# Probabilistic Seismic Hazard Analysis of Baluchistan and Hazard Deaggregation of Quetta using Geoinformatics Techniques

**By**

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**(2017-NUST-MS-GIS- 00000204982)**

**A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Remote Sensing and GIS**

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**August 2021**

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# DEDICATION

***Dedicated to my exceptional parents whose tremendous support and cooperation led me to this wonderful accomplishment.***

# ACKNOWLEDGEMENTS

I am grateful to Almighty Allah whose countless blessings gave me the strength to complete this research work.

I want to express my most sincere gratitude to my supervisor Dr. Javed Iqbal (IGIS, NUST) for giving me an opportunity of doing my thesis under his supervision. It was his sincere guidance which kept me in the right direction throughout the course of my research work. I would like to thank committee members Mr. Junaid Aziz khan (IGIS, NUST) and Mr. Sohail Anwar (GSP, ISLAMABAD) for their support, suggestions and encouragement throughout my Thesis work.

I would also like to pay special thanks to Mr. Asad-ur-Rahman for his expert advice and guidance in my work. Each time I got stuck in something, he came up with the solution. Without his help I wouldn't have been able to complete my thesis.

Finally and most importantly, I am in debt to my parents and siblings for their encouragement and unconditional support throughout my MS program. They always prayed for my success and provided every facility during my academic career. I dedicate this thesis to my Parents.

***SABA JAVEED***

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# LIST OF ABBREVIATIONS

| **Abbreviation** | **Explanation** |
|---|---|
| ASCE | American Society of Civil Engineers |
| BCP | Building Code of Pakistan |
| CMT | Centroid Moment Tensor |
| DBE | Design Bases Earthquake (10% PE in 50 years) |
| FMD | Frequency Magnitude Distribution |
| GR | Gutenberg-Richter |
| GSHAP | Global Seismic Hazard Assessment Program |
| IBC | International Building Code |
| ISC | International Seismological Center |
| MCE | Maximum Credible Earthquake (2% PE in 50 years) |
| MMI | Modified Mercalli Intensity |
| MSZ | Makran Subduction Zone |
| NESPAK | National Engineering Services, Pakistan |
| NGA | Next Generation Attenuation (Relationships) |
| NORSAR | Norwegian Seismic Array |
| PE | Probability of Exceedance |
| PGA | Peak Ground Acceleration |
| PMD | Pakistan Meteorological Department |
| PSHA | Probabilistic Seismic Hazard Analysis |
| QTZ | Quetta Transverse Zone |
| RP | Return Period |
| SD | Standard Deviation |
| SA | Spectral acceleration |
| SLE | Service Level Earthquake (69% PE in 50 years) |
| UHS | Uniform Hazard Spectra |
| USGS | United States Geological Survey |
| WCB | West Collision Boundary |

# ABSTRACT

Seismic Hazard Assessment (SHA) is most fundamental part of earthquake risk mitigation and management. Pakistan has quite a complex Seismo tectonic environment, with Arabian, Eurasian, and Indian plates colliding at different rates. In this research, probabilistic seismic hazard assessment and deaggregation approach for Baluchistan has been performed using area source model. For model development, an earthquake catalogue has been updated by compiling the events from national and international databases from year 1900 to 2020. For surface level hazard assessment, ground motion prediction equations (GMPEs) are appropriately used. To cope with uncertainty in Equations, the Logic Tree Approach is also used. Surface hazard maps are developed for Peak ground acceleration at 2%, 5%, 10%, 25% and 69% probability of exceedance in 50 years. The Uniform Hazard spectra (UHS) has been generated for major cities of Baluchistan. Surface level Uniform hazard spectra (UHS) graphs for Quetta and Gawadar city are developed at 69% 10% and 2% probability of exceedance which is SLE, DBE and MCE Level respectively. Hazard Deaggregation Analysis for Quetta is also carried out to estimate the percentage of hazard contribution of all the seismic source (faults, tectonic plates) to the city. Results of Deaggregation Analysis gives better understanding of seismic risk to cities. Surface Hazard PGA Maps, uniform hazard spectra (UHS) and hazard deaggregation Analysis have many practical applications in structural designing and performance evaluation of existing structures. These curves and maps would help for disaster risk mitigation and management policies.

## *CHAPTER 1*

# INTRODUCTION

### 1.1 Background information

Human creations are under the influence of natural forces, which are mainly in the benefit of mankind but sometimes resulted in disasters on human creation. In natural disasters, Earthquakes are considered the most devastating events to the lives, property, and the economy of human beings. In the natural hazards, earthquake contributes 60% of the total fatalities recorded all over the world. In the twentieth century, about 17000 persons per year have been killed due to earthquakes. (Chen et al., 2000). The earthquake also has a bad impact on the economy of countries, the 2005 Kashmir earthquake of Pakistan results in the loss of economy about $5 billion (Rossetto & Peiris, 2009), and 2011 Tohoko japan earthquake losses the economy of about $369 billion. To reduce the losses of lives and economy, the structure should be designed so that it can withstand any earthquake. In order to design these structures, a proper seismic hazard analysis should be done. The hazard analysis of Pakistan is carried out using a probabilistic approach based on GIS. Pakistan lay in South Asia, between the latitude of $24^{O}$ and $37^{O}$ N and longitude of $61^{O}$ and $76^{O}$ E, and occupied a total area of 796,095 square kilometres. Pakistan has a diverse geological and tectonic history, because of its location at the convergence of the Indian, Eurasian, and Arabian plate boundaries(Rafi et al., 2012). Pakistan is one of the most seismically active countries on the world. The southern part of Pakistan is highly seismically active as it has a wide range of active faults and main plate boundary. And Arabia plates is continuously subducting beneath Indian plates which results into subduction zones called as makran subduction zone. The active Himalayan belt, produced by the slow collision of Eurasian and Indian plates, extends through the northern part of Pakistan (Aitchison et al., 2007).

Pakistan and its surrounding region experience a severe degree of seismic hazard as a result of this complex geotectonic environment. Several significant earthquakes have hit the country in the last century, including the Kashmir earthquake in 2005 of magnitude 7.6 and 8.1 magnitude of earthquake and tsunami in Makran in 1945 (Durrani et al., 2005). Southern Pakistan consists of four tectonic regions: 1) Indus Platform 2) Makran Chagai Trench 3) the Indian Ocean and 4) Axial Belt which is also known as Sulaiman-Kirthar ranges (Waseem et al., 2019). Several studies have been conducted on Probabilistic Seismic Hazard Analysis (PSHA) of Pakistan to assess seismically prone areas of Pakistan.

In 1986 first study was performed to estimate the seismic hazard of Pakistan. This study was conducted to design criteria to develop Pakistan building code. Earthquake catalogue from 1905 to 1979 were collected from Instrumentally recorded databases and then based on Modified Mercalli intensity scale and whole country was divided into four seismic zones (Seismic Provisions, 2007). After that, a complete probabilistic seismic hazard analysis (PSHA) was conducted (Zhang et al., 1999) by Global Seismic Hazard Assessment program. Later on, the Global Seismic Hazard Assessment Program (GSHAP) carried out Probabilistic seismic hazard analysis of Pakistan using the classical approach by cornel 1968 and McGuire 1978 (McGuire, 1978).

Several studies on Seismic hazard analysis of Pakistan have been carried out in past decade. In 2001, PSHA was carried out using the conventional classical cornel-McGuire approach by (M. A. Shah, 2011) and updated seismic hazard maps were developed. After that in 2012 another study was conducted to developed improved seismic hazard maps of Pakistan. uniform hazard spectra (UHS) and hazard curves ware developed for various cities of Pakistan by (Zaman & Warnitchai, 2012). In 2018, hybrid approach of Spatially smoothed seismicity and Conventional Area Source (Frankel, 1995) was conducted by Earthquake Model of the Middle East to developed seismic hazard maps of Pakistan (Şeşetyan et al., 2018).

## 1.2 Seismic Hazard Analysis (SHA)

Seismic hazard analysis (SHA) of any area is the technique of estimating ground shaking at a specific location. In order to decrease the seismic risk to the structure, Structures are generally constructed to withstand a particular amount of ground shaking without major damage. The degree of ground shaking used to construct a structure is referred to as design ground motion. Certain parameters influence the estimation of the design ground motion for an area (Kramer 1996). Due to uncertainty in the size, time and location of earthquake events, it is very difficult to specify the ground shaking parameters. Seismic hazard assessment (SHA) is assessed using two approaches across the world.

### 1.2.1 Deterministic Seismic Hazard Assessment (DSHA)

Deterministic Seismic Hazard Analysis (DSHA) is a method for Determining the Seismic Risk at a Specific Location. This approach is based on the hazard contribution at the study area by the surrounding seismic source (Huang et al., 2012). In the beginning, the DSHA process was used to assess the ground motion risk in response to a specific seismic situation. Instead of providing the possibility of ground shaking incidence for different return periods, the DSHA methodology directly provides the worst-case scenario. Moreover, the standard DSHA approach fails to account for magnitude and location uncertainty. Deterministic seismic hazard analysis consists of four main steps (Figure 1):

1) The first step in the DSHA methodology is to locate any active seismic sources able to cause considerable ground motion close to the site.
2) The Second step is estimation of distance from source to site distance. It is the estimation of shortest distance between sources to site. This distance may be the epicentral or hypo central distance.
3) The selection of attenuation relationships, also known as GMPEs, is the third step. The goal is to forecast the amount of shaking or ground motion characteristics like PGA and SA. (Barani et al., 2014)
4) The controlling ground motion is set to the greatest ground motion possible at the location determined in the previous step. The controlling earthquake's magnitude at a specific distance is generally used to quantify the seismic hazard at the area (huang et al., 2012).

### 1.2.2 Probabilistic Seismic Hazard Assessment (PSHA)

Since 1970, the PSHA approach has been the extensively used method for estimating ground motion. The Cornell (1968) technique established a basis that was later adopted by the majority of researchers. The PSHA approach was refined after Cornell and became the Cornell-McGuire approach. This is often referred to as the traditional or conventional PSHA (Cornell, 1968). The PSHA approach considers multiple uncertainties in earthquake magnitude, location, and recurrence rate. As a result, the PSHA approach provides a framework for identifying, quantifying, and combining uncertainty in an organized manner (Kramer, 1996). PSHA consists of four main steps (Figure 2).

### Step 1: Identification of source zones:

Identification of seismic sources is a very important step in PSHA because Seismic sources are considered to have the potential to generate seismic ground motions. Sources could be point sources, line sources (active faults) or area sources based on seismicity. (Khaliq et al., 2019a).

### Step 2: Seismicity of Seismic Source Zones:

Second step in measurement of PSHA in seismicity measurement of source zones. Earthquake recurrence is measured which represents the seismicity of source zones identified in step one (Beitr, 1945). The seismicity of sources is assumed to be evenly distributed when characterizing them.

### Step 3: Selection of Attenuation Equations:

Selection of attenuation relation is third and very important step. Attenuation equations are GMPEs developed by regression analysis based on distance from source to site and earthquake magnitude. GMPEs are used to calculate peak ground acceleration, peak ground velocity and spectral acceleration.

### Step 4: Probability of Exceedance:

Fourth and final step in PSHA in determination of exceedance probability (PE). Probability of exceedance is measured concerning hazard curve. Hazard curves give the value of the annual frequency of ground motion (figure 2).

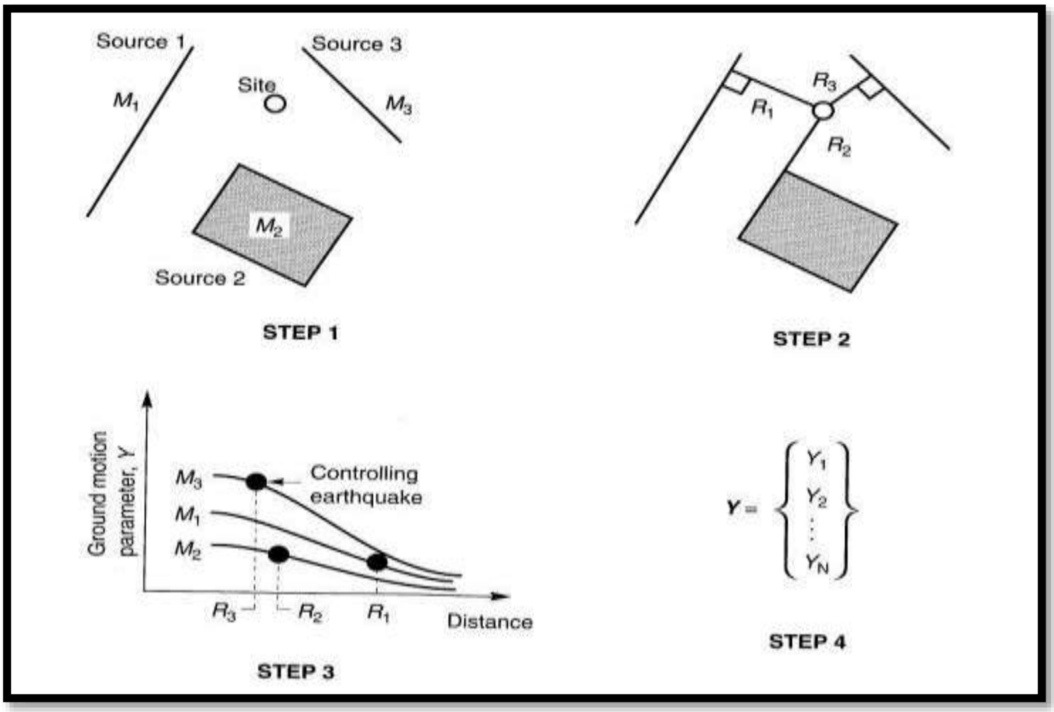


Figure 1. Basic steps of probabilistic seismic hazard analysis (PSHA) (Beitr, 1945).

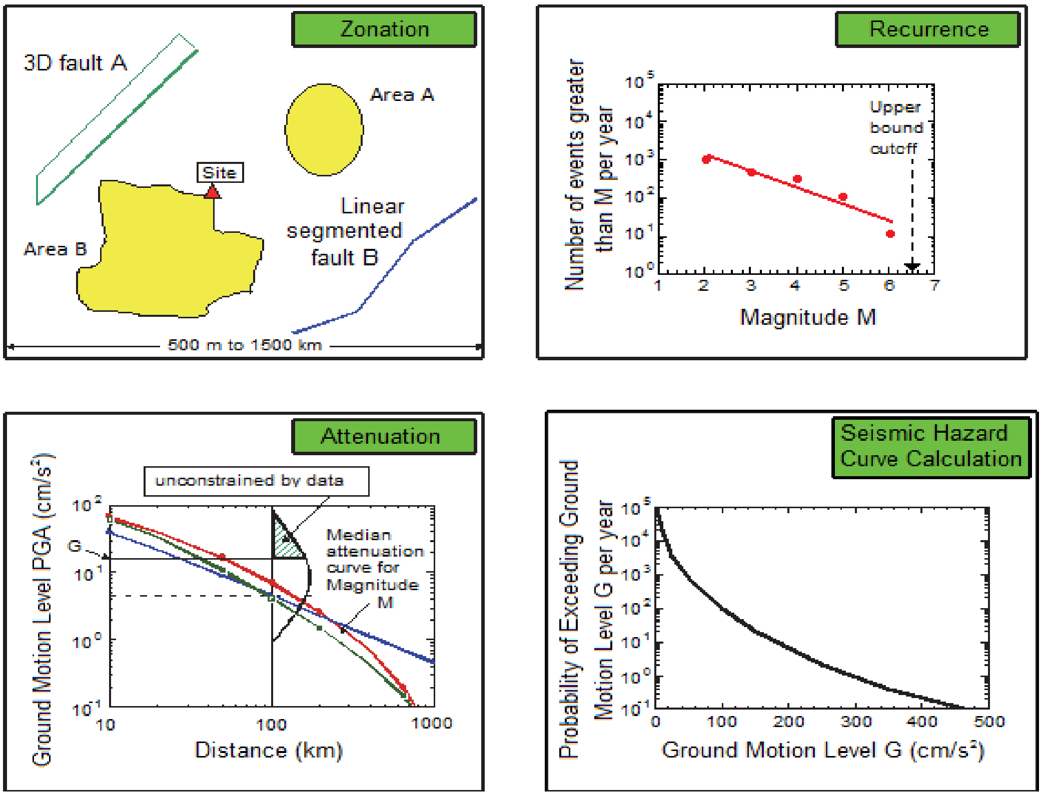


Figure 2. Methodology of deterministic seismic hazard analysis (Kramer, 1996).

## 1.3 Literature Review

A. Rahman et al., (2019) created an updated probabilistic seismic hazard assessment method using the US National Seismic Hazard Maps and the Earthquake Model for the Middle East (EMME). Several national and international datasets were used to create an updated earthquake catalogue. Modelling 110 crustal fault sources, including the Makran Subduction Zone (MSZ), was done using a combination of traditional area sources and smoothed gridded seismicity. They have utilized their slip rate that is derived from worldwide Earthquake Model Databases. Ground Motion Prediction Equations were established using Next Generation Attenuation (NGA) to assess the hazard at bedrock. For 10% and 2% PE in 50 years (time frame), new hazard maps for Peak Ground Acceleration and Spectral Acceleration at natural periods of 0.2sec, 1sec, and 2sec were created. Uniform hazard spectra (UHS) and updated hazard curves for many major Pakistani cities has been developed. To update the zoning map of Pakistan, Probabilistic Seismic Hazard study of Pakistan have been done by (Waseem et al., 2020) by using recent Ground Motion Prediction Equations, Updated Compiled Earthquake Catalogue and Updated Source Models. The resulting map clearly shows that active faults, such as those in the Makran subduction zone and Hindu Kush region, possess a severe seismic risk. Suleiman range in Pakistan has the highest seismic hazard, with a PGA of 0.40 cm/sec for a return time of 475 years. Balakot, Muzaffarabad, Islamabad, Gilgit, and Chitral are the most dangerous places in Pakistan.

Karachi is situated in a tectonically active area. For probabilistic and deterministic seismic hazard techniques, (Waseem et al., 2019) performed the re-assessment of Karachi's seismic hazard by compiling new active faults and seismic sources and incorporating of maximum possible historical earthquake data. According to a deterministic seismic hazard assessment, peak ground acceleration (PGA) in Karachi is 0.19 - 0.99 g, with the maximum value cantered on the Nagar Parker fault, which is the most dangerous to the metropolis. In 50 years, the ten percent probability of exceeding is between 0.21-0.25g for Karachi.

To produce seismic curves and uniform hazard spectra of spectral acceleration, Khaliq et al., (2019b) carried out the (PSHA) Approach for the surface ground motion assessment of Peshawar city. The PGA for Peshawar was calculated to be 0.23, 0.34, 0.39, and 0.45g at 143 ,475, 975, and 2475 years return period respectively considering the flat rock site conditions. Later on, Local site effects were included in the computation of surface Hazard Assessment. According to the NEHRP, the soil was classified as class C or D. Amplification factors were found using two techniques: NEHRP and Borcherdt. Shear wave velocity was used as a proxy for topographic slope to determine amplification factors.

Seismic hazard microzonation of the Islamabad metropolitan region was done by S. Khan & Khan, (2018) in terms of ground motion caused by seismic waves and the type of the soil profile underneath the area. The National Earthquake Hazard Reduction Program (NEHRP) classified soils into classes C and D based on cumulative SPT-N values from geophysical boreholes. Two techniques were used to calculate the ground surface spectral acceleration: soil response analysis using the shear wave propagation method, and NEHRP and Borcherdt amplification factors.

A seismic hazard is a type of natural disaster that occurs when an earthquake occurs. The geometric mean of spectral acceleration created Microzonation maps were computed using two techniques, and ground shaking intensity at different return periods. (Waseem et al., 2018) carried out the microzonation study and created macro-seismic hazard maps for Northern Pakistan. A probabilistic seismic hazard analysis was done using the EZ-FRISK numerical algorithm. The analysis was carried out on a $0.1^{o}$ rectangular grid. Based on the Seismogenic and focal depth of the earthquakes, the entire area was split into shallow and deep zones. A total of 19,373 earthquakes events were included in the compilation. Through visual inception, Ground Motion Prediction Equations (GMPEs) were carefully selected by using local data. GMPEs for deep depth earthquakes were selected by Literature study. The GMPEs were used in both deep and shallow zones using a logic tree approach. For the different return periods, ground motion data were acquired in the form of contour maps. The PGA and spectral acceleration (SA) values were calculated at 0.2 sec (Ss) and 1 sec (Sa), the resulting maps for the research area showed that ground motion is most frequent in the northeast of the region. And (Waseem et al., 2018) concluded that Pakistan's existing construction code underestimates the risk of earthquakes.

Nwe & Tun, (2016) carried out seismic hazard study of Mandalay city using a combination of GIS technologies and the AHP Model. Seismological, Geological, and Geotectonic conditions were used to create Seismic Hazard maps. With the availability of separate Raster Maps, an integrated Seismic Hazard Map was created. The main parameters that were used to generate the integrated Seismic hazard assessment (SHA) map were raster maps of Peak ground acceleration (PGA), Liquefaction Potential Index, geology, slope, local soil condition and site condition. They classified integrated seismic hazard maps into high, moderate, low, and shallow hazard zones. It was concluded that Seismic hazard microzonation (SHM) maps would be extremely beneficial in calculating seismic risk and developing disaster mitigation measures. The catastrophic earthquakes in Kashmir (2005) and Quetta (2008) demonstrate that earthquakes have devastating social and economic consequences that can last a decade or more. A seismic hazard assessment was carried out by (Sultan, 2015) in several parts of Pakistan to assure the safety of existing and future constructions. To compute the ground motion of Pakistan's geographical region, the PSHA Approach was used. Seismic hazard was assessed using Seismo-tectonic maps, earthquake source delineation maps, historical earthquake catalogues, and GSHAP data. The resulting maps give information on the location and nature of seismic activity in that region, which will assist engineers and government authorities in selecting on building designs that would resist a severe earthquake.

According to GSHAP project 1999, Central Asia is one of the world's most earthquake - prone areas due to its complex seismicity. It has Eurasian and Indian plates, which collided and caused some of history's most significant events. It has typical faults, reversal faults, and strike-slip faults. (Ullah et al., 2015) used Area source and various kernel approach for probabilistic seismic hazard assessment (PSHA). These approaches were performed for Central Asia by Earthquake Model Central Asia (ECMA). The seismic hazard was calculated using macro seismic intensity, and a regional seismic risk map was created using Open Quake software. Using various techniques, the maximum hazard that was detected in the region had an intensity of 8 over a 475 year return time. The main difference between the two techniques is related to Seismo-tectonic zoning.

In 1986 seismic hazard assessment (SHA) was performed by the Federal Ministry of Housing and Works. They formulated the first building codes of Pakistan (PBC 1986). These Seismic provisions of the 1986 building code were based on the Uniform building code of 1982 (Naseer et al., 2010). Instrumentally recorded catalogues from 1900 to 1979 were used for hazard assessment. According to (PBC 1986) The Modified Mercalli Intensity (MMI) scale has been used to divide Pakistan into four seismic zones (Rossetto & Peiris, 2009). After the Kashmir earthquake in 2005, the government decided to revise the building code of Pakistan (PBC 1986). In 2005 a devastating earthquake was hit the Kashmir and northern area of Pakistan and brought significant damage to the building and economy of different cities of Pakistan, including Islamabad. National engineering services Pakistan (NESPAK) performed Cornell (1968) and McGuire (1978) approach and developed updated hazard maps of the country. The study resulted in a new updated building code of Pakistan (BCP 2007). According to (Seismic Provisions, 2007), Pakistan was divided into five zones based on peak ground acceleration values (A. Shah et al., 2013).

Earthquakes have long been considered to be the cause of landslides. Hundreds of landslides occurred across the Himalayan region after the earthquake in Kashmir in October 2005. The landslide database was created using GIS technology, ASTER satellite pictures, local geological conditions, slope, elevation, land cover, and faults within the area. Agricultural areas, fault lines, rivers, and severely damaged rocks such as shale, slate, clastic deposits, and limestone have all been reported to be more prone to landslides. One-third of the region was also found to be very susceptible to future landslides, requiring rapid mitigation (Khattak et al., 2010).

Table 1. Comparison of current study with past studies.

| **Study** | **GSHAP** | **PMD and NORSAR** | **NESPAK** | **Zaman et al.** | **EMME** | **Current Study** |
|---|---|---|---|---|---|---|
| **Year** | **1992-1999** | **2007** | **2007** | **2012** | **2014** | **2021** |
| **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. | (Cornell 1968; McGuire 1976) Using OPENQUAKE. |
| **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 seismicity in two different models. | 12 seismic area sources with background spatially seismicity |
| **Earthquake Catalogue** | Pre-historic (before 1900) and historic (1900-1997) earthquake Catalogue with Mw > 5. | 102 years (1905-2007) earthquake catalogue with Mw > 4.8. | 102 years (1904-2006) earthquake catalogue with Mw > 4.5 | 107 years (1902-2009) Earthquake catalogue with Mw > 4.5. | Pre-historic (before 1900) and historic (1900- 2006) earthquake Catalogue with Mw > 4. | Pre-historic (before 1900) and historic (1900- 2020) earthquake catalogue with Mw > 4. |

Continue.

| Study | GSHAP (Zhang et al. 1999) | PMD and NORSAR | NESPAK | Zaman et al. (2012) | EMME (2014) | Current study |
|---|---|---|---|---|---|---|
| **GMPEs** | Only single GMPE of (Huo and Hu 1992) was used for ground motion estimation.<br>No multiple GMPEs were used to account for the epistemic uncertainty. | GMPE of (Ambraseys et al. 2005) was used.<br>No multiple GMPEs were not used to account for the epistemic uncertainty. | GMPE of (Boore et al. 1997) was used.<br>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)<br>Intermediate: Y97(0.5), AB03(0.5)<br>Deep: Y97(1.0) | Multiple GMPEs for different earthquake environments were used. Active shallow crustal region: AK14(0.35), CY08(0.35), AC10(0.2), Z06(0.1)<br>Stable shallow crustal region: AB06(0.4), C03(0.25), T97(0.35)<br>Deep Seismicity: Y97(0.5), LL08(0.5) | Multiple GMPEs for different earthquake environments were used.<br>For crustal faults, very shallow and shallow: three NGA west 2 GMPEs BA11(0.50),<br>And Y97(0.5), |
| **Results** | 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.<br>PGA values for major cities are also given. | Arithmetic 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. | Hazard results are Presented in mean ground motion. The PGA (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 Quetta and Gawadar. |

## 1.4 Seismo-Tectonic Environment of Region

Plate tectonics theory has provided a theoretical framework to understand the tectonic and geological characteristics of the earth. Plate tectonics properly explains the information regarding the boundaries of major tectonics and the characteristics inside tectonic plates. This theory is becoming more broadly acknowledged in light of GPS data, seismicity, and fault plane solutions. The Himalayan mountain range was formed when the Indian plate collided with the Eurasian plate. Pakistan is situated between three continental plates: the Indian, Eurasian, and Arabian plates. The Indian plate collided with the Eurasian plate at 37 to 42 mm/year, forming the Himalayan mountain range in the north. And due to converging of Eurasian and Indian plates, major earthquakes occur, leading to high seismic hazard to the area (Chen et al., 2000)**.**

Hindu Kush and Pamir ranges are complex subduction zones. Hindu Kush range has a length of 800km and is located from Afghanistan to northern Pakistan and china. Pamir ranges is located in Tajikistan. These ranges are situated in the northwest part of Pakistan, which is considered a center of deep earthquakes**.** (Negredo et al., 2007). The southern part of Pakistan is under the Eurasian plate, where Arabian plates subducts under the Eurasian plated (with the rate of 37 to 42 mm/year) that is forming subduction zone called makran subduction zone and this tectonic activities results in the seismic incidents around Makran region (Stoneley, 1974).

Chaman fault is the junction between Eurasian and Indian plate. In the southern part of Chaman faults and the eastern part of the subduction zone, the Ornach-Nal fault (left lateral transform fault) is present. The Sulaiman-Kirthar mountain ranges and a well-known strike slip fault (Chaman fault) are the results of the inclined collision. Between these two plates, the rate of lateral shearing is around 3.0 cm/year.(M. A. Khan et al., 2008).

In the east of WCB, another complex structure The Quetta Transverse Zone (QTZ) is present (figure 3). The QTZ is made up of many folds and thrust faults (the Ghazaband and the Ornach-Nal fault) that are connected to the Indian-Eurasian plate boundary(Quittmeyer & Jacob, 1913). Iran has Minab faults, including the Zagros fold and thrust fault, on the west side of the Makran area (Cedex & Ge, 2015).

In the western Pakistan, The fold and thrust belts of the Suleiman and Kirther belts run 600 kilometres south from Khuzdar before folding in the Quetta Syntaxes to the southeast. Major left-lateral strike-slip faults, such as Chaman, Ghazaband, and Ornach-Nal, have also formed (Bannert and Raza 1992). Due to the Indian plate's counterclockwise rotation relative to the Eurasian plate over its entire length, the slip rate of these left-lateral strike-slip faults is around 30 mm/year (M. A. Khan et al., 2008). In the north part of this fold and thrust range, faults such as Kohlu, Mekhtar, and Ziarat can be identified (Geology Tectonics of Pakistan KazmiJan1997, n.d.)

On satellite images, the Kirthar fault is a prominent N-S trending lineament. This region has a number of earthquake epicentres that have been linked to this fault. The Suleiman range has two left-lateral wrench faults on the range's eastern and western margins. On the eastern side, the Chaudhan fault and the Domanda fault form a left-lateral fault system. Three N-S trending faults on the western side (Figure 3).

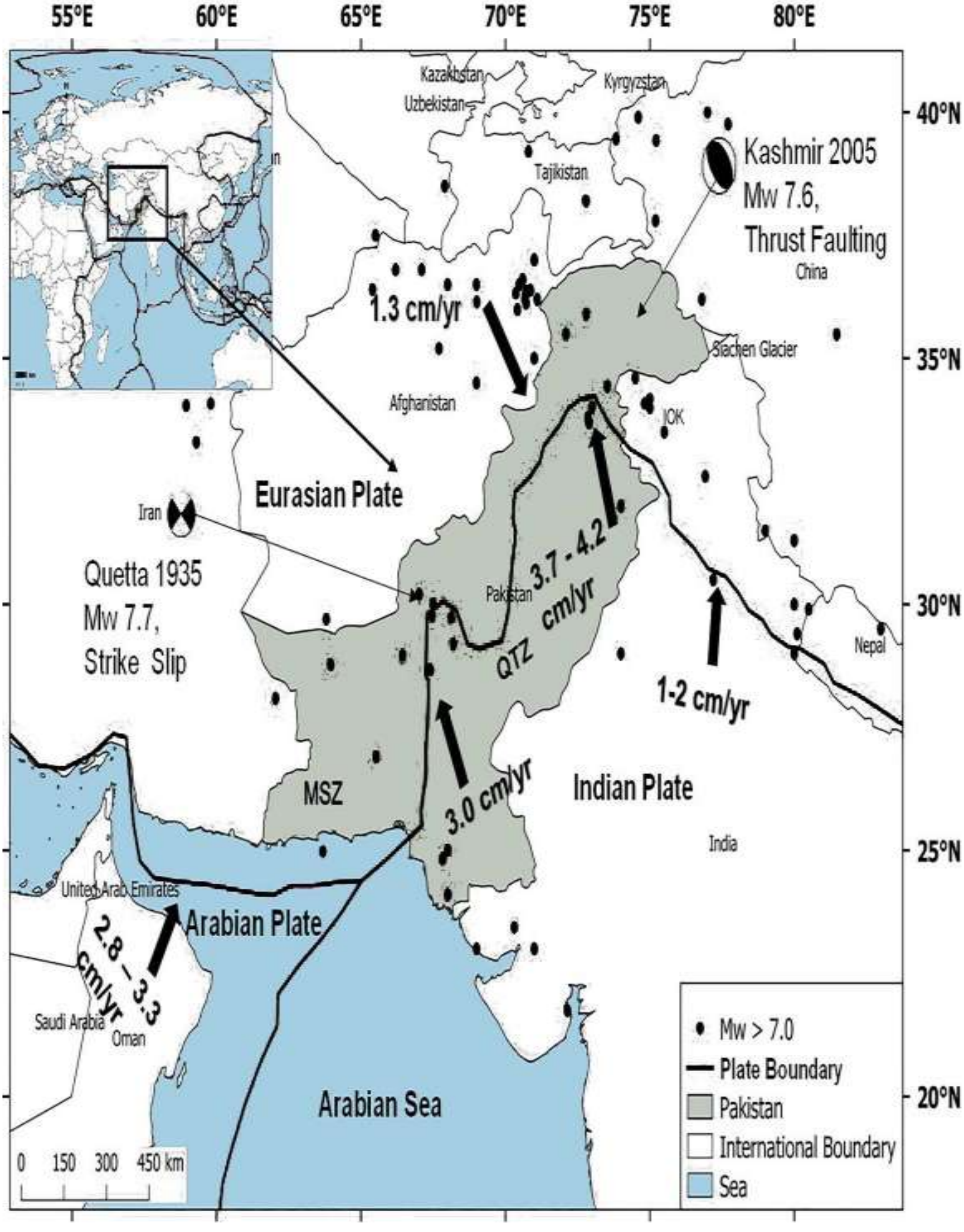


Figure 3. Tectonic setting of Pakistan and adjoining regions. Sella, Dixon and Mao (2002), Bird, (2003), Jade, (2004), and Vernant et al., (2004).

## 1.5 Rationale

On 8th October 2005, Kashmir was hit by a devastating earthquake. According to government officials, huge amount of fatalities were found. Seventy-three thousand people died and almost 140,000 people were injured. This devastation results from ignorance of construction practice based on the seismic hazard of an area. After that in 2007, a different organizations such as NESPAK, NORSAR (2007) and PMD (2007) made attempts to assess seismic hazard of the country.

The mentioned studies used a catalogue of earthquake events up to 2005. Outdated ground motion prediction equations (GMPE's) were used. Previous studies considered a negligible amount of crustal faults in modelling. only few studies have used crustal faults such as (Zaman & Warnitchai, 2012), they have used 13 crustal faults. So there is a need to update the hazard maps of a country based on active crustal faults, updated earthquake catalogue and ground motion prediction equations (NGA). Pakistan has a rich historical and cultural heritage that dates back to the origins of civilization. This feature also emphasizes the necessity for a more effective and efficient method to save all critical structures.

In this research, updated PSHA was performed based on the improved stock of knowledge. The first objective was to develop an earthquake recurrence model. For that, an Updated earthquake catalogue from 1900 to 2020 were compiled and several other improvement were made for PSHA assessment. Updated ground motion prediction equations (GMPEs) were used. Second objective was to estimate the Spectral Acceleration of an area at different time intervals. Improved uniform hazard spectra were generated for Quetta and Gawadar. The third objective was hazard deaggregation analysis of Quetta for different return periods.

## 1.6 Objectives

1. To develop a Probabilistic Earthquake Recurrence Model for Baluchistan.
2. To conduct the surface level probabilistic seismic hazard analysis for Baluchistan.
3. To conduct the Seismic Hazard Disaggregation analysis for Quetta city.

## 1.7 Area of Applications

- Structural Engineers can use seismic hazard assessment for calculations of seismic load to structures. Moreover, it can be used to design earthquake-resistant structures. It can also be used for evaluating the safety of existing structures.
- Urban planners and policy makers can use seismic hazard analysis for land use planning and designing to get sustainable development for seismically active areas of the country.
- Seismic hazard analysis can also be used to assess vulnerability and risk to socioeconomics of the seismically prone areas.
- Seismic hazard maps can be used for emergency preparedness for disasters management authorities of a country.
- Insurance companies can use for seismic hazard maps for making insurance policies of prone area

## *CHAPTER* 2

# MATERIALS AND METHODS

### 2.1 Study Area

Baluchistan is Pakistan's biggest province, comprising nearly 44% of the country's total landmass. It is between the longitudes of 71° and 61° East and the latitudes of 32° and 25° north. Its southern boundary comprises almost two-thirds of Pakistan's coastline. Baluchistan is a largest province of Pakistan situated in southwest of Pakistan that covers 347,190 square kilometers. The whole province of Baluchistan is located in an earthquake-prone area. Past earthquakes in the province have been destructive. Quetta is located near the world-famous Chaman Fault. Seismically, the Chaman fault is moderately active. In the southern part of Chaman faults and the eastern part of the makran subduction zone, Ornach-Nal faults (the left lateral transform fault ) is present (A. Shah et al., 2013).

Makran subduction zone is a seismically active region that is inside a high-risk seismic tectonic zone. Makran is a seismically active zone; earthquake statistics show that the studied region was shocked more than 1000 times by minor to moderate magnitude earthquakes ranging from 3.5 to 5.9 (Pakistan Metrological Department and NOSAR, 2007). For earthquake data collection, Baluchistan (study area) and the surrounding area having geographical limits of 23o-32o N and 59o -72o E are considered areas of influence. So, it is considered that an earthquake can cause damage up to 200km beyond its center (Ahmad, 2016). So area up to 200km from study area (which is called area of influence) is considered as study area (figure 5).

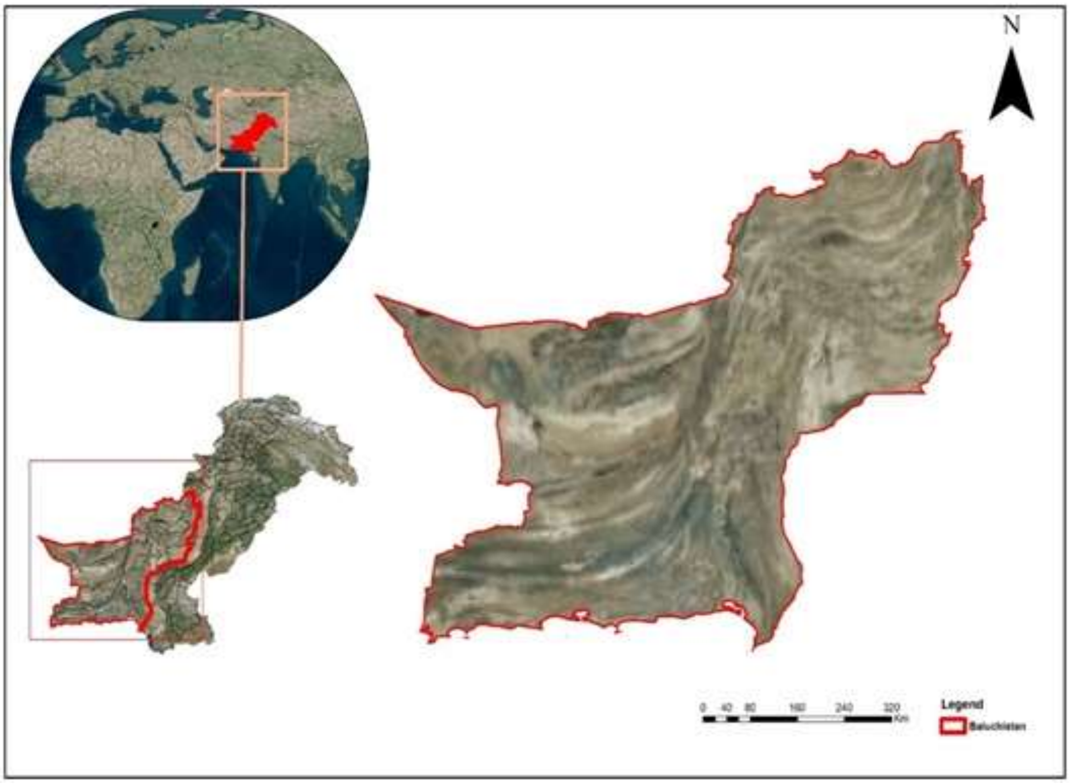


Figure 4. Study area map of Baluchistan.

Figure 5. Map showing the area of influence and area of interest.

Table 2. Types of dataset used in the research

| No. | DATA | SOURCES |
|---|---|---|
| 1 | Earthquake Data | PMD, ISC, GSP and USGS |
| 2 | Seismic sources | NESPAK |
| 3 | Geological Data | GSP Islamabad |

Table 3. Types of software used in the research

| Software | Description |
|---|---|
| **OPENQUAKE v3.3.0** | Seismic hazard and Risk calculation software developed by Global Earthquake Model (GEM). |
| **Grapher** | Grapher is a full-featured scientific graphing package, allowing the user to import data in many formats, create and combine a wide variety of 2- and 3-D plot types, and customize the plots in infinite detail |
| **Arc Map** | Arc Map is used for mapping of earthquake hazard results |
| **ZMAP V07** | MATLAB tool used for declustering of earthquake catalogue and seismic parameters determination |

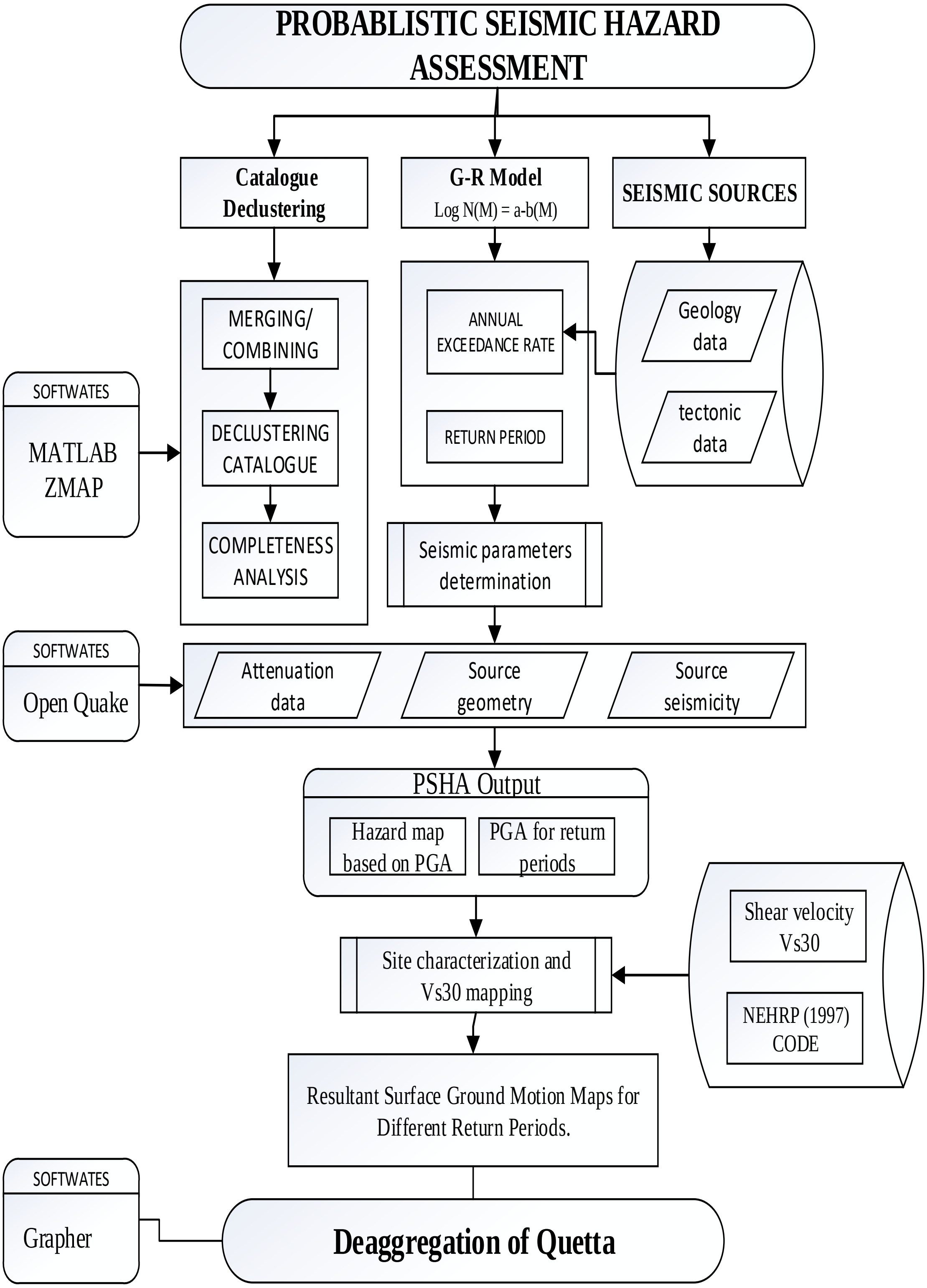


Figure 6. Complete methodology flowchart of the study.

## 2.2 METHODOLOGY

### 2.2.1 Development of Updated Earthquake Catalogue

For earthquake data collection, Baluchistan (study area) and the surrounding area having geographical limits of $23^o$-$32^o$ N and $59^o$ -$72^o$ E are considered areas of influence. So, it is considered that an earthquake can cause damage up to 200km beyond its center (Ahmad, 2016). So area up to 200km from study area (which is called area of influence) is considered. The first step in conducting a seismic hazard study is to conduct a hazard assessment using PSHA, which requires a complete data collection of the past earthquake occurrences of an area. The earthquake catalogue helps in the identification of seismic sources as well as the creation of a recurrence law. Over the period of 1900 to December 2020, earthquake data for the area of influence was acquired from several international and local sources. A total of 12,000 events were collected from various sources. For updated earthquake events, Historical earthquake events from 1900 to 1964 were combined with instrumental earthquake occurrences from 1900 to December 2020. Earthquakes catalogue ware gathered from a variety of national and international databases. For example, National Earthquake Information Center (NEIC), National Geophysics Data Center (NGDC), International Seismological Center (ISC), Global Centroid Moment Tensor (GCMT), and USGS are some of the international databases. Pakistan Meteorological Department (PMD) and Pakistan Geological Survey (GSP) were used as local sources. Each earthquake event in the catalogue shows a detail of longitude, latitude, time, depth, magnitude, and source. Because earthquake data was gathered from a variety of sources, the merged catalogue contains duplicated occurrences. Duplicate events were removed from the catalog based on priority order. Table 4 shows the number of events and types of the magnitude of each event from the catalogue. After merging catalogs from several national and international sources, the Duplication of earthquake events was eliminated in Excel. The earthquake catalog was decreased from 12000 to 7588 events once the duplicate was eliminated. The earthquake catalog helps in the identification of seismic sources as well as the establishment of a recurrence law.

### 2.2.2 Magnitude Homogenization

As earthquake data was gathered from multiple sources, it came in various magnitudes, including Mw, ML, MS, Mb, and MD. The earthquake catalogue must be homogenized to designate seismic sources in hazard assessment methods. Homogenization is in terms of magnitude scales. The PMD and NEIC primarily report body wave magnitudes (Mb). The ISC database, contains the surface wave magnitudes MS and moment magnitude Mw. In order to homogenize the magnitudes, Regression Analysis is used to construct magnitude conversion equations for events that are given in two different magnitudes scales.

### 2.2.3 Declustering of Earthquake Events

Declustering is the process of separating Earthquake Independent events (main shocks) from Dependent events (foreshocks and aftershocks). Earthquake occurrence are considered independent and occur at random intervals in probabilistic seismic hazard analysis (PSHA) (Poissonian distribution method). Foreshocks and aftershocks are dependent occurrences because they occur before and after the big shocks.

Table 4. Relationships developed for converting $mb$ and $M$S to $Mw$.

| No. | Relationship type | Conversion relationships |
|---|---|---|
| **1** | Mw & MS ≤ 6.2 | Mw = 0.535MS+2.69 |
| **2** | Mw& MS > 6.2 | Mw = 0.895MS + 0.53 |
| **3** | Mw & Mb | Mw = Mb + 0.103 |
| 4 | Mw & ML | Mw = ML |

Table 5. Earthquake database sources and their priority orders.

| Period | Sources | N | Order | Magnitude Types |
|---|---|---|---|---|
| **1900-2020** | USGS | 1855 | 1 | Mw, Mb, $M_L$, $M_D$ |
| **1900-2020** | ISC-GEM | 6000 | 2 | Mw, Mb, $M_L$, $M_D$, Mw |
| **1909-2020** | NGDC | 700 | 3 | Mw, Mb, $M_L$, $M_D$ |
| **1976-2016** | GCMT | 980 | 4 | Mw, Mb, Mw |
| **1910-2018** | PMD | 3000 | 5 | Mw, Mb, $M_L$, Mw |
| **1973-2019** | GSP | 4288 | 6 | Mw, Mb, $M_L$ |
| **1800-1969** | (Quittmeyer & Jacob, 1979) | 450 | 7 | Mw, Mw |
| **1818-1945** | (Ambraseys & Douglas, 2004) | 1000 | 8 | Mw, Mw |

**Where;**

$N$ = number of events, $MS$ = surface wave magnitude, $mb$ = body wave magnitude, $ML$ = local magnitude, $Mw$ = moment magnitude, $MD$ = duration magnitude.

Table 6. Composite earthquake catalogue.

**COMPOSITE EARTHQUAKE CATALOGUE OF PAKISTAN - (Updated 01-January, 2019 to 31-December, 2020)**

| Date | | | Time | Location | | Depth | Magnitude Type | | | | Converted | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Month | Day | | Latitude | Longitude | (Km) | Mb | Ms | ML | Mw | Mw | |
| 2019 | 1 | 1 | 05:08:07 | 34.87 | 71.71 | 8 | | | 2.9 | | 2.9 | PMD |
| 2019 | 1 | 1 | 6:10:58 AM | 37.6556 | 69.6811 | 0 | 3.5 | | | | 4.0 | ISC |
| 2019 | 1 | 1 | 07:21:22 | 36.59 | 71.22 | 140 | | | 3.1 | | 3.1 | PMD |
| 2019 | 1 | 1 | 5:26:43 PM | 37.5818 | 71.9496 | 92.3 | 3.5 | | | | 4.0 | ISC |
| 2019 | 1 | 1 | 8:50:42 PM | 36.4118 | 71.1504 | 188 | 3.6 | 3.4 | | | 4.1 | ISC |
| 2019 | 1 | 1 | 10:06:45 PM | 36.5673 | 71.474 | 107 | 4.2 | 2.9 | | | 4.6 | ISC |
| 2019 | 1 | 1 | 10:22:18 PM | 35.9525 | 71.3675 | 197.7 | 3.4 | | | | 3.9 | ISC |
| 2019 | 1 | 1 | 23:40:32 | 36.69 | 71.22 | 198 | | | 2.4 | | 2.4 | PMD |
| 2019 | 1 | 2 | 6:14:40 AM | 36.9145 | 70.2956 | 0 | 3.6 | 3.5 | | | 4.1 | ISC |
| 2019 | 1 | 2 | 7:16:48 AM | 34.8833 | 73.8226 | 24.5 | 4.2 | 3.3 | 3.4 | | 4.6 | ISC |
| 2019 | 1 | 2 | 11:13:34 | 36.5 | 71 | 145 | | | 3 | | 3 | PMD |
| 2019 | 1 | 2 | 4:51:08 PM | 36.4405 | 70.7431 | 205.8 | 4.1 | 4.2 | | | 4.5 | ISC |
| 2019 | 1 | 2 | 8:42:02 PM | 28.4183 | 66.6934 | 0 | 3.5 | 3 | 3.6 | | 4.0 | ISC |
| 2019 | 1 | 3 | 12:22:05 AM | 37.9313 | 70.2982 | 0 | 3.4 | | | | 3.9 | ISC |
| 2019 | 1 | 3 | 1:36:25 AM | 36.3568 | 70.0177 | 0 | 3.1 | | | | 3.7 | ISC |
| 2019 | 1 | 3 | 6:56:22 AM | 34.8845 | 73.5961 | 0 | 3.9 | 2.8 | | | 4.3 | ISC |
| 2019 | 1 | 3 | 7:37:16 AM | 37.6624 | 70.5884 | 0 | 3.4 | | | | 3.9 | ISC |
| 2019 | 1 | 3 | 10:53:2 AM | 37.4489 | 71.4699 | 155.9 | 2.7 | | | | 3.3 | ISC |
| 2019 | 1 | 3 | 2:57:27 PM | 36.8774 | 69.8756 | 0 | 3.3 | | | | 3.8 | ISC |

As a result, these foreshocks and aftershocks had to be taken out of the catalogue. Declustering is the process of removing major shocks from aftershocks and foreshocks. The combined catalogue consists of temporal and geographical events, which are called Foreshocks and aftershocks. In this technique, main shocks (independent events) are removed from aftershocks and foreshocks (dependent events). Declustering was performed for the current study using all four of the proposed relationships in the ZMAP program (Wiemer, 2001). ZMAP is a MATLAB script file that contains de-clustering techniques. Different relationships have been established for declustering, e.g. (Gardner & Knopoff, 1974), GRUENTHAL, UHRHAMMER (1986) and (Reasenberg, 1985). Results from all four declustering algorithms are shown in (table). According to the remaining events, clustered events GARDNER and KNOPOFF (1974) is recommended as the best method for declustering (Amini, 2014).

So for this study, declustering of events by an algorithm developed by (Gardner & Knopoff, 1974) was used for further analysis. The algorithm used for de-clustering of the current catalog is “GARDNER AND KNOPOFF”.

### 2.2.4 Magnitude Uncertainty and Data Completeness

The difference between recorded and real seismicity of the region is called incompleteness of catalog. The incompleteness of the catalogue is considered as an uncertainty of the earthquake catalogue. For seismic hazard assessment study, the uncertainty of data should be removed by completeness analysis (Rydelek & Sacks, 1989). Several methods have been used for catalog completeness analysis concerning time and magnitude. For this study, we have used cumulative visual method (CUVI) for catalogue completeness.

Table 7. Number of events after declustering.

| Method | Total events | No. of clusters | Events remained | Events removed (%) |
|---|---|---|---|---|
| **Gardner & Knopoff (1974)** | 7588 | 1505 | 2200 | 64% |
| **Reasenberg (1985)** | 7588 | 555 | 5057 | 34% |
| **Uhrhammer (1986)** | 7588 | 1254 | 3237 | 46% |
| **Gruenthal (Zare et al., 2014)** | 7588 | 1164 | 1538 | 74% |

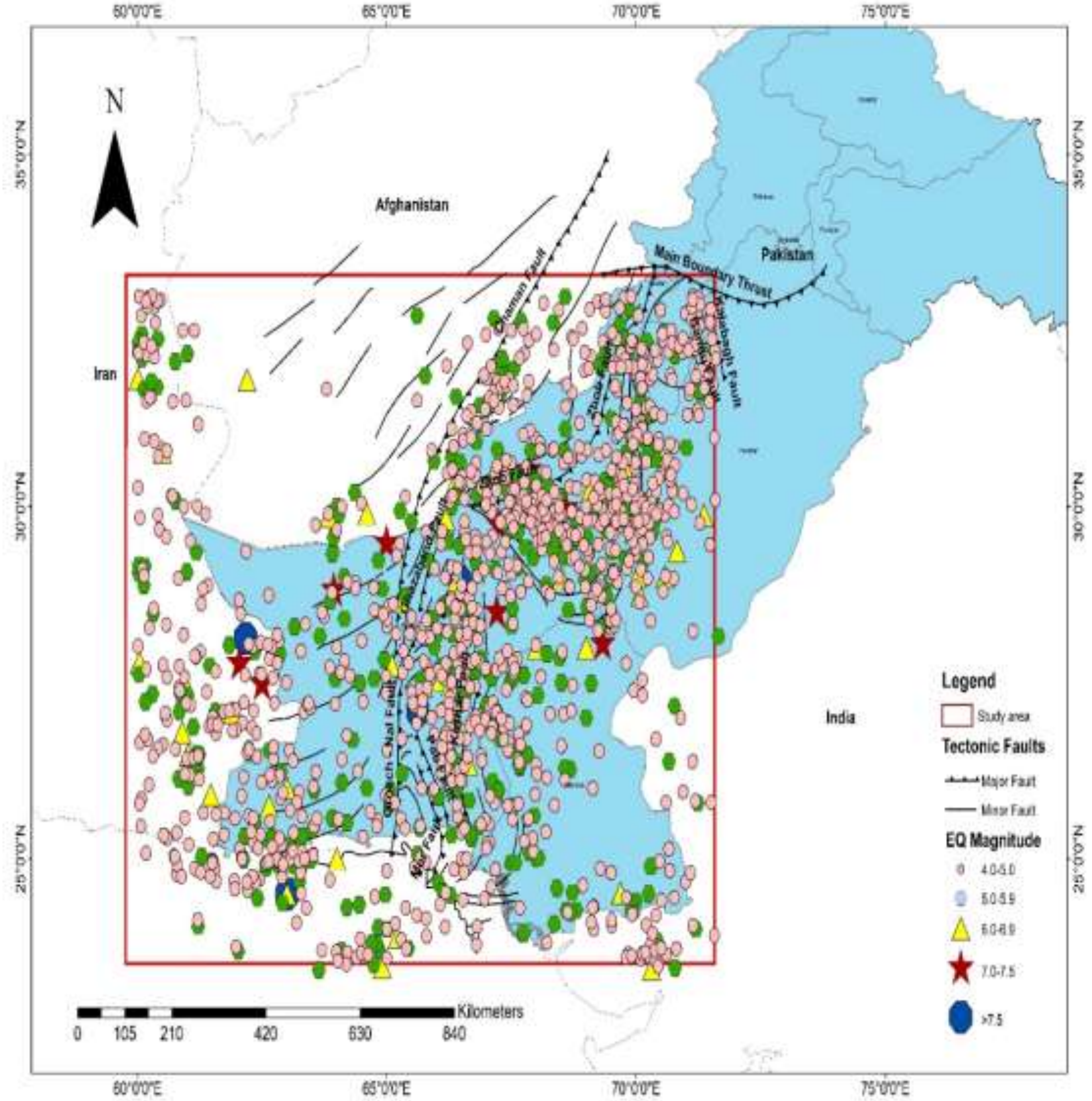


Figure 7. Declustered earthquake events.

### Cumulative Visual (CUVI) Method

CUVI method is a graphical method where declustered catalog was divided into magnitude classes i.e. 4-4.5, 4.5-5.0, 5.0-5.5 etc. to the maximum magnitude of catalog (Tinti & Mulargia, 1985). For each magnitude class, a graph is produced between the cumulative number of events (N) and the time period (year). The completeness period of the catalogue (Cp) is defined as the starting point of the straight line that displays the stable trend, and the magnitude of that point is defined as the magnitude of completeness (Mc). Graphs and table show the completeness analysis results for each magnitude class (Stepp, 1972).

### 2.2.5 Seismogenic and Focal Depths

Seismogenic depth ($D_{seis}$) is the maximum depth observed in any Seismogenic zone. The depth of the earthquake event, is dependent on Size of the earthquake generated by any active faults. For a better understanding of any region's tectonic region and seismic hazard, focal depth is very important (Yano et al., 2017). After declustering and completeness analysis, focal depth of region was determined. Earthquake having depth of (0-50km) was considered a shallow earthquake and (depth>50km) of earthquake events was considered as a deep earthquake. According to the statistics in (figures 9), shallow earthquakes comprise the majority of Pakistan's seismicity. Deep earthquakes account for only 17% of the total, whereas shallow earthquakes account for 83%. Based on focal depths, the study depicted the variation of Pakistan's historical seismicity. Furthermore, according to PMD and NORSAR, (2007) 80 percent of historical seismicity is shallow (depth 50 km), while only 20% of previous earthquake rates have focal depths of 50 to 320 km.

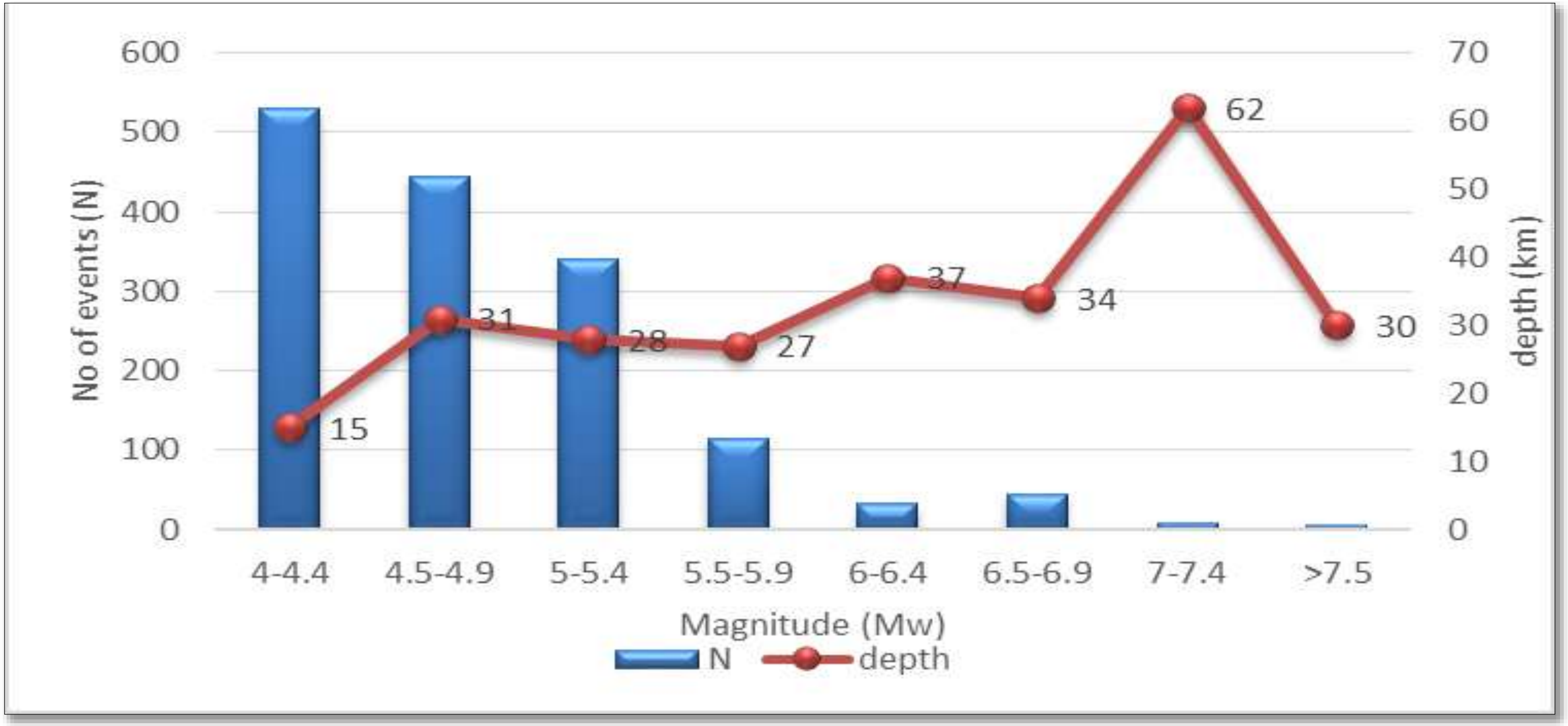


Figure 8. Seismogenic and focal depths analysis of the study area.

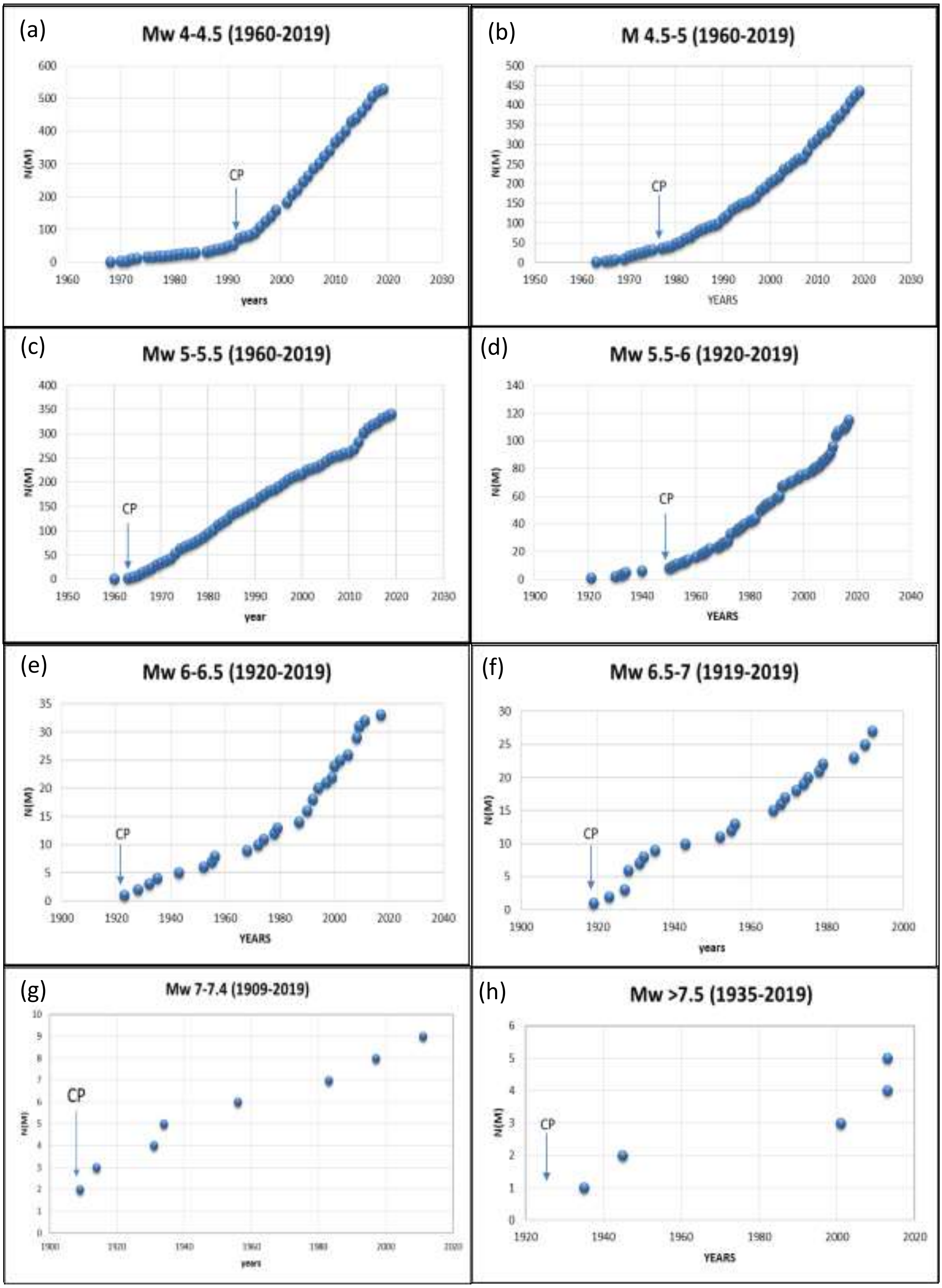


Figure 9. . Graphs of completion period of magnitudes Mw (a) 4.0 – 4.4, (b) 4.5 – 4.9, (c) 5.0 – 5.4, (d) 5.5 – 5.9, (e) 6.0 – 6.4, (f) 6.5 – 6.9, (g) 7.0 – 7.4, (h) 7.5 – 7.9.

### 2.2.6 Development of Updated Area Source Model

Area source model are used to represent regions with homogeneous seismicity in seismic hazard assessment. In the areas where tectonic data is limited, these geographical sources are commonly employed in the modelling of seismicity patterns. In seismic source zoning, seismicity was coupled with homogeneous geology tectonic zones, tectonic settings, and the faults characteristic of that tectonic zone. In literature, there are various studies that have defined area source zones for Pakistan that include (Rafi et al., 2012), (Zhang et al., 1999), (NESPAK, 2007) and (S. Khan & Khan, 2018). Pakistan and its surroundings are divided into twelve (12) crustal source zones in this study (Figures 9, 10).

Because the seismic hazard is decreased when big area sources are chosen, small area sources are defined and preferred over large area ones. This is referred to as spatial smearing (National Research Council, 1988). The seismicity pattern, active crustal faults in the region, and concepts of the Global Seismic Hazard Assessment Program (Giardini et al., 1999) and Earthquake Model Middle East are used to delineate area sources (Danciu et al., 2018). The area sources in this study are based on a more recent catalogue with a larger number of earthquake occurrences. Furthermore, while defining area sources, the Seismo-tectonic of the region is carefully studied and properly considered. These are the factors that distinguish this study from previous ones. The value represents the proportion of small and big magnitudes (S. Khan & Khan, 2018).

### 2.2.7 Regression Analysis

Seismicity Parameters “a”, “b” and “Mc” were calculated through Regression Analysis. ZMAP Software was used for Regression Analysis.

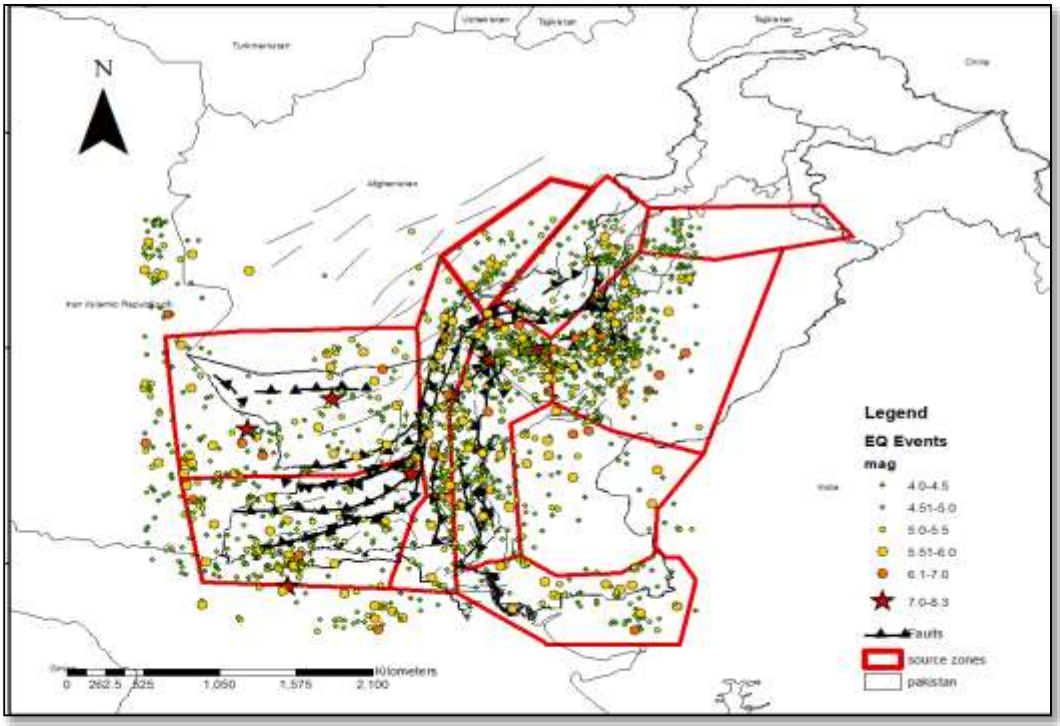


Figure 10. Zones Seismic source zones in the region divided based on uniformity of events and faults associated with them.

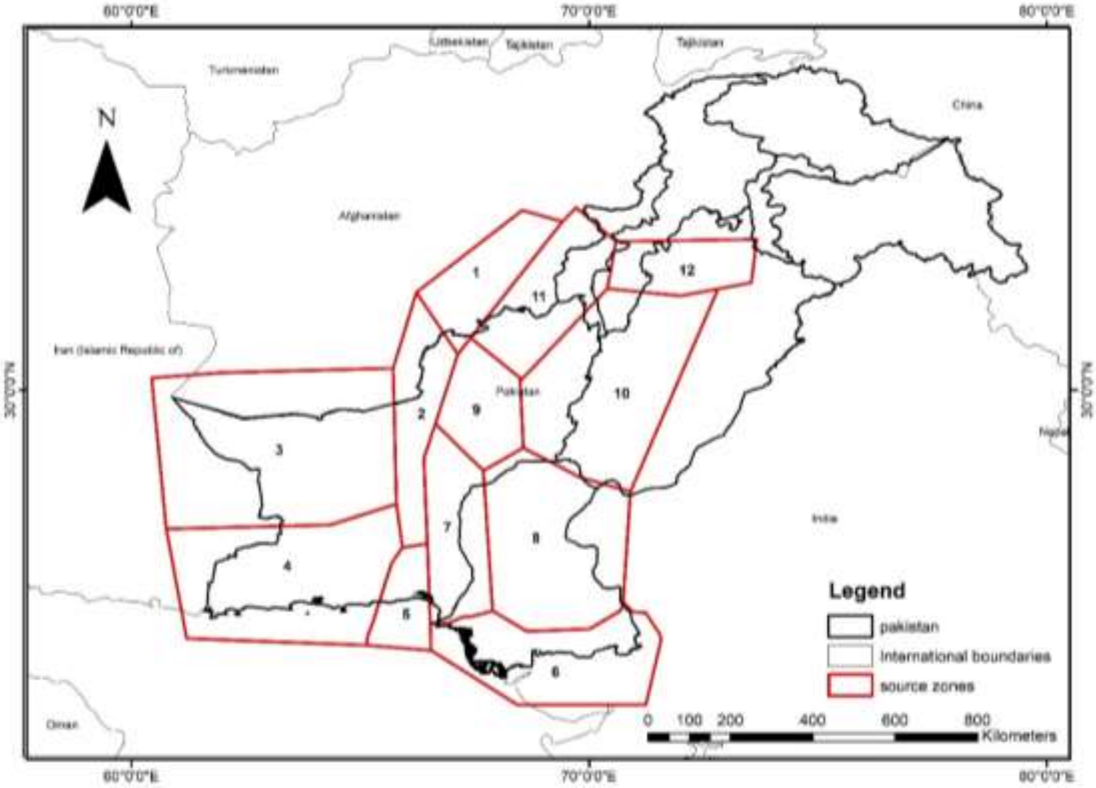


Figure 11. Area source zones.

Regression Analysis was done by plotting magnitude versus logarithm of cumulative frequency for derivation of seismicity parameters. MATLAB was used for ZMAP TOOL. After the generation of seismicity parameters, the Activity rate (λ) was calculated for each magnitude by using the formula given in equation 1. The activity rate (λ) of each source zone was calculated and zone 2 shows highest activity rate for small magnitude of the earthquake. Figure shows the activity rate per year and return period for each earthquake magnitude for all zones (Beitr, 1945). The models for finding “a” and “b” parameters are based on the Gutenberg-Richter magnitude recurrence relation.

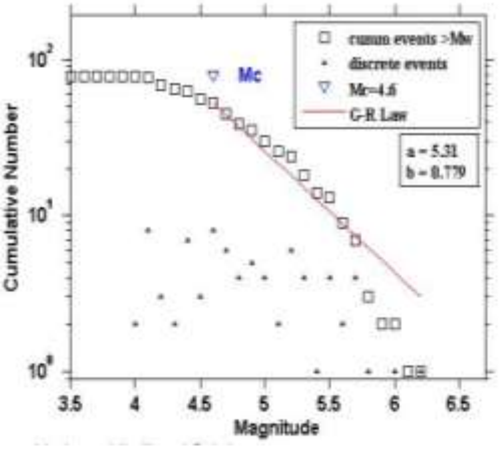
### 2.2.8 Gutenberg-Richter Recurrence Law

This law explains the greater rates for smaller earthquakes and for bigger magnitude earthquakes lower rates in accordance with observations. The maximum likelihood approach (Gardner & Knopoff, 1974) and the Gutenberg-Richter magnitude distribution formula (1974) are used to compute the recurrence rates for area sources:

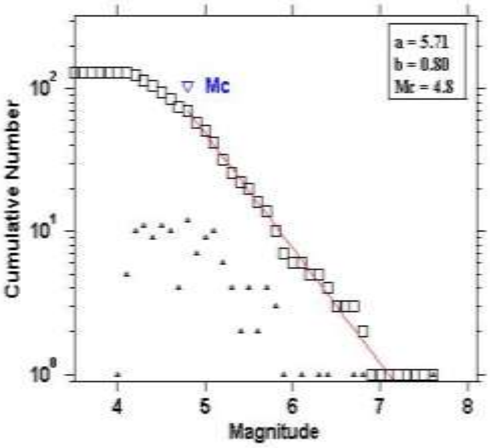
$$\boldsymbol{\lambda = e^{(\alpha-\beta mo)} * \left[e^{(-\beta(m-mo))} - e^{(-\beta(mmax-mo))}\right] \frac{1}{\left[1-e^{(-\beta(mmax-mo))}\right]}} \qquad \textbf{(1)}$$

Where; λ = Mean annual rate of exceedance, α = a*ln [10] and β = b *ln [10].

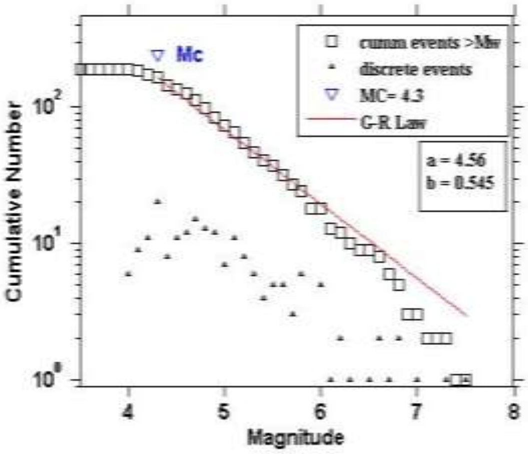
The conventional G–R relationship contains an infinite magnitude ranges. For engineering reasons, a small magnitude effect is not interesting (S. Khan et al., 2018).



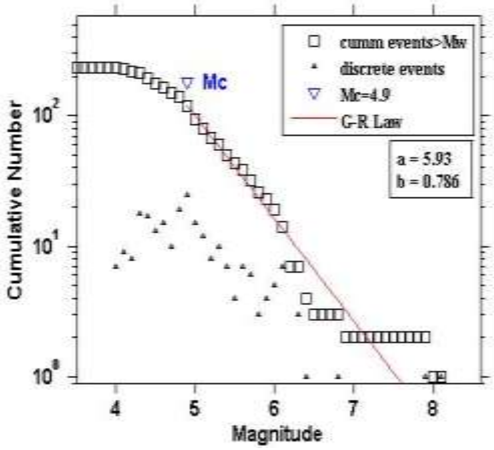
**Zone 1**



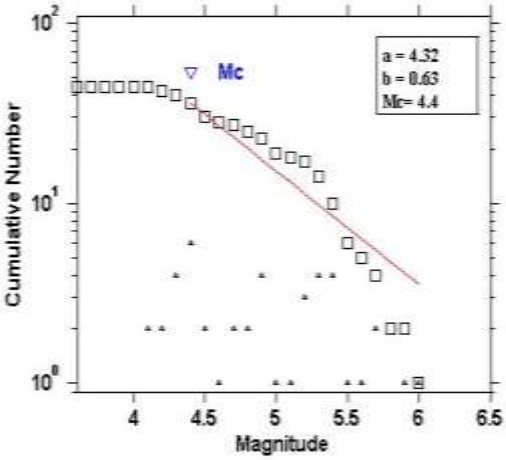
**zone 2**



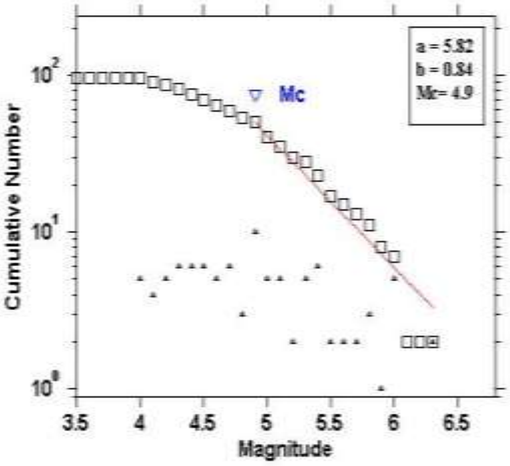
**Zone 3**



**zone 4**

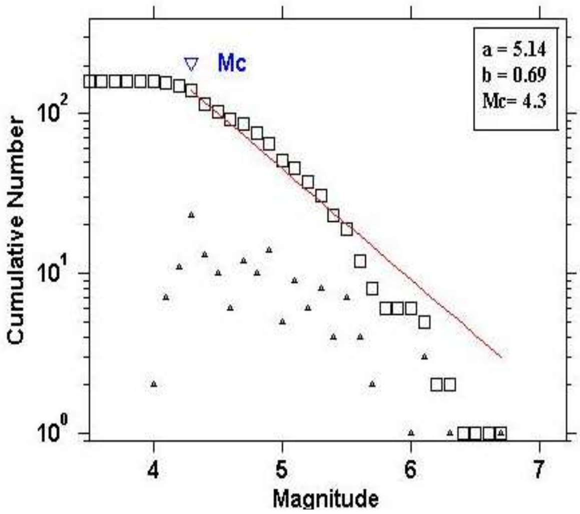


**Zone 5**

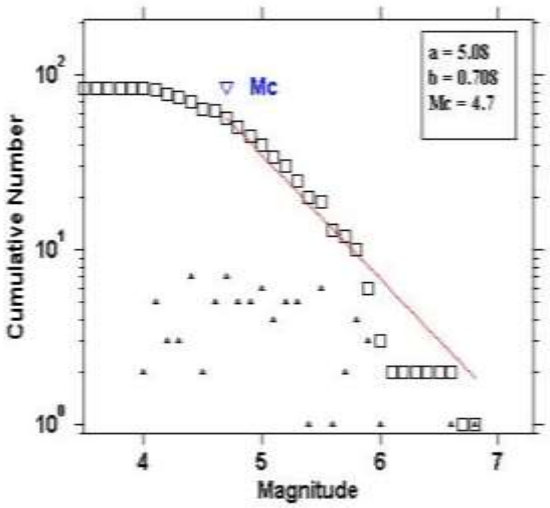


**zone 6**

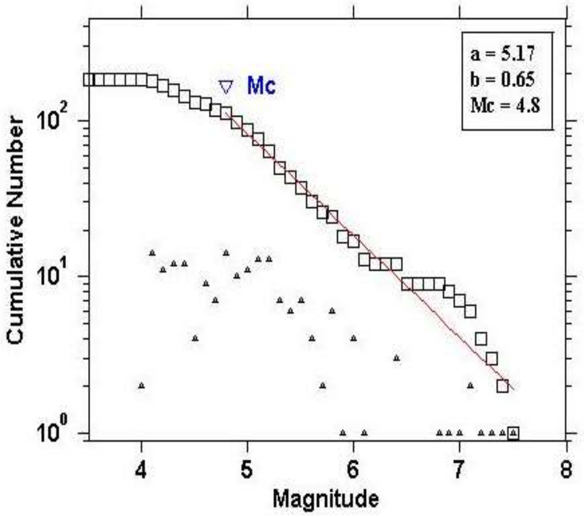
Figure 12. Regression analysis for zones (1-6).



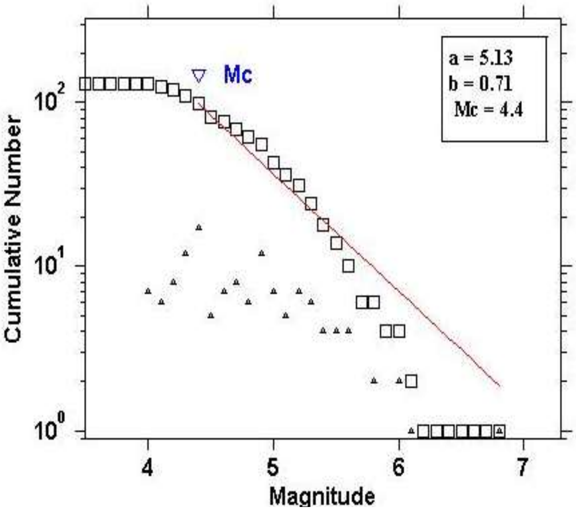
**Zone 7**



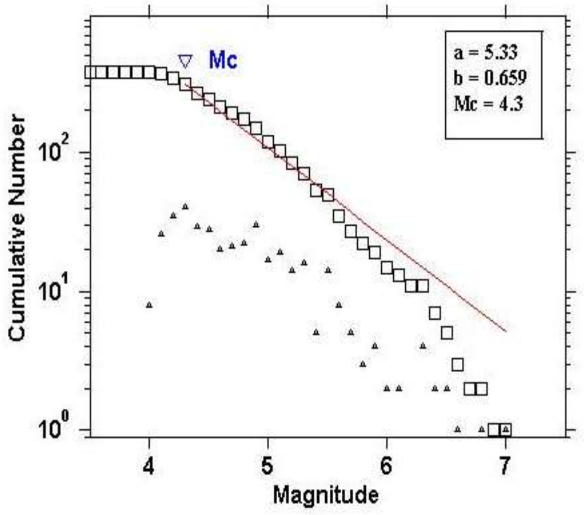
**Zone 8**



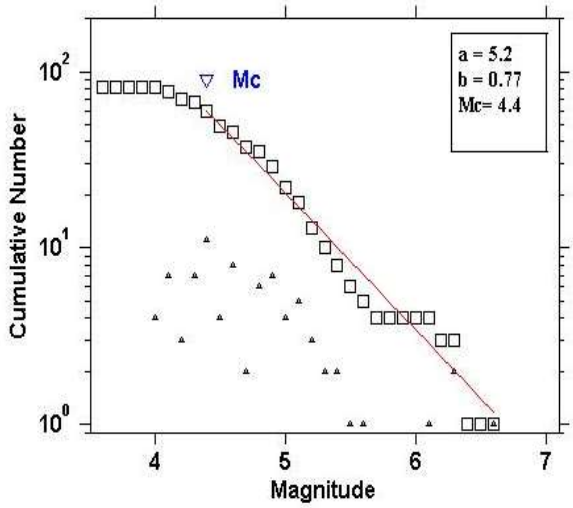
**Zone 9**



**Zone 10**



**Zone 11**



**Zone 12**

Figure 13. Regression analysis for zones (7-12) (Aki, 1965).

Table 8. Seismicity parameters for each seismic source zone defined in the model.

| **Zones** | **a** | **b** | **α** | **β** | **Mc** | **Dseis** | **$M_{max}$** | **λ** |
|---|---|---|---|---|---|---|---|---|
| **1** | 4.09 | 0.82 | 10.25 | 2.16 | 4.6 | 28 | 6.7 | **4.90** |
| **2** | 5.03 | 0.90 | 9.17 | 1.89 | 4.8 | 24 | 7.4 | **5.01** |
| **3** | 3.29 | 0.65 | 8.98 | 1.73 | 4.3 | 30 | 7.9 | **7.95** |
| **4** | 3.61 | 0.66 | 10.82 | 2.07 | 4.9 | 25 | 7.8 | **12.60** |
| **5** | 3.63 | 0.69 | 10.04 | 2.26 | 4.4 | 30 | 8.2 | **2.75** |
| **6** | 3.67 | 0.76 | 8.45 | 1.75 | 4.9 | 32 | 5.9 | **4.27** |
| **7** | 4.31 | 0.78 | 11.98 | 2.40 | 4.3 | 25 | 6.7 | **10.97** |
| **8** | 5.34 | 0.92 | 9.51 | 2.00 | 4.7 | 22 | 6.8 | **4.47** |
| **9** | 5.19 | 0.78 | 8.04 | 1.54 | 4.8 | 20 | 7.5 | **22.40** |
| **10** | 3.48 | 0.60 | 10.16 | 2.07 | 4.4 | 34 | 6.1 | **6.46** |
| **11** | 3.93 | 0.79 | 12.32 | 2.30 | 4.3 | 23 | 6.8 | **6.46** |
| **12** | 4.32 | 0.63 | 10.16 | 2.19 | 4.4 | 19 | 6.1 | **4.07** |

### 2.2.9 Ground Motion Prediction Equations (GMPEs)

A ground motion prediction equation (GMPE) is a statistical model that predicts the degree of ground shaking and related uncertainty at a given location. It uses predictive variables such as earthquake magnitude, fault mechanism, source to site distance, local site characteristics and so on to estimate ground motion parameters including PGA, peak ground velocity, and spectral acceleration during various vibration periods.

Ground motion parameters like PGA and SA are calculated using ground motion prediction equations as a function of earthquake magnitude, source-to-site distance, and local site characteristics at a given location. The GMPEs are empirically developed for a specific region, a significant seismic hazard component, using regression analysis statically. For regression analysis, strong ground motion records and geology of that region are required. In Pakistan, strong-motion records are either unavailable or accessible in limited quantities. This makes it difficult to create GMPEs that are particular to Pakistan's tectonic conditions. The main alternative in the absence of locally generated GMPEs is to use the attenuation equation developed in other tectonically and geologically comparable locations to Pakistan. In the previous seismic hazard studies for Pakistan, the aforementioned alternate was used. NORSAR (2007) and NESPAK (2007) used GMPEs, which were developed for shallow active tectonic regions of Europe and the Middle East and Western North America (WNA). They justified that the seismo-tectonic and geological setting of Pakistan resembled those areas. The PSHA study of Afghanistan was carried out in 2007 (Boyd, Mueller and Rukstales, 2007).

In that study, two different GMPEs, one for shallow earthquakes (0-50 km) and the other for deep earthquakes (50-250 km), were used. Both of those GMPEs were obtained from the studies conducted for WNA, Europe, and the Middle East. The same reason, resemblance of geologic and tectonic features and lack of local GMPEs was used as justification. Similar to Afghanistan, Pakistan also has various earthquake environments such as Shallow and deep earthquakes. For every earthquake environment, the wave propagation effects along with the excitation of seismic energy vary. In order to consider these effects in current PSHA study, various GMPEs are used for every earthquake environment.

In the current study, GMPEs by (Youngs et al., 1997) and (Atkinson & Boore, 2011) are used to assess ground motion for earthquakes in the intermediate (50-100 km) and deep (100-250 km) levels. As shown in the logic tree, (Youngs et al., 1997) is employed for earthquakes with depths ranging from 50 km to 250 km, but (Atkinson & Boore, 2011) is only employed for intermediate (0-50 km) seismicity (Figure 15). The ground motion for the Makran Subduction Zone is computed using three GMPEs with a probability weight of 0.50 established by (Youngs et al., 1997). The GMPEs used are based on the most recent knowledge of ground motions in their respective areas (Petersen et al., 2015).

## 2.3 Probabilistic Seismic Hazard Assessment (PSHA)

Open Quake software (a free open source software and code for seismic hazard and risk calculations created by the global earthquake model (GEM) facility team) is used in probabilistic seismic hazard assessment. This software has many calculators for performing seismic hazard assessments.

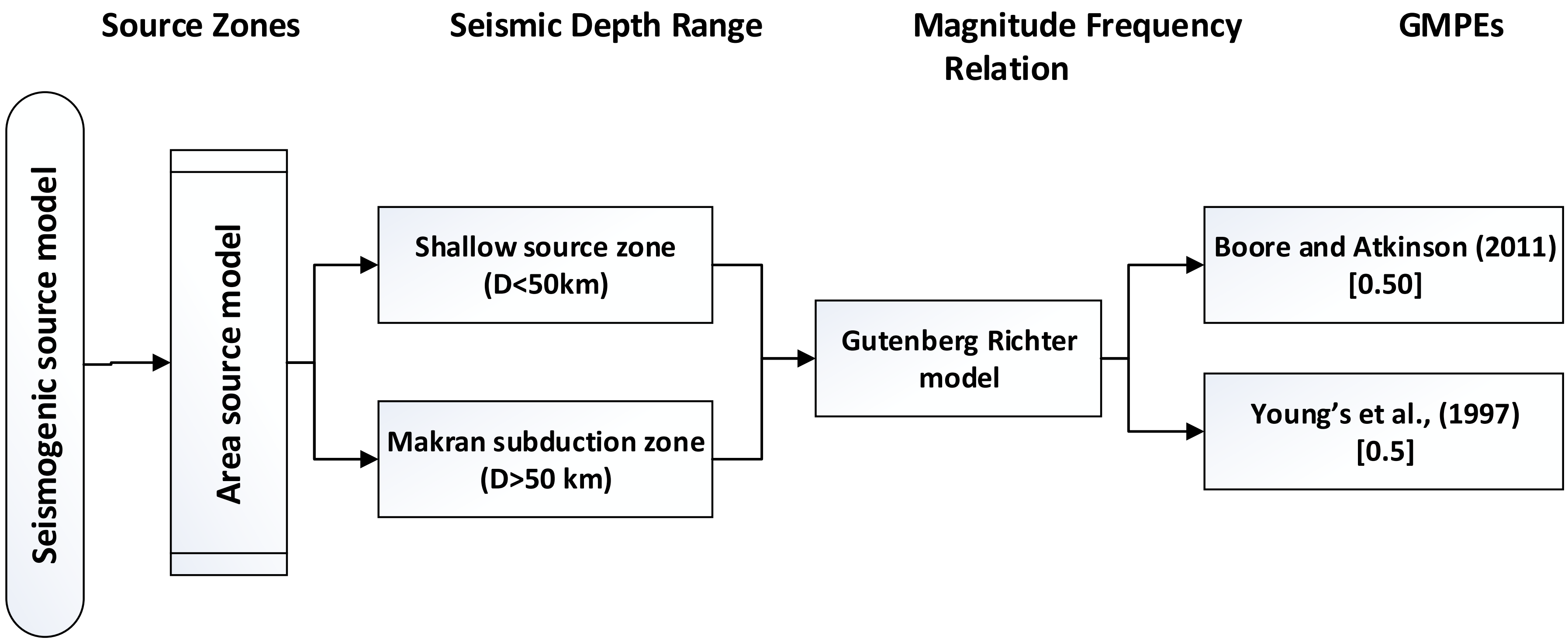


Figure 14. Logic tree for ground motion prediction model.

The classical PSHA calculator is used in this current study which incorporates the methodologies developed by the Cornell (Cornell, 1968). This open-source software has an updated information of seismic hazard assessment and is equipped with advanced and highly developed ground motion prediction equations (GMPEs). Additionally, it allows providing the input model of complex seismic sources by incorporating the logic tree structure to determine the seismic hazard curves and probabilistic ground motions for a specific region or site. This GEM developed software constitutes of a series of PYTHON and JAVA codes (Pagani et al., 2014)

In this study, the seismic hazard for Pakistan is estimated. The whole region of interest is divided into grid cells of size 0.1° in latitude and longitude, respectively. This division has resulted in 58,992 sites. hazard maps have been developed from the mean hazard curves for mean PGA for 69%, 10%, 5%, 2% and 0.5% probability of exceedance (PE) in 50-years corresponding to 43, 147, 475 (Design Basis Earthquake DBE level), 975 and 2475 (Maximum Credible Earthquake MCE level) return periods, respectively. The logic tree technique (figure 15) is used to incorporate modeling uncertainty in these contour maps for two types of earthquake sources and GMPEs. These hazard maps are based on a reference site condition that is specified to be the boundary between National Earthquake Hazard Reduction Program (NEHRP) classes B and C with an average shear-wave velocity at surface level.

### 2.3.1 Hazard Assessment at surface

The degree and nature of surface ground movements, as well as the physical characteristics of structures, have a significant influence on the threat of damage to structures at the surface. Direct observation of ground motion in response to seismic energy and comparison of that reaction to the shaking resonance of structures built on the site would be a more direct approach of assessing hazard at the ground surface for seismic risk at the site. For evaluation of seismic hazard at surface mostly two methods are used. The H/V micro tremor approach, the Nakamura methodology, the response spectrum method, and the frequency domain amplification method (Green's function method) are some of the alternatives. Developing seismic site characterization maps, which are frequently used for earthquake mitigation, awareness, response, and recovery, requires estimating site effects. Seismic site characterization maps are generated using the averaged shear-wave velocity of the top 30 meters of the ground surface (Vs30) (Borcherdt, 1997).

### 2.3.2 NEHRP (1997) Soil Classification

The USGS seismic site characterization web database for active tectonic categories is used to characterize the soil in this research. The soils are categorized into soil sites ‘B’, ‘C' and ‘D' according to NEHRP (1997) guideline (FEMA, 2003). Soil site classification based on NEHRP (1997) code for the current study is summarized in table 9. These Vs30 values are used to develop the Baluchistan shear wave velocity map.

## 2.4 Seismic Hazard Deaggregation

For a given site, seismic hazard is the annual probability of exceedance (PE) of a ground motion parameter (PGA or SA) based on the combined effect of all earthquake magnitudes and distances from all possible seismic source zones.

Therefore, the resultant seismic hazard is not related with any particular earthquake magnitude (Mw) and distance (R).

The hazard is divided into its contributions from different earthquake sources to highlight the events contributing most to the seismic hazard. This process is called disaggregation. The disaggregation gives better insights and improved understanding of the seismic hazard from different seismic sources. It also provides a much clearer picture of the expected ground motions at any particular site of interest and can be useful in making certain engineering decisions (M. Z. Rahman et al., 2020).

The magnitude (M), source to site distance (R), and epsilon (ε) are the three major deaggregated source characteristics that are taken into account during deaggregation. Epsilon is the standard deviations (σ) by which the logarithmic SA of ground motion generated by a specific M, R pair varies from the GMPE-estimated median ground motion value.

The current study is focused on the seismic hazard deaggregation of Quetta region for PGA and SA for different time periods. The results are discussed in chapter 4.

Table 9. NEHRP (1997) site classification standard followed by different soils.

| Site Classes | Definitions |
|---|---|
| A | Hard rock with shear wave velocity >1500 m/s |
| B | Rock with shear wave velocity to (760–1500 m/s) |
| C | Very dense soil and soft rock with shear wave velocity (360–760 m/s) |
| D | Stiff soil with shear wave velocity (180–360 m/s) |
| E | Soil with shear wave velocity <180 m/s |
| F | Site-specific evaluations |

## *CHAPTER 3*

# RESULTS AND DISCUSSIONS

The results of current study are presented in seismic surface hazard maps for Peak Ground Acceleration (PGA) for 2%, 5%, 10%, 25% and 69% probability of exceedance in 50 years. Earthquake Exceedance rate and return period are also determined for each zone. Uniform hazard spectra (UHS) for Quetta and Gawadar city are also drawn at various return periods. Hazard deaggregation analysis is also carried out to estimate the percentage of hazard contribution of all the seismic sources to the Quetta city. The results obtained in the present study for P.E of (0.02, 0.01, 0.004, 0.002 and 0.001) for period of 50 years are acceptable. These results can be compared with the previous studies as well as GSHAP map. For some cities the values differ from the previous studies due to the fact that we have used catalogue up to 2020, while the last study comprises of events till 2016.

## 3.1 Earthquake Recurrence Model

Annual exceedance rates for each seismic source zone was calculated. Annual exceedance rates define the number of times a magnitude of interest will come in the zone. Zone 9 showed higher annual exceedance rate for magnitude 4.0 earthquake to be 22 times (figure 14). While zone 11 showed the lowest annual exceedance rate for magnitude 4.0 earthquake to be 2 time approximately (table 15). Return period defines the number of years for a magnitude of interest to repeat itself in a single zone. In this study for magnitude 4.0 earthquake zone 9 showed lowest return period of 0.04 and zone 5 with higher return period of 0.36 for magnitude 4.0 earthquake (table 10).

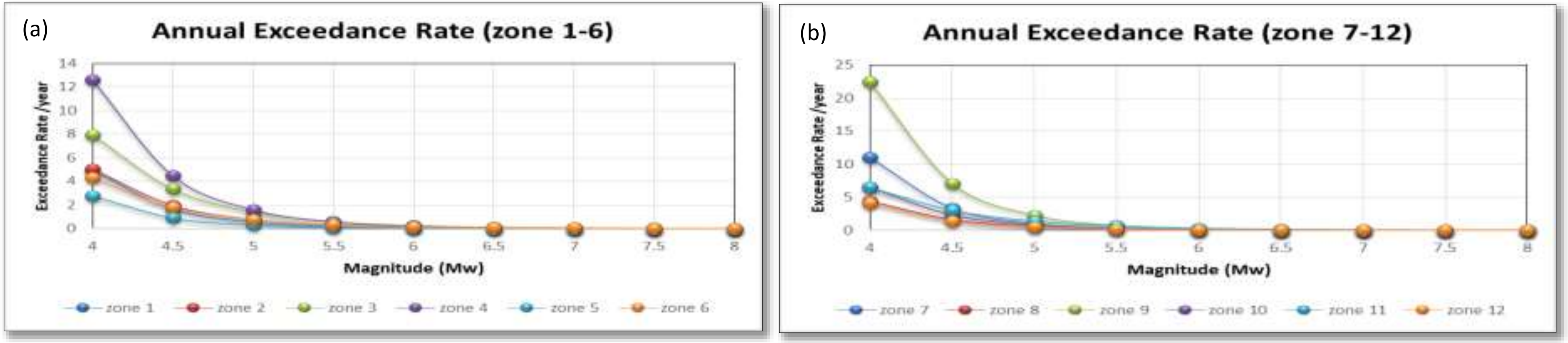


Figure 15. Annual exceedance rates for seismic source zones (a) Zone 1-6 and (b) Zone 7-12.

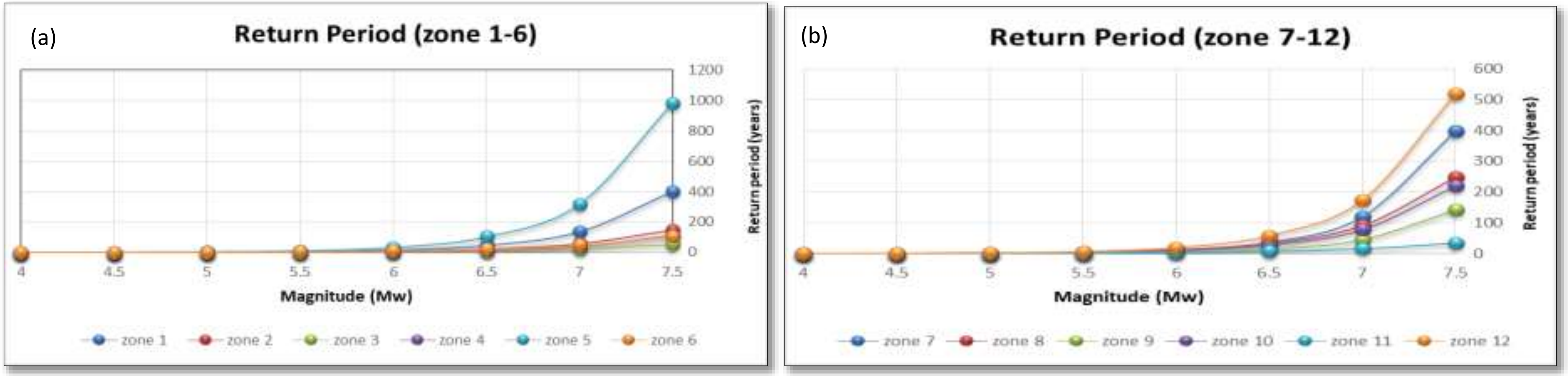


Figure 16. Return period for seismic source zones (a) Zone 1-6 and (b) Zone 7-12.

Table 10. Seismicity parameters for 12 area sources using the maximum likelihood method (Aki, 1965).

| **Zones** | **Activity rate (α)** | **β** | **Mc** | **Mmax** | **λ** | **Return period (year)** |
|---|---|---|---|---|---|---|
| **1** | 10.25 | 2.16 | 4.6 | 6.7 | 4.90 | 0.20 |
| **2** | 9.17 | 1.89 | 4.8 | 7.4 | 5.01 | 0.20 |
| **3** | 8.98 | 1.73 | 4.3 | 7.9 | 7.95 | 0.13 |
| **4** | 10.82 | 2.07 | 4.9 | 7.8 | 12.60 | 0.08 |
| **5** | 10.04 | 2.26 | 4.4 | 8.2 | 2.75 | 0.36 |
| **6** | 8.45 | 1.75 | 4.9 | 5.9 | 4.27 | 0.23 |
| **7** | 11.98 | 2.40 | 4.3 | 6.7 | 10.97 | 0.09 |
| **8** | 9.51 | 2.00 | 4.7 | 6.8 | 4.47 | 0.22 |
| **9** | 8.04 | 1.54 | 4.8 | 7.5 | 22.40 | 0.04 |
| **10** | 10.16 | 2.07 | 4.4 | 6.1 | 6.46 | 0.15 |
| **11** | 12.32 | 2.30 | 4.3 | 6.8 | 6.46 | 0.15 |
| **12** | 10.16 | 2.19 | 4.4 | 6.1 | 4.07 | 0.25 |

## 3.2 Surface seismic hazard maps

A shazard map represent the different level of seismic hazard associated with earthquake on a map for a particular region. Seismic hazard maps are beneficial because these help to reduce the damage caused by any future earthquake. The seismic hazard maps are the ultimate products of any probabilistic seismic hazard assessment. In this current study, seismic hazard maps are developed for Baluchistan. These maps include the peak ground acceleration (PGA) at different time periods (0.2s, 1.0s, 2.0s) 43, 145, 475, 975 and 2475 years return period (50 year time frame) respectively.

### 3.2.1 Vs30 Mapping

The USGS seismic site characterization web database for active tectonic categories is used to characterize the soil in this study. The soils of the study area have velocity values between 180 to 900 m/sec, so according to NEHRP (1997) guideline site is classified into sites ‘ B’, ‘C' and ‘D' (FEMA, 2003). All the Districts of Baluchistan were classified into type C and D classes based on average velocity value shown in the table 11.

### 3.2.2 Peak Ground Acceleration (PGA) Maps

The earthquake causes the shaking of ground and eventually the velocity is recorded by seismic stations. The variation of velocity is generally called acceleration. So, during earthquake the ground also experiences acceleration. During an earthquake, the peak ground acceleration (PGA) is the greatest increase in velocity recorded by any seismic station (USGS). Consequently, PGA hazard maps show the probability of exceedance of future peak ground acceleration by future earthquake in a certain time for a particular site. In this study, five PGA maps are drawn for baluchistan.

For all maps, the hazard is related with activity rate (α values) of seismic source zones. PGA across baluchistan is in the range of 0.02-0.20g, 0.02-0.36g, 0.05-0.42g, 0.05-0.49g and 0.08-0.56g corresponding to the 43, 175, 475, 975 and 2475 years return period. The predicted PGA at the MCE level is almost 1.54 times the PGA value at DBE level in every part of baluchistan. Furthermore, this is very clear from Figures 19 to 23 that seismic hazard is dominating in western Pakistan (Pishin, Quetta, Ziarat, Qilla Saifullah, Mastung, and Sibi) and southwestern Pakistan (Gwadar, Turbat, Panjgoor, and Kharan). These high seismic hazard areas are located in areas ehere seismicity activity rate are higher.

Results of peak ground acceleration (PGA) of this study are compared with earlier studies (i.e. GSHAP 1999; PMD & NORSAR 2007; EMME 2014; Zaman 2016 and NESPAK 2007) (see Table 12). This study depicts high hazard level for south-western (Makran region) as compared to the previous studies. The high hazard values in the current study could be related to the use of improved hazard model and latest seismic data. Another reason is the use of a number of GMPEs for different earthquake environments in this study in contrast to the use of a single GMPE for all of the earthquake environments in the past studies. Uniform hazard spectra is plotted for PGA and SA for different return period. The maximum and minimum limits of the hazard spectra illustrate the variation of uniform hazard spectra within the city. The seismic hazard is reasonably agreeing with the tectonic and geological environment of the area. The level of seismic hazard is quite high in area of the country which depicts the reality that several number of major earthquake have occurred there earlier, as a result most devastating earthquake can be anticipated in that area.

## 3.3 Deaggregation Results

Figure 26 is showing the seismic hazard disaggregation analysis results for Quetta. The disaggregation was performed for DBE level PGA that corresponds to 475 years return period. The purpose of disaggregation analysis is to obtain accurate insights and a better understanding of relative contributions of the seismic hazard from various Seismo-genic sources in connection with magnitude-distance-epsilon. The disaggregation results for PGA and SA of different return periods (figure 27) distinctly show the contribution of various seismic sources for a particular level of earthquake. Similarly, for various magnitude levels, the importance of nearly located earthquakes can be displayed. It has been historically reported that mega earthquakes result in lower frequency ground motions. These ground motions can propagate over extended distances (PMD and NORSAR, 2007).

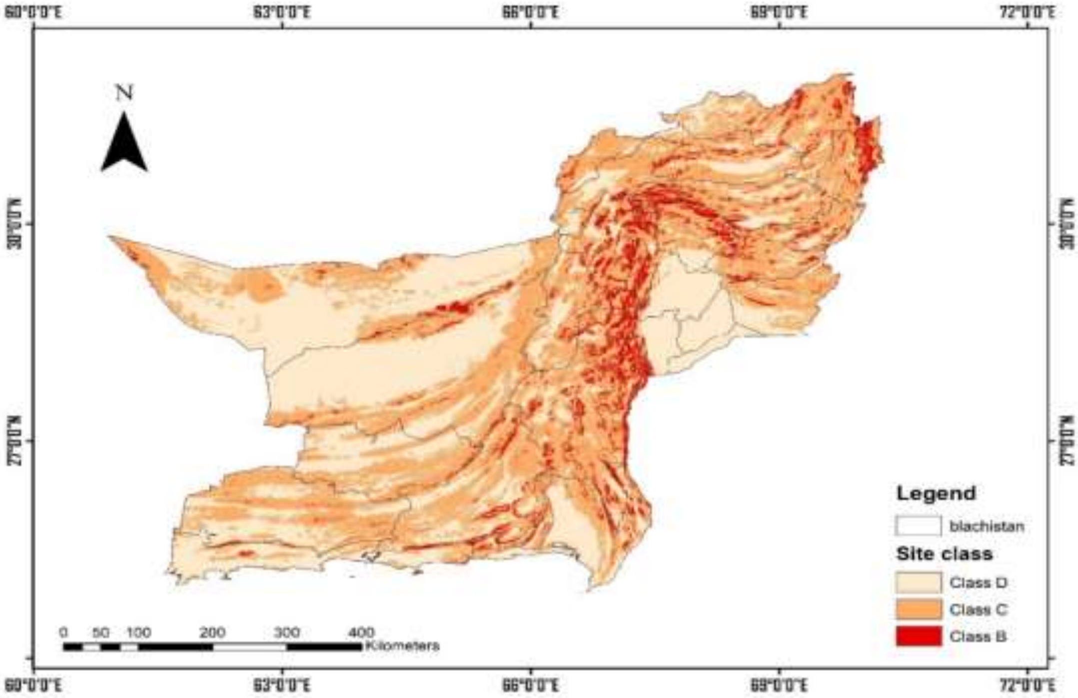


Figure 17. Soil Classification Map Based on shear wave velocity (NEHRP Method).

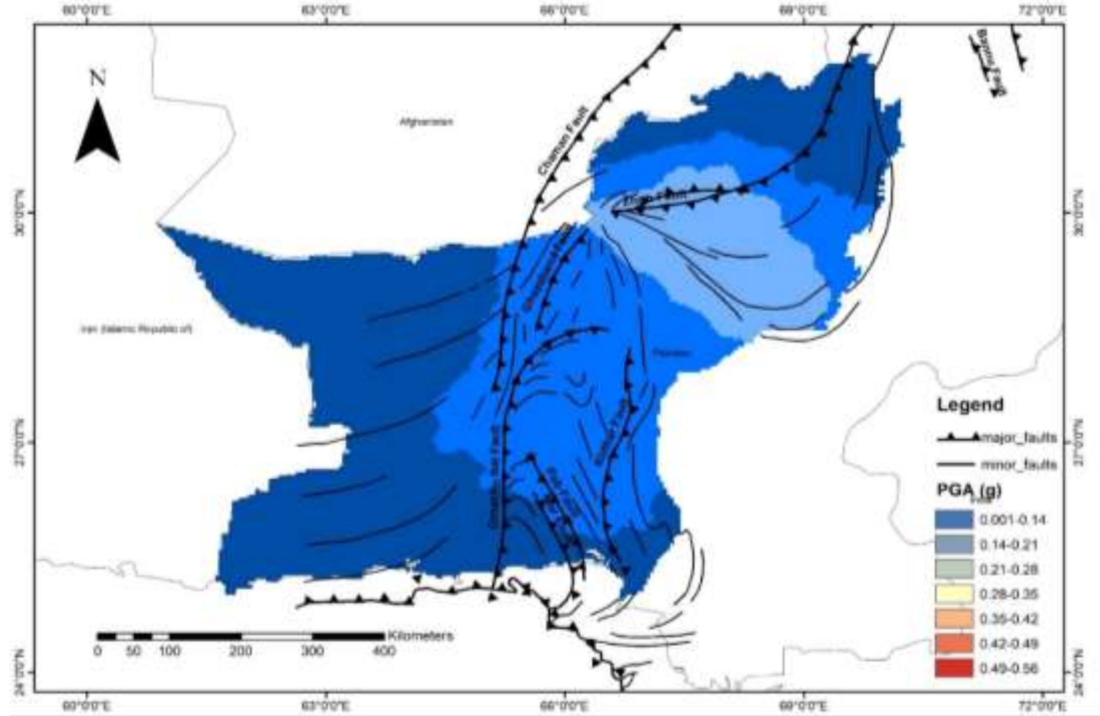


Figure 18. Peak ground acceleration at 69% probability of exceedance at 50 years (50 years return period) (SLE level)

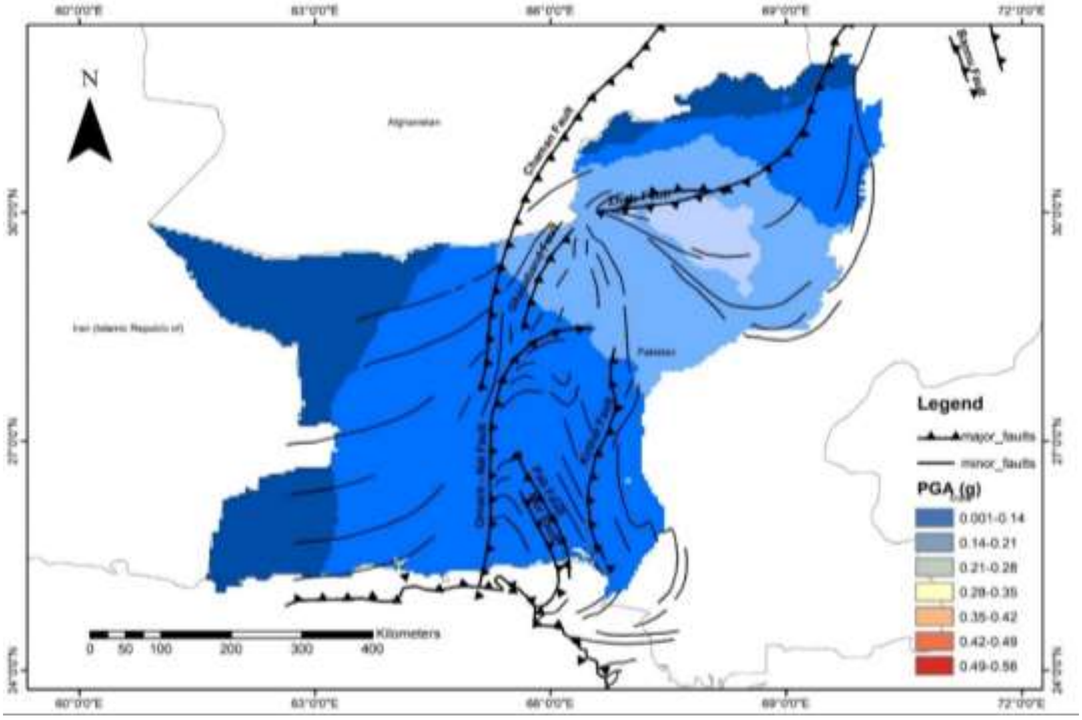


Figure 19. Peak ground acceleration at 25% probability of exceedance at 50 years (145 years return period).

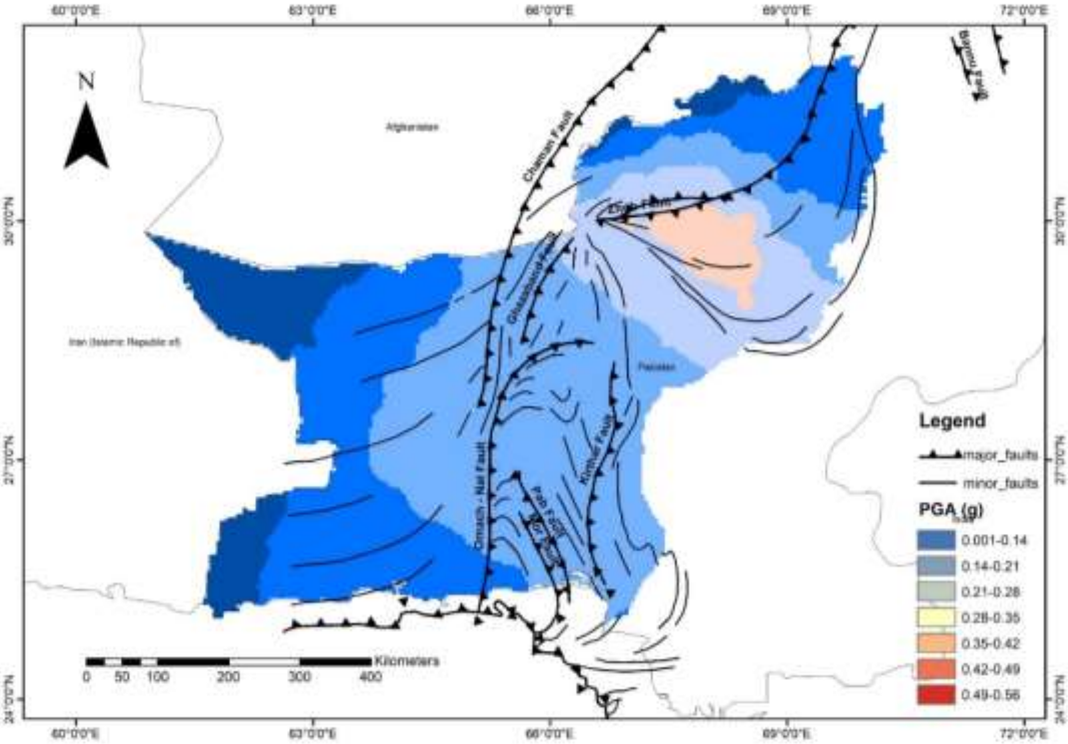


Figure 20. Peak ground acceleration at 10% probability of exceedance at 50 years (475 years return period) (DBE Level).

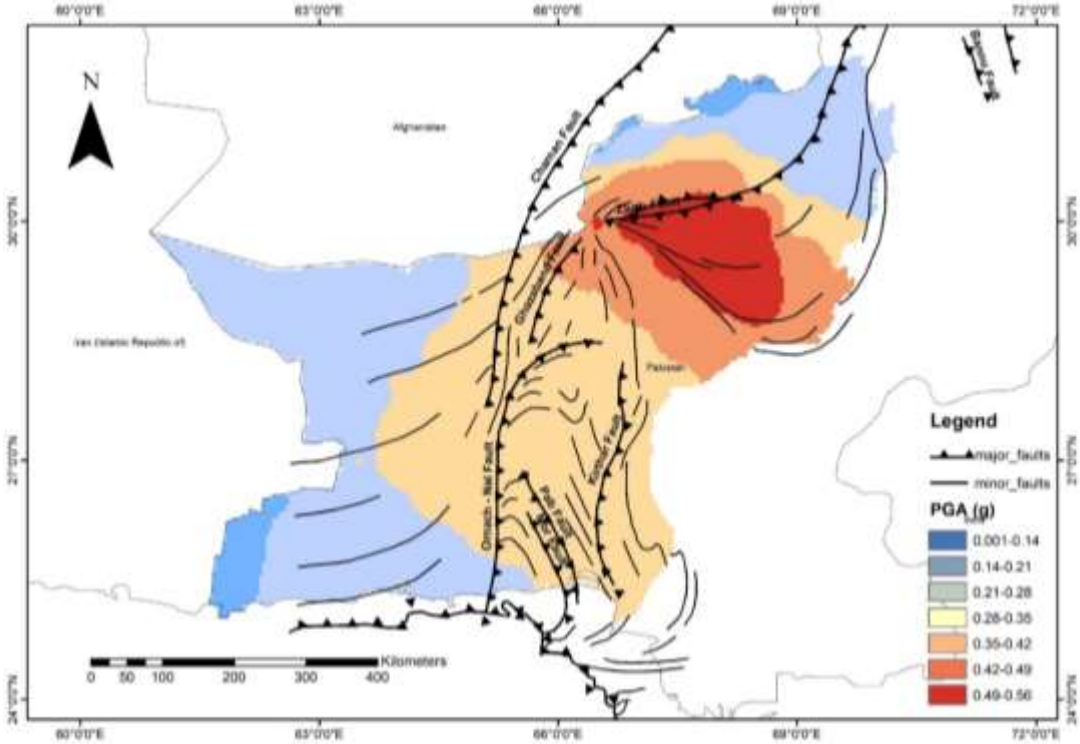


Figure 21. Peak ground acceleration at 5% probability of exceedance at 50 years (975 years return period).

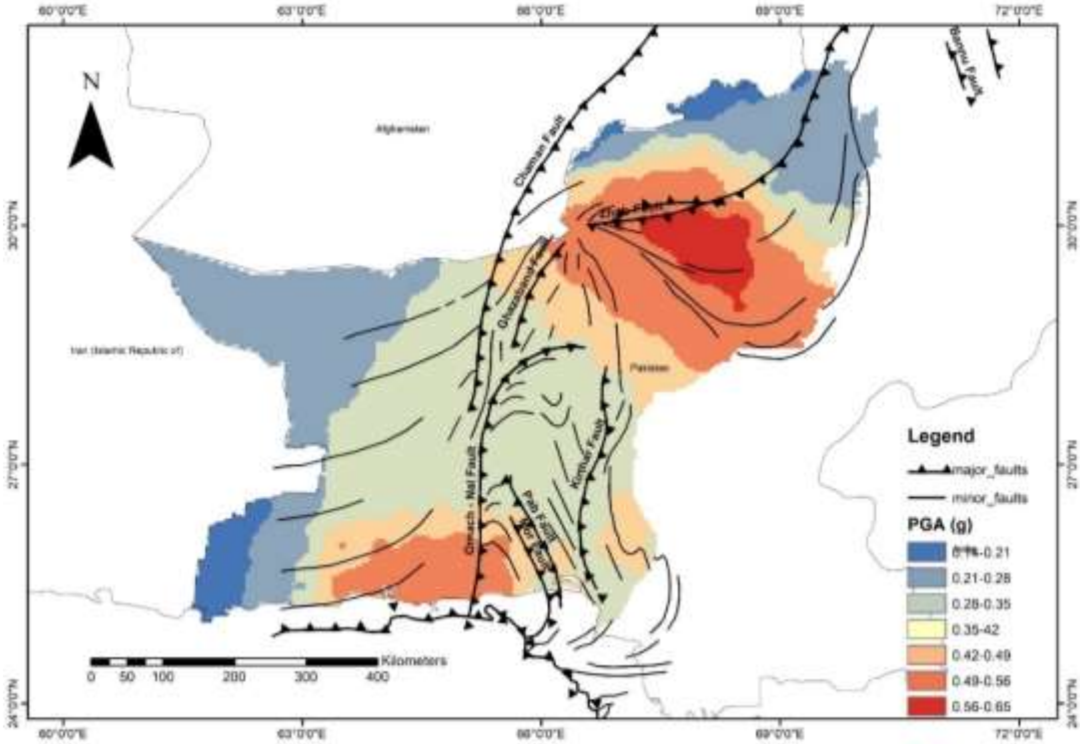


Figure 22. Peak ground acceleration at 5% probability of exceedance at 50 years (2475 years)

Table 11. Velocity (vs30) and acceleration (g) value at the ground surface for return periods.

| **Districts** | **Long** | **Lat** | **Vs30 (m/sec)** | **SC** | **Acceleration(g) at different periods** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **50 year** | **150 years** | **475 yrs.** | **974 yrs.** | **2475 yr.** |
| Quetta | 66.98 | 30.18 | 315.83 | D | 0.20 | 0.27 | 0.35 | 0.43 | 0.56 |
| Gawadar | 62.29 | 25.25 | 228.62 | D | 0.11 | 0.14 | 0.20 | 0.28 | 0.35 |
| Ziarat | 67.72 | 30.39 | 467.59 | C | 0.21 | 0.27 | 0.37 | 0.47 | 0.57 |
| Sibi | 67.88 | 29.55 | 203.67 | D | 0.24 | 0.31 | 0.42 | 0.52 | 0.63 |
| Nasirabad | 67.91 | 28.20 | 196.40 | D | 0.19 | 0.25 | 0.34 | 0.42 | 0.51 |
| Zhob | 69.47 | 31.35 | 347.78 | D | 0.14 | 0.18 | 0.26 | 0.32 | 0.38 |
| Pishin | 67.01 | 30.59 | 322.60 | D | 0.18 | 0.24 | 0.33 | 0.42 | 0.51 |
| Panjgur | 64.09 | 26.97 | 279.16 | D | 0.14 | 0.21 | 0.28 | 0.35 | 0.44 |
| Musakhel | 69.96 | 30.85 | 733.99 | C | 0.14 | 0.19 | 0.26 | 0.32 | 0.39 |
| Mastung | 66.78 | 29.88 | 238.85 | D | 0.22 | 0.28 | 0.39 | 0.48 | 0.59 |
| Loralai | 68.60 | 30.38 | 283.80 | D | 0.17 | 0.24 | 0.32 | 0.39 | 0.48 |
| Lesbela | 66.71 | 25.87 | 340.54 | D | 0.15 | 0.21 | 0.29 | 0.36 | 0.45 |
| Killa saifullah | 68.37 | 30.70 | 335.96 | D | 0.17 | 0.23 | 0.31 | 0.38 | 0.47 |
| Killa Abdullah | 66.71 | 30.81 | 526.60 | C | 0.13 | 0.19 | 0.26 | 0.32 | 0.39 |
| Khuzdar | 66.61 | 27.82 | 394.85 | C | 0.15 | 0.21 | 0.29 | 0.36 | 0.44 |
| Kharan | 65.42 | 28.59 | 270.87 | D | 0.15 | 0.21 | 0.29 | 0.36 | 0.44 |
| Kech | 63.01 | 26.16 | 468.32 | C | 0.13 | 0.17 | 0.25 | 0.32 | 0.40 |
| Kalat | 66.59 | 29.65 | 542.79 | C | 0.20 | 0.27 | 0.36 | 0.45 | 0.54 |
| Jhel Magsi | 67.46 | 28.28 | 226.24 | D | 0.17 | 0.25 | 0.33 | 0.40 | 0.49 |
| Jaffarabad | 68.19 | 28.28 | 198.31 | D | 0.20 | 0.26 | 0.36 | 0.44 | 0.53 |
| Dera bugti | 69.16 | 29.04 | 447.96 | C | 0.12 | 0.27 | 0.38 | 0.46 | 0.56 |
| Chagai | 64.69 | 29.31 | 248.25 | D | 0.14 | 0.19 | 0.26 | 0.33 | 0.41 |
| Bolan | 67.67 | 29.23 | 219.58 | D | 0.22 | 0.29 | 0.39 | 0.48 | 0.59 |
| Barkha | 69.57 | 29.90 | 407.44 | C | 0.15 | 0.21 | 0.28 | 0.36 | 0.43 |

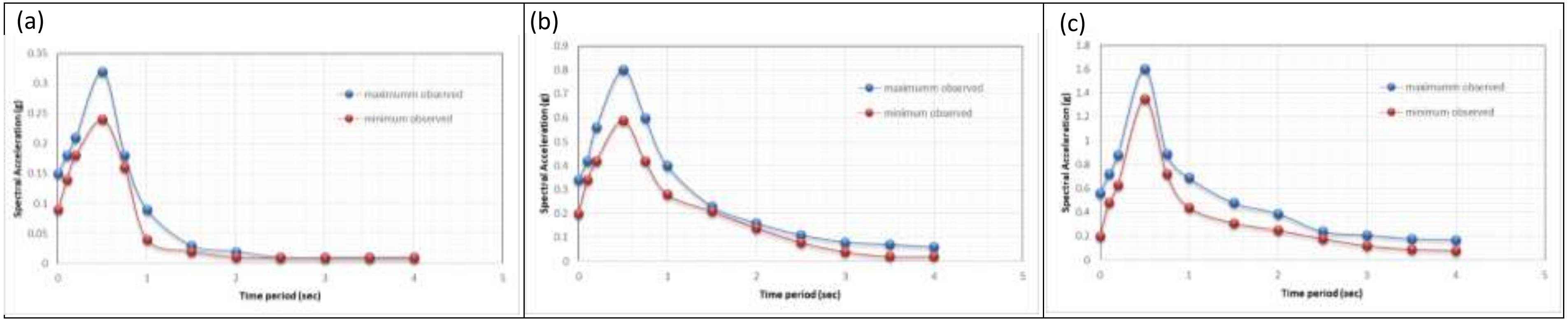


Figure 23. UHS of Quetta (a) SLE (b) DBE (c) MCE LEVEL.

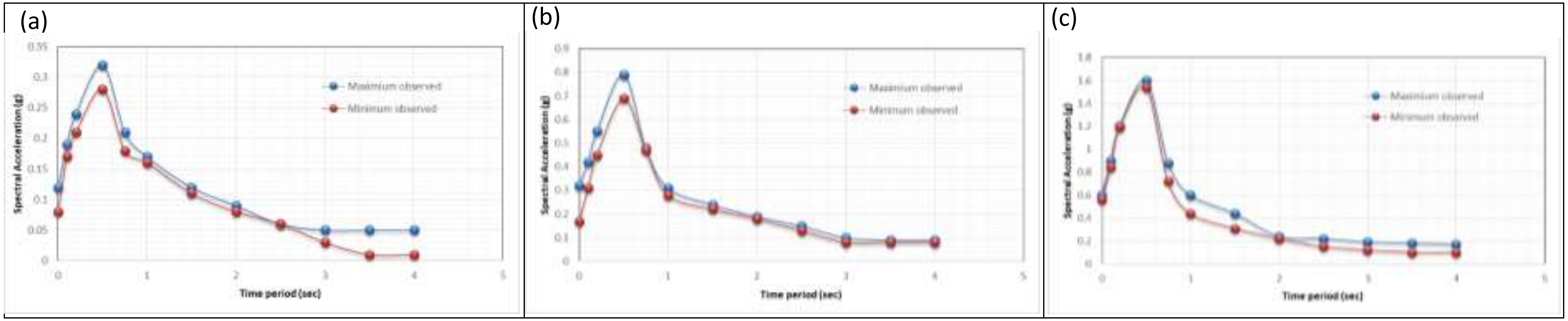


Figure 24. UHS of Gawadar (a) SLE (b) DBE (c) MCE LEVEL.

Table 12. Comparison of PGA (g) values of this study, for DBE level, for Quetta city with the previous studies (i.e. GSHAP 1999; PMD & NORSAR 2007; NESPAK 2007 and EMME 2014).

| **Seismic Parameters** | **GSHAP (Zhang et al., 1999)** | **PMD-NORSAR (2007)** | **NESPAK (2007)** | **EMME (2014)** | **Current study** |
|---|---|---|---|---|---|
| **PGA** | 0.4 | 0.39 | 0.32 | 0.32 | 0.42 |
| **SA (0.2 sec)** | - | 1.61 | - | - | 0.81 |
| **SA (1.0 sec)** | - | 0.40 | - | - | 0.45 |
| **SA (2.0 sec)** | - | 0.22 | - | - | 0.25 |

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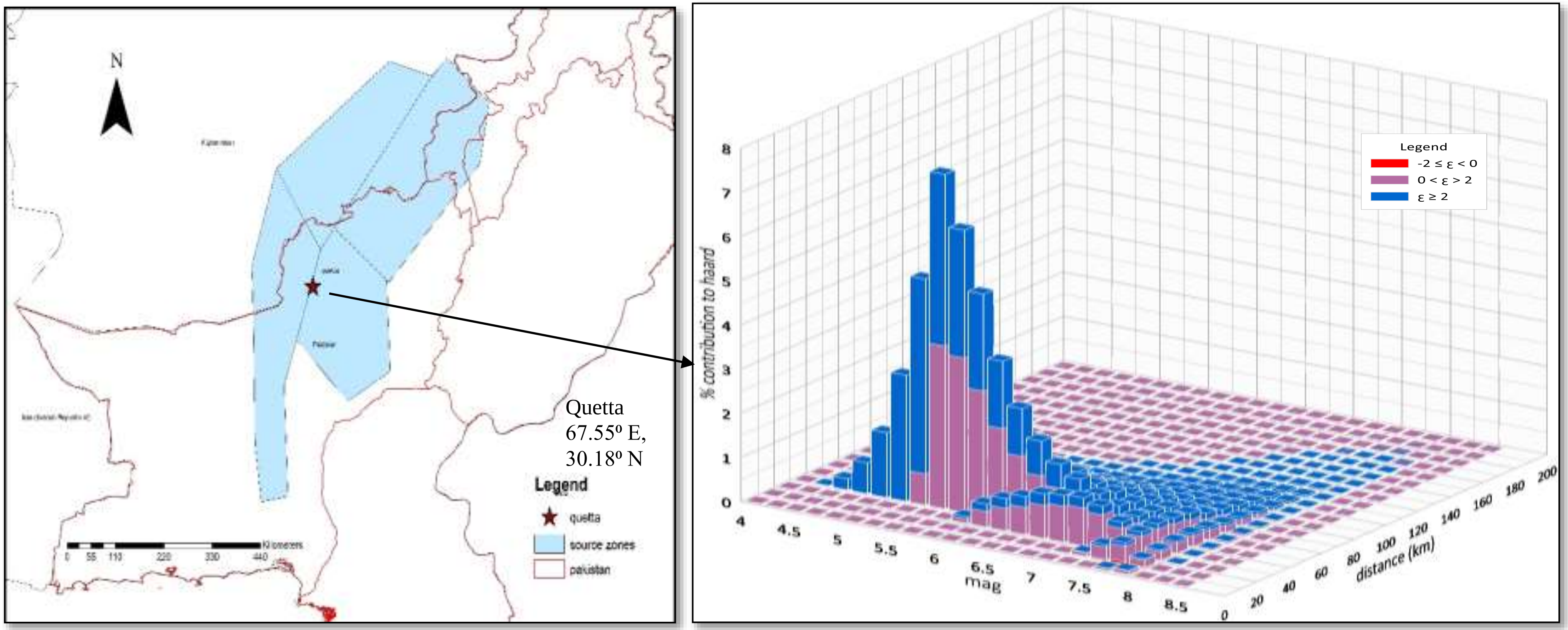

Figure 25. Deaggregation on NEHRP BC rock of PGA (0.33g) at 69% PE in 50 years (475 years).
Mean ($\boldsymbol{R}$, $\boldsymbol{M}$, $\boldsymbol{\varepsilon}$) = 48km, 5.7.2 Mw, 1.50

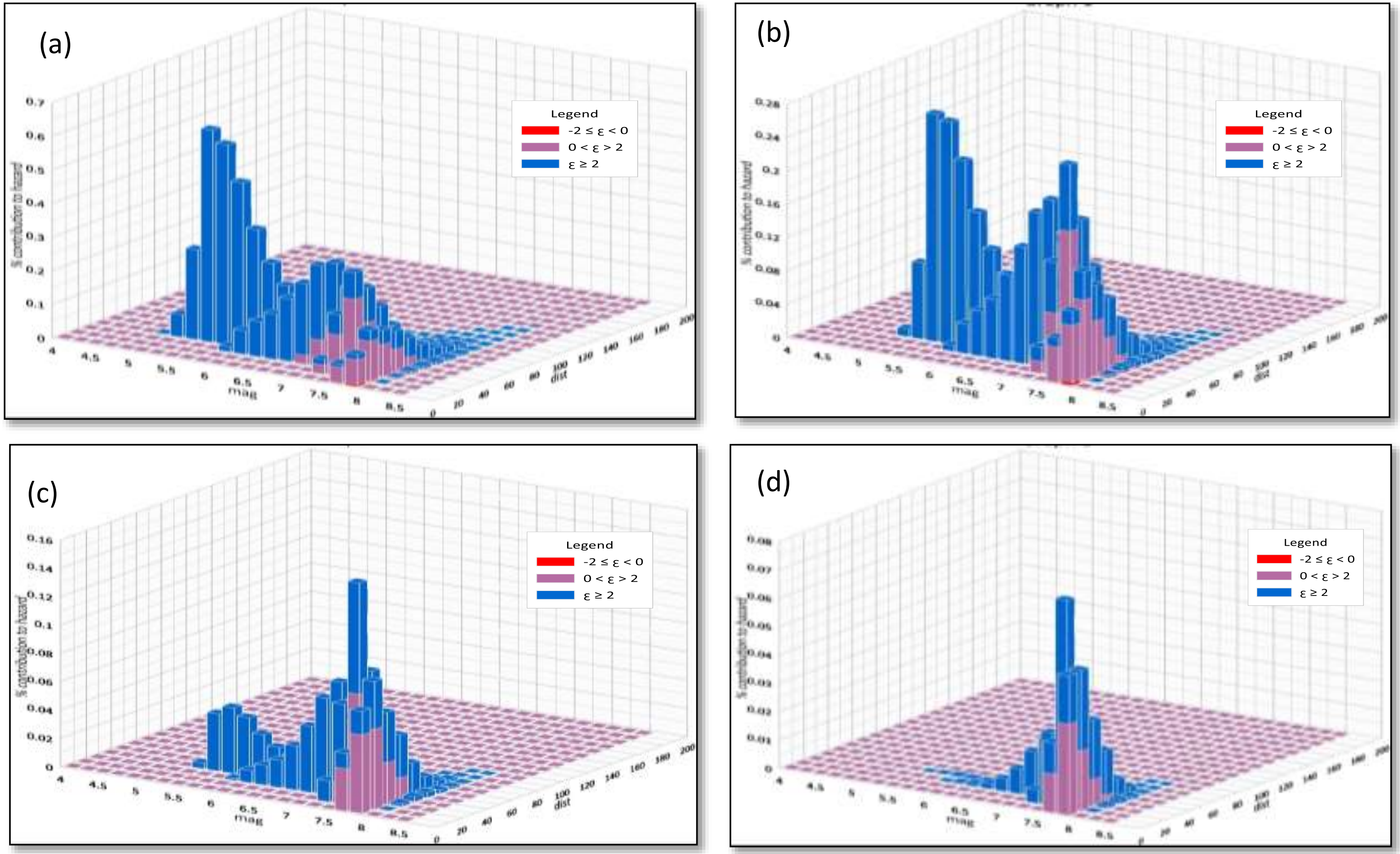

Figure 26. Seismic hazard deaggregation of PGA at (a) 2% PE in 50 years (b) 5% PE in 50 years (c) 10% PE in 50 years (d) 25 % PE in 50 years.

*CHAPTER 4*

# CONCLUSTION AND RECOMMENDATIONS

The updated seismic hazard analysis of southern Pakistan has improved the understanding of seismic hazard of the area. An updated earthquake catalogue are developed from national and international databases from year 1900 to 2020 and updated PGA maps are prepared, this study would be considered as reference in future. The conventional area source model is employed to assess the seismic hazard using an up to date recompiled earthquake catalogue. To cater the epistemic uncertainties in GMPEs, the logic tree approach has been used. Hazard maps are developed for PGA at various time periods for 69%, 25%, 10%, 5% and 2% PE in 50 years (Time Frame). The updated hazard maps are considered to be relatively more improved as compared to the earlier studies because the latest earthquake catalogue and improved GMPEs are used. The hazard maps will have a very good impact on the seismic risk mitigation of Pakistan by improving the construction practice throughout the country. Moreover, to provide insight into which earthquake event has major contribution to the seismic hazard of each of major cities, a distance, magnitude and epsilon deaggregation is carried out. The M-R- ε deaggregation results shows a general behavior for deaggregation plots for PGA return period of 475 years. Consequently, more hazard occur on the area of the country which has high seismicity and major devastating events occurred on that region.

## 4.1 Conclusions

- A fully updated, comprehensive, and composite catalog of historically and instrumentally recorded earthquake events (1900-2020) has been developed, which will be extremely useful for future research.

- PSHA has been done on 0.10° x 0.10 ° grid for Baluchistan, hazard maps of peak ground acceleration (PGA) for 69%, 10%, 5%, 2% and 25 % PE have been developed.
- The uniform hazard spectra (UHS) for Quetta and Gawadar and hazard maps for Baluchistan on a 0.10° x 0.10 ° grid has been created by Probabilistic Seismic Hazard Analysis. Any future structural design and analysis work will benefit from these curves and maps.
- For all maps, the hazard is adequately consistent with seismic activity rates (a values) of all seismic source zones.
- The PGA value for Baluchistan is in the range of 0.02 – 0.20, 0.02 – 0.36, 0.05 – 0.42, 0.05 – 0.49 and 0.08 – 0.56 g corresponding to the 43, 145, 475, 975 and 2475 years return period. The hazard values are mostly higher near the plate boundary.
- The pattern of seismic hazard variation for this study looks analogous to the past studies (i.e. GSHAP; NESPAK 2007), but the seismic hazard level is higher.
- The seismic hazard maps of PGA depict the effect of deep sources in the south-western parts of Pakistan.
- Seismic hazard looks dominating in western Pakistan (Pishin, Quetta, Ziarat, Qilla Saifullah, Mastung, and Sibi) and southwestern Pakistan (Gwadar, Turbat, Panjgoor, and Kharan).
- The seismic hazard deaggregation analysis presented in the current study for Quetta city demonstrate that the main seismic hazard contribution for major cities comes from closer earthquakes.

## 4.2 Recommendations for Further Research

- The investigation of crustal faults and the Makran subduction zone has a significant gap. On the crustal faults, hardly any research has been done.
- There are only few ground motion prediction equations (GMPEs) for Pakistan due to inadequate instrumentation. The number of seismographs installed around the country should be expanded to improve the country's seismic hazard assessment.
- The country's earthquake risk can be reduced by adequately implementing the building code provisions. Building codes should be followed while designing new constructions. On the other side, existing structures must be reinforced before the next major disaster strikes.
- National and Provincial Disaster Management Agencies must have all of the resources they need to mitigate as best they can in the case of a natural disaster.

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