Development of an Early Earthquake Loss Assessment Framework for Pakistan

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This is to certify that the report titled

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At the end, we would dedicate this work to our parents who inspired us to learn and helped us with their prayers.

ABSTRACT

Pakistan is located in a seismically active area. Several severe earthquakes have struck the region in recent history, killing thousands and destroying infrastructure worth millions. An Earthquake Loss Assessment Framework is the need of the hour. The framework will provide reliable estimates of human and economic losses due to earthquakes. These results will be used to organize and direct search and rescue activities in the earthquake affected area.

An Earthquake Loss Assessment Tool is developed for estimating earthquake losses in real time. The tool uses geographic, geologic, demographic and building inventory data to calculate the human and economic losses in near real time. A review of available literature is also presented to develop a general understanding of the topic.

During the literature review, it was determined that no attenuation relationship is available specifically for Pakistan. Therefore, Ambraseys (2005) attenuation relationship was used for ground motion attenuation. Similarly, it was observed that building vulnerability curves for all building classes of Pakistan were not derived. GESI (2001) vulnerability curves were utilized for the purpose of determining the Mean Damage Ratio for different building classes. The results obtained were compared and were satisfactory.

Initially, the tool is applicable to the provinces of Punjab, Sindh, Balochistan, KPK and FATA. Other regions are not yet covered due to unavailability of data. The Awaran Earthquake of 2013 and Kashmir earthquake of 2005 was used as a case study for validation of the tool. The results obtained are satisfactory keeping in view the accuracy and suitability of data and models utilized in the development of this tool.

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ABBREVIATIONS

ARE	Annual Rate of Exceedance.
BCP	Building Code of Pakistan.
CATS	Consequence Assessment Tool Set.
CRED	Center for Research on the Epidemiology of Disasters.
DR	Damage Ratio.
DSHA	Deterministic Seismic Hazard Assessment.
ELE	Earthquake Loss Estimation.
ELER	Earthquake Loss Estimation Routine.
EM-DAT	Emergency Events Database.
EPC	Emergency Preparedness Canada.
EPEDAT	Early Post Earthquake Damage Assessment Tool.
FEMA	Federal Emergency Management Agency.
GEM	Global Earthquake Model.
GIS	Geographic Information System.
GMPE	Ground Motion Prediction Equation.
GNP	Gross National Product.
HAZUS	Hazard United States.
InLET	Internet based Loss Estimation Tool.
JMA	Japanese Meteorological Agency.
KPK	Khyber Pakhtunkhawa.
MDF	Mean Damage Factor.
MDR	Mean Damage Ratio.
MFR	Mean Fatality Ratio.
MIR	Mean Injury Ratio.

NERIES	Network of Research Infrastructure for European Seismology)
NESPAK	National Engineering Services of Pakistan.
NHEMATIS	Natural Hazards Electronic Maps and Assessment Tools Information System.
NIBS	National Institute of Building Science.
PAGER	Prompt Assessment of Global Earthquakes for Response.
PGA	Peak Ground Acceleration.
PGD	Peak Ground Displacement.
PGV	Peak Ground Velocity.
PMD	Pakistan Meteorological Department.
POE	Probability of Exceedance.
PSHA	Probabilistic Seismic Hazard Assessment.
SSHAC	Senior Seismic Hazard Analysis Committee.
UNDRO	United Nations Office of the Co-ordinator of Disaster Relief.
USGS	United States Geological Survey.
WAPMERR	World Agency for Planetary Monitoring and Earthquake Risk Reduction.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Earthquakes are one of the most destructive forces of nature and are responsible for majority of human and economic losses every year. Looking several thousand years back into the history, we see the destruction of ancient cities of Atlantis in Greek mythology and Taxila in the Indus valley Civilization (Coburn and Spence, 2002). In recent decades, major earthquakes in Messina (Italy), Tangshen (China), Tokyo and Kobe (Japan) and Kashmir (Pakistan) have been severely affected by earthquakes.

According to the Cambridge database, at least 1248 lethal Earthquakes were reported in the 20th century. The enormity of their damage can be assessed by the fact that they caused approximately 1685000 reported deaths around the world. It should be kept in mind that the total death toll might be larger than this reported figure. Small earthquakes with few fatalities may not have been reported. Deaths in remote and hard-to-reach areas may have been ignored and about 87 of the significant earthquake events in the database have no figure for casualties. According to the EM-DAT International Disaster Database maintained by CRED, earthquakes have claimed an average of 27000 lives per year since the 1990s. In addition to the human losses, earthquakes are also responsible for economic losses. These economic losses are either due to direct damage and collapse of the infrastructure or due to business and trade interruption in the days following an earthquake. The 1248 recorded earthquakes in the 20th century caused economic loss equivalent to $1 trillion (Coburn and Spence, 2002). This figure was adjusted to the money value in 2000. The economic loss due to an earthquake may severely affect the Gross National Product (GNP) of a country for that year. This will eventually result in increasing the country’s national debt and crippling local and national economies. The highest earthquake economic loss (as %GNP) was reported by Coburn and Spence (2002) as follows:

- Nicaragua 1972, loss of 40% GNP.
- El Salvador 1986, loss of 31% GNP.
- Guatemala 1976, loss of 18% GNP.
- Greece 1999, loss of 12.8% GNP.

Pakistan is known to lie in a seismically active region. On 31st May 1935, a deadly earthquake of magnitude 7.5 struck Quetta, and caused 30000 to 60000 deaths (Dowrick, 2009). The scale of devastation caused by the earthquake is obvious from the figures below:

Figure 1.1: Bruce Road, Quetta. Before the 1935 Earthquake

Figure 1.2: Bruce Road, Quetta. Devastation after the 1935 Earthquake

Although modern design codes include seismic provisions for the design of structures but they have been unsuccessful in minimizing the earthquake damage specially in developing countries primarily due to the fact that majority of the building stock in these countries is either pre-code or the design codes are not properly implemented. Moreover, the population explosion and the trend to migrate towards urban localities have increased the population density, making multi-storey structures in urban centers more exposed to earthquake damage. Use of inferior construction materials and adopting poor construction practices has played its part in aggravating the situation. Hence, the building stock in majority of the developing countries is highly vulnerable to earthquake damage.

Freeman (1932) is considered to be the first person to seriously treat the topic of Earthquake Loss Assessment. He reviewed Earthquake damage data due to various earthquake events and related the damage to Insurance. His work serves as the foundation of Earthquake Loss Assessment studies. Steinbrugge, Algermissen, Lagorio and others prepared a series of loss estimates for major metropolitan areas of the U.S in the 1960s. After the emergence of Probabilistic Loss Assessment in the 1980s, the Loss Assessment methods improved and were used in the process of Policy Making (Petak and Atkinson, 1982). Later in the 1990s, sophisticated Loss Assessment Models began to emerge like HAZUS earthquake loss estimation software by NIBS and FEMA (Whitman et al., 1997). These first models largely focused on United States. A large number of models have been developed for various regions and countries like Australia, New Zealand, Southeast Asia, Taiwan, China, Canada and Latin America. The next level of the Loss Estimation Modeling is the development of a Global Earthquake Loss Assessment Model. A good example of this is the GEM (Global Earthquake Model) Framework.

However, little work has been done to develop a Loss Assessment Model for developing countries especially for those located in highly active seismic regions like Pakistan.

1.2 KASHMIR EARTHQUAKE OF 2005

A strong earthquake of magnitude (Mw) 7.6 struck the northern areas of Pakistan on 8th October, 2005 at 08:50 in the morning. The epicenter of the main event was located approximately 19 km NE of Muzaffarabad, the capital of Azad Jammu and Kashmir, having a focal depth of 26 km (Source: USGS). The main event was followed by around 1000 aftershocks that continued for several days after the main event. The earthquake caused devastation over an area of 30,000 km^2, resulting in more than 80,000 fatalities, 200,000 injured people and more than 4 million people were rendered homeless after the dreadful event. The major affected towns in Pakistan were Muzaffarabad, Balakot, Bagh, Rawalakot, Batagram, Mansehra, Abbotabad, Murree and Islamabad. Initial relief and rescue operations were hindered by the difficult terrain, bad weather and damaged approach roads. (EERI Special Earthquake report, Dec. 2005).

1.3 RESEARCH AIMS AND OBJECTIVES

The Primary purpose of this study is to develop a Loss Estimation Framework for developing countries that is robust and gives reliable estimates of Earthquake Losses and applying this framework to the study region (Pakistan).

- To develop a real time, user friendly Earthquake Loss Estimation Model that takes into account low level of construction, improper implementation of design codes and high population density.
- To develop an automated Loss Estimation Framework that can be operated by people do not possessing advanced knowledge about Earthquake Engineering.
- To test and validate the framework to the study region by comparing the estimated losses to reported losses in the Awaran earthquake of 2013.
- To provide reliable estimates of Human Losses to help and direct search and rescue efforts to areas adversely affected by an Earthquake.
- To provide reliable estimates of Economic Losses for effective distribution of resources, which are limited in a developing country like Pakistan.

Although not included in the scope of this study, this model can be used to simulate probable events to predict Losses and aid Policy Making in terms of:

- ✓ Future Urban Development.
- ✓ Future Insurance Policies.
- ✓ Implementation of Design Codes.
- ✓ Adoption of standard construction practices.

1.4 STRUCTURE OF THE THESIS

This Thesis presents the process of developing an Earthquake Loss Assessment Framework for Pakistan. Chapter 1 of the thesis provided a general Introduction and aim of the research.

Chapter 2 covers the literature review and provides a detailed description of the processes used to develop the Earthquake Loss Assessment framework

Chapter 3 describes in detail the data required for the study region and also the models that were used in the study.

Chapter 4 deals with the implementation of the methodology for Earthquake Loss Assessment. It includes a detailed description of the steps performed in order to estimate losses due to earthquakes.

Chapter 5 presents the results obtained by performing Earthquake Loss Assessment for Pakistan for a past event. It also includes the comparison of the obtained results with actual observed results.

Chapter 6 discusses the conclusions of the study and provides recommendations for work in the field of Earthquake Loss Estimation in Pakistan.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides background knowledge and introduction to the concepts used in developing an Earthquake Loss Estimation model. Earthquake Loss Estimation essentially employs principles from Mathematics, Probability and Statistics, Natural Sciences, Economics and Sociology. Earthquake Loss Estimation consists of three basic components:

- Hazard Module.
- Damage Module.
- Loss Module.

These modules will be discussed in details later.

2.2 EARTHQUAKE LOSS ESTIMATION

Earthquakes are one of the most deadly phenomena of nature posing significant threat of damage to human life and property. Every year thousands of people lose their life, property and business due to earthquakes. Earthquake hazards can be of several types, as listed below:

- Ground Shaking.
- Landslides.
- Liquefaction.
- Structural Hazards.
- Tsunami.
- Fires triggered by Earthquakes
- Earth retaining structures failure.

While all of the above listed hazards can cause serious damage to life and property, the most important of them is Ground Shaking, which is the only hazard included in this study.

Earthquakes Loss/ Risk modeling can be used as the basis for determining insurance premiums and probable maximum losses that would follow an earthquake (Rauch and Smolka, 1992). It can also be used by town planners and development authorities to reduce existing hazards, plan for future emergencies and mitigate harmful impacts of earthquakes. In case of an earthquake, ELE (Earthquake Loss Estimation) model can be used to assess the damaging effects of the earthquake and its spatial distribution for efficient distribution of resources for rescue and rehabilitation efforts.

The lack of complete understanding of earthquake phenomenon and the uncertainties associated with it, all risk/loss estimation studies are essentially an extrapolation into the future (Coburn and Spence, 2002). The accuracy of Earthquake Loss/Risk Estimation models is essentially dependent upon accuracy of the building and demographic data incorporated into the model and the equations and modules used in the process.

2.3 SEISMIC RISK

The term “Seismic Risk” was formally defined by international agreement, in an International Convention organized by the United Nations Office of the Co-ordinator of Disaster Relief (UNDRO) in 1979. Seismic Risk refers to the expected losses to the elements at risk due to an earthquake for a given future time period or exposure time. Seismic risk describes the cost of damage done to infrastructure by an earthquake (Kythreoti, 2002)

Seismic hazard relates to all the physical phenomena induced by an earthquake that affect human life and infrastructure such as ground shaking, landslides, tsunamis, liquefaction and earthquake triggered fires. Seismic risk reflects the threat posed by earthquakes to human life, property, business and infrastructure. The seismic risk of an earthquake occurring in an unpopulated area would be zero, regardless of the magnitude and intensity of the earthquake (Kythreoti, 2002) because the earthquake can cause no damage to infrastructure and human life in this case.

Dowrick (1987) defined Seismic Risk as:

$$\text{Seismic Risk} = (\text{Seismic Hazard}) \times (\text{Vulnerability}) \times (\text{Value}) \qquad (2.1)$$

Where:

Vulnerability is the amount of damage at a given site due to a certain degree of seismic hazard. It is expressed as a ratio of Cost of damage to the total value of the damaged item. Value is the total cost of exposed infrastructure. This relationship is shown in the figure below:

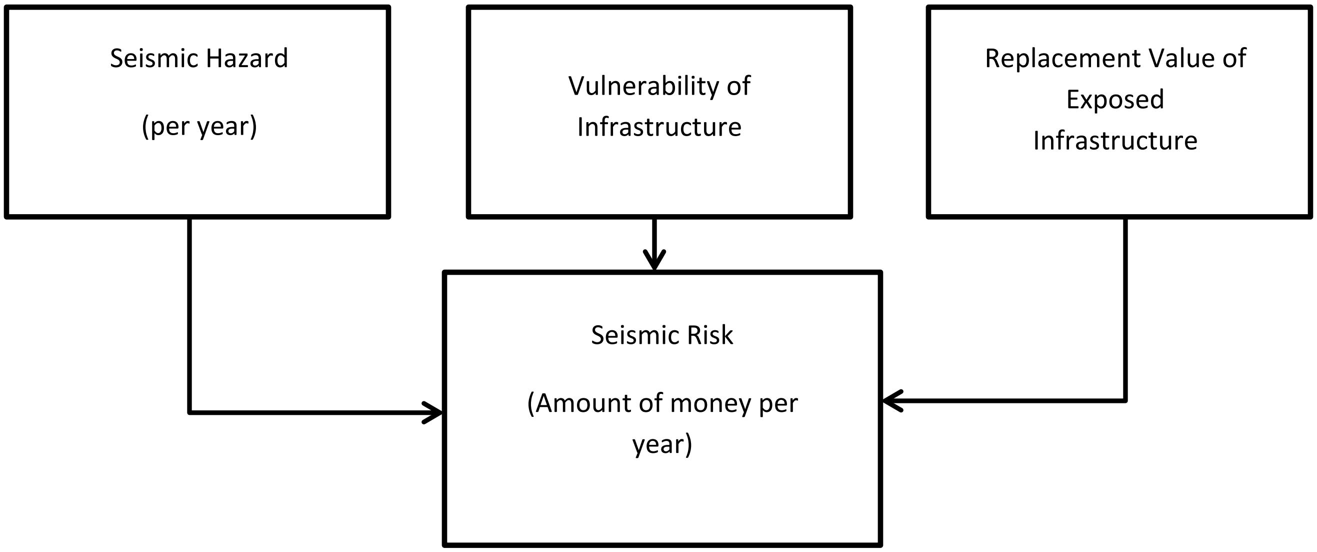


Figure 2.1 : Earthquake Risk Assessment, after Kythreoti (2002)

$$R = \sum_{i=1}^{n} \sum_{j=1}^{m} \left(H_i \times V_{ij}\right) \times C_j \qquad (2.2)$$

Where: H_i is the seismic hazard (i=1 to n)

V_{ij} is the vulnerability of each jth element (Exposed Infrastructure, lives and businesses) with respect to the ith hazard at a given site.

C_j is the value of jth element exposed to seismic hazard (cost of construction in case of infrastructure or number of people exposed to the seismic hazard).

The above mentioned three main components of Seismic risk/loss are discussed in detail below:

2.4 SEISMIC HAZARD:

The first of the three main components is the Hazard Module, which involves determining the potential of a seismic hazard in quantitative terms. It incorporates historic information such as magnitude, frequency and location of past seismic events as well as scientific information to evaluate the probability of seismic shaking exceeding a certain magnitude during a certain time interval. Seismic hazard can be expressed as maximum acceleration, velocity or displacement (Kythreoti, 2002). These maximum values are attributed as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Peak Ground Displacement (PGD) respectively. The ground shaking may trigger landslides, fires, tsunamis or liquefaction but these effects will not be considered in this study.

The evaluation of Seismic Hazard at a given location can be achieved by either using a Deterministic Approach or a Probabilistic Approach. The detailed description of the two approaches and the differences between the two is presented below:

2.4.1 DETERMINISTIC SEISMIC HAZARD ASSESSMENT:

Deterministic Seismic Hazard Assessment (DSHA) gives ground motion at a given site due to one or a series of seismic events due to specified seismic sources. The seismic event that is selected for the analysis is generally the maximum magnitude earthquake occurred in the past, without any regard to its probability of occurrence. This type of hazard assessment aims to identify and model the worst possible outcome due to an earthquake (Kythreoti, 2002). DSHA is used for assessing seismic hazard to specific structures like dams, power plants, nuclear reactors etc.

The first step in this process is to identify major seismic source in the region of interest. After that, the nearest fault to the specific site is selected and maximum potential earthquake is selected either by using historical data or by examining the size and nature of the fault (Margottini, 1992). The earthquake is assumed to occur at a point along the fault that is closest to the specified site. The ground motion at the given site due to the event can be calculated using relevant attenuation relationship. This method is considered to be adequate for the hazard assessment of a given site or structure. But the location and characteristics of faults in a given region is not always known precisely and the use of maximum intensity of earthquake might give results that are over-conservative.

2.4.2 PROBABILISTIC SEISMIC HAZARD ASSESSMENT:

Probabilistic Seismic Hazard Analysis (PSHA) involves a detailed probabilistic analysis of all the major seismic sources and magnitudes in a given region. PSHA results in a probabilistic description of seismic hazard using hazard curves. A hazard curve is the relationship between the probability of exceedence and seismic hazard (ground motion) for a specified time interval, usually one year. The probability of exceedence is therefore termed as Annual Rate of Exceedence (ARE). A typical seismic hazard curve is shown below, reproduced from Ahmad, (2008):

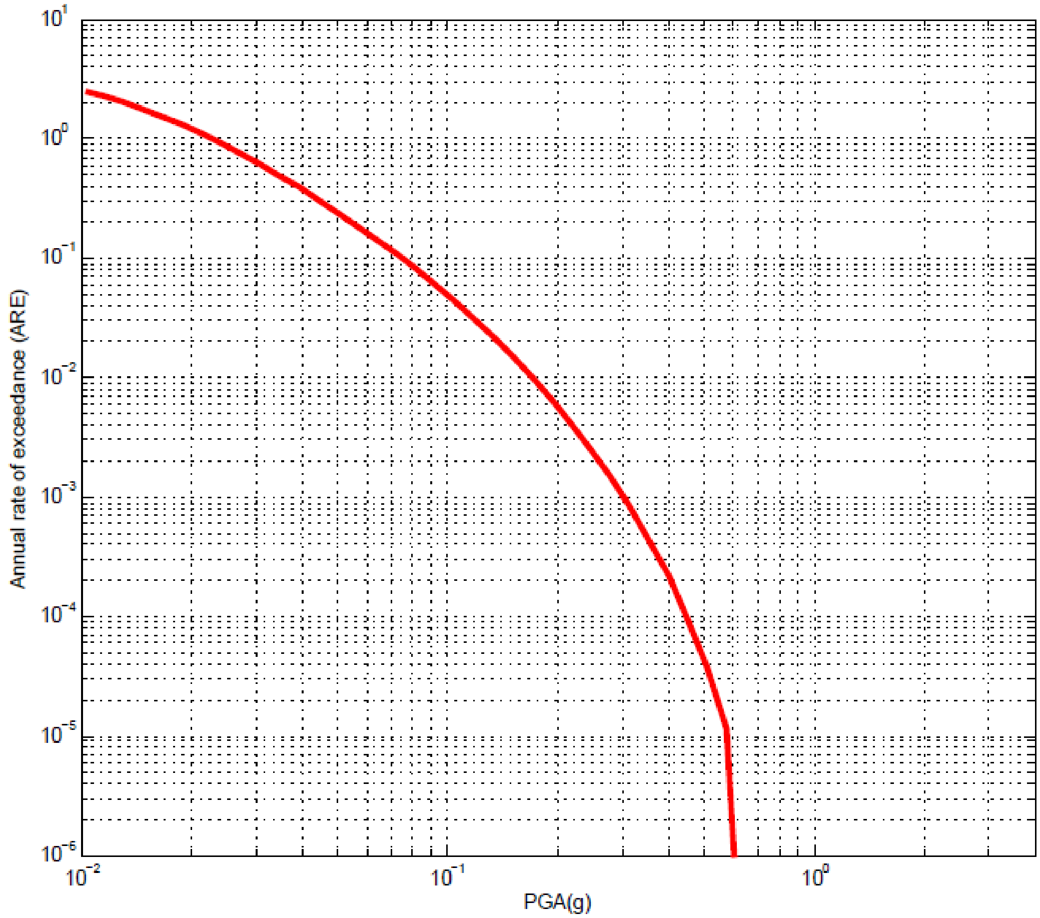


Figure 2.2 A typical Seismic Hazard Curve, after Ahmed, 2008.

PSHA incorporates all possible combinations of earthquake magnitudes and distances, for all seismic sources in a given region. DSHA is a subset of PSHA and PSHA includes the maximum magnitude earthquake with a certain probability assigned to it (Thenhaus and Campbell, 2003).

McGuire (2001) suggests that the choice of seismic hazard assessment should be based on the intended end use of the results. In any given scenario, the results from the seismic hazard assessment will be used for some sort of decision making. These decisions might be related to the selection of design and retrofitting policies, levels of insurance for earthquake losses, training and planning for emergency responses, plans for long-term earthquake recovery and rehabilitation etc.

McGuire also argues that PSHA is suitable for quantitative decision making while DSHA is more suitable for qualitative decision making. The choice of seismic hazard assessment based on the end use is summarized in the table below:

Decision to be taken	**Predominant Approach**
Seismic Design levels	Probabilistic Approach
Retrofit design	Probabilistic Approach
Insurance/Reinsurance	Probabilistic Approach
Long term recovery plans (local)	Deterministic Approach
Long term recovery plans (regional)	Probabilistic Approach
Training and plans for emergency response	Deterministic Approach

Table 2.1:Examples of Earthquake Decisions, after McGuire (2001)

From the above discussion, we conclude that Probabilistic Approach for Seismic Hazard Analysis is more suitable for Earthquake Loss Estimation studies.

The following section discusses in detail the PSHA methodology and its different components:

2.4.3 MODERN PSHA METHODOLOGY AND ITS COMPONENTS:

Cornell (1968) is considered to be the pioneer of the subject of PSHA (Kythreoti, 2002). The modern use of PSHA methodology is primarily based upon his work. Thenhaus and Campbell (2003) summarized the PSHA method as the solution of the following expression of the total probability theorem:

$$\lambda\,[X \geq x] = \sum_{Sources\ i} v_i \int_{M_o}^{M_{max}} \int_{R|M} P[X \geq x|M,R] f_M(m) f_{R|M}(r|m)\, dr\, dm \qquad (2.3)$$

Where:

$\lambda\ [X \geq x]$ is the annual frequency that the ground motion at a site exceeds the chosen level x.

v_i is the annual earthquake occurrence rate for seismic source i.

M_o is the minimum magnitude of engineering significance for the seismic source.

M_{max} is the maximum magnitude for the seismic source.

$P[X \geq x|M,R]$ is the conditional probability of ground motion exceeding a given magnitude M and distance R.

$f_M(m)$ and $f_{R|M}(r|m)$ are the probability density functions for earthquake magnitude and distance from the source to site distance respectively.

In practice, Equation 2.3 is solved for every seismic source i (Thenhaus and Campbell, 2003). The probability of ground motion exceeding a chosen level x is given by the following equation:

$$P[X \geq x] = 1 - e^{(-t\lambda[X \geq x])} \qquad (2.4)$$

Cornell (1968) proposed the following steps for PSHA:

1) Identification of seismic sources in the region of interest. These seismic sources might be seismically active faults or areas of uniform seismicity in case the fault structure and seismic characteristics are not very well known.
2) Development of models for earthquake recurrence rates of the identified sources. This model describes the chances of earthquake occurrence within each source during a specified time interval.
3) Development of attenuation relationships to predict the ground motion at a given site some distance away from the source of earthquake. These attenuation relationships relate ground motion parameters (PGA, PGV, PGD etc) to source site distance.
4) Finding the probability of ground motion occurrence at a site due to all possible seismic sources. This step integrates the effects of different earthquake events at different distances from the studied site and determines the probability of ground motion exceeding a certain level.

The Flow chart of PSHA methodology is given below, reproduced from Thenhaus and Campbell (2003):

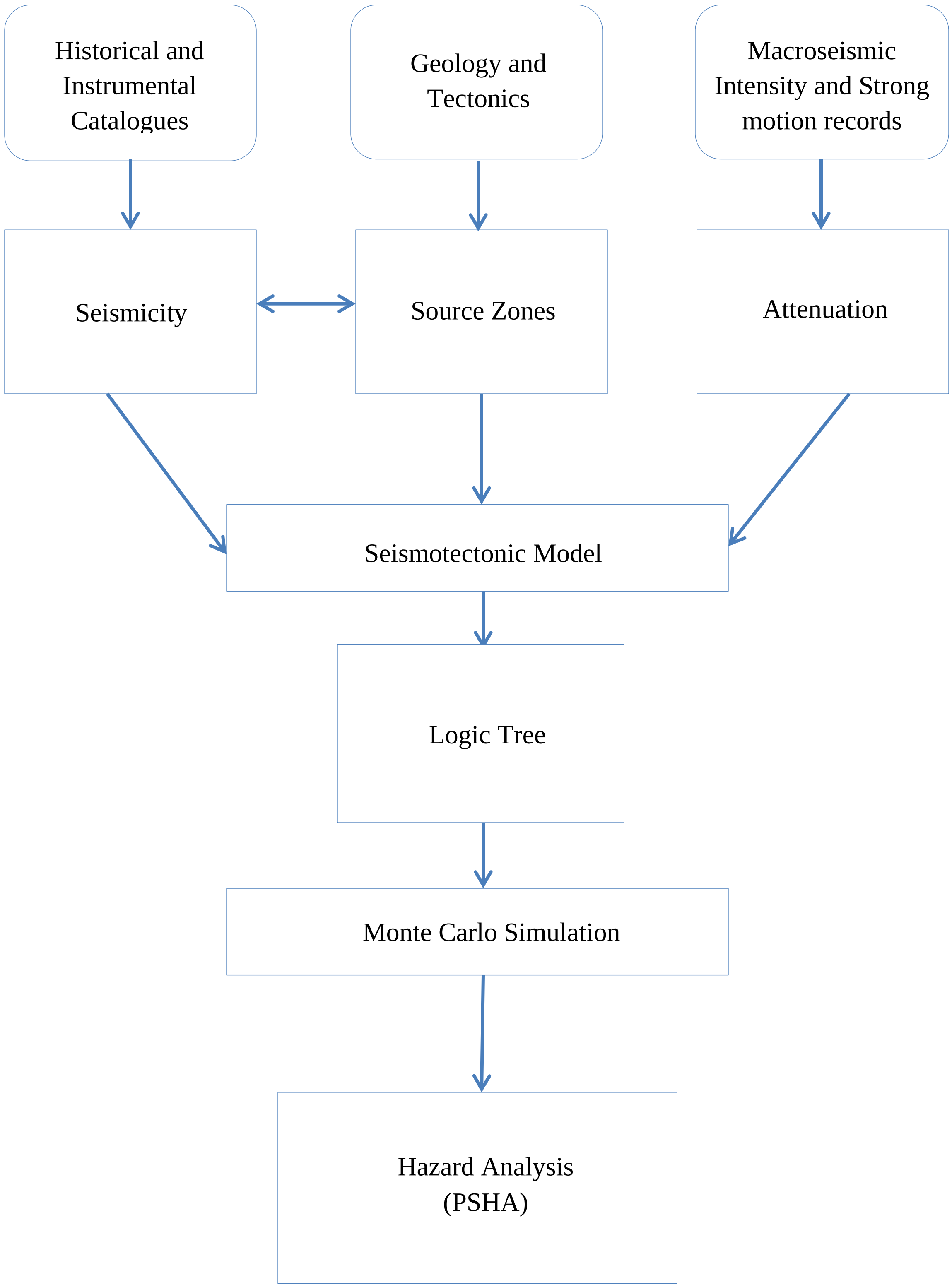


Figure 2.3: PSHA methodology Flowchart, reproduced from Thenhaus and Campbell

The steps involved in the Probabilistic Seismic Hazard Assessment are described below:

1) Identification of Seismic sources in the area:

The very first step in the PSHA method is the identification of all the potential seismic sources. This identification is necessary because PSHA requires source to site distance and the magnitude of the earthquake. The source to site distance is taken from the epicenter of the probable earthquake to the site under consideration. Earthquake sources can be identified as linear faults or seismic source zones. In areas where location and seismic characteristics of faults are well known, the seismic sources are defined as linear features representing the fault. The probable earthquakes for Probabilistic Seismic Hazard Analysis are located along this line (fault). However, if earthquake faults and their characteristics are not well known in the area of interest, the seismic source interpretations are not unique (Thenhaus 1983, 1986) and the seismic sources are defined as regions of uniform seismicity. These regions depict a cluster of past earthquake occurrences and are essentially a combination of multiple faults. This system of faults can be considered as a source zone and the seismicity can be assumed to be roughly uniform within the boundaries of the system. Identification of the seismic source zones can be done by geographically delineating seismic source zones and seismically active faults (Thenhaus and Campbell, 2003). The defined locations and identified seismicity characteristics of the seismic sources constitute the Seismo-tectonic model.

Although differences in seismicity and geology may exist between different area-sources but seismicity within an area-source is considered equally distributed. (PMD- NORSAR, 2007). This assumption allows the treatment of seismicity within a zone as uniform. However, the differences between different area-sources causes the PSHA to give higher values of ground motion in locations that are near to the area-sources (Abrahamson, 2006).

2) Earthquake Recurrence Frequency:

The earthquake recurrence relationships define the frequency with which the earthquakes are expected to occur for each seismic source identified in the previous step. This step is an important part of PSHA whereas it is not included in DSHA because only DSHA considers only one scenario earthquake and then simulates it to find the seismic hazard at the site under consideration. Earthquake Recurrence Frequency relationships are developed by performing a statistical analysis of catalogues of earthquakes for each area. The Earthquake catalogues are of two types:

- **Instrumental Catalogues:** These catalogues are records of earthquakes obtained through instrumental detection of earthquakes. The Instrumental earthquake catalogues for 20th century are almost complete due to different advancements in earthquake detection and measurement techniques and instruments (Coburn and Spence, 2002). World Wide Standard Seismograph Network was founded in 1960s with an aim to provide standardized seismographic stations around the world, which greatly improved the accuracy of Instrumental Catalogues.
- **Historical Catalogues:** Instrumental catalogues contain information for the time that is relatively recent as compared to the geological timescale of seismic activity. Historical catalogues are difficult to compile with certainty due to reliance on secondary sources of information (Coburn and Spence, 2002).

The primary equation for earthquake recurrence relationship is the Gutenberg-Richter relationship (Gutenberg and Richter, 1954):

$$\log N(m) = a - bm \tag{2.5}$$

Where:

$N(m)$ is the annual number of earthquakes having a magnitude equal to or greater than m, and a and b are constants for the seismic source determined from the statistical analysis of historical records of the sources.

The basic assumption in developing an earthquake recurrence relationship is that the system of faults follows the Gutenberg-Richter power law distribution up to the maximum magnitude.

Although the Gutenberg-Richter relationship covers an infinite range of magnitudes but it is common to disregard very small earthquakes that have very little significance from engineering point of view and that are not capable of producing significant damage. For instance, all earthquakes having magnitude smaller than a certain magnitude M_o may be neglected. In the same way, maximum magnitude for a seismic source should be determined by studying its seismicity in case of area sources and length in case of faults. A relationship between fault length and magnitude can be used to determine maximum magnitude. Wells and Coppersmith (1994) gave such relationships between fault length and magnitude. The equations are:

$$\log(\mathrm{SLR}) = -3.22 + 0.69\ \mathrm{Mw} \tag{2.6}$$

$$\log(\mathrm{RLD}) = -2.44 + 0.59\ \mathrm{Mw} \tag{2.7}$$

This modified Gutenberg-Richter relationships with lower and upper bounds is known as the truncated Gutenberg-Richter recurrence relationship. The lower limit on the magnitude reduces the calculations required to assess the probabilistic seismic hazard but at the same time introduces some inaccuracies because an earthquake with small magnitude occurring near the site of interest may cause more damage than the earthquake with higher magnitude and higher source to site distance. The exclusion of these low magnitude earthquakes might produce underestimated hazard results. On the other hand, the use of maximum magnitude also introduces inaccuracies in the PSHA process. The high magnitude will result in higher levels of ground motion near the area-source zones as the seismicity is uniformly distributed in these zones. This will make the PSHA results overestimated.

Earthquake recurrence relationships assume Poisson arrival times in PSHA methodology. This means that the probability that an earthquake will produce ground motion equal to or greater than the specified value is independent of occurrence of other earthquake events (PMD-NORSAR, 2007).

3) Attenuation relationships:

Attenuation relationships or Ground motion prediction equations (GMPEs) are empirical relationships to estimate the strength of ground motion reaching the site of interest due to a specified earthquake event occurring at some distance from the site of interest. Attenuation relations relate the ground motion parameters to the distance between the source of earthquake and the site under study. The rate with which the ground motion decays is dependent upon the magnitude of the earthquake that generated the ground motion (Douglas, 2003). The analysis of ground motion data of different earthquakes also tells us that the decay rate of ground motion also depends upon the distance from the source. For an attenuation relationship to function properly, it is important that the seismic source should be characterized according to its fault rupturing mechanism including depth to top and bottom of rupture, fault dip and style (Strike-slip, normal or reverse) etc. (Thenhaus and Campbell, 2003). A wide range of attenuation relationships are available and are used in the PSHA process (Campbell, 1985).

Different attenuation relationships have been derived for various parts of the world. Derivation of an attenuation relationship for a specific part of the world requires a large set of strong motion records and detailed geologic information of the area including the tectonic environment of the region. From the above statement, it follows that development of an attenuation relationship requires a very dense network of seismographs. Unfortunately, no such dense network exists in the study region and therefore no attenuation relationship exists for the region. However, attenuation relationships derived for other regions of the world can be used in the study region with reasonable accuracy. Chapter 3 covers in detail the use of attenuation relationship in the study region.

4) Ground motion probabilities:

The last step in PSHA method is to calculate the probabilities of ground motion equaling or exceeding a certain magnitude for all sources at the site of interest. Equations 2.3 and 2.4 are used to calculate the probabilities. The result of this part is generally a hazard map of the area showing the intensity of ground shaking hazard at the site of interest due to different seismic sources with a certain probability of exceedence in a given time interval. These hazard maps can be very important for use in different engineering applications such as development of seismic zoning maps for building codes, selecting design values for large structures like dams, power plants etc.

Uncertainties in PSHA method:

Uncertainties in PSHA method can have a significant effect on the results of PSHA. Therefore, it is important to cater for these uncertainties. These uncertainties are divided into two classes; Aleatory variability and Epistemic variability (SSHAC, 1997). The details of these uncertainties are discussed below:

- **Aleatory uncertainty:** The word Aleatory means “depending on the throw of a dice” and is derived from Latin “aleator”, meaning “a dice player” (Oxford Online Dictionary). This type of uncertainty depends upon uncertain events and comes from the data used in the PSHA. This generally includes randomness associated with the estimation of a certain parameter such as magnitude, location etc. of an earthquake event. This type of uncertainty is catered for directly by mathematical integration (Thenhaus and Campbell, 2003).
- **Epistemic uncertainty:** The word Epistemic means “relating to knowledge and its validity” and is derived from Greek “epistemes”, meaning “Knowledge” (Oxford Online Dictionary). This type of uncertainty comes from the lack of complete knowledge about the models used to predict different parameters. This type of uncertainty is taken care of by using a model that includes a logic tree to incorporate multiple hypotheses (Thenhaus and Campbell, 2003)

2.4.4 COMPUTER CODES FOR PSHA:

A number of software codes are available commercially for Probabilistic Seismic Hazard Assessment. Some of them are publicly available and are free to use, while others are distributed commercially. Some of the codes might not be very user friendly because they are primarily the result of research and development efforts and are more focused on the use of software rather than the end users.

The following section deals with a brief description of these software and their key characteristics:

1) FRISK 88M™ :

FRISK 88M™ Version 2.05 was developed by Risk Engineering Inc. It models point sources by default but can also model area sources depending upon the user specified length to width ratio of the rupture. The location and depth of hypocenter are uniformly distributed. This software has the capability to model faults as three dimensional (3d) sources instead of linear elements. A logic tree structure is present in the software model which takes care of the epistemic variability in the modeling process. The inputs into the program require that the user must have background knowledge about the subject of earthquake engineering and seismology.

2) EZ-FRISK (Robin McGuire):

EZ-FRISK was developed by Risk Engineering Inc. By default it models point sources but can also model area sources. Hypocenter depth can be fixed or random, according to the choice made by the user. The location and depth of the hypocenter are uniformly distributed. This program was originally developed for PSHA of specific sites but newer versions contain a gridded-seismicity module that can be used for PSHA at regional level.

3) OpenSHA (U.S Geological Survey):

OpenSHA (Open Seismic Hazard Assessment) was developed by United States Geological Survey. OpenSHA can model earthquake sources as points, lines and area sources. This software accommodates aleatory variability in the modeling. Rupture can move along or down the dip, but is limited to the fault plane.

4) CRISIS (2007):

CRISIS was developed at National Autonomous University of Mexico in 2007 to compute seismic hazard. It is a user friendly software with easy to use input procedures and GUI (Graphical User Interface). This software can model earthquake sources as points, lines and area sources. The attenuation relationships are built-in into the software and in addition, the user can define his/her custom attenuation relationship as well.

The above section discussed a number of software available for the Probabilistic Seismic Hazard Assessment method. It must be kept in mind that these are not the only ones available in the market. The selection of a suitable software from a list of available software requires that the user has a clear idea of the requirements and restrictions of the task and the software. As obvious from the above discussion, each software is specific to some conditions. Some software products allow the use of custom attenuation relationships while others do not. Some software products have the ability to generate maps as output while others simply generate hazard curves. The end user must know what he/she requires and in what form?

2.4.5 PREVIOUS PSHA STUDIES IN THE PAKISTAN:

Before the devastating earthquake of 2005, very little attention was given to seismic hazard assessment in Pakistan. The 2005 earthquake proved to be very disastrous in terms of economic and human losses and it was inevitable that detailed hazard assessment should be done for future earthquake risk reduction and for developing a standard Building Code of Pakistan (BCP). Several studies were done for the purpose of Probabilistic Seismic Hazard Assessment in the region of Pakistan. This section discusses various PSHA studies carried out in the region and the methodology used for the Probabilistic Seismic Hazard Assessment in the study region of Pakistan.

Following studies are not the only ones performed for PSHA in Pakistan:

1) **PSHA study by Mona Lisa et al. for Potowar region.**
2) **PMD NORSAR PSHA study for Pakistan and Azad Jammu and Kashmir.**
3) **PSHA study by NESPAK for development of BCP 2007.**
4) **PSHA study for Pakistan by Saeed Zaman, Teraphan Ornthammarath and Pennung Warnitchai et al. in 2012.**

The detailed description of the above mentioned studies is as follows:

1) **Mona Lisa et al. study for Potowar region:**

   Potowar region extends from the capital of Pakistan, Islamabad to the city of Peshawar, the provincial capital of KPK province. The area was divided into four seismotectonic zones. Gutenberg-Richter model was used for determining the earthquake recurrence frequency from the earthquake catalogue consisting of 813 earthquake events for the period of 1904-2002. Due to non-availability of a specific attenuation relationship for Pakistan, the attenuation relationships of Ambrasseys et al (1996) and Boore et al. (1997) were utilized. EZ-FRISK software was used for the Probabilistic Seismic Hazard Analysis. The author concluded that the sites of Islamabad, Rawalpindi and Peshawar are very hazardous due to high population densities in the region and poor quality of construction.

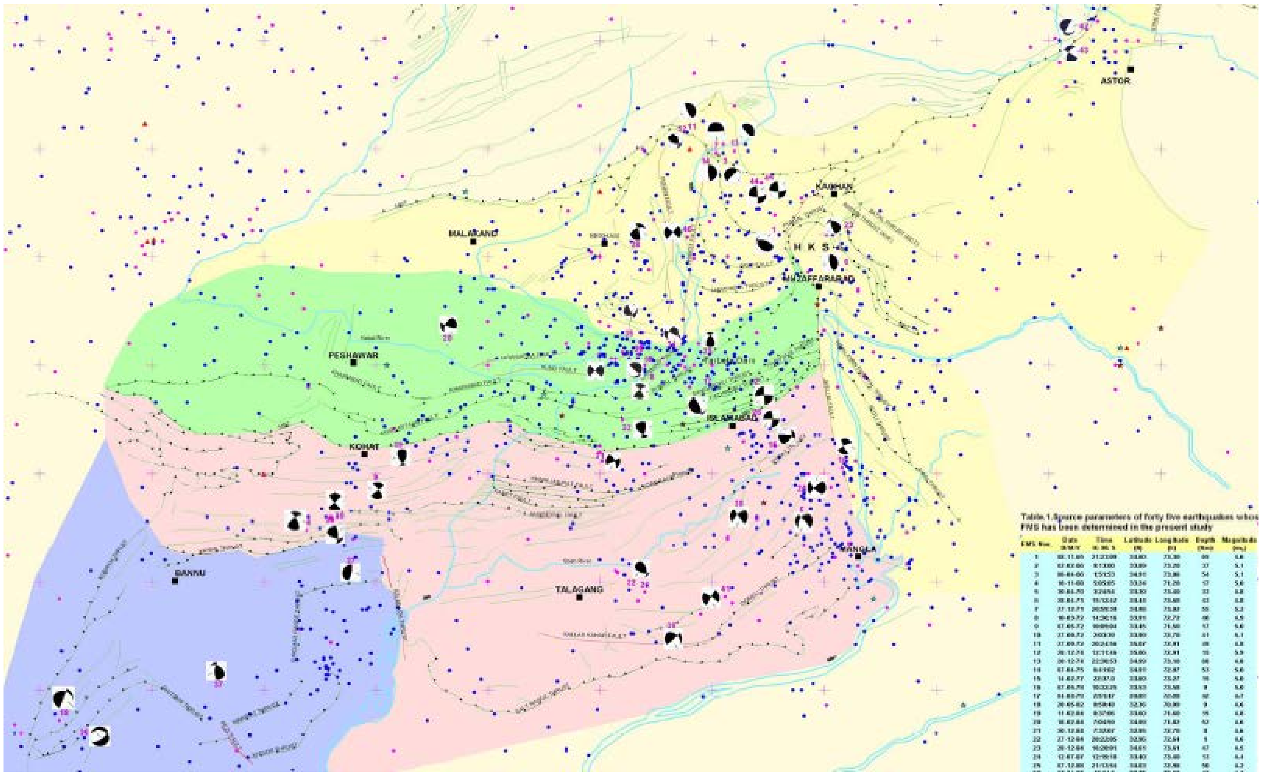


Figure 2.4: Siesmic Zonation map from Mona Liza et al. (2005)

2) **PMD NORSAR PSHA study for Pakistan and Azad Jammu and Kashmir:**

Pakistan Meteorological Department (PMD) and Norwegian Seismic Array (NORSAR) performed a Probabilistic Seismic Hazard Assessment of Pakistan. CRISIS (Ordaz et al, 2003) was utilized in the study. The region was divided into 19 zones including some portions of the neighboring countries of Iran, Afghanistan and India based on the knowledge about seismicity of the region and known fault systems. The basis for this zonation is the basic assumption that seismicity within one zone is uniformly distributed. The distribution of the region into zones is shown in the figure below:

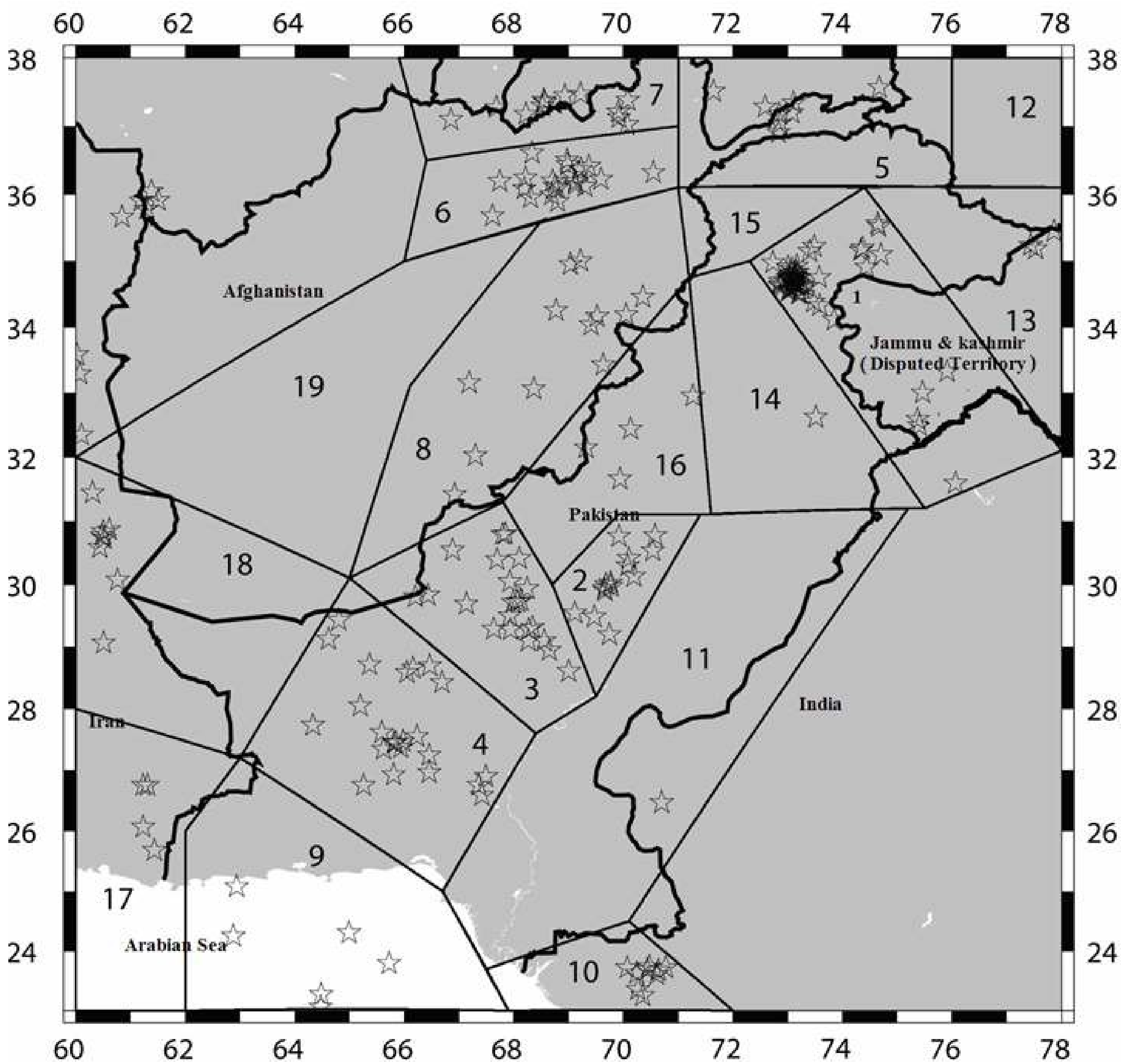


Figure 2.5: Seismic zones of Pakistan from PMD-NORSAR (2007)

A large catalogue of earthquakes using the data from PMD and other International sources was developed. Gutenberg-Richter model was utilized for earthquake recurrence frequency determination. A large number of earthquakes in the catalogue were shallow earthquakes. To take this into account, the attenuation relationship of Ambraseys et al. (2005) was modified and used in the CRISIS software. The hazard map obtained as a result is shown in the figure below:

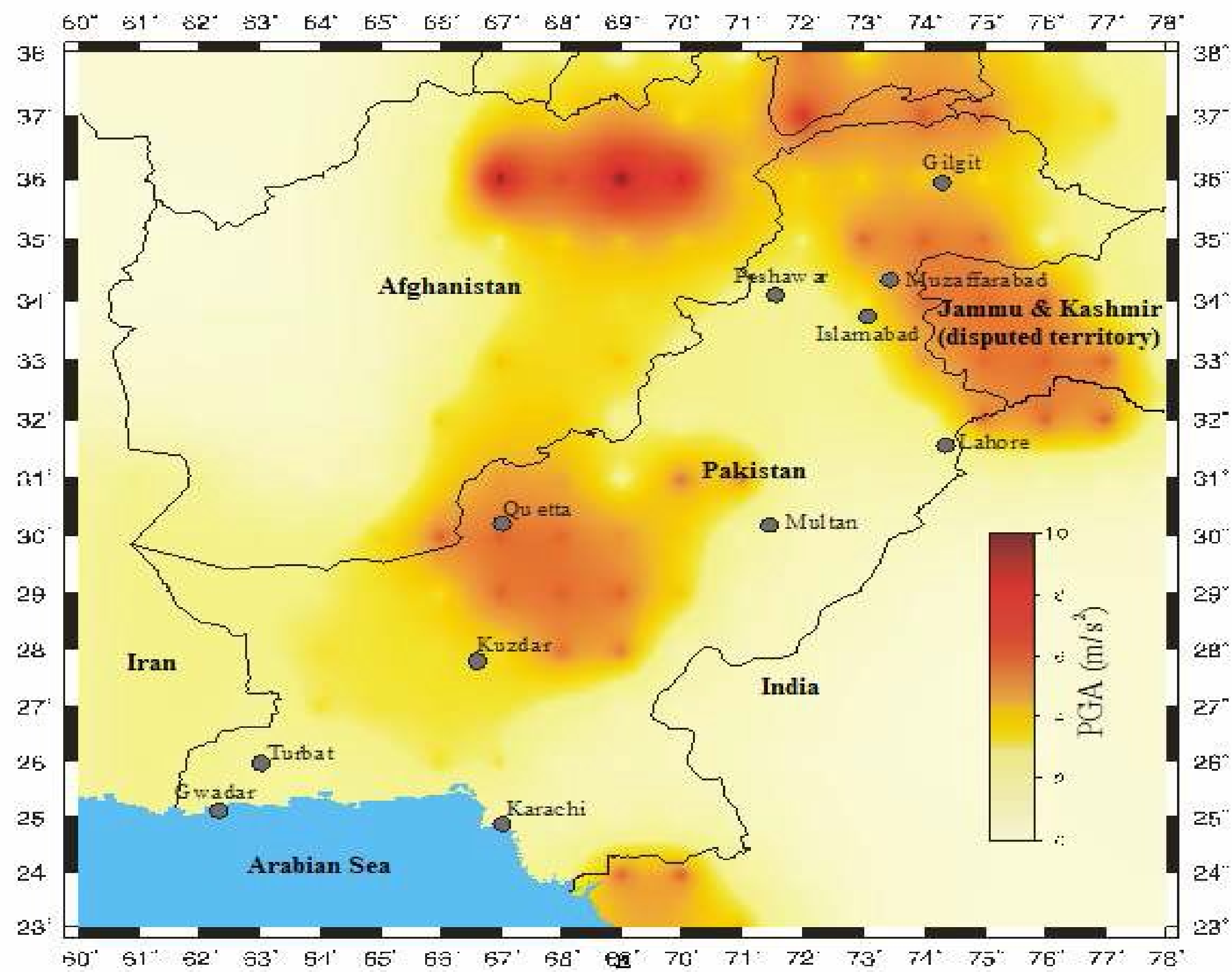


Figure 2.6: Seismic hazard map of Pakistan prepared for PGA for 500 years return period.

3) PSHA study by NESPAK for BCP, 2007:

In 2007, National Engineering Services of Pakistan (NESPAK) conducted a PSHA study for seismic zonation of Pakistan. NESPAK utilized instrumental earthquake catalogues that had earthquake event data since 1904. Prior to 1904, the data was available in historical catalogues in the form of published reports and literatures. NESPAK divided the area into 17 area source zones. NESPAK used Gutenberg-Richter model for determining the Earthquake Recurrence Relationship. Since the unavailability of a large set of strong motion recordings, there was no attenuation relationship for the study region, NESPAK used Boore et al. (1997) for attenuation of ground motion. The analysis was carried out using EZ-FRISK software, already explained in the preceding section. The result was obtained in the form of a seismic hazard map, on the basis of which Pakistan was divided in to 5 seismic zones. A detailed figure showing the seismic zonation of Pakistan, reproduced from the Building Code of Pakistan (BCP 2007) follows:

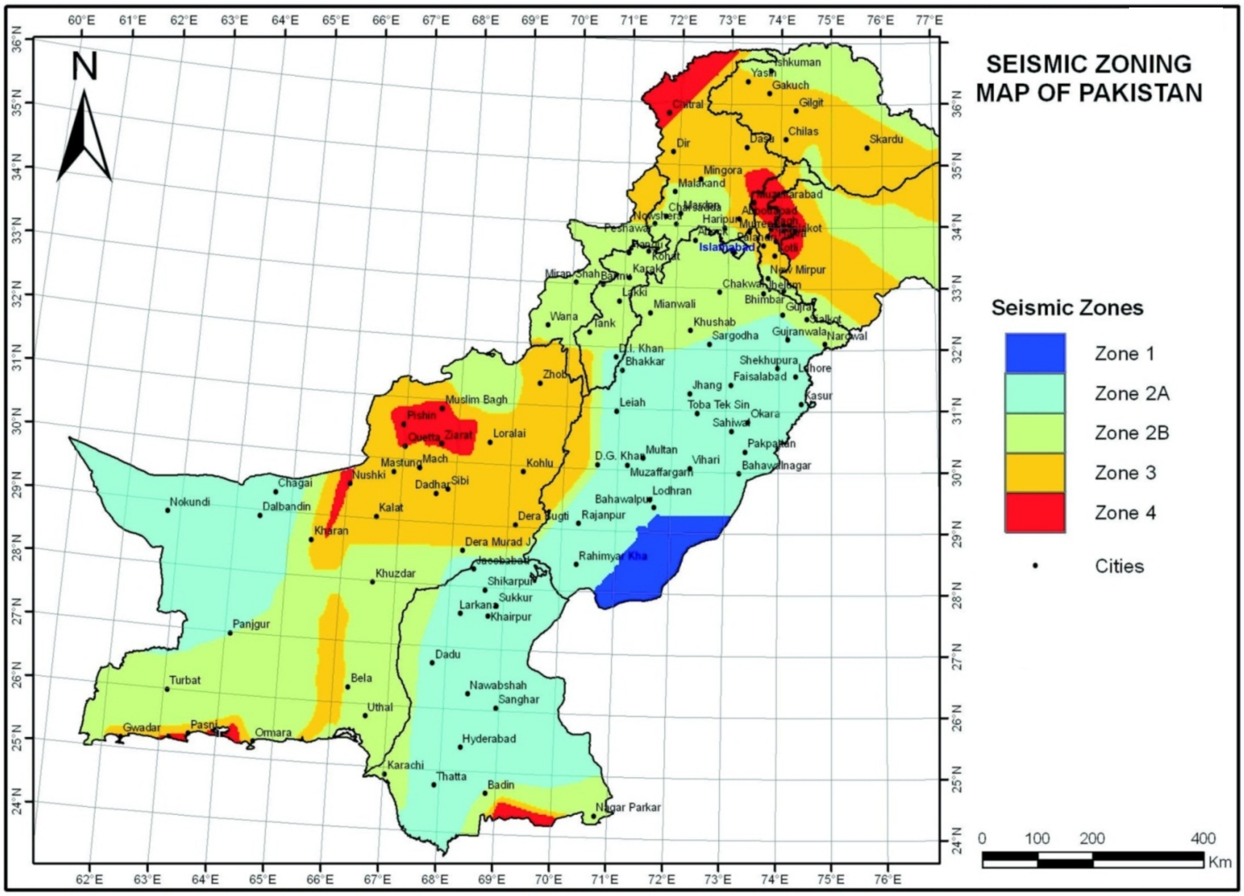


Figure 2.7: Seismic zonation map for Pakistan, NESPAK , BCP (2007)

4) **PSHA study for Pakistan by Saeed Zaman, Teraphan Ornthammarath and Pennung Warnitchai et al. in 2012:**

In 2012, Saeed Zaman, a Doctoral student at the Asian Institute of Technology (AIT), Thailand conducted a PSHA study for Pakistan using the same methodology as used for U.S National Seismic Hazard Maps. It also employed Logic tree Structures for accommodating Epistemic Uncertainty. A new earthquake catalogue was compiled for the study by combining 5 different earthquake catalogues. The probability of earthquake was assumed to be a Poisson Distribution, which means that the earthquake events were considered to be independent of each other. Therefore, dependent events like aftershocks and foreshocks were eliminated from the earthquake catalogue, a process known as declustering (Zaman, Ornthammarath, Warnitchai, 2012). The final catalogue contained

5911 earthquake events from 1902 to 2009. The earthquake recurrence frequency was modeled by Gutenberg-Richter model. The analysis was performed by using the USGS PSHA software. The results were obtained in the form of Hazard Maps. These results were compared with the hazard maps prepared by NESPAK for BCP (2007) and GSHAP (1999).

2.4.6 USE OF PSHA IN LOSS ASSESSMENT:

The above section dealt with the detailed discussion on the seismic hazard which is the first module of Earthquake Loss Assessment model. However, the methodology discussed in the previous section is used to evaluate the seismic hazard of future earthquakes. The application of PSHA in the process of Loss Assessment is discussed below:

1) **Identification of seismic sources:**

As discussed above, the first step in PSHA methodology is to identify the location and seismicity characteristics of seismic sources. In case of Earthquake Loss Assessment, we do not need to identify potential faults and area sources beforehand. Earthquakes generally occur on plate boundaries or on known faults. Post-Earthquake Loss Assessment requires only the location and magnitude of the earthquake that has already occurred. The information about the location and magnitude of an earthquake is published regularly by different agencies like USGS (United States Geological Survey), JMA (Japanese Meteorological Agency), PMD (Pakistan Meteorological Department) and several others. However, these measurements contain some errors which can affect the end results of an Earthquake Loss Assessment. The following section deals with these uncertainties.

The uncertainties associated with the measurements of an earthquake are:

- Uncertainty in epicenter location.
- Uncertainty in magnitude determination.

Uncertainties in epicenter location are influenced by three factors (Pavlis, 1986):

1) Error in measuring the arrival time of seismic waves.
2) Error in modeling the travel times.
3) Error due to assuming linearity of earthquake location problem.

Errors in arrival time measurements can be attributed to noise in the seismic signal and dominant frequency of the signal. Errors in modeling depend primarily upon the seismic velocity model used for epicenter location. The last type of uncertainty is only valid for linearized and least square methods of determining the epicenter (Husen and Hardebeck, 2010). The details of these methods lie in the domain of seismology and will not be discussed here.

2) **Earthquake catalogue:**

The second step in PSHA methodology was to develop an earthquake recurrence frequency relationship. This relationship was used to evaluate the possibility of an earthquake occurrence by studying historical and instrumental catalogues. However, in Earthquake Loss Assessment methodology, we do not need to define the recurrence relationship because it estimates the losses after the earthquake. Instead, we develop a synthetic earthquake catalogue to account for the uncertainties of magnitude and location of an earthquake. The development of this catalogue is achieved through the use of Monte-Carlo method which randomizes the errors in the earthquake location and magnitude.

Use of Monte-Carlo simulation method for PSHA:

The Monte-Carlo simulation method has been used previously for PSHA by Musson (1999) for determination of design earthquakes in seismic hazard analysis, by Musson (2000) for seismic hazard analysis of the U.K, by Shapira (1983) for earthquake risk estimation and by Johnson and Koyanagi (1988) for seismic hazard analysis of Hawaii. This method is based upon the basic approach of PSHA of Cornell (1968) but follows a stochastic approach by generating synthetic earthquake catalogue through the use of Monte-Carlo simulations. This method handles uncertainties in the earthquake measurement very well. The controlled use of random numbers is used for developing the synthetic catalogue. This process is straight forward and easy to understand but can be very slow computationally if large number of simulations are used. An example of Monte-Carlo simulation is reproduced below from Musson (2000).

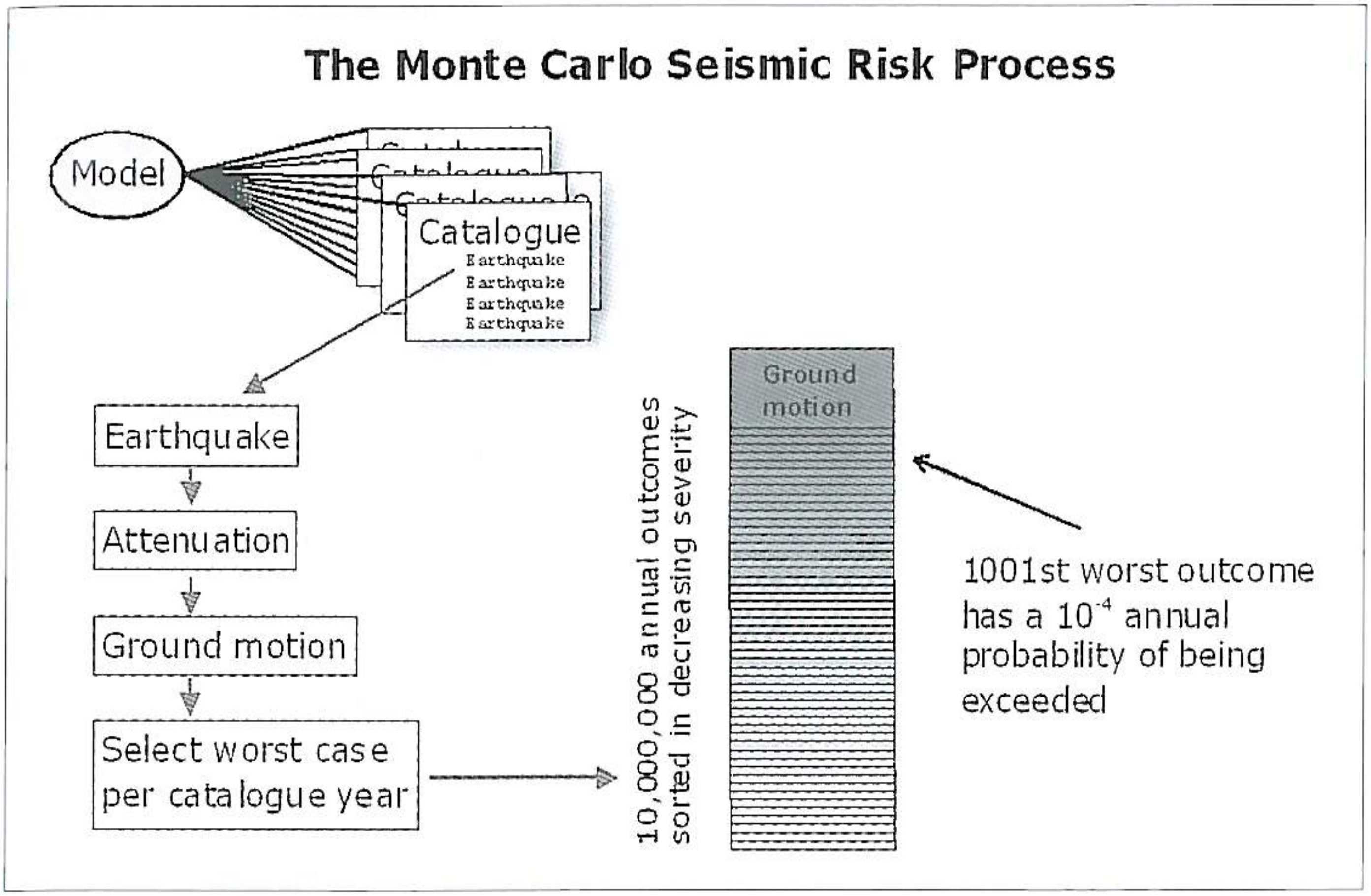


Figure 2.8: Monte Carlo approach in seismic hazard

If sufficiently large number of simulations is used in the Monte-Carlo method, it gives hazard results similar to the approach conventionally used, as suggested by Cornell (1968).

EQRM software developed by Geoscience Australia and MoCaHAZ (Monte-Carlo based Seismic Hazard Assessment) software developed by Stefan Wiemer of ETH, Zurich, Switzerland employ Monte-Carlo simulations for seismic hazard assessment (GEM1 Hazard, Overview of PSHA Software, Technical Report, 2010-2)

3) **Attenuation relationship:**

The earthquake catalogue produced in the previous step is used to determine the level of ground shaking at different locations having different distances from the epicenter. A suitable attenuation relationship is used for this purpose. The area under study is divided into small sectors depending upon the requirement of the study. If the division is finer, the results will be more accurate but the computation time required for running the model will be large. For example, entire provinces, districts, tehsils, Union Councils or neighborhoods can be used as the sectors. In case of neighborhood division, the results will be very accurate and there will be a separate ground shaking measurement for each neighborhood in the area but the computation time will be very high. On the other hand, if the division is made on province level, the time required for calculation will be less but the results might be inaccurate to an inacceptable level. The compromise between computation time and accuracy has to be made keeping in mind the resources available and the aim of the study. The distance between the source and site is taken as the distance between the earthquake epicenter and the geometric centroid of the sector area. This process is repeated for all earthquakes in the synthetic catalogue for all sector areas. The result of this process is a synthetic catalogue of different levels of ground shaking for each sector area.

4) **Probability Calculations:**

The final step in the PSHA methodology was to compute the probabilities of ground shaking equaling or exceeding a specified value, for all sources. In Earthquake Loss Estimation, the probability of exceedence is specified and the level of ground shaking corresponding to that probability is selected for every sector. The result of this step is a hazard map, which shows the level of ground motion at each sector for given probability of exceedence.

2.5 SEISMIC DAMAGE:

The second module of Earthquake Loss Assessment is the damage module. It calculates the damage at each site due to earthquake hazards determined in the previous step. This module determines the vulnerability of infrastructure and human population towards earthquake hazards.

2.5.1 VULNERABILITY:

Vulnerability is defined as the degree of loss to which an element is at risk due to a certain level of hazard (Coburn and Spence, 2002). Seismic Vulnerability is the degree of loss to which a certain element is at risk due to a certain level of seismic hazard (level of ground shaking).Vulnerability of a structure can be measured in many ways, such as the Damage factor, which is defined as the degree of loss in terms of percentage of maximum loss (0 to 100%).

Damage Factor for a group of buildings is called Mean Damage Factor (MDF). Damage Factor is also known as Damage Ratio (DR) or Mean Damage Ratio (MDR) (Kyriakides, 2008). The maximum loss is actually the replacement value or the repair value of completely collapsed structure. So, the damage factor is the ratio of the damage induced to the total cost of the structure. In case of human loss, the damage factor is the ratio of number of people killed to the total population (Coburn and Spence, 2002). The damage module requires detailed information regarding the attributes of the assets at risk. This information is very critical to the damage module, because the accuracy and correctness of this information will be responsible for accurate results, while inaccuracies and incorrect assumptions in this information will induce errors in the results obtained. The level of information is also an important concern, because as the level of information goes finer, the accuracy increases and the cost of developing the database increases as well as the time and capacities required for the development.

Khater, Scawthorn and Johnson (2003) suggest that the damage module require the following information regarding the elements at risk of damage due to a certain level of earthquake hazard:

1) **Location of elements:**

   The location of the elements in the area of interest is an important input. If the exact co-ordinates of an element are known, the soil characteristics at the site can be determined accurately which gives the most accurate results. While on the other hand, if only the province name is known, uniformity of soil and site characteristics will be assumed, and general site characteristics will be used which will not generate very accurate results. However, it must be kept in mind that developing a very detailed and accurate database of elements is a very tiresome job and requires huge finances. Somewhere between these two extremes lies a compromise that is good enough to be used in the model and is light on the pocket as well.

2) **Values at risk:**

   The value of the elements at risk must be known in order to determine the damage from a defined level of earthquake hazard. Vulnerability is generally specified in terms of Damage Factor, which is the ratio of induced damage to the total cost (Value of an element). To convert the DF of a specific element into Damage, we have to multiply it with the value of that particular element. However, collecting information regarding the cost of each element at risk is quite an impossible job. One way of doing this is to calculate the total area of the building, structure or any element and multiply it with per unit cost of construction. Different journals and handbooks publish regularly the unit costs in different regions. In the absence of any other data, unit cost may be obtained from experienced quantity surveyors and construction managers. It should be remembered that the cost of construction may vary from place to place due to availability of cheap materials, labor and other facilities in specific regions.

3) Structure type:

Building codes throughout the world include provisions regarding the design of structures against earthquakes and lateral forces. With the research and development (R&D) activities being carried on in the field of Earthquake Engineering, new techniques have been developed such as base isolation, mass dampers etc. to minimize the loss of infrastructure and human lives. The information about how the structures resist the lateral forces of an earthquake is very important in the damage module. The behavior of each type of structures in an earthquake is different from the other depending upon the mechanism to resist lateral forces of earthquake. Some structure types like Mud houses, unreinforced brick masonry houses are very weak in a seismic event and have a high chance of complete collapse. Other structures like reinforced concrete shear wall, Reinforced concrete frame structures with bracing are quite good against an earthquake and there is an intermediate category as well. The detailed building inventory data must contain information regarding the type and condition of each structure in order to get reasonable results from the damage module.

4) Occupancy/Use:

This factor is specifically related to the human losses induced in an earthquake. The type of building in terms of its usage is also an important factor to be considered in determining the vulnerability of a structure. The occupancy of a structure greatly influences the damage that can occur in case of an earthquake. Residential houses and apartments have less chance of human losses than a crowded cinema or subway station. Moreover, the critical facilities like hospitals and fire stations are designed to resist much larger forces of an earthquake than ordinary structures. In an ideal situation, the use or occupancy of every structure is determined to get the damage induced due to an earthquake, but in real situations this is not possible due to limitations of funds and resources. This information is often described in terms of number of people per house.

Vulnerability curves are used to describe the damage induced due to an earthquake. In the hazard module, the earthquake hazard at each site due to an earthquake event was computed. Vulnerability curve relates the earthquake hazard at each site to the damage induced, through damage ratio. A vulnerability curve describes damage ratio as a function of ground shaking intensity. A typical vulnerability curve is reproduced from Khater, Scawthorn and Johnson (2003):

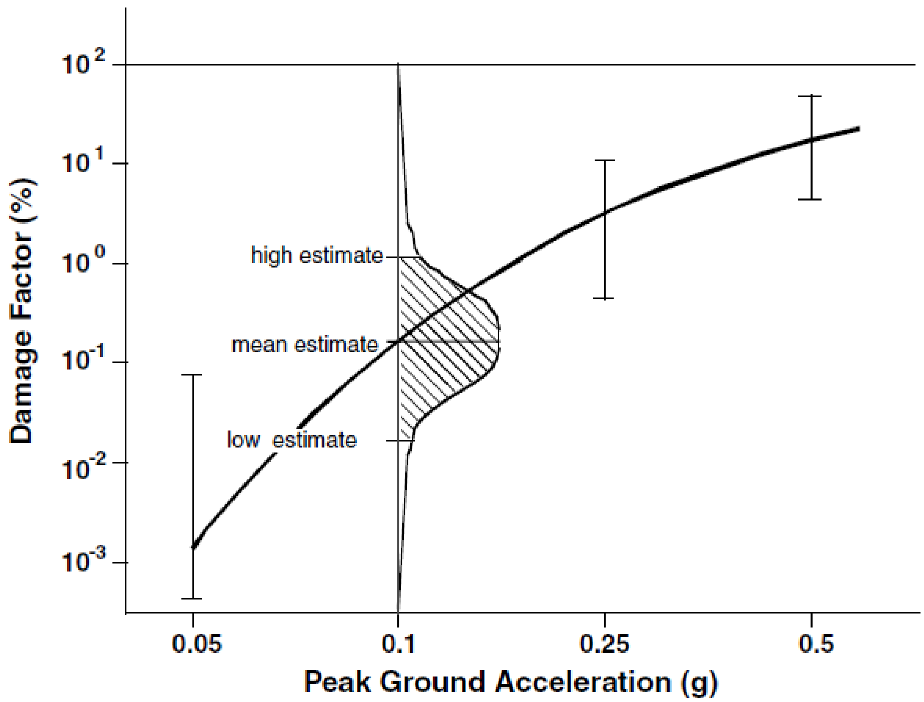


Figure 2.9: A typical Vulnerability curve from Khater, Scawthorn and Johnson (2003)

Another way of describing the damage induced by a certain level of earthquake hazard is by using Fragility curves. While vulnerability curves give the damage ratio corresponding to certain level of earthquake hazard, fragility curves give the probability of some undesirable event (for example, light damage, heavy damage or complete collapse) corresponding to a level of earthquake hazard (Porter, 2003). For example, a fragility curve may give the probability of collapse of a structure corresponding to different levels of ground shaking. Different damage states are defined for a structure that may vary from light, moderate damage to complete collapse of the structure. A separate fragility curve for every damage state is developed. For every value of earthquake hazard (ground shaking), there is a certain probability of occurrence of each damage state. A typical plot of vulnerability and fragility curves is reproduced below from Porter, 2003:

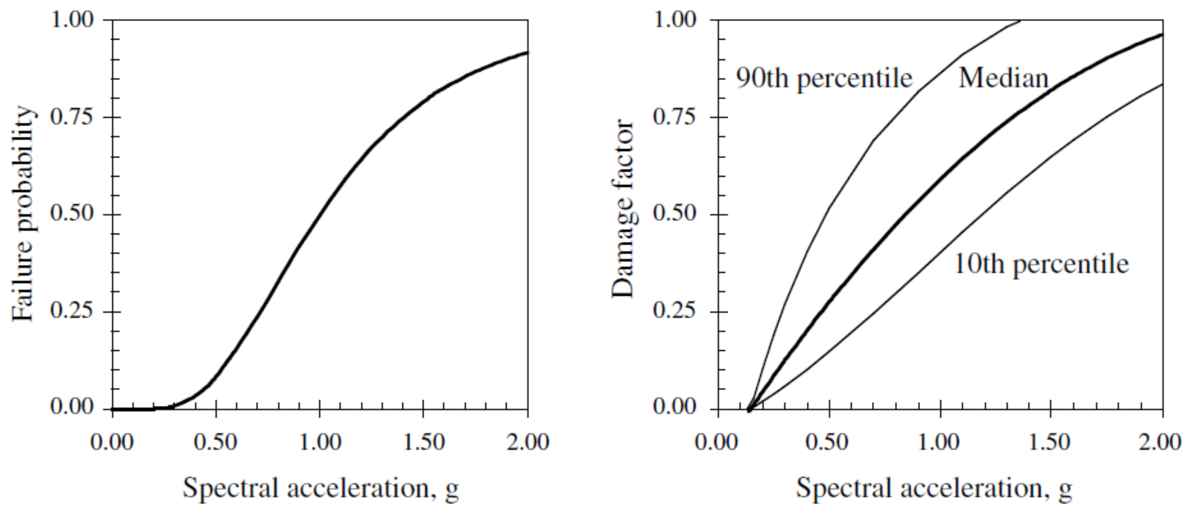


Figure 2.10: A typical Vulnerability (Right) and Fragility (Left) curve from Porter (2003)

Various methods are available for the development of Vulnerability curves. Statistical method, Expert opinion method and Analytical methods are used to generate vulnerability curves (Porter, 2003).

- Statistical method of vulnerability function development is empirical and relies on historical records of earthquake losses and the intensities of ground motion. This approach can be useful only if sufficient data is available on which analysis can be done.
- Expert opinion method requires the estimation of loss or damage by an expert. This method does not require expensive and unavailable data, which makes it more suitable for areas having no historical records of earthquake losses. However, it can generate inaccurate results if the experts have no prior experience of particular structural types and systems. Moreover, this method has not scientific basis on which to test the method.
- Analytical method requires three general steps to develop vulnerability functions. The first step is to carry out the structural analysis of the structures to determine the response of structures in an earthquake. Then the response of structures is entered into component fragility functions to determine their damage states. Finally, the cost of damage of all

components is summed up to obtain the total damage or loss. This procedure is repeated many times for different levels of earthquake intensity to get a vulnerability curve.

Like many other developing countries, surveys were not done to assess the damage after an earthquake due to which there are no historical damage records.

The use of vulnerability functions for the study region is discussed in detail in chapter 3.

2.5.2 BUILDING INVENTORY:

Developing the building inventory database is a very important part of Earthquake Loss Estimation method. Since the earthquake hazard is distributed spatially, the spatial distribution of building inventory must be known in order to obtain acceptable earthquake loss estimates. Good quality statistical information is required for the development of such a database. Kythreoti (2002) had access to such data for Cyprus, which was utilized for Risk Assessment of Cyprus (Khan, 2011). However, un-availability of good quality statistical data is an issue in most of the developing countries including the study region. The census data (of 1998) available for the study region includes the number of housing units classified into either Kuccha (Adobe structures) or Pucca (Masonry or Reinforced Concrete structures). There is no distinction between Masonry and Reinforced concrete structures while the behavior of these structures in an earthquake is significantly different. The number of housing units is projected forward to the current year using the growth rate furnished by the census report. However, this does not completely represent the prevalent situation (Khan, 2011). There are several methods to determine the number and types of buildings.

- One method is to conduct a full scale site survey which is a costly and time consuming process. It also requires a large number of people considering the scale of the study area (i.e.: the whole country).
- Another method to develop building inventory for a region is to use remote sensing data (Satellite imagery and aerial photographs). Several studies have been conducted by using this approach such as Estrada et al. (2000) in Turkey for 1999 Kocaeli earthquake, Yusuf et al. (2002) in India for 2001 Gujarat earthquake and Chiroiu et al. in India for 2001 Bhuj earthquake (Khan, 2011).

The above mentioned methods require too much time and resources. In the absence of both of these, a simple approach is to use the census data (Khan and Qureshi, 2014)

2.6 LOSS MODULE:

The last module of the Earthquake Loss Estimation method calculates earthquake losses and casualties from earthquake damage calculated in the second module.

For calculation of Earthquake economic losses, detailed information regarding the total cost of the structures damaged by the earthquake must be known because the damage of the structures is expressed as percentage of the total cost of structures. The total losses incurred due to an earthquake event also depend upon the constraints imposed by the insurance loss model (Khater, Scawthorn and Johnson, 2003). The detailed estimation of earthquake economic losses involves the input of information regarding the insurance policies and terms. However, collecting that information and creating a database is not an easy task, specially keeping in view the scope of this study. For the purpose of this study, only the total cost of the structures will be incorporated in the loss calculation module.

Casualty estimation is a very complex and uncertain process depending upon a number of factors including the damage level, occupancy rate etc. (Ferreira, Oliveira, and Mota de Sá, 2010). The casualty values vary significantly from one earthquake to other (Coburn and Spence, 2002). Nunez (2000) studied the human casualties data from Izmit earthquake of 1999 and showed that the number of casualties increase with the increase in building damage, as shown in the figure.

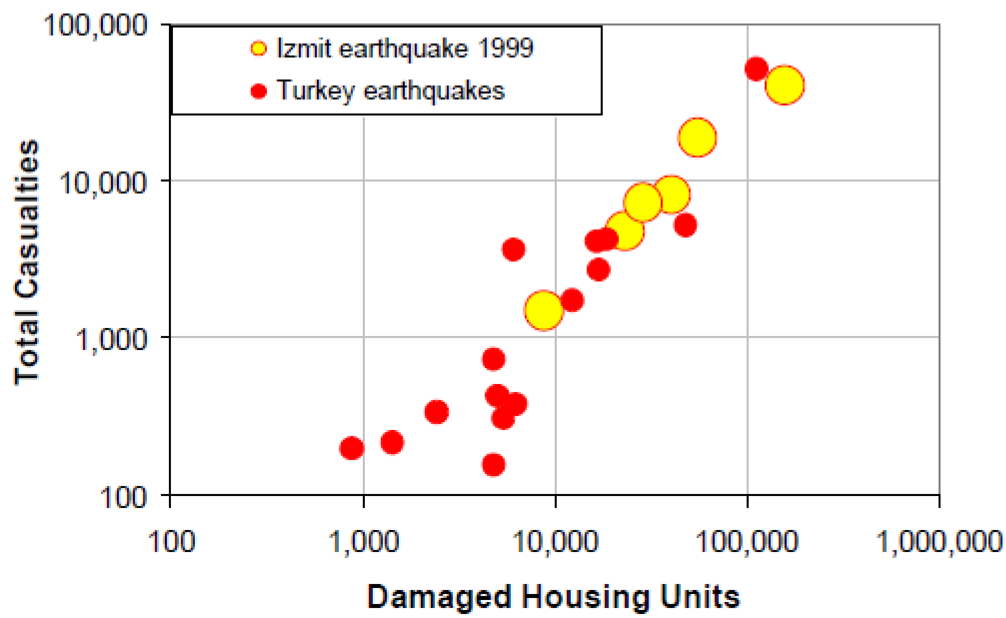


Figure 2.11: Relationship between total casualties and damaged housing units from various earthquakes data ,after Nunez (2000)

In the event of an earthquake, timely estimation of human casualties and injuries can greatly help in rescue and rehabilitation operation. Therefore, it is important to know how much of the population is affected from an earthquake and also the extent of the damage done. For the calculation of Human casualties due to an earthquake, different models are available. Some of these models are discussed below:

- Similar to the economic losses where the mean damage ratio was used to express the economic loss as a percentage of total cost, mean fatality ratio and mean injury ratio are used to describe the number of fatalities and injured people as a percentage of total population. Kythreoti (2002) used this method to develop a relationship between MDR (Mean Damage Ratio) and MIR (Mean Injury Ratio) and MFR (Mean Fatality Ratio) by observing data from past earthquakes. This method however cannot be applied to the study region because of non-availability of detailed reports on historical earthquakes and fatalities.
- The development of HAZUS® by FEMA (Federal Emergency Management Agency) and NIBS (National Institute of Building Sciences) proved to be a major development in the field of earthquake loss assessment. (Whitman et al. 1997). The program is modular which allows users to limit the program to the areas of their interest. The program categories injuries based on whether the injured requires slight medical care, serious medical care or the injured is dead before the arrival of medical personnel. The program contains a default database of built environment (Khater, Scawthorn and Johnson, 2003). However, the built environment in the study region is quite different from the built environment of U.S, for which the software was primarily developed.
- Jaiswal et al. (2009) developed an empirical model for casualty estimation for to be used by USGS. The relationship related the shaking intensity with the number of casualties, based on the analysis of past history. Jaiswal used the relationship for Pakistan but only fatalities were given by the model and no details on the extent of injuries were given (Khan, 2011).

The methods discussed above relate the shaking intensity of an earthquake to the number of injuries and fatalities. However, the number of casualties and injuries are affected by a number of factors such as:

- Damage Levels.
- Occupancy.
- Entrapped occupants.
- Time of the day.
- Rescue capabilities.
- Behavior of people in the event of an earthquake.

2.6.1 CASUALTY MODEL BY COBURN AND SPENCE (1992)

Coburn and Spence proposed a casualty model that takes into consideration the population per building, time of the day, response time, number of people entrapped and building type. Coburn and Spence gave different factors for these attributes. This model can be used for earthquake preparation, rescue and response building measures (Khan, 2011). This model can be applied to the study region by modifying the factors used in the model because the quality and type of structures in the study region is different from that of other parts of the world. Moreover, the population per building is higher especially in rural parts of the study region. In an earthquake, casualties can occur due to a number of reasons such as machinery accidents, heart attacks, fires and landslides triggered by earthquakes etc. (Coburn and Spence, 2002). However, this model only considers the fatalities caused by structural damage due to an earthquake. The casualties due to structural damage are represented by K_s. The number of fatalities due to collapse of any particular building type b, is given by:

$$K_{sb} = D_b \times [M1 \times M2 \times M3 \times \{M4 + M5(1 - M4)\}] \quad (2.8)$$

Where:

D_b is the total number of collapsed buildings of type b.

$M1$ is Population per building.

$M2$ is Occupancy at the time of earthquake.

$M3$ is the number of occupants trapped by the collapse of the structure.

$M4$ is the Mortality at collapse.

$M5$ is the Mortality after the collapse.

Coburn and Spence model is particularly useful for the study region since no historical records of earthquake fatalities exist that could have been used to develop an empirical relation between the shaking intensity and injuries or casualties.

The Coburn and Spence model is discussed in detail in Chapter 4.

2.7 COMPUTER PROGRAMS AVAILABLE FOR ELE:

A variety of software are available worldwide to calculate economic, human and social losses due to earthquakes. A particular software is designed in keeping in mind the parameters of the region in which it is intended to be used. Unfortunately, no such model/software exists specifically for the study region. This section briefly introduces some of the important software available for the purpose of earthquake loss estimation. For detailed description, the reader is advised to read the user manual of each software.

- **CATS:**

  CATS (Consequence Assessment Tool Set) was developed by Science Applications International Corporation (SAIC) and is owned by FEMA. It is used to assess the consequences of natural and technological disasters including earthquakes, hurricanes, terrorist attacks etc. (Samuels, 2009). It uses ESRI ArcView as the GIS Platform. The software includes ground shaking, tsunamis, fire and ground failure as the earthquake hazards and was tested for various earthquakes of the past such as Northridge, Kobe, Izmit etc. (Daniell, 2009). The software not only calculates the hazards due to a disaster but also determines the consequences of the hazards by integrating the location and availability of resources into the model. (Samuels, 2009).

- **ELER:**

  ELER (Earthquake Loss Estimation Routine) is a multilevel methodology developed by NERIES (Network of Research Infrastructures for European Seismology) in collaboration with Imperial College, NORSAR and ETH Zurich (Daniell, 2009). From ELER v 3.0, the software has the capability of using User-Defined GMPEs (Ground Motion Prediction Equations) (ELER v3.0 User Manual, 2010). ELER uses land cover mapping and distribution of population in an area to develop building inventories at regional levels (Erdik et al. 2010). The software has two modules namely Earthquake Hazard Assessment (EHA) and Earthquake Loss Assessment (ELA). The EHA module uses ground motion intensity and parameters while ELA uses parameters from EHA as well as population and building distribution information. The Latest version of ELER (v 3.1) also includes a module for Pipeline damage and economic losses.

- **NHEMATIS:**

  Natural Hazards Electronic Map and Assessment Tools Information System) is a software developed for Canada, and is similar to HAZUS for United States. It contains many national databases of Canada. It was originally developed for EPC (Emergency Preparedness Canada) but later on transferred to EmerGeo. The software uses ESRI ArcGIS as the GIS base. The software can assess vulnerabilities to different hazards including earthquakes. In addition to ground shaking, it also considers secondary effects of earthquakes. The software also includes a GPS based setup which is used to locate an expert on hazard map in the area and facilitate the interpretation of the hazard map (Daniell, 2009).

- **EPEDAT:**

  EPEDAT (Early Post Earthquake Damage Assessment Tool) was developed for California Office of Emergency Services by EQE International Inc. to model building and human damages and estimate casualties from the earthquake parameters obtained from CUBE (Daniell, 2009). CUBE is an earthquake broadcast system operated by CalTech and USGS jointly. EPEDAT receives earthquake magnitude and location data from CUBE and uses faults and seismicity data to locate the most probable source of the earthquake, and projects the earthquake hazard to the affected areas through ground motion models and calculates the final loss estimates by integrating building and human distribution information (Eguchi et al. 1997).

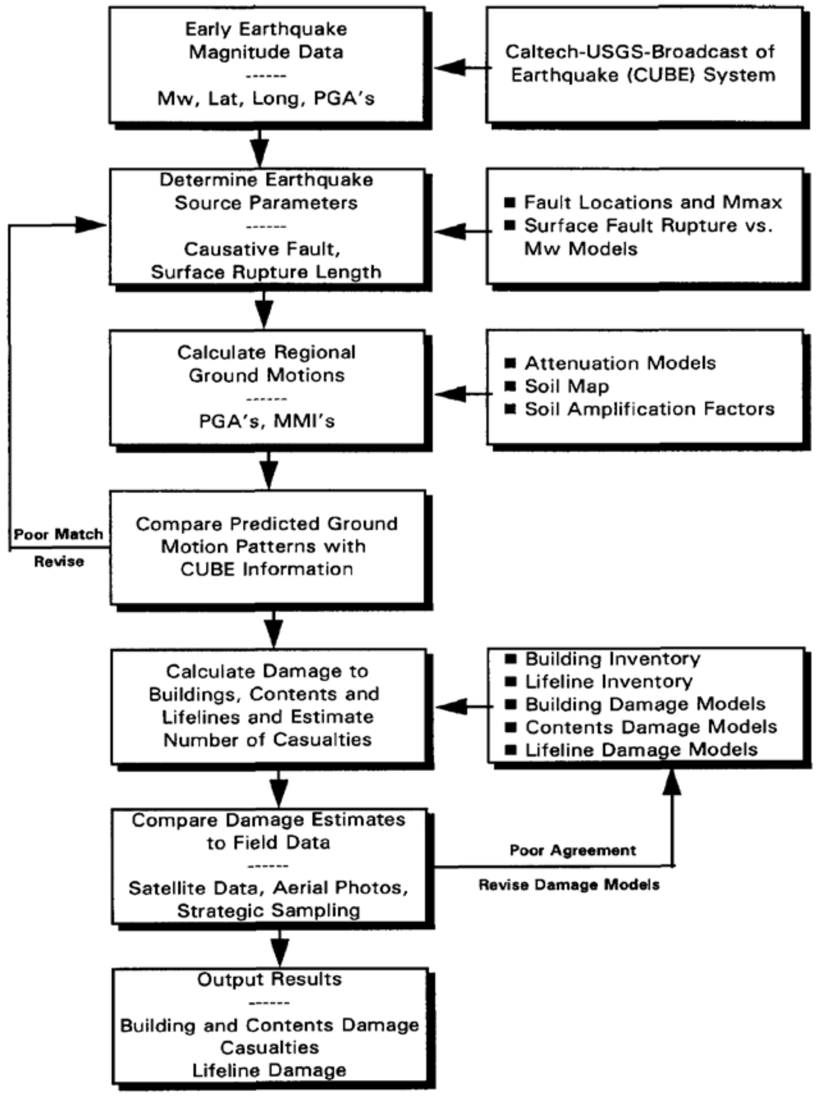


Figure 2.12: Flowchart for EPEDAT reproduced from Eguchi et al. (1997)

- **HAZUS:**

  As already explained in the PSHA section, HAZUS (Hazard US) is a multi-hazard tool initially developed for earthquake hazards (Ground shaking, liquefaction, rupture and landslide etc.). It was developed and owned by FEMA (Federal Emergency Management Agency) and NIBS (National Institute of Building Sciences). The software is for use in United States only and cannot be utilized in other parts of the world. However, software working on similar methodology have been developed for various parts of the world such as NHEMATIS (for Canada) and HAZ-Taiwan (for Taiwan) and MAEviz (for middle American states). The later versions of the software covered other hazards as well such as flood, winds, hurricanes etc. The software is now known as HAZUS-MH (Hazard US-Multihazard) (FEMA website, 2014).

- **Extremum:**

  Extremum software is a set of tools developed at Extreme Situations Research Center Ltd., Seismological Center, Institute of Environmental Geosciences, Russian Academy of Sciences and Emercom in the 1990s (Frolova et al. 2009). It contains a building stock model for the entire world with at different scales. The sources and accuracy for the building inventory is variable. At some places, the model has been produced by actual field data, whereas at other places, the model has been developed using the information published in different Conferences on earthquake engineering or satellite imagery. The integration of building inventory with population distribution, hazard and exposure data, the software calculates damage and losses to infrastructure and human population. The software is developed for use in the entire world, however it requires calibration with a past event in order to be used in different regions (Daniell, 2009)

- **InLET:**

  InLET (Internet based Loss Estimation Tool) is the first online tool for estimation of losses due to an earthquake in the region of California, developed by the University of California and ImageCat Inc. It incorporates large GIS databases and uses simplified HAZUS damage functions for the calculation of losses (ImageCat Inc, 2008). The software is programmed in a way that it takes realtime USGS ShakeCast notifications of earthquakes and calculates earthquake losses without any user input.

- **PAGER:**

  PAGER (Prompt Assessment of Global Earthquake for Response) is a USGS rapid response MMI (Modified Mercalli Intensity) based system to determine the population exposure to significant earthquakes throughout the world. In case of an earthquake, PAGER collects intensity related information from people in the region through a series of online questions. PAGER rapidly estimates the impact of an earthquake by comparing the number of people exposed to ground shaking and its severity with economic loss and casualty model based on past earthquakes in each zone, country or region. (USGS website, 2014). Currently, PAGER only considers primary effects of an earthquake, that is the ground shaking.

- **QLARM:**

  QLARM is developed by WAPMERR (World Agency for Planetry Monitoring and Earthquake Risk Reduction) and is a tool for estimation of building losses and fatalities for the entire world focusing on developing countries. It requires time of earthquake occurrence, Magnitude, Location and depth as input. In order to make up for the non-availability of accurate building stock data, the software has been calibrated for 1000 earthquakes for which the building damage and human casualty data was available. (WAPMERR website, 2014).

From the above discussion, it is obvious that majority of the research and development work in the field of Earthquake Loss Estimation has been done in developed countries. Although some models are applicable in developing countries but they have limited applicability and use due to non-availability of accurate data. Earthquake Loss Estimation needs to be given its due importance in developing countries which are characterized by low level of construction, high density of population, low awareness level and high risk of damage in case of an earthquake.

CHAPTER 3

KEY PARAMETERS REQUIRED FOR THE STUDY REGION

3.1 INTRODUCTION:

The first two chapters outlined the general methodology of Earthquake Loss Assessment and discussed in detail the components of the process. The methodology remains the same for any region of the world. However, parameters like geology, demographics, building inventory etc. are variables that are different for every part of the world. This chapter describes the parameters that are required for the study region. The topics covered in this chapter are as follows:

- Division of area into suitably small areas.
- The geology of the study region including the nature and location of main faults, responsible for major earthquakes in the past.
- Details of attenuation relationships available for ground motion prediction and selection of an appropriate relationship to be used in the process of Earthquake Loss Assessment. As discussed earlier, no attenuation relationship exists specifically for the region under study. Therefore, attenuation relationships for similar regions should be utilized for the study region.
- Details of demographic data.
- Details of building inventory development.
- Selection of Vulnerability relationships to be used in the process of Earthquake Loss Assessment. If vulnerability curves are not available for the region, suitable vulnerability curve may be selected that was developed for similar regions.

3.2 DIVISION OF AREA:

Before performing an Earthquake Loss Assessment, the study region needs to be divided into small areas. The intensity of earthquake shaking will be assumed to be the same within each of these areas. This division needs to be very fine in order to obtain results with higher accuracy. However, the division of study area into extremely small regions will increase the computational time required to perform Earthquake Loss Assessment. Moreover, the availability of required data at the desired level of division is another important issue that needs to be considered. Thus, a compromise between time of computation and accuracy of results has to be made. In this study, the division is done at Union Council level, which is the smallest administrative unit of Local Government in Pakistan.

The Union Council level maps of Pakistan were digitized. The Union Councils were represented as Polygon features in ArcGIS. These maps were used to calculate the centroids of the union councils. The distance from the epicenter of an earthquake event and the centroid of a particular union council was used in the process of determining the intensity of ground shaking at the union council.

3.3 PROBABILISTIC SEISMIC HAZARD ASSESSMENT:

As discussed in the literature review, the first module of the Earthquake Loss Estimation framework is the Hazard Module. Probabilistic Seismic Hazard Assessment will be used for the purpose of Loss Estimation. The parameters required for this module are discussed below:

- **Seismic Source Identification:** The first step in the Probabilistic Seismic Hazard Assessment is the seismic source identification. This can be very tricky due to our incomplete knowledge of the entire geology/structure of earth. The location and characteristics of seismic sources are not known sometimes. The data available immediately after an earthquake event is limited to magnitude and location only. Therefore, it is obvious that the process of source identification cannot be performed after the event has occurred because of large amount of time required for it. To solve this problem, the study region has been divided into 34 seismic source zones, with each zone having defined seismic characteristics. The earthquake event is assumed to occur at the fault that has the same characteristics as those of the seismic source in which it occurs. The length of rupture is proportional to the magnitude of the earthquake and its orientation is parallel to that of the fault on which the earthquake occurs. The length of rupture due to an earthquake is given by Wells and Coppersmith (1994) relation given below:

$$\log(RLD) = -2.44 + 0.59\, M_W \tag{3.1}$$

- **Earthquake Catalogue:**

  As mentioned earlier, the process of Earthquake Loss Estimation suffers from uncertainties, one of which is the Aleatory uncertainty. This type of uncertainty is taken care of by using a probabilistic approach. For this purpose, a synthetic catalogue of earthquake events is created using Monte-Carlo Simulation. Monte-Carlo simulation is a technique that uses random numbers to generate a probabilistic distribution of a probabilistic quantity. This technique can be successfully applied to the process of Earthquake Loss Estimation, given that sufficiently large number of simulations are run. But the number of simulations also influence the time needed for Loss estimation. Therefore, the number of simulations should be kept large enough to obtain sufficiently accurate results and at the same time small enough to obtain the loss estimation results in time.

- **Attenuation of Ground Motion:** As already explained, the strength of ground shaking decreases as the seismic waves move away from the source. This decrease is described by empirical relationships called attenuation relationships or Ground Motion Prediction Equations (GMPEs) that estimate the intensity of ground motion at a site located at some distance away from the source of earthquake. A general from of an attenuation relationship is given below (Campbell, 2003):

$$\ln Y = c_1 + c_2 M - c_3 \ln R - c_4 R + c_5 F + c_6 S + \varepsilon \tag{3.2}$$

  Where:

  Y is the strong motion parameter of interest.

  M is the magnitude of the earthquake event.

  R is the distance between the earthquake source and the site of interest.

  F is the faulting mechanism of the earthquake.

  S is a measure to define local site conditions beneath the site of interest.

  ε is the error term.

  The terms $c_1, c_2, c_3, c_4, c_5, c_6$ are constants. Some of these constants are known to depend upon the tectonic environment in which the earthquake occurs (Campbell, 2003).

  We are interested to find out the strength of ground shaking at the centroids of the union councils. The centroids of the union councils were already calculated. The distance between the centroids and the epicenter will be used as R in the attenuation relationship.

No attenuation relationship has been derived specifically for the study region. Although a number of attenuation relationships have been used in the study region but none of them is based on strong motion data from Pakistan. In this study, Ambraseys et al. (2005) relationship will be used based on the following:

1. Khan (2011) compared the results from this relationship with actual observed data from 2005 Kashmir earthquake and found out that the relationship gives satisfactory results.
2. The data used in the derivation of this relationship came from Europe and Middle East, which also has shallow earthquakes similar to the area under current study (Bhatti et al., 2011).
3. The database used for the derivation of the relationship also contained 3% data from the Himalayan region (Mona Lisa et al., 2005).
4. PMD-NORSAR recommended this relationship for the study region (Bhatti et al., 2011)

Ambraseys et al. (2005) relationship is given below:

$$\log(a) = 2.522 - 0.142M_W - (3.184 - 0.314M_W)\log\sqrt{(d^2 + 7.6^2)} + 0.137\,S_S + 0.05S_A - 0.084F_N + 0.062F_T - 0.044F_O \tag{3.3}$$

Where:

M_W is the moment magnitude.

d is the distance from the epicenter to the centroid of the union council.

S_S is a factor which is 1 for soft soil, 0 otherwise.

S_A is a factor which is 1 for stiff soil, 0 otherwise.

F_N is a factor which is 1 for normal fault, 0 otherwise.

F_T is a factor which is 1 for thrust fault, 0 otherwise.

F_O is a factor which is 1 for other faults, 0 otherwise.

The above equation can be simplified as:

$$\log(a) = f(M_W, d, F_N, F_T, F_O) + 0.137S_S + 0.05S_A \quad (3.4)$$

The soil terms S_S and S_A are obtained through shear wave velocities of the soil. A table below gives the values of shear wave velocities for determining the soil terms mentioned above.

Soil Type	**Shear wave velocity**	**S_S**	**S_A**
Soft Soil (S)	V_{S30}< 360m/Sec	1	0
Stiff Soil(A)	360< V_{S30}< 750 m/Sec	0	1
Rock (R)	750m/Sec < V_{S30}	0	0

Table 3.1: Soil parameters and shear wave velocities

The shear wave velocities for each union council are determined by using the data from the study carried out by USGS. USGS determined the shear wave velocities for Pakistan using a 1 km by 1 km grid. These maps are available online at "The Global V_{S30} Server of USGS". These velocities were plotted as a shape file in ArcGIS and the average shear wave velocity for a union council was determined by calculating the average of all the points lying within the boundary of a union council.

- **Calculation of probabilities:**

  The last step in the probabilistic seismic hazard assessment is the calculation of probability of ground motion equaling or exceeding a specified value. This can be done by solving the probability equation mentioned in the literature. Another method, which is now in use is to use Monte-Carlo simulation technique to evaluate the probability. The synthetic catalogue that was produced in the second step is propagated to the union councils by using the attenuation relationship. In this way, each union council has a set of ground shaking values, with each value representing an earthquake event at the source. In this method, the ground shaking values for each union council are arranged in the order of decreasing magnitude. The largest value has the least probability of occurrence and the lowest value has the highest probability of occurrence. For example, a synthetic catalogue of 1000 events was generated and propagated to the union councils. Now, each union council has a set of 1000 PGA values. Each of these sets are arranged in decreasing order. The value that has 10% probability of occurrence (POE) is the value that is 101st from the top. After this step, each union council has its own defined level of ground shaking. This is used to determine the vulnerability of buildings in each union council.

3.4 VULNERABILITY:

To determine the vulnerability of building infrastructure towards earthquake hazard, vulnerability curves are used. These curves relate the strength of ground shaking at the site to MDR (Mean Damage Ratio). MDR is a ratio of damage caused by given strength of ground shaking at the site to maximum damage that can be caused. In other words, MDR describes the damage in terms complete collapse.

3.4.1 VULNERABILITY CURVES:

Vulnerability curves are derived for different types of structures depending upon their behavior in the event of an earthquake.

Different researchers have developed vulnerability curves for building types in Pakistan, such as:

- Rafi (2012) developed fragility curves for Adobe structures in Pakistan.
- Sohaib (2011) developed vulnerability curves for Reinforced Concrete Frame structures in Pakistan.

But vulnerability curves for complete building inventory of Pakistan have not been developed yet. GeoHazards International (GHI) developed a Microsoft Excel software, based on the methodology developed by Global Earthquake Safety Initiative (GESI) pilot project in 2001. It is a simple Excel Sheet software that takes input about the type of structures and their level of construction and develops vulnerability curves from the given information. The curves developed by this method were also used by Khan (2001) for developing an Earthquake Risk Assessment Framework for Pakistan, and by Qureshi (2014) to conduct an Earthquake Risk Assessment of KPK province of Pakistan. This software will be used to develop vulnerability curves for Pakistan taking into account the type and level of construction in Pakistan.

3.4.2 BUILDING INVENTORY:

The performance of different types of buildings in an earthquake varies. Consequently, each building type has its own vulnerability curve. Therefore, before assessing the seismic vulnerability of the area under study, it is important to classify the building inventory into these classes. Common types of buildings are:

- **Adobe Structures or Mud Wall Structures:** These structures are non-engineered and are preferred in rural areas of the study region due to their low cost. However, these structures are also found in some urban areas as well. These are constructed from mud or mud bricks with Mud mortar used as a binding agent between the bricks. These structures perform very poorly in an earthquake and thus are highly vulnerable to earthquake damage. Adobe Structures form 14.6% of the built environment of Pakistan (Lodi, 2012), which is alarming because of high vulnerability of these structures in the event of an earthquake. The occupancy of adobe structures in Pakistan is 2 to 8 persons per house (Lodi, 2012).

Figure 3.1: Typical Adobe construction in Pakistan, reproduced from World Housing Encyclopedia.

- **Dhajji Structures:** These structures are very commonly found in the hilly areas of Pakistan. These comprise of a wooden frame with masonry infill. The wooden frames include lateral bracing members that can use to counter lateral loading. This was one of the reasons that these structures behaved well in Kashmir (2005) earthquake. ERRA also recommended the construction of these structures in the rehabilitation phase after Kashmir earthquake 2005. These structures can have more than one storeys and have a flat mud and timber roof or inclined roof with metallic sheets.

Figure 3.2: Dhajji Structures, reproduced from e-architect.co.uk

- **Stone Rubble Masonry structures:** These structures are commonly found in hilly areas of Pakistan. These structures are normally preferred in areas where stones for such construction are available in abundance. These structures are either constructed by placing undressed stone in mud mortar or in dry form. These structures are highly vulnerable to earthquakes as demonstrated by the Kashmir earthquake 2005.

Figure 3.3: Failure of Stone Masonry walls in Kashmir 2005 earthquake, reproduced from EERI report, 2005.

- **Unreinforced Brick Masonry:** These structures are very common in rural and urban areas of Pakistan. In rural environments, these structures are usually single storey high while in urban centers these can go up to three storeys high. These structures make up 62.38% of Pakistan's built environment (Lodi, 2013). These structures have load bearing walls constructed with bricks laid in mud mortar or cement mortar. Due to abundance of clay, a major ingredient of bricks, these structures are comparatively cheaper than Reinforced concrete structures, which makes these structures a preferred choice for a large majority of Pakistan's population. For single storey structures, the roof is generally made up of Timber, corrugated galvanized iron sheets or steel girder while for higher structures, reinforced concrete slab is provided (Lodi, 2013). The lack of proper joints between roof and walls, and between the walls themselves make these structures highly vulnerable to earthquake hazards.

Figure 3.4: Failure of an unreinforced brick masonry wall in Muaffarabad, (EERI report, 2005)

- **Unreinforced Block Masonry:** This type of structures is similar to Unreinforced Brick Masonry structures except that precast concrete blocks are used in place of bricks. This type of construction contributes 3.3% of the entire building stock of Pakistan (Lodi, 2012). These structures are usually common in areas where clay is not readily available for the manufacture of bricks and high transportation costs of bricks from large distances make it uneconomical. For example, this type of construction is common in Karachi due to availability of cement and aggregate and unavailability of clay as a local material.
- **Reinforced Concrete Buildings with masonry infill:** These structures are constructed using reinforced cement concrete with masonry bricks or concrete blocks as infill. This type of construction is most popular in urban regions of Pakistan due to its relatively high cost, availability of materials, machinery and technical expertise in urban areas. These structures make up 7.64% of the building stock of Pakistan. (Lodi, 2013). Although the design and construction expertise required for the construction of these structures is

available in major urban centers of Pakistan, the poor implementation mechanism make the quality of RCC buildings in Pakistan between poor and average (Lodi, 2013).

Figure 3.5: Reinforced Concrete frame structure with masonry infill in Karachi, from Lodi, (2013)

In this study, building inventory is developed for 4 classes namely:

- Adobe Structures.
- Unreinforced Masonry Structures.
- Reinforced Concrete Structures with masonry infill.
- Reinforced Concrete Frame Structures.

The vulnerability curves for these structures are obtained from the Microsoft Excel program of GESI.

3.4.3 HUMAN LOSSES:

For determining the number of casualties, Coburn and Spence Model will be used which was discussed in the literature. The model requires the building occupancy data, which is available from the census record of 1998. Various factors involved in the estimation of casualties are determined from the guidelines provided by Coburn and Spence for the model. Further discussion on the application of this model in the process of Earthquake Loss Assessment is covered in Chapter 4.

CHAPTER 4

IMPLEMENTATION OF EARTHQUAKE LOSS ASSESSMENT

4.1 INTRODUCTION:

This chapter describes the methodology of Earthquake Loss Assessment Framework and its various components. The following section discusses in detail the specific steps carried out to perform Loss Assessment for the study region.

4.2 HAZARD MODULE:

The first module in the Earthquake Loss Assessment Framework is the Hazard Module. This module gives the earthquake hazard at the site of interest due to an earthquake event that occurred at some distance from the site of interest. As already discussed in the literature, Probabilistic Seismic Hazard Assessment is recommended for use in Earthquake Loss Assessment framework. Conventional PSHA studies are conducted for the purpose of predicting future seismic hazard at the site of interest. Therefore, the conventional approach uses historical and instrumental seismicity along with earthquake recurrence relationships to determine the earthquake hazard at the site of interest. However, this study is a little different from the conventional approach in the sense that the earthquake has already occurred and the magnitude and location of the earthquake is already known. Therefore, the use of past earthquake catalogues and recurrence relationships is not required.

In this study, the hazard due to a particular earthquake event is calculated at the centroids of union councils. For this purpose, the administrative boundaries of the union councils were digitized using ArcGIS. This resulted in a shapefile that contained polygon features representing union councils of Pakistan. The centroids of the polygons were calculated and stored in the attribute table of the polygons. The study region was divided into 19 seismic zones based on the study conducted by PMD-NORSAR in 2007. These seismic zones were also digitized into a separate shapefile. These zones are characterized on the basis of fault type and fault orientation. Once the user inputs the magnitude and location information of the earthquake event, the location of the epicenter is checked against all seismic zones. The fault type and orientation of the zone in which the epicenter lies, is assigned to the earthquake event.

In the next step, synthetic earthquake catalogues are generated to take into account uncertainty in the process of determining the magnitude and location of the earthquake. This technique is known as Monte-Carlo Simulation and requires a large number of simulations for the results to be accurate. But at the same time, large number of simulations can take a lot of computation time. For the purpose of this study, number of simulations is selected to be 1000 keeping in view the computation time required for running the simulations.

4.2.1 CREATION OF SYNTHETIC CATALOGUE OF RANDOM EVENTS:

After the user inputs the location information and magnitude of the earthquake, 1000 random events are generated to cater for the Aleatory uncertainty. The uncertainties in determining the location and magnitude of an earthquake are as follows:

- The uncertainty in locating an earthquake is 25 to 35 km (Wyss, 2011).
- Kythreoti (2002) carried out a sensitivity analysis for depth of earthquake and used 15% variation in depth of an earthquake.
- The uncertainty in magnitude for new randomly generated earthquake is ± 0.2 M_w

The random events are generated within these limits to counter the uncertainty associated with the calculation of the above mentioned parameters.

4.2.2 ATTENUATION OF GROUND MOTION:

The next step is to predict the strength of ground shaking at the centroids of the union council. The centroids of the union councils are already calculated and stored in the attribute table of the polygon features representing the union councils of Pakistan. The shortest distance between the centroid and the EFL is considered for attenuation.

The shape file containing the shear wave velocities (V_{S30}) for the region of Pakistan is overlaid on the digitized map of the area. The values for the shear wave velocities are averaged over the area of the union council and one value of shear wave velocity is calculated for each union council. Based on this average shear wave velocity, the values for Stiff Soil factor (S_S) and Soft Soil factor (S_A) are determined. The table below shows the values for the factors with respect to the average shear wave velocity:

Soil Type	**Shear wave velocity**	**S_S**	**S_A**
Soft Soil (S)	V_{S30}< 360m/Sec	1	0
Stiff Soil(A)	360< V_{S30}< 750 m/Sec	0	1
Rock (R)	750m/Sec < V_{S30}	0	0

Table 4.1: Values of soil parameters according to shear wave velocities

These values for S_A and S_S are the site soil condition to be used in the attenuation relationship. Ambraseys (2005) attenuation relationship will be used for this study. The parameters required for the use of this relationship are listed below along with the method of their incorporation into the Earthquake Loss Assessment methodology:

Parameter	**Description**	**Method to obtain the parameter**
M_W	Moment Magnitude	Input by the user. This can be obtained from different strong motion detection agencies like PMS, USGS, JMA etc.
Latitude, Longitude and depth	Location information of the epicenter of earthquake.	Input by the user. This can be obtained from different strong motion detection agencies like PMS, USGS, JMA etc.
Geographic properties of the site of interest.	Boundaries and centroid of the union councils of the area.	The maps were digitized and their centroids were calculated and stored in the attribute table of each union council.
Geologic properties	The type of fault and its orientation.	These properties are obtained by overlaying the seismic zones shapefile over the digitized map.
Site Soil Conditions	Soft soil factor (S_S) and stiff soil factor (S_A).	These are obtained by comparing the average shear wave velocity with the values from table 4.1

Table 4.2: Parameters for ground motion attenuation.

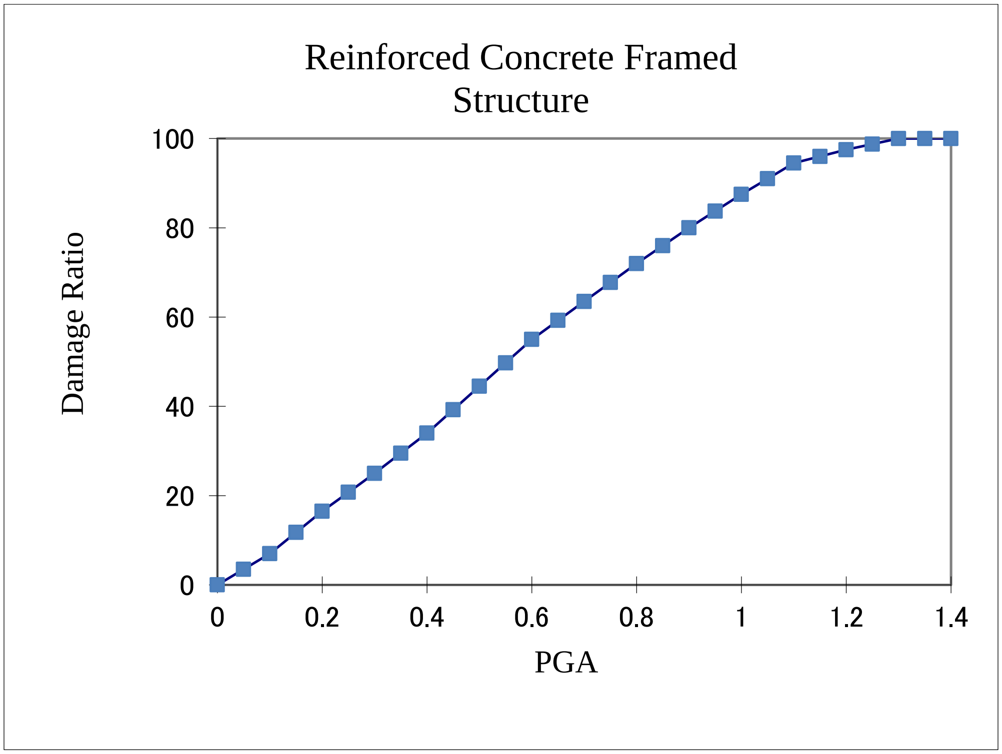
The attenuation of ground motion to the centroids of the union councils resulted in a catalogue of earthquake events for each union council. The event with 10% POE is selected for each union council. The process of selection is described below:

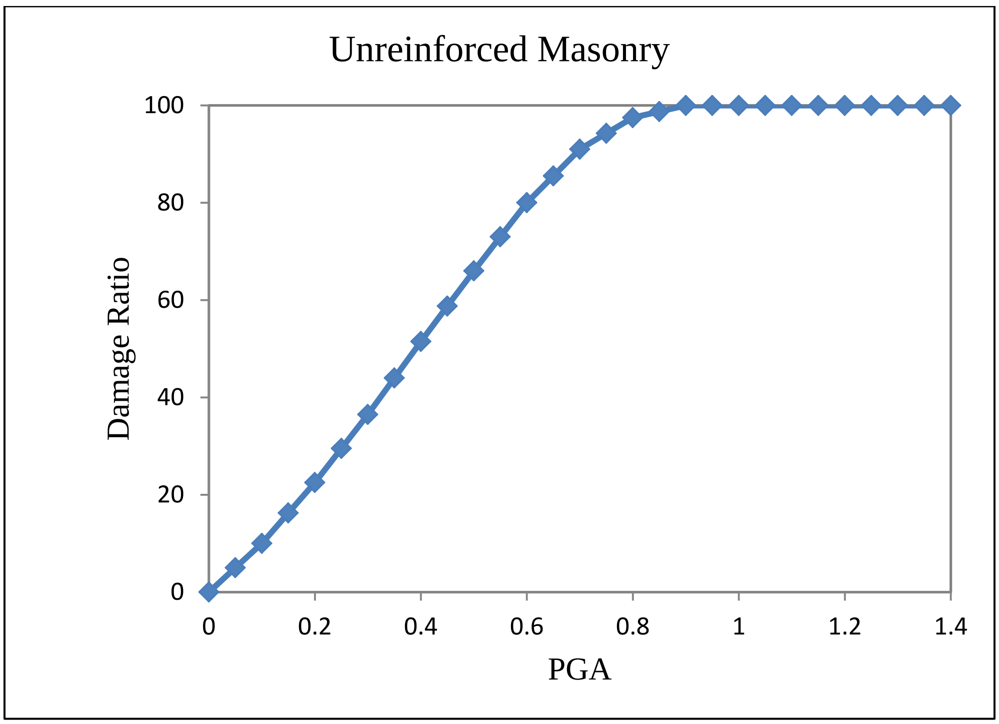
1. Arrange all events in the order of decreasing magnitude. The event at the top has the highest magnitude and the event at the bottom has the least magnitude.
2. The event at the top has the highest return period, least frequency and least probability, while the event at the bottom has the least return period and highest frequency and probability.
3. The event with 10% POE is the one which has 10% of the events above it.
4. In this study, 1000 events were selected, so the event with 10% POE will be the 101st event from the top.

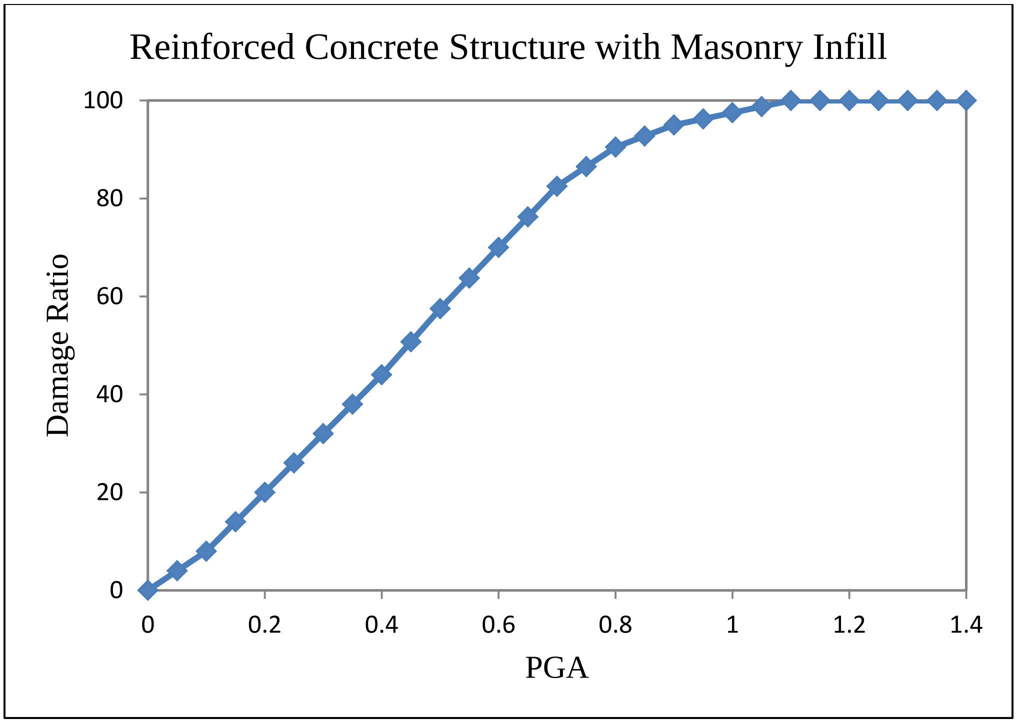
In this way, the event with 10% POE is selected for every union council. This results in the development of a hazard map. This hazard map shows the spatial distribution of earthquake hazard due to a certain earthquake event. It must be kept in mind that the earthquake hazard in this case is ground shaking only. This value of earthquake hazard for each union council is stored in the attribute table of the union council. This will be used subsequently in the determination of economic and human losses.

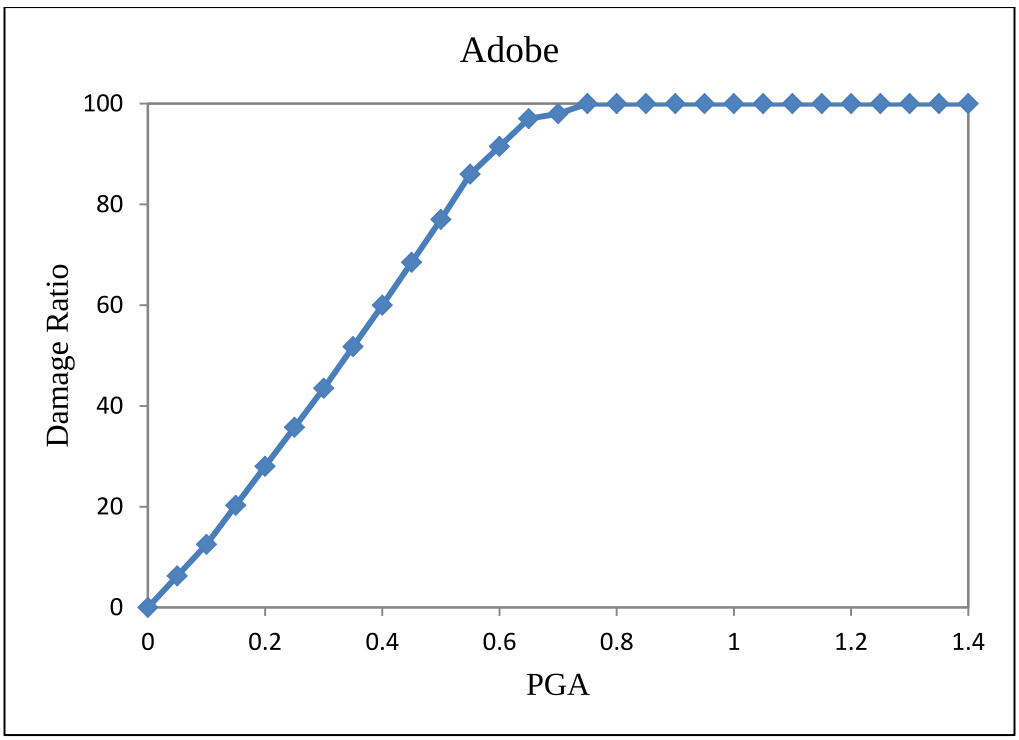
4.3 DAMAGE MODULE:

The hazard module gave values of earthquake hazard for each union council. These values are utilized in the damage module to determine the damage due to a particular level of earthquake hazard. The damage is determined from vulnerability curves, which relate the level of earthquake hazard to MDR (Mean Damage Ratio). The vulnerability curves obtained from the GESI Microsoft Excel program for the building classes are shown below:


Reinforced Concrete Framed Structure
Damage Ratio
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
PGA


Unreinforced Masonry
Damage Ratio
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
PGA


Reinforced Concrete Structure with Masonry Infill
Damage Ratio
0
20
40
60
80
100
0
0.2
0.4
0.6
0.8
1
1.2
1.4
PGA


Adobe
Damage Ratio
0
20
40
60
80
100
0
0.2
0.4
0.6
0.8
1
1.2
1.4
PGA

These curves are obtained by the following procedure:

- Enter a number from 0 to 6 to determine the type of building. The values for each type of building are shown in table 4.3. In this case, the values of 2, 3, 5 and 6 are entered for the building classes.

0	Wood
1	Steel
2	Reinforced Concrete
3	Reinforced Concrete Infill
4	Reinforced Masonry
5	Unreinforced Brick Masonry
6	Adobe

Table 4.3: Values for type of building

- Enter a number from 0 to 3 to determine the quality of design of the building. The corresponding values are shown below:

0	Engineered with Seismic Design
1	Engineered without Seismic Design
2	Non-Engineered without Seismic Design
3	Non-Engineered, no Seismic Design and Poor Proportions

Table 4.4: Values to define the quality of design

- Enter a number from 0 to 3 to define the quality of construction. The corresponding values are shown below:

0	Excellent quality with good supervision of Seismic elements
1	Good quality with some supervision of Seismic elements
2	Moderate quality with no supervision of Seismic elements
3	Poor quality with no supervision of Seismic elements and unskilled workers

Table 4.5: Values to define the quality of construction.

- Enter a number from 0 to 1 to define the quality of material used for construction. The values are obtained from the table shown below:

0	Good quality material
1	Poor quality material of poor maintenance of building

Table 4.6: Values to define the quality of construction materials

Suitable values are selected to obtain the vulnerability curves for the building classes. These curves are then utilized to determine the MDR for each building class. Damage in terms of money can be calculated by multiplying the obtained MDR with total cost of construction. The cost of construction can be determined by multiplying the covered area with the unit cost of construction, which is normally used for the purpose of cost estimations. In this study, there is no access to data regarding covered area and considering the scope of the project, it is not possible to conduct a physical survey. In addition, the number of storeys is also not known, since the covered area increases with increasing storeys. Considering this, the results are displayed in terms of MDR.

4.4 HUMAN CASUALTIES:

The methodology used by GESI for the development of Vulnerability curves defines 4 damage states.

- Damage state 1: No damage at all, slight or moderate damage.
- Damage state 2: Extensive damage.
- Damage state 3: Partial collapse.
- Damage state 4: Complete collapse.

The GESI Microsoft Excel program also gives the distribution of building stock in different damage states with respect to the level of ground shaking. The casualty model used in this study requires the number of collapsed buildings for the estimation of human deaths and injuries. For this, the curve representing damage state 4 for each building class is used. These curves give the percentage of the building stock in damage state 4 for different values of ground shaking hazard. The number of casualties for building class b is given by:

$$K_{sb} = D_b \times [M1 \times M2 \times M3 \times \{M4 + M5(1 - M4)\}] \quad (4.1)$$

Where:
D_b is the total number of collapsed buildings of type b.
$M1$ is Population per building.
$M2$ is Occupancy at the time of earthquake.
$M3$ is the number of occupants trapped by the collapse of the structure.
$M4$ is the Mortality at collapse.
$M5$ is the Mortality after the collapse.

The detailed description of these factors is given below:

- **M1, Number of people per building:** The number of people per building varies with the location of the building and cultural trends. It is different for rural and urban environments. Population per building also depends upon the type of structure. If the building is a RC structure, it may consist of multiple storeys and will have higher value of M1. In developing countries like Pakistan, this is quite high as compared with that of the developed countries. In the census data of 1998, average household size is given. The factor M1 is taken equal to the average household size of the census data.
- **M2, Occupancy at the time of earthquake:** The factor M2 represents the number of people that are present inside the building at the time of earthquake. This value depends upon the following factors:
  - Rural or Urban environment. In rural environment, most people are outide during the day while in urban environment, people are indoors at offices, schools etc.
  - Time of the earthquake. At night, almost all of the people are inside the buildings while during the day, the number of people inside the buildings decrease.
  - Day of the week. If it is a week day, most of the people will be at work or at school while if it is a week end, people might be outside.
  - Winter or summer season. In Pakistan, people living in rural environment prefer to sleep outside in summers.

- **M3, the number of occupants trapped by collapse:** During an earthquake, if a building collapses, not all of the occupants are trapped inside. Some people might succeed in getting out of the building before total collapse occurs. This factor depends upon the type of buildings and height of the structure, because in weak unreinforced masonry structures, collapse may be immediate without any time to escape outside while in RC structures there may be sufficient time available for the occupants to leave the building before the collapse. Coburn and Spence (1992) suggested that the number of occupants that are trapped by the collapse of the building is less for low rise buildings and high for buildings with multiple storeys.
- **M4, injury distribution at collapse:** If a building collapses during an earthquake, people may suffer from injuries that vary by severity and type. Some people will die immediately due to these injuries while others might be saved if medical help is provided to them in time. The following table describes a simple scale to quantify the injuries and deaths. This is based upon the four point triage classification of injuries:

Triage	Injury Category	Un-Reinforced Masonry	RC	Rubble Stone
1	Dead or cannot be saved	20%	40%	20%
2	Life threatening cases needing immediate medical attention	30%	10%	25%
3	Injury requiring hospital treatment	30%	40%	30%
4	Light injury not necessitating hospitalization	20%	10%	25%

Table 4.7: Values of M4 for different building classes

- **M5, Post collapse mortality:** Some of the people trapped inside the collapsed structure will suffer from major injuries and will die immediately, while other suffering from light injuries might be saved if immediate rescue and medical help is provided. The number of people saved from the collapsed building depends crucially upon the effectiveness of the search and rescue operation. It also depends upon the type of building. For reinforced concrete structures, the time required to evacuate injured people will be long because of heavy cutting and lifting required to reach the injured. Similarly, for multi storey structures, the amount of debris will be very large, and heavy mechanical work will be required to reach the injured people. In the event of a large earthquake, where majority of the population is affected and the people are unable to organize initial search and rescue operations themselves, the post collapse mortalities increase significantly. Some of the factors that affect the search and rescue activities are manpower, mechanical power, resources, communication infrastructure, weather conditions and techniques used for the search and rescue operation. The following table gives values of M5 for different situations:

.

Situation	**Masonry**	**RC**
Community incapacitated by high causality rate	95%	99%
Community capable of rescue operation	50%	80%
Community + emergency squad after 12 hours	70%	85%
Community + emergency squads+ search & rescue expert after 36 hours	50%	70%

Table 4.8: Values of M5 for different situations

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION:

The methodology described in the previous chapter is used to estimate the losses due to the Awaran earthquake of 2013. As discussed earlier, the framework consists of three modules namely:

- Hazard Module.
- Damage Module.
- Loss Module.

5.1.1 COMPARISON OF ELA FRAMEWORK:

The Earthquake Loss Assessment Framework was used to estimate earthquake losses due to recent earthquakes in the study region. The results obtained are compared to determine the validity of the Earthquake Loss Assessment Framework.

The framework was validated for Awaran earthquake of 2013 and Kashmir earthquake of 2005.

5.1.2 EARTHQUAKE INFORMATION:

Earthquake 1:

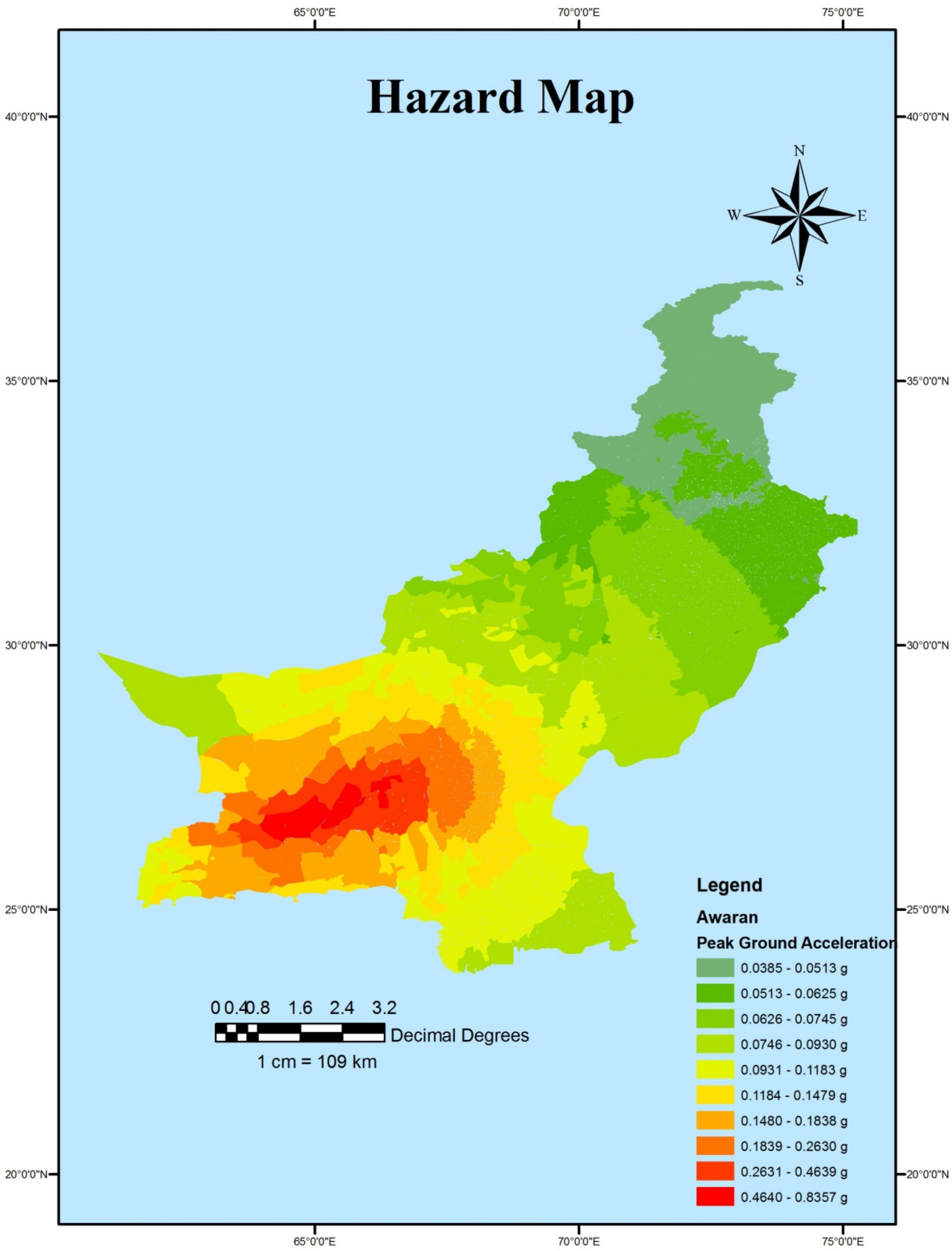
Location: 26.951°N 65.501°E depth=15.0 km, 61 km NNE of Awaran, Pakistan

Magnitude: 7.7

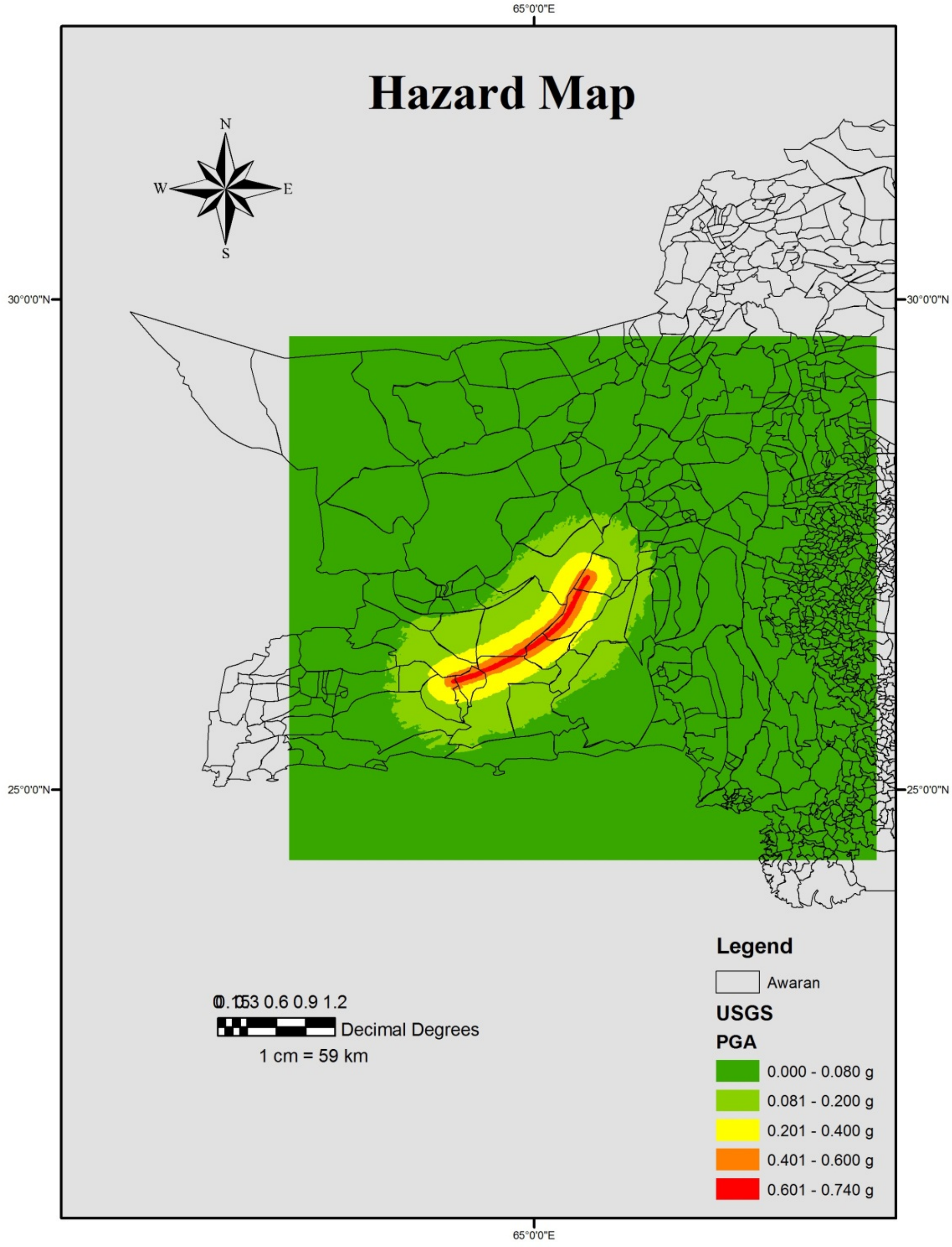
Time: 11:29 UTC

Date: 24th September, 2013.

The Seismic Hazard Map of Awaran Earthquake of 2013 obtained through the software is shown below:



For validation of the hazard map, ShakeMap of the mentioned earthquake was obtained from USGS (United States Geological Survey) Hazard Program's website and shown below:

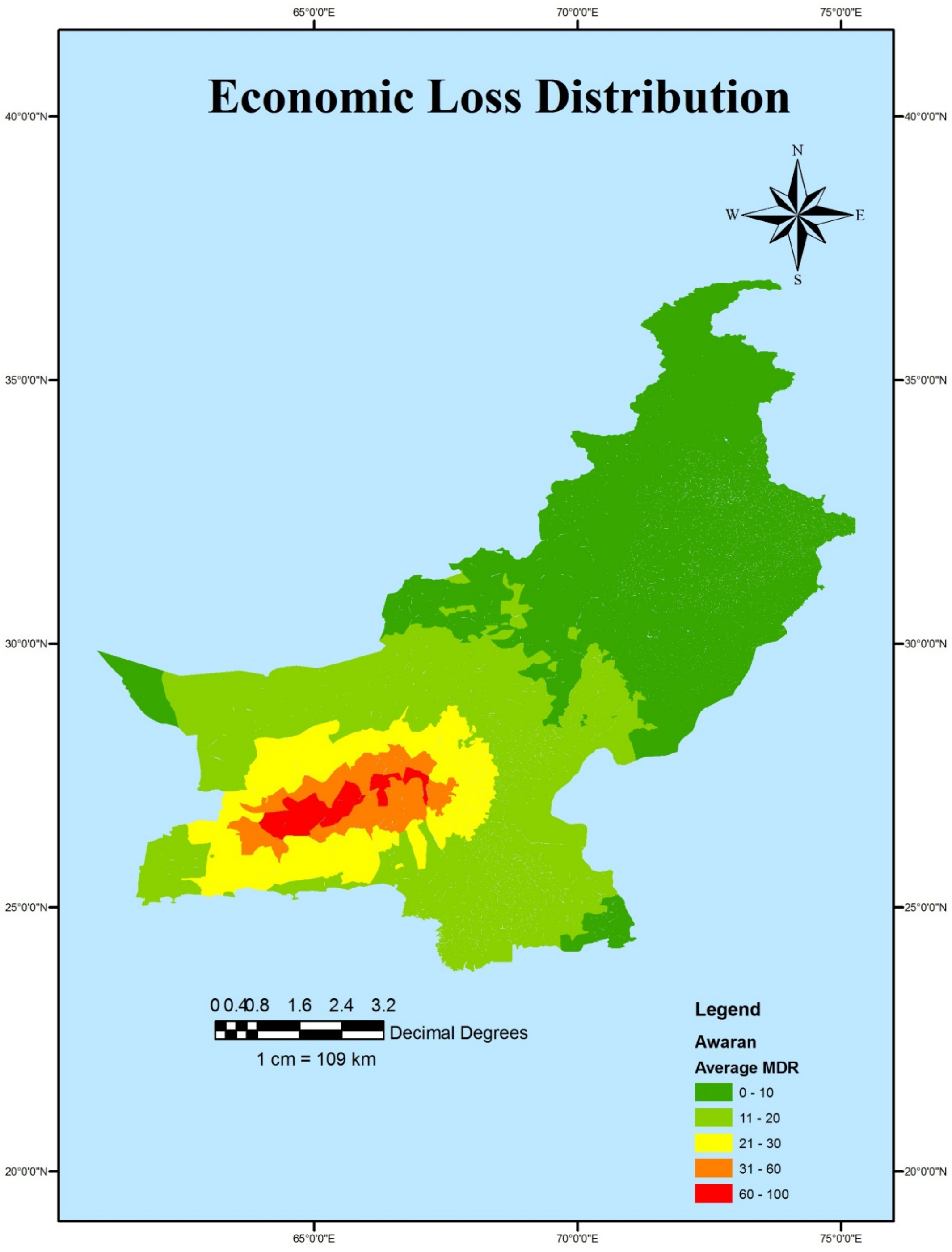


The observed difference in the values of earthquake shaking between the two maps is because of the fact that the USGS generates these maps based on a 1 km by 1 km grid, while the hazard generated in this study uses a union council as a single area element. A union council is not a regular square element as the one used by USGS, and its area is larger than a 1 km by 1 km square. This means that a union council contains many 1 km by 1 km squares. Therefore, the seismic hazard value obtained for the union council is an average of all the squares contained within the union council.

Moreover, the USGS uses different attenuation relationships than this study. Therefore, the difference in the values of seismic hazard between the two maps is justified. The seismic hazard map obtained through this study is reasonably close to that generated by USGS.

5.2 SEISMIC VULNERABILITY:

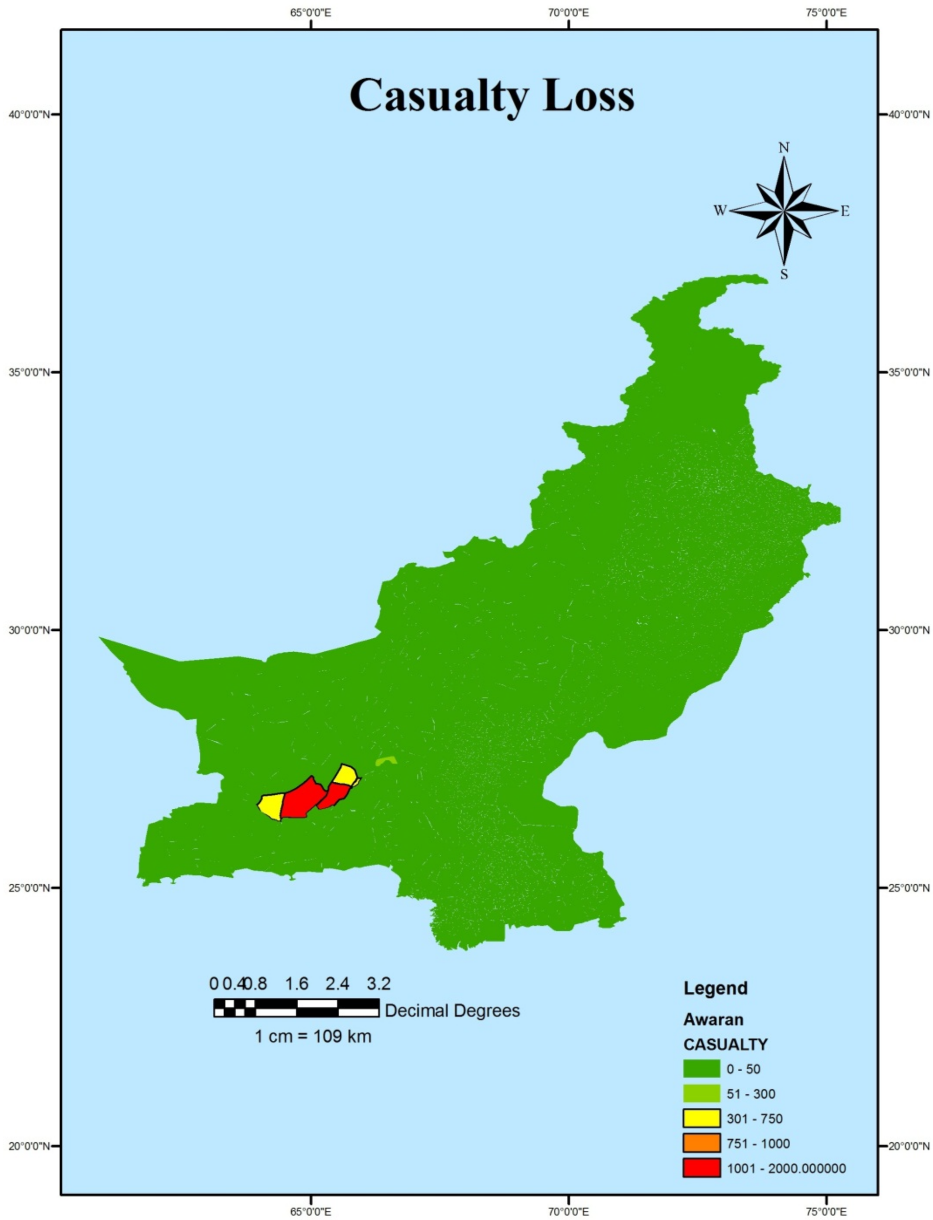
In the next step, the vulnerability of buildings to specified earthquake hazard is determined by using GESI vulnerability curves for each building type. The vulnerability curves give the result of damage in terms of MDR. The MDRs for each building class are obtained through this step. The unavailability of cost of construction or covered area restricts the seismic damage to be demonstrated in the form of per cent MDR. The MDRs for different building classes are averaged and a single MDR for each union council is obtained. The spatial distribution of MDR is shown below:


Economic Loss Distribution
65°0'0"E
70°0'0"E
75°0'0"E
40°0'0"N
35°0'0"N
30°0'0"N
25°0'0"N
20°0'0"N
N
W
E
S
0 0.4 0.8 1.6 2.4 3.2
Decimal Degrees
1 cm = 109 km
Legend
Awaran
Average MDR
0 - 10
11 - 20
21 - 30
31 - 60
60 - 100

After the Awaran earthquake, no survey was conducted to determine the level of economic loss at union council level. Therefore, it is not possible to compare the obtained economic loss to actual observed values. However, the values of MDR can be converted at any time in the future if cost of construction is available.

5.3 HUMAN CASUALTIES:

Coburn and Spence model for Human casualties is used for Awaran earthquake. The results obtained from the model are shown below:



Earthquake 2:

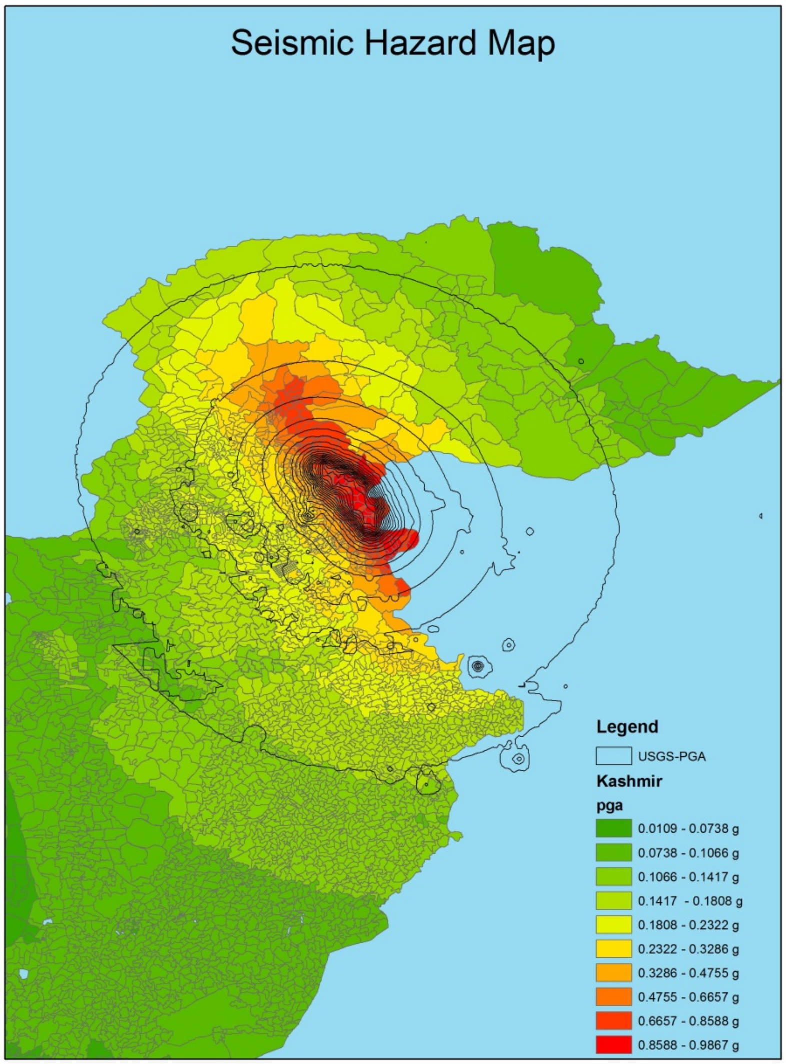
Location: 34.493°N, 73.629°E

Depth= 26.0 km

Magnitude: 7.6

Time: 08:50 AM UTC

Date: 08th October, 2005.



The map shows hazard map generated by the software is overlaid by the USGS hazard map. The results are consistent. The population and building inventory data for Kashmir at union council level is not available. Therefore, economic and human loss data cannot be calculated for Kashmir. However, hazard map generated by the software gives satisfactory results.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 INTRODUCTION:

An Earthquake Loss Assessment model works in two ways:

- It can provide good estimations of earthquake losses after the earthquake. This is very beneficial for response, rescue and recovery operations and can save precious human lives. In addition, it also gives the estimate of financial losses that have been incurred due to an earthquake. This is useful in estimating the amount of financial resources required for the rehabilitation of towns and cities damaged by the earthquake. In a developing country like Pakistan, it becomes very important to have an idea of the distribution of losses due to limited amount of resources available for the rescue and rehabilitation operation. The efficient distribution of human, financial and material resources can save many lives.
- It can also be used to determine the potential risk of a future earthquake by simulating scenario earthquake events. This can help in:
    1) Earthquake risk mitigation measures.
    2) Spreading of future risk.
    3) Building development control.
    4) Improved communication infrastructure.
    5) Response capacity building.
    6) Awareness and preparedness among common people.

  In this view, Earthquake Loss Assessment Framework can work as Earthquake Risk Assessment Framework. The results of these scenario events can be used to develop

This study was carried out to develop a framework for determining earthquake losses in the study region. The framework was developed using PSHA methodology currently in practice throughout the world. The results of this framework were found to be reasonable when compared with the actual values from past earthquakes in the region. This chapter discusses the conclusions of the study that was carried out and provides recommendations for future work in this field.

6.2 CONCLUSIONS:

Earthquake Loss Assessment framework for Pakistan was developed and validated by USGS data. The results obtained are in agreement with the USGS data. An application for ArcGIS was developed to determine Earthquake Losses in the region.

- Hazard maps were developed for the earthquakes of Kashmir 2005 and Awaran 2013. These maps were compared with the hazard maps obtained from USGS. The results obtained from the software are consistent with the USGS maps keeping in view the scope and level of Loss estimation.
- GESI vulnerability curves were utilized to determine building damage in terms of MDR. As covered area is not available at UC level, the maps for MDR are generated.
- GESI collapse curves are utilized for determining percentage of collapsed buildings to estimate human losses. Coburn and Spence model was utilized for estimating casualties.

6.3 RECOMMENDATIONS FOR FUTURE WORK:

After the results obtained by the current study, following recommendations are made for future work in the field of Earthquake Loss Estimation in Pakistan:

- Loss assessment of the entire Pakistan should be done by incorporating the areas left in the current study. Demographic, geologic and building inventory data of those areas should be obtained and used to develop a model for the entire country.
- In the current study, the data from population census of 1998 was utilized by projecting it to the current year. Although, it is a reasonable procedure but this is not a substitute for accurate census results. The last census for Pakistan was conducted in the year 2011, but the results have not been published yet and therefore are not available for public use. As soon as the data from the latest census is made available, it should be used in the Earthquake Loss Assessment model for Pakistan.
- Building inventory data for the current study was obtained from the Census of 1998. The scope of this study dictated that more advanced methods like satellite imagery and field surveys could not be conducted for this study. In future, projects should be undertaken to develop a detailed and precise building inventory of Pakistan by employing more advanced and state-of-the-art procedures.

- As mentioned previously, the attenuation relationship utilized in this study was not specifically derived for Pakistan. Specific attenuation relationships for Pakistan should be developed.
- In the current study, only ground shaking hazard of earthquakes was considered. In future, studies should be done to develop Earthquake Loss Assessment Models that incorporate other hazards like fires, landslides, mudslides and tsunamis etc.
- Earthquake Losses other than due to ground shaking such as interruption to business, communications breakdown should be studied in detail.

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