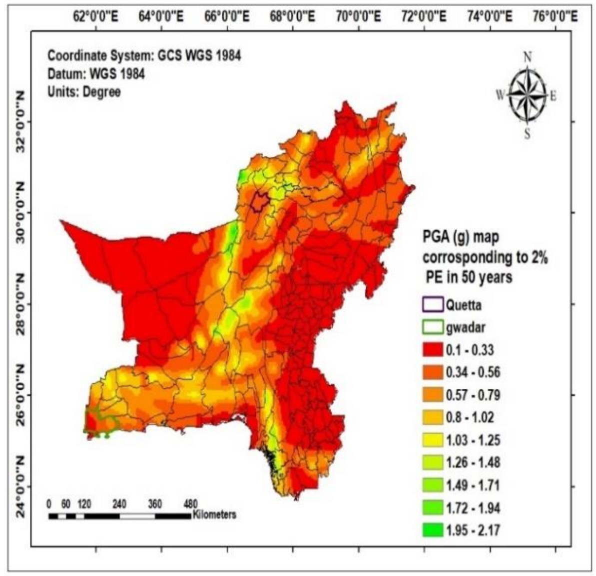


(h) SA (0.1s) g map for 2 % PE

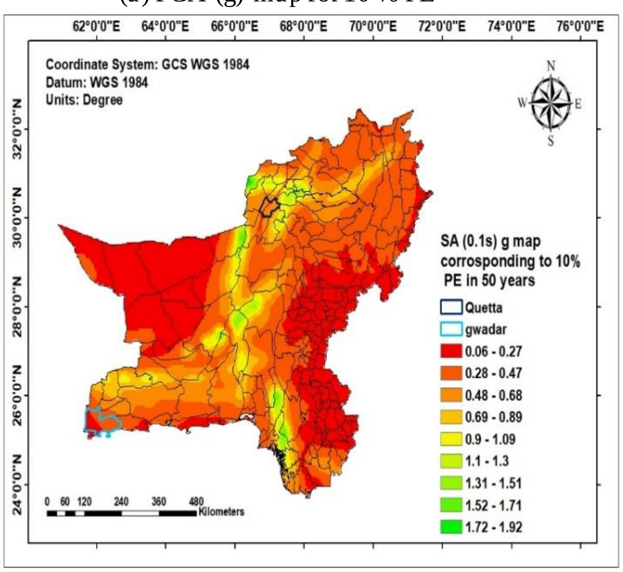
Figure 4.1 Seismic Hazard Maps of Peak Ground Acceleration (a & b) and Spectral Acceleration values (c, d, e, f, g & h) for 10 % and 2 % PE in 50 years by using set of Hybrid GMPEs



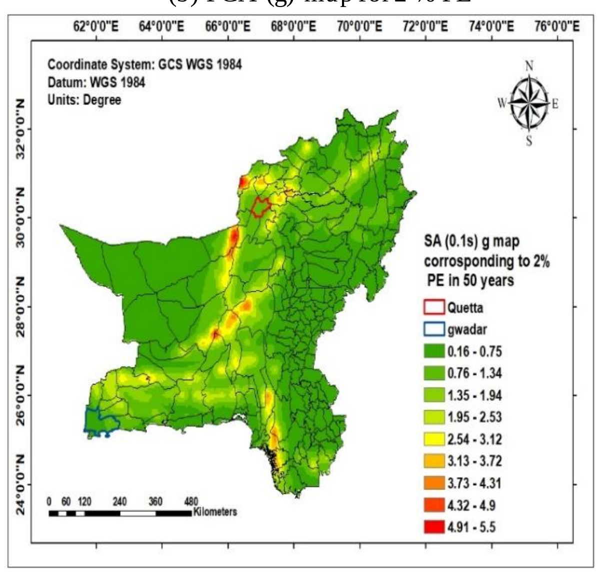
(a) PGA (g) map for 10 % PE



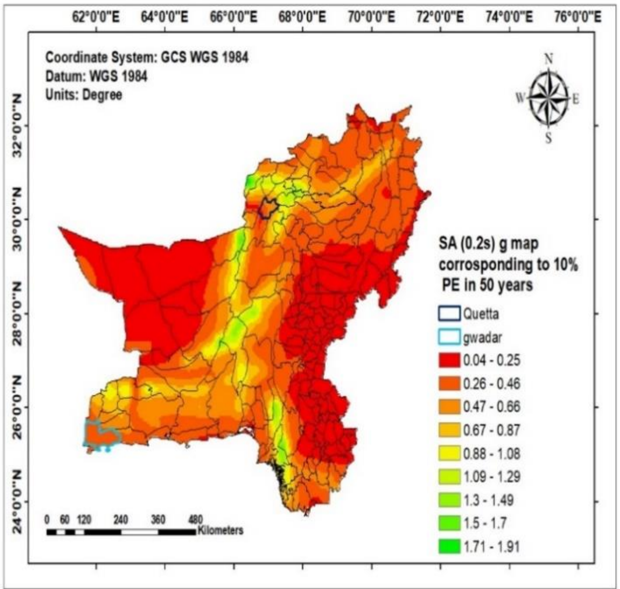
(b) PGA (g) map for 2 % PE



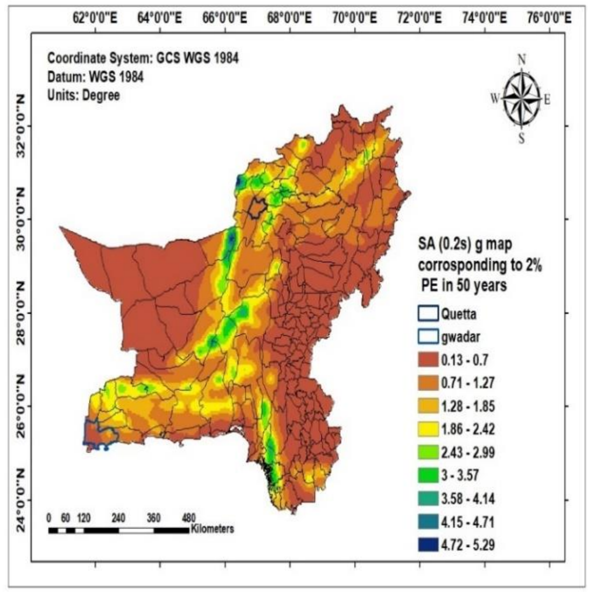
(c) SA (0.1s) g map for 10 % PE



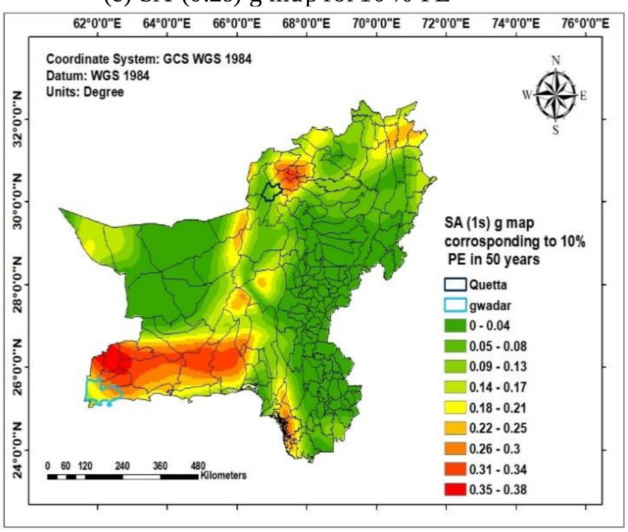
(d) SA (0.1s) g map for 2 % PE



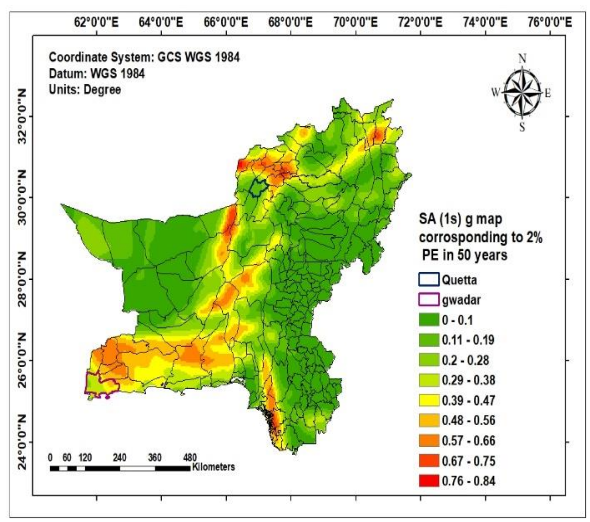
(e) SA (0.2s) g map for 10 % PE



(f) SA (0.2s) g map for 2 % PE

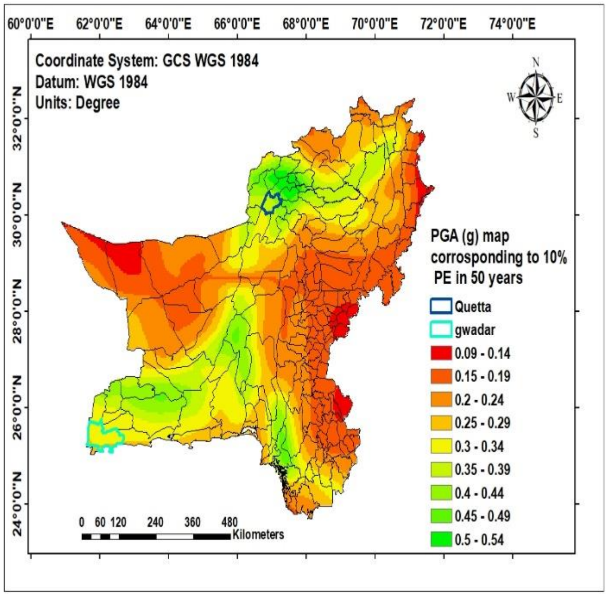


(g) SA (0.1s) g map for 10 % PE

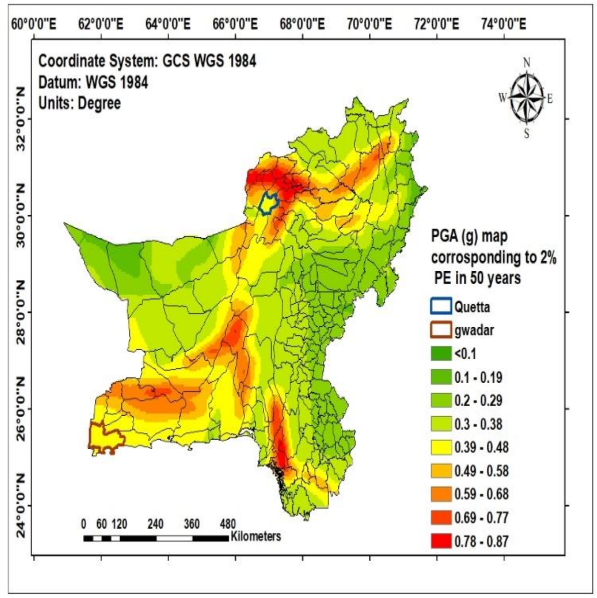


(h) SA (0.1s) g map for 2 % PE

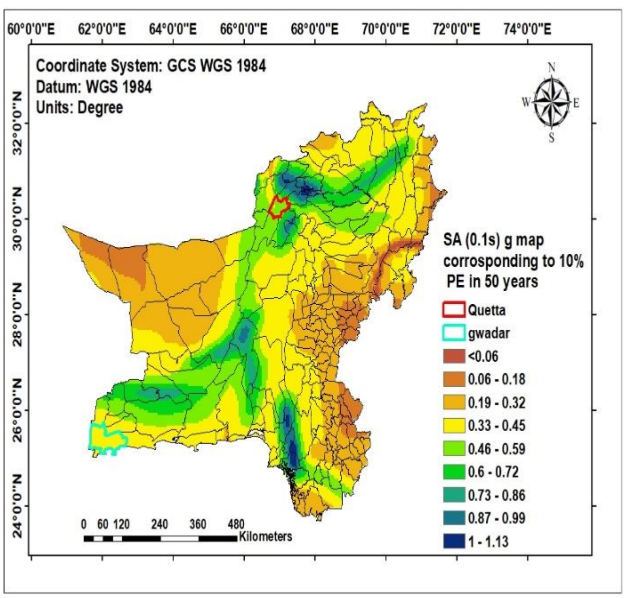
Figure 4.2 Seismic Hazard Maps of Peak Ground Acceleration (a & b) and Spectral Acceleration values (c, d, e, f, g & h) for 10 % and 2 % PE in 50 years by using set of GMPEs developed by NGA WEST 2



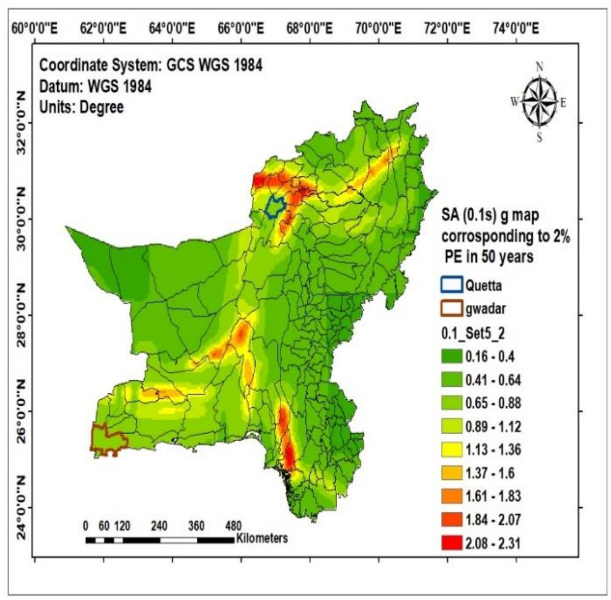
(a) PGA (g) map for 10 % PE



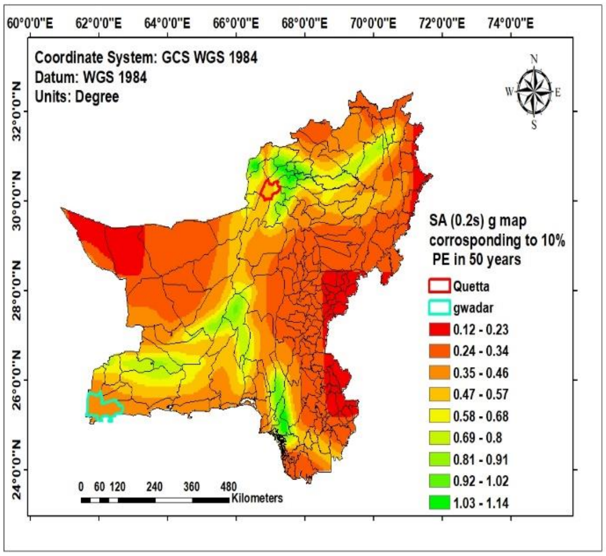
(b) PGA (g) map for 2 % PE



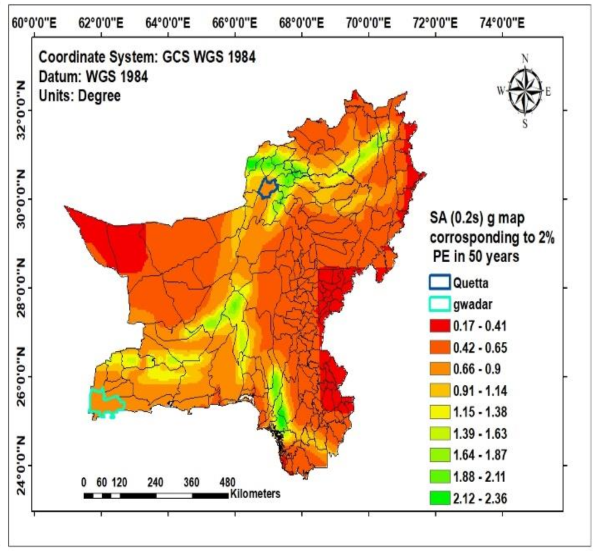
(c) SA (0.1s) g map for 10 % PE



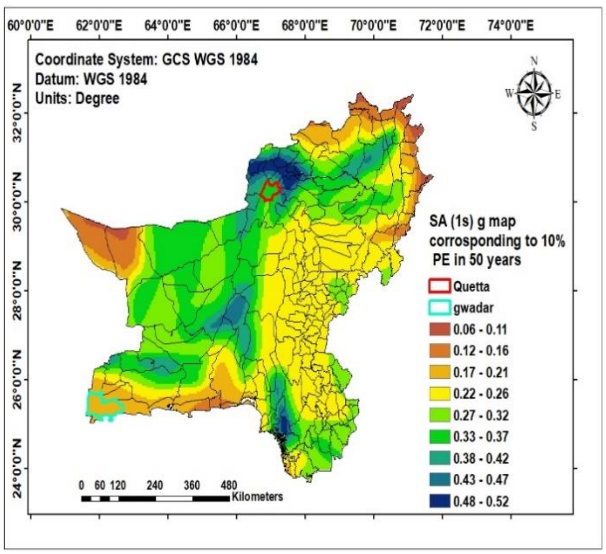
(d) SA (0.1s) g map for 2 % PE



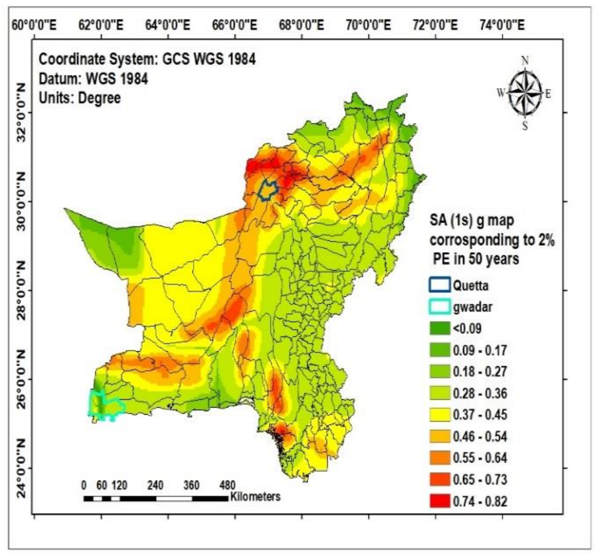
(e) SA (0.2s) g map for 10 % PE



(f) SA (0.2s) g map for 2 % PE



(g) SA (0.1s) g map for 10 % PE using set of non-NGA GMPEs



(h) SA (0.1s) g map for 2% using set of non-NGA GMPEs

Figure 4.3 Seismic Hazard Maps of Peak Ground Acceleration (a & b) and Spectral Acceleration values (c, d, e, f, g & h) for 10 % and 2 % PE in 50 years by using set of non- NGA GMPEs

Table 4.1 and Table 4.2 represents the lowest and maximum range of PGA and SA values obtained by performing the analysis using different set of GMPE's along with the range given in Pakistan Building code 2021.

Table 4.1 PGA and SA values for 2% Probability of Exceedance (PE) in 50 years

Sets	Period (s)	This Study				BCP 2021			
		Quetta		Gwadar		Quetta		Gwadar	
		Min	Max	Min	Max	Min	Max	Min	Max
HYBRID Set 1	PGA	0.51	0.54	0.47	0.54				
	0.1	0.84	0.99	0.68	0.91				
	0.2	0.92	1	0.74	0.91	0.8	1.4	1.4	1.6
	1	0.4	0.46	0.34	0.39	0.25	0.45	0.3	0.35
HYBRID Set 2	**PGA**	0.47	0.64	0.39	0.55				
	0.1	0.72	1.25	0.45	0.71				
	0.2	0.69	1.18	0.69	0.93	0.8	1.4	1.4	1.6
	1	0.39	0.55	0.27	0.32	0.25	0.45	0.3	0.35
NGA Set 1	PGA	0.25	0.73	0.25	0.9				
	0.1	0.41	0.73	0.17	1.74				
	0.2	0.86	1.62	0.47	2.32	0.8	1.4	1.4	1.6
	1	0.08	0.45	0.2	0.58	0.25	0.45	0.3	0.35
NGA Set 2	PGA	0.34	0.56	0.1	0.79				
	0.1	0.76	1.34	0.16	1.34				
	0.2	0.71	1.85	0.13	1.27	0.8	1.4	1.4	1.6
	1	0.11	0.38	0.11	0.56	0.25	0.45	0.3	0.35
(NON-NGA) Set 1	PGA	0.39	0.58	0.39	0.48				
	0.1	0.65	1.12	0.65	0.88				
	0.2	0.66	1.14	0.66	0.9	0.8	1.4	1.4	1.6
	1	0.37	0.64	0.01	0.45	0.25	0.45	0.3	0.35

(Table spanning header: **2% PE in 50 years**)

As shown above in hazard maps, seismic hazard threat in northern Baluchistan is moderately high and distributed smoothly mostly in southern Baluchistan. The seismic hazard maps of spectral acceleration for short period (0.2 seconds) and for 1-second period corresponding to a probability of exceedance of 2% in 50 years using hybrid set of GMPE, has a value between 0.42 to 2.68 g and 0.15 to 0.66 g respectively. Similarly, seismic hazard maps of spectral acceleration for short period (0.2 seconds) and for 1-second period corresponding to a probability of exceedance of 2% in 50 years using NGA WEST 2 set of GMPE, has a value between 0.7 to 5.29 g and 0.1 to 0.84 g respectively. In both cases, high peak acceleration is found in northern Baluchistan region (Quetta, Ziarat, Chaman and Mastung). Chaman fault, Ghazaband fault, Panjgur and Ziarat fault are responsible for higher hazard level. The Makran Subduction Zone, Hoshab fault and Ornach-nal fault is observed to be the cause of the predicted hazard levels in southwest Baluchistan (Gwadar, Panjgur and Ormara) but in case of spectral acceleration for 1-second period, values are higher in southwest Baluchistan as compared to northern Baluchistan using NGA WEST 2 set of GMPEs. Similar trend is followed for 10 % probability of exceedance in 50 years.

Table 4.2 PGA and SA values for 10% Probability of Exceedance (PE) in 50 years

10% PE in 50 years					
Sets	**Period (s)**	**This Study**			
		Quetta		**Gwadar**	
		Min	Max	Min	Max
HYBRID Set 1	PGA	0.38	0.4	0.26	0.35
	0.1	0.57	0.6	0.46	0.52
	0.2	0.56	0.71	0.51	0.55
	1	0.3	0.33	0.18	0.26
HYBRID Set 2	**PGA**	0.33	0.49	0.27	0.32
	0.1	0.46	0.7	0.34	0.45
	0.2	0.55	0.85	0.33	0.54
	1	0.31	0.36	0.13	0.21
NGA Set 1	PGA	0.17	0.39	0.04	0.39
	0.1	0.57	1.07	0.05	0.56
	0.2	0.33	1.06	0.33	0.82
	1	0.06	0.27	0.12	0.32
	2	0.05	0.06	0.05	0.14
NGA Set 2	PGA	0.12	0.42	0.12	0.34
	0.1	0.06	0.89	0.06	0.47
	0.2	0.04	0.87	0.26	0.46
	1	0.05	0.21	0.14	0.3
(NON-NGA) Set 1	PGA	0.3	0.49	0.25	0.34
	0.1	0.46	0.59	0.33	0.45
	0.2	0.47	0.8	0.35	0.46
	1	0.27	0.39	0.17	0.21

Table 4.3 Comparison of 2% PE in 50 years with previous studies

2% PE in 50 years									
Sets	**Period (s)**	**This Study**		**Zaman (2012)**		**Waseem (2020)**		**Rehman (2021)**	
		Quetta	**Gwadar**	**Quetta**	**Gwadar**	**Quetta**	**Gwadar**	**Quetta**	**Gwadar**
HYBRID Subset 1	PGA	0.54	0.54						
	0.1	0.99	0.91						
	0.2	1	0.91						
	1	0.46	0.39						
HYBRID Subset 2	PGA	0.64	0.55			0.5	0.54		
	0.1	1.25	0.71						
	0.2	1.18	0.93			1.16	1.1		
	1	0.55	0.32			0.39	0.48		
NGA Subset 1	PGA	0.73	0.9						
	0.1	0.73	1.74						
	0.2	1.62	2.32						
	1	0.45	0.58						
NGA Subset 2	PGA	0.56	0.79	0.7	1.5			0.9	0.6
	0.1	1.34	1.34						
	0.2	1.85	1.27					1.9	1.4
	1	0.38	0.56					0.7	0.55
(NON-NGA) Set 1	PGA	0.58	0.48						
	0.1	1.12	0.88						
	0.2	1.14	0.9						
	1	0.64	0.45						

Table 4.4 Comparison of 10% PE in 50 years with previous studies

		10 % PE in 50 years							
Sets	**Period (s)**	**This Study**		**Zaman (2012)**		**Waseem (2020)**		**Rehman (2021)**	
		Quetta	**Gwadar**	**Quetta**	**Gwadar**	**Quetta**	**Gwadar**	**Quetta**	**Gwadar**
HYBRID Subset 1	PGA	0.4	0.35						
	0.1	0.6	0.52						
	0.2	0.71	0.55						
	1	0.33	0.26						
HYBRID Subset 2	PGA	0.49	0.32			0.29	0.29		
	0.1	0.7	0.45						
	0.2	0.85	0.54						
	1	0.36	0.21						
NGA Subset 1	PGA	0.39	0.39						
	0.1	1.07	0.56						
	0.2	1.06	0.82						
	1	0.27	0.32						
NGA Subset 2	PGA	0.42	0.34	0.4	0.8			0.35	0.25
	0.1	0.89	0.47						
	0.2	0.87	0.46					0.79	0.7
	1	0.21	0.3					0.24	0.25
(NON-NGA) Set 1	PGA	0.49	0.34						
	0.1	0.59	0.45						
	0.2	0.8	0.46						
	1	0.39	0.21						

PGA and SA values using different set of GMPEs, for a 10% and 2% probability of exceedance in 50 years are compared with previous studies are shown in Table 4.3 and Table 4.4 . Higher PGA and SA value are obtained by using NGA WEST 2 GMPE’s as compared to hybrid and non-NGA based GMPE’s. In current study and existing literature, there are various causes which are responsible for the difference in predicted hazard levels like an updated earthquake catalogue and an updated active crustal faults data. Because of which “a” and “b” values change accordingly which has great impact on the hazard calculation. The data shown here can be utilized to determine the hazard levels of locations in the region under study for design purposes and structural analysis. These findings can be effectively used by professional structural designers to reduce seismic risk by designing earthquake-resistant infrastructure. The updated hazard maps shown here can be used by the different organizations and agencies to develop effective disaster preparedness, mitigation, and emergency readiness and management strategies. These findings can be used to develop effective disaster risk reduction measures in the country.

CHAPTER 5

5. Conclusions and Recommendations

5.1 Conclusion

This thesis presented an updated seismic hazard maps of Baluchistan province and the surrounding areas, produced from PSHA study conducted using different set of GMPEs. Logic tree approach is used to overcome seismic sources and ground motion prediction equation's uncertainties. Three different sets of GMPEs are used. Using NGA WEST 2 GMPEs, maximum value of spectral acceleration for short period (0.2 seconds) for Quetta corresponding to 2 % probability of exceedance in 50 years is 1.85 g and for Gwadar is 1.27 g. This value reduced to 1.18 g and to 0.93 g for Quetta and Gwadar respectively using Hybrid set of GMPEs. Due to the major active faults and the Makran subduction zone, the hazard is noticeably greater in the northern and southern regions of Baluchistan province. The hazard maps of this study reveal that the pattern of hazard variation is comparable to that of several earlier studies, but these maps are updated and have more realistic values of PGA and SA because of the updated versions of earthquake catalogue and active crustal fault data which influence the seismic constants "a" and "b" values, which has great impact on the hazard calculation.

5.2 Recommendations

- For the province of Baluchistan, a seismic risk assessment should be conducted, and the hazard analysis can then be coupled with it to evaluate the risk levels.
- Tsunami hazard evaluation should be conducted as it was not included in this study
- The crustal faults have received very little attention. Exploration of crustal faults and the Makran subduction zone both have significant gaps.
- For Pakistan, GMPE need to be created. It might have two sets of equations, one for subduction zones and one for active crustal regions.

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